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POWER QUALITY AND EMC ISSUES WITH FUTURE ELECTRICITY NETWORKS

JOINT WORKING GROUP

C4.24/CIRED

MARCH 2018

POWER QUALITY AND EMC ISSUES WITH FUTURE ELECTRICITY NETWORKS

JWG C4.24/CIRED

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J. DESMET	BE		

ISBN : 978-2-85873-421-4

EXECUTIVE SUMMARY

The electric power system is undergoing changes that significantly impact power system operation and design. These changes include:

- Proliferation of distributed generation, including renewables (wind and solar power, etc.) and storage;
- Proliferation of power electronics interfaced loads, which are connected to the grid;
- Integration of microgrids operating in connected or islanded modes;
- Integration of advanced distribution automation applications also known as smart distribution applications.

The impact of these changes on power quality has been discussed quite intensively, and some of discussions were summarized in books and papers. However, a systematic overview study and assessment of the severity of the overall impact was missing.

It was therefore decided by CIGRÉ Study Committee C4 and CIRED to establish the Joint Working Group (JWG) C4.24: "Power Quality (PQ) and Electromagnetic Compatibility (EMC) Issues associated with future electricity networks" in late 2013. Its scope was to create an inventory of knowledge on this subject, with the aim of such an overview.

The JWG activity also included a collaboration with the IEEE Working Group (WG) "PQ Issues with Grid Modernization", whose scope and objectives were similar.

The JWG started the work in September 2013 with the aim to address the PQ and EMC issues in future grids, in particular, the following:

- Impact of new types of devices connected to the distribution network as production (DG) or consumption (load), especially devices with an active power electronics interface and their emissions;
- Overview of "Smart Grid" and PQ;
- Changes in probability of interference (a device does not operate as intended, gets damaged or experiences a reduction in life time) due to increased levels of emission, decreased immunity or by increased transfer to susceptible equipment;
- Issues surrounding PQ in microgrids;
- Trends that are expected in the Volt-VAR control of distribution systems and possible impact on power quality;
- Impact of automatic and manual feeder reconfiguration on PQ parameters;
- Issues with PQ associated with demand side management in a network with bi-directional power flows and exchanges of energy;
- New measurements techniques associated with hardware and software technological developments and new type of PQ disturbances;
- New mitigation methods to ensure EMC in future electricity networks;
- Economic issues for ensuring a good PQ in future grids.

The work done by the JWG was concluded at the end of 2017 in a TB with ten sections and nine appendices. Each section comes with its own conclusions, which are organized in a format: "Findings", "Recommendations" and "Open Issues".

Proliferation of distributed generation and modern loads

The proliferation of distributed generation and modern loads, an important change in the power system, has determined the JWG to start its TB with a "State of the art" of power electronics (PE) interfaced devices, which summarizes the different topologies used within various distributed generation devices and modern loads, with focus on converters, electrical vehicles and lamp technologies. These PE, whose benefits include increased efficiency, lower cost, and reduced packaging size, are important sources of waveform distortions (high levels of harmonic content of higher frequencies, flicker, etc.), but they can also be the key to mitigate distortion, when the proper technology is employed.

Overview of "Smart Grid" and PQ

The overview performed by the JWG concluded that what matters most to customers connected to the future electricity network (smart grid) are three performance indicators:

- The price for using the network (the network tariff),

- The reliability,
- The power quality.

Safety and environmental issues also matter and may be added to the above list.

The transition to the smart grid can be briefly associated to:

- Solar panels connected to the low-voltage networks will result in overvoltages;
- The switching frequency of the converters in wind turbines causes high-frequency signals flowing into the grid;
- Harmonics are generated by EV chargers;
- The repeated starting of heat pumps can result in visible light flicker.

The JWG also payed attention to the concept of "hosting capacity approach", namely to determine how much of new production can be connected to the grid (at a certain location, to a certain feeder or to the grid as a whole) based on the comparison of a set of performance indices with each index limit. Once any of those indices exceeds its limit, the hosting capacity is reached.

Connecting more generation than the hosting capacity will result in the grid no longer being able to provide acceptable reliability and power quality to its customers.

Changes in probability of interference

The on-going changes in the power systems have impacted the emissions, the immunity and the transfer of disturbances. All these impacts affect the probability of electromagnetic interference. In accordance with IEC terminology, the JWG distinguished between "disturbances" (any deviation from the ideal voltage or current) and "interference" (damage or malfunction of end-user equipment), but what matters in the end is the compatibility among different devices and between devices and the grid.

The expected changes in the power system can be categorized into three different types, each having the potential to impact the probability of interference:

- Changes in production:
  - Shift from large conventional production units to small units connected to low-voltage (LV) and medium-voltage MV) networks;
  - Shift to non-dispatchable renewable energy (solar and wind power);
  - Shift from synchronous machines to power-electronic interfaces.
- Changes in consumption:
  - Replacement of existing types of equipment with more energy-efficient alternatives; introduction of new types of equipment;
  - Proliferation of small devices;
  - Almost complete shift to active power-electronic interfaces.
- Changes in the grid:
  - Underground cables;
  - Power-electronics equipment;
  - Increased use of power-line communication;
  - Changes in protection and control.

The JWG also made a distinction between changes in:

- Emission of power quality disturbances;
- Immunity against power quality disturbances;
- Transfer of disturbances (e.g. as quantified by the transfer impedance) between an emitting source and a susceptible device.

The JWG didn't intend to present a quantitative measure of the expected change in probability of interference but to make, based on an inventory of published information together with expert knowledge within the joint working group, a qualitative assessment of which aspects need to be addressed to prevent a future large increase in the probability of interference.

The main aim of the JWG was to identify new potential cases of interference due to increased levels of emission, decreased immunity or by increased transfer to susceptible equipment.

An overview of findings, recommendations and open issues is given.

Integration of microgrids

Microgrids offer distinct advantages to customers and utilities: improved energy efficiency, minimization of overall energy consumption, reduced environmental impact and improved reliability of supply, for the former, as well as loss reduction, congestion relief, voltage control, or security of supply and more cost-efficient electricity infrastructure replacement, for the latter.

Microgrids have therefore been proposed as novel distribution network architecture within the so called smart grid concept, capable to exploit the full benefits from the integration of a large number of small to medium DERs (less than around 1 MW) into LV and MV electricity distribution systems.

Microgrids can be classified according to the type of power distribution in:

- Line-Frequency AC (LFAC),
- DC,
- High- Frequency AC (HFAC),
- Hybrid DC and AC coupled.

LFAC are more common but in order to ensure that loads are supplied with a high degree of supply continuity and PQ, and to facilitate an easier interconnection of the DER, a low voltage DC distribution system (DC microgrids) has been considered for commercial facilities, buildings and for critical customers requiring high PQ.

The JWG has performed an overview of the PQ phenomena associated to the microgrids and discusses the PQ issues in LFAC microgrids and DC microgrids.

Integration of advanced distribution automation applications

Another important change in the power system is the integration of advanced distribution automation (ADA) applications also known as smart distribution applications.

The JWG evaluates the impact of three ADA applications on PQ, namely:

- Volt/VAR control and volt/VAR optimization,
- Feeder reconfiguration,
- Demand side management.

When discussing the Volt/VAR control and volt/VAR optimization, the JWG made a distinction between "discrete VVC" (based on switching, like transformer tap-changers or capacitor banks) and "continuous VVC" (based on a controllable source of reactive power like the voltage-source converter in a solar panel). Both methods will maintain the voltage within the regulatory limits, but their additional impact on PQ is rather different.

In the chapter dedicated to feeder reconfiguration, the JWG presents a range of scenarios, including feeder reconfigurations as a result of network faults as well as normal network operation, under which PQ parameters will be affected. While automatic feeder reconfiguration has a larger impact on PQ parameters like short interruptions, manual reconfiguration can also affect PQ parameters like long interruptions.

The JWG's approach on demand side management (DSM) distinguished two general types of DSM:

- Energy Efficiency and Energy Conservation DSM programs, when less efficient types of equipment are being systematically replaced;
- Direct DSM control of (specific types of) electrical equipment.

The impact of DSM on PQ is evaluated according to three aspects:

- Network related effects (PQ emission issues),
- End-user related effects (PQ immunity issues),
- Direct vs. Indirect DSM (EMI issues).

New measurements techniques

Continuous evolution of hardware and software technologies, which are quantified by better performing measurement chains, including sensors and Intelligent Electronic Devices (IEDs) makes possible in smart grids to perform permanent voltage and current measurement or monitoring at a PQ grade.

The JWG discusses measurement locations, new hardware and software available for PQ monitoring and assessment as well as proposals for new PQ indices or new methods to calculate PQ indices.

In future systems a balance should be found between power quality monitoring with traditional PQ analyzers and with non-traditional devices such as relays and controllers, which are used for daily network operation, and Advanced Metering Infrastructure (AMI) including meters with power quality measurement capabilities. This will allow to keep PQ related investments and costs at acceptable levels.

New mitigation methods

Mitigation methods in future smart grids will still be required to ensure EMC. Beside well-known classical methods, also novel methods are needed in order to address the developments indicated in the previous chapters.

The mitigation can be applied either to customer side (installation) or to network side and the JWG has distinguished and classified them as follows:

- Methods requiring additional mitigation equipment:
- Methods not requiring additional mitigation equipment:

These methods are detailed by the JWG and associated to the PQ disturbances, which are mitigated.

Economic Issues for Power Quality

In the electricity market environment, it is also important to develop a market mechanism to limit voltage variations and harmonic emissions, and to setup proper market mechanisms. The market mechanism should be well-designed to fairly represent the cost of maintaining power quality, as well as the values of pollution absorptions at different locations.

A proper market mechanism for PQ could provide incentives or penalties for the market players to reduce the harmonic voltage distortion levels, the current unbalance, etc. Such market mechanism can also form the basis for future regulation on voltage quality and act as a base for future network markets.

Further work

Power quality will continue to play an important role in the power systems. The transition to the smart grid will sooner result in a higher demand for power quality knowledge. The future for power quality research may however be different from what we are used to from the past experience.

Finally, the JWG identifies in this TB potential areas for further studies, fundamental research and development in the field of future network and PQ:

- The use of power-electronic converters, which is a part of end-user equipment, to introduce damping at harmonic frequencies should be seriously investigated.
- Further studies, including fundamental research, are needed for several types of disturbances that were almost not present in the grid before the large-scale introduction of active power electronics. This concerns especially: interharmonics; DC components and low-frequency subharmonics ("quasi-DC"); components above one or two kHz ("supraharmonics").
- The shift of resonances to lower frequencies requires a new look at harmonic propagation studies and voltage quality limits.
- Research and studies are needed after the immunity of modern equipment with active power electronics interfaces against all kinds of voltage disturbances. Such research and studies should result in recommendation for equipment manufacturers to avoid lack of immunity.
- Further studies on LFAC and DC microgrids are required. They should answer to questions such as which of them are easier to implement, if they can efficiently co-exist facilitating symbiosis like DC smart home within a LFAC smart city.
- Studies are needed towards quantifying the adverse impact on power quality of different microgrid control algorithms.
- Guidelines are needed on what are acceptable sizes and numbers of voltage steps in distribution networks. Experience is needed on standardized methods to measure and analyse rapid voltage changes.
- Studies are needed, both simulations and measurements after damping provided by the low and medium-voltage networks and by equipment connected to it. Information on damping is needed for estimating the amplification of harmonic levels due to resonances and also to estimate the overvoltages due to capacitor energizing.
- The impact of repeated switching transients on end-user equipment should be investigated.
- Etc.

Members from the JWG have published a number of papers presenting the on-going work:

1. "CIGRE/CIRED Working Group C4.24 – Power quality and EMC issues associated with future electricity networks – status report," Proceedings of conference CIGRÉ Symposium 2015, Lund, Sweden, May 27-28.
2. "CIGRE/CIRED Working Group C4.24 – Power quality and EMC issues associated with future electricity networks – status report," Proceedings of conference CIRED 2015, Lyon, France, June 15-18, 2015.
3. "Volt-var control and power quality (CIGRE/CIRED/IEEE C4.24)," Proceedings of conference CIRED 2015, Lyon, France, June 15-18, 2015.
4. "CIGRE/CIRED Working Group C4.24 – New measurements techniques in future grid," Proceedings of conference CIRED 2015, Lyon, France, June 15-18, 2015.
5. "Ongoing work in CIGRE working groups on supraharmonics frompower electronic converters," Proceedings of conference CIRED 2015, Lyon, France, June 15-18, 2015.
6. "Supraharmonics from Power Electronics Converters - Contribution to the ongoing work in CIGRE/CIRED/IEEE working group C4.24," Compatibility and Power Electronics (CPE) 2015, Costa da Caparica, Portugal, 24-26 June 2015
7. "CIGRE/CIRED JWG C4.24 Power Quality and EMC Issues associated with future electricity networks – status report," CIGRE 2016, Paris, France, August 21-26, 2016.
8. "Power Quality in the Future Grid – Results from CIGRE/CIRED JWG C4.24," Proceedings of conference IEEE PES ICHQP conference, Belo Horizonte, Brazil, October 16-19, 2016.
9. "Power quality Concerns in Implementing Smart Distribution-Grid Applications," IEEE Transactions on Smart Grid, vol. 8, issue 1, p. 391-399, Jan 2017.
10. S. Rönnberg, M. Bollen, R. Langella, F. Zavoda, J.P. Hassler, P. Ciufo, V. Cuk, J. Meyer, "The expected impact of four major changes in the grid on the power quality – a review," Cigre Science & Engineering • N°8 June 2017.
11. "Consequences of Smart Grids for Power Quality - Overview of the Results from CIGRE Joint Working Group C4.24 CIFRE/CIRED," Proceedings of conference ISGT EUROPE 2017, Torino, Italy, September 26-29 2017.

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INDEX OF TERMS AND DEFINITIONS

All terms and definitions provided in this section are for the purpose of this CIGRE/CIRED JWG Report.

Abbreviations, Acronyms, and Symbols

ADA	Advanced Distribution Automation Advanced Data Acquisition
ADAQ	Advanced Data Acquisition
AIS	Air Insulated Switchgear
A/D	Analogue/Digital
AMI	Advanced Metering Infrastructure
APF	Active Power Filter
ASD	Adjustable Speed Drive
BLSP	Bulk Load Supply Point
BPL	Broad Power Line
CAIDI	Customer Average Interruption Duration Index
CCP	Customer Connection Point *A CCP is considered to be a PCC if more than one system user is connected, either now or in the future.*
CFL	Compact Fluorescent Lamp
CFSM	Converter-Fed Synchronous Machine
CHB	Cascaded H-Bridge
CHP	Combined Heat and Power
CIGRE	(Conseil International des Grands Réseaux Électriques
CIRED	International Conference on Electricity Distribution (Congrès International des Réseaux Électriques de Distribution)
CIS	Customer Information System
CRT	Cathode Ray Tube
CSC	Current Source Converter
CSI	Current Source Inverter
CT	Current Transformer
CCV	Cycloconverters
CVT	Capacitive Voltage Transformer
DCC	Direct Continuous Components
DER	Distributed Energy Resource
D-FACTS	Distribution FACTS
DFIG	Doubly-Fed Induction Generator
DG	Distributed Generation
DMS	Distribution Management System (*part of the SCADA/DMS system used in the Distribution System Operator Control Centre that typically includes system analysis, simulation and optimization functionality*)
DR	Demand Response

DSM	Demand Side Management
D-STACTCOM	Distribution STATCOM
DSO/DNO	Distribution System/Network Operator
DVR	Dynamic Voltage Restorer
EHV	Extra High Voltage (from 300 kV up to 1200 kV)
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EMS	Energy Management System (*part of the SCADA/EMS system used in the Transmission System Operator Control Centre that typically includes AGC, Network Applications, Forecasting and Scheduling functionality*)
ESS	Energy Storage System
EU	European Union
EV	Electric Vehicle
FACTS	Flexible AC transmission systems
FC	Flying Capacitor or Capacitor Clamped
FCI	Fault Current Indicator
FDIR	Fault Detection, Isolation and Restoration
FFT	Fast Fourier Transform *A numerically more efficient version of a mathematical technique referred to as "Digital Fourier Transform" used for performing, analysing and interpreting harmonic measurements. In depth knowledge of these mathematical techniques is normally not necessary but interested readers are referred to text books on power quality and/or signal processing.*
FL	Fault Location
FLISR	Fault Location, Isolation and Service Restoration
FO	Fibre Optic
FPI	Fault Passage Indicator
FRT	Fault-Ride-Through
FV	Frequency Variations
GCM	Grid Connected Microgrid
GIS	Gas Insulated Switchgear
GIS	Geographic Information System
GIC	Geomagnetically Induced Currents
GPS	Global Positioning System
GTO	Gate Turn-Off Thyristor
HFACM	High Frequency Alternative Current Microgrids
HSE	Harmonic State Estimation
HTTP	Hypertext Transfer Protocol
HV	High Voltage (from 35 kV up to 230 kV)
HVAC	Heating Ventilation and Air Conditioning
ICT	Inductive Current Transformer

IEC	International Electrotechnical Commission
IED	Intelligent Electronic Device
IEEE	The Institute Of Electrical And Electronic Engineers Inc.
IETF	Internet Engineering Task Force
IGBT	Insulated-Gate Bipolar Transistor
IGCT	Integrated Gate-Commutated Thyristor
IM	Isolated Microgrid
IP	Internet Protocol
IPFC	Interline Power Flow Controller
IT	Instrument Transformer
ITHD	Current Total Harmonic Distortion
ITIC	Information Technology Industry Council
IVT	Inductive Voltage Transformer
WG	Joint Working Group
LAN	Local Area Network
LCD	Liquid Cristal Display
LED	Light Emitting Diode (Lamp)
LCI	Load Commutated Inverter
LFACM	Line-Frequency Alternative Current
LN	Logical Nodes
LI	Long Interruption
LV	Low Voltage (below 1.0 kV)
MAIFI	Momentary Average Interruption Frequency Index
MLR	Multiple Linear Regression
MMC	Modular Multilevel Converter
MV	Medium Voltage (from 1.0 kV up to 35.0 kV)
NPC	Neutral Point Clamped
OLTC	On Load Tap Changer
OMS	Outage Management System
Pst	Short-term flicker severity
Plt	Long-term flicker severity
PCA	Principal Component Analysis
PCC	Point of Common Coupling
PE	Power electronics
PET	Power electronics transformers or solid-state transformers
PFC	Power factor correction
PLC	Power Line Communication
PMSG	Permanent Magnet Synchronous Generator
PMU	Phasor Measurement Unit

POC	Point of Connection
PQ	Power Quality
PQR	Power Quality and Reliability
PQM	Power Quality Monitoring
PT	Potential Transformer
PS	Pumped-storage
PV	Photovoltaic
PWM	Pulse width modulation
RE	Renewable Energy
RMS	Root Mean Square
RTU	Remote Terminal Unit
RVV	Rapid Voltage Variations
SAIDI	System Average Interruption Duration Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition (*the system used to provide operational data such as voltage and power flows to the system operator control centre*)
SCIG	Squirrel-Cage Induction Generator
SCR	Silicon Controlled Rectifier
SFC	Static Frequency Converters
SFTP	SSH (Secure Shell) File Transfer Protocol
SG	Smart Grid
SI	Short Interruptions
SiC	Silicon Carbide
SMES	Superconducting Magnetic Energy Storage
SMTP	Simple Mail Transfer Protocol
SQL	Structured Query Language
SSR	Sub Synchronous Resonance
SST	Solid-State Transformers
STATCOM	Static synchronous compensator
SVC	Static VAR Compensator
SVV	Slow Voltage variations
TB	Technical Brochure
TCR	Thyristor Controlled Reactor
TCSC	Thyristor-Controlled Series Capacitor
THD	Total Harmonic Distortion
TMS	Transmission Management System
TSE	Transient State Estimation
TSO	Transmission System Operator
TV	Television

UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
UPS	Uninterruptable Power Supply
VAr	Volt-Ampere reactive
VD	Voltage Dips
VRES	Variable renewable energy source
VSC	Voltage source converter
VSD	Variable-speed drive
VSI	Voltage source inverter
VSSE	Voltage Sag (Dip) State Estimation
VT	Voltage Transformer
VTHD	Voltage Total Harmonic Distortion
VU	Voltage Unbalance
VVC	Volt and VAr Control
VVO	Volt-VAr Optimisation
VPP	Virtual Power Plant
VU	Voltage Unbalance

Common Terms

Disturbance	The term "disturbance" is used here to include a continuous situation of PQ "pollution", distortion and interference, as well as discrete and transient events.
System Operator	The term "system operator" here is widely used for the operator or owner of a transmission or distribution system, the organisation responsible for power quality, and the organisation which holds contract with connected customers (i.e. system users). The legal and commercial arrangements differ widely between countries. In many countries, the system operator is part of a wider utility which may also include generation (i.e. vertically integrated utilities).
System User	The term "system user" is widely used for a device or installation (or organisation) which is connected to the electric power system. This includes users of power (demand, load) and generators. A Distribution System may be considered to be a "System User" of a Transmission System (and, occasionally, the reverse).
Transducer	A voltage or current transformer which transforms the basic parameter (variable) to be monitored (for example HV voltage or current) into an appropriate signal input to the PQ monitor. The term does not include any data sampling or analogue/digital conversion. There is no assumption here of the technology used: inductive of capacitive or any combination. Not to be confused with the same term used for an electronic device intended to connect/interface instrument transformer with the local data acquisition devices (e.g., RTU's).
DSM	*A set of measures, actions and interventions, initiated with specific purpose by end-users and/or network operators, or a third party (e.g. energy suppliers), aimed at changing and/or rescheduling power demands of a group of loads, load sector(s), part of a system, or a whole system, in order to produce desired changes in the actual amounts and/or time-patterns of*

power demands supplied at the dedicated point(s) of delivery for end-use consumption of electricity.

1. INTRODUCTION

The increasing complexity of the electric power network and its management, growing demand and service quality expectations such as greater grid reliability, efficiency and security as well as environmental and energy sustainability concerns have triggered the next major step in the evolution of the electric power system towards a flexible power network or "Smart Grid". Achieving this result requires the implementation of new technologies in power systems, including renewable energy sources (RES) and storage, distributed generation (DG) and latest information and communication technologies.

Power quality is an important aspect of the power system, which cannot be neglected, and an adequate power quality guarantees the necessary compatibility between consumer equipment and the grid.

The main factors influencing power quality are: generation equipment, end-user equipment and the grid itself. Each of these are expected to see significant changes in future electricity networks, and thus it is expected that power quality and EMC issues will also likely change.

1.1 SMART GRID AND PQ

Maintaining and improving PQ levels in today's evolving networks remains a critical task, which is often, if not always, assumed to be one of the very basic aspects of the assessment of the overall system performance. A large potential for achieving higher PQ levels is coming from "smart grid" technologies and related operational concepts and principles, as these will result in increased levels of observability and data exchange, improved network flexibility and introduction of new tariffs aimed at empowering customers. "Smart grids" should also provide functionalities and services for maintaining high levels of security, sustainability and affordability of electricity supply. However, "smart grids" of the future will result in increasingly complex electricity networks, featuring significantly higher penetration levels of variable renewable-based DG, introducing new highly efficient, intelligent and flexible control, monitoring and communication systems and incorporating various demand-responsive and demand-manageable resources and technologies. The levels and nature of supply-demand interactions in future electricity networks will change significantly, shifting the actual system operating and loading conditions well outside the traditionally assumed ranges, limits and physical boundaries. If not managed correctly, this might actually result in a deterioration of PQ performance levels in "smart grids", where of particular concerns are increased dynamics of two-way power flows, higher harmonic emissions, dc offsets and unbalances, as well as more frequent occurrence of switching transients, voltage sags/swells and short interruptions. Equally important issues are increased sensitivity of end-users modern power electronics equipment and their interference with power line carrier signals and other grid communication systems, i.e. interference between the equipment and control signals on supply and demand sides. It is generally expected that "supply-side" solutions will not be sufficient for the "smart grid" transformation of existing electricity networks, i.e. that additional strong support and contributions are expected to come from "demand-side", where demand for electricity should be actively controlled and coordinated with adaptable and flexible power flows between the grid and evolved demand-manageable loads.

It should be noted here that the term power quality, as used by CIGRE, includes both voltage quality and continuity of supply.

1.2 PQ AND EMC ISSUES

Two primary categories of issues related to PQ and EMC have been identified:

- At the consumer equipment (load) level, which is connected to the distribution system,
- At the power system level, that is on both distribution and transmission systems.

The issues being addressed in detail in this brochure are:

- The emissions by new types of devices connected to the distribution network as production (DG) or consumption (load), especially devices with active power-ele tronics interface including equipment connected to low-voltage and installations connected to higher voltage levels. This required the evaluation of new measurement techniques, including a closer look at the frequency response of existing instrument transformers and sensors.
- The positive and negative impact of new smart distribution applications such as Volt &VAR control, feeder reconfiguration and demand side management on power quality in the distribution system.

- The impact of power quality issues at the distribution level on the transmission system.

1.3 OVERVIEW OF THE TECHNICAL BROCHURE

In addition to this introductory chapter, this brochure contains other ten chapters and a number of appendices, where some case studies involving PQ in future electricity networks are given.

Each chapter comes with its own conclusions, which are structured as "Findings", "Recommendations" and "Open issues".

2 summarizes different topologies of Power Electronics (PE) interfaces used within various modern devices for the efficient conversion, control, and conditioning of electric energy. A substantial part of all devices connected to the grid have a PE interface, which is an application of semiconductor-based devices. The focus in this chapter is on inverters, electric vehicles (EV) and lamp technologies.

3 provides some observations on the relations between "smart grids" and "power quality" and how future research on power quality, an important performance indicator, plays a role in the transition to a future smart grid

4 provides information on the on-going changes in the power systems, which have impacts on emission and immunity as well as the transfer of disturbances, all this impacting the probability of electromagnetic interference. A distinction is made between changes in emission of disturbances; changes in immunity against disturbances; and changes in transfer of disturbances.

5 details the microgrids classification in AC and DC microgrids, according to the type of power distribution. It also discusses the challenges brought in by the concept of PQ management in a microgrid network.

6 describes the impact on PQ of an advanced distribution automation application such as VVC that has evolved over time to be more than simply coordinated switching of capacitor banks and tap changers.

7 describes the impact on PQ parameters of the feeder reconfiguration, another advanced distribution automation application, under two scenarios: feeder reconfigurations as a consequence of network faults as well as normal network operation.

8 is dedicated to demand side management (DSM), which can be classified in: energy efficiency and energy conservation DSM programs (less-efficient types of equipment are being replaced with efficient-less power consuming equipment), and direct DSM control of electrical equipment (peak shaving, load shifting programs to decrease the maximum power demand or losses).

9 emphasizes characteristic aspects of measurement techniques used in smart grids such as: location, hardware and software used or to be used for measuring different types of disturbing phenomena. It also presents proposals for new power quality indices.

10 presents expected trends in mitigation. After a short review of well-established mitigation methods, which will be still useful in the future, new mitigation methods that might become important for future grids are classified according to features like type of mitigation or voltage level of application. Some of them are described in more detail and discussed with respect to their overall impact on PQ.

11 introduces harmonic emission issues caused by power electronics based converters and DC technologies applied to the grid in recent years. Besides strengthening the power grid, another possible solution is using market mechanisms. Possibilities of limiting voltage variations and harmonic emissions with certain market methods are discussed. The purpose is to economically balance the costs for grid strengthening at the distribution planning stage.

2. NEW DEVELOPMENTS IN POWER ELECTRONICS

2.1 INTRODUCTION TO POWER ELECTRONICS

Power Electronics (PE) is the application of semiconductor-based devices for the efficient conversion, control, and conditioning of electric energy. Power electronics systems, as pertains to this document, function by using semiconductor devices as switches, operating in switching mode to control or modify a voltage or current. The efficiency of power electronic apparatus may approach as high as 98%–99%. The modern age of PE began with the introduction of thyristors (Silicon Controlled Rectifier, SCR and thyristor is synonymous) in 1956. Nowadays, in addition to the traditional silicon low-power low frequency devices, there are several types of power electronics devices available for high-power and high-frequency applications. However, silicon seems to have reached its limit in term of losses which have a large impact on cost and converter volume. In recent years, Silicon Carbide (SiC) and Galium Nitride (GaN) devices have started to replace silicon devices. The main advantage of SiC and GaN devices is the possibility of increasing the switching frequency and at the same time reducing the losses. The filtering requirement is reduced and the reduction of losses improves the efficiency of the converter as well as reducing the required cooling capability, i.e. volume and cost.

In general, the term "power electronics building block" is a known concept for designing modular PE systems that incorporates integration of power devices, gate drives, and other components to functional blocks. Typical applications of PE include: conversion of AC to DC, conversion of DC to AC, conversion of an unregulated DC voltage to a regulated DC voltage, and conversion of an AC power source from one amplitude and frequency to another amplitude and frequency, and sometimes with bidirectional capabilities. Benefits of power electronics devices include increased efficiency, lower cost, and reduced packaging size. The versatility and reliability of electronic devices combined with advances in circuit topologies and controls has resulted in technologies that replaced what has been traditionally done by electromagnetic and electromechanical systems.

2.1.1 PE converters topologies

Power electronics circuits convert one magnitude or frequency of a voltage or current waveform to another and are hence called "converters". The converter, handles the power transfer from the input to output, or vice versa, and is constituted of power semiconductor devices acting as switches, plus passive devices (inductor and capacitor). The controller is responsible for operating the switches according to specific algorithms by monitoring physical quantities (usually voltages and currents) measured at the system input and/or output.

There are different classifications of converters. Converters can be grid commutated or self-commutated based on the type of switch. During the last decades there was a shift from grid-commutated to self-commutated converters. The former uses diodes and thyristors (SCR), while the latter uses transistors or any kind of self-commutated thyristors, such as Gate turn-off thyristor (GTO), Insulated-gate bipolar transistor (IGBT) or the integrated gate-commutated thyristor (IGCT). Some other materials are also used for different applications but the main challenge of designing PE is to reduce cost and volume.

Another type of classification can be based on the relationship between input and output:

- AC-DC Converter. This converter produces a DC output from an AC input. This type of converter is also known as "Rectifier" and is a current source converter (CSC) or a self-commutated voltage source converter (VSC). In addition, to the traditional grid-commutated thyristor rectifiers it is difficult to meet requirements in IEC and IEEE standards, and the size of the passive power-factor-correction (PFC) components is bulky. In low voltage applications it is usual to find a diode rectifiers stage with active PFC with a switching device on the DC side and many different control strategies. A rectifier is typically used as a front-end circuit in many end-user applications.
- DC-AC Converter. This type of converter, also described as "Inverter", is a circuit that converts a DC source into a sinusoidal AC voltage to supply AC loads. This converter can use an SCR rectifier operating in the inversion mode or a VSC. Examples of the former is usually found in synchronous motor variable-speed drive (VSD) or wind turbine generator, frequently termed as naturally commutated current source inverter (CSI) or load commutated inverter (LCI). Examples of the later include the voltage source inverter (VSI) such as the interface of

photovoltaic (PV) solar farms to the grid. A VSC, in contrast to CSC, does not require AC voltages for its switching operations.

- DC-DC Converter. It is useful when a load requires a specified (often regulated) DC voltage or current but the source is at a different or unregulated DC value. For example, 5 V may be obtained from a 12 V source via a DC-DC converter. Some well-known converter topologies are: boost, buck, book-bust, flyback, or SEPIC. These will not be directly connected to the ac grid, but can still have impact on the power quality as part of grid-connected equipment. They may be used for higher power applications in conjunction with energy storage.
- AC-AC Converter. This converter is used to change the frequency of an AC power source. Converters that have the same input and output fundamental voltage frequency are called "AC voltage controller" or "AC regulator". Applications include a common light-dimmer circuit and speed control of an induction motor. When both voltage magnitude and fundamental frequency are changed, the circuits are called "cycloconverters", which is a classical grid-commutated SCR topology. When fully self-commutated switches are used, this class of circuit is called "Matrix Converter". The most common way of achieving AC-AC conversion is "indirectly", by using AC-DC and DC-AC converters through an intermediate DC link. Broadly speaking, cycloconverters present the following drawbacks: complicated technique requiring three three-winding transformers, and a complex structure with a large number of power semiconductors. Since these devices always provide a sub-synchronous frequency output, they do not allow starting up to synchronous speed from the electronic device itself. Significant amount of reactive power is required by cycloconverter technology. With a matrix converter, the need for a DC bus is eliminated, the weight and size is reduced, the reliability is improved, and the complexity decreased. The matrix converter has several other advantages over indirect type power frequency converters by providing sinusoidal input current and output voltage waveforms, with minimal higher order harmonics and no sub-harmonics.

2.1.2 Control in PE converters

In general, the control of PE converters involves a wide range of functions, from the generation of the switching patterns for the power semiconductor devices to the provision of ancillary services under different applications. Depending on the implemented control methods, the power electronic converters may exhibit different dynamic behaviors, and subsequently bring in different power quality challenges. Basically, a control system of a PE converter can be divided into three major control layers:

- Generation of switching patterns, further separated into two main groups for voltage source converters:
  - Pulse width modulation (PWM) in either open-loop or closed-loop. This method uses a constant switching frequency, which results in sideband and/or switching frequency harmonics depending on the modulation strategies, e.g. continuous PWM or discontinuous PWM.
  - Hysteresis control of instantaneous current or power in closed-loop, which results in a variable switching frequency and thus a wideband harmonic distortion at the converter output.
- Input/output current/voltage control, which is generally used to perform reference tracking and disturbance rejection. However, in addition to these two basic control requirements, this second control layer can also be used to perform a number of ancillary services, such as active filtering of low-order harmonics within the control bandwidth, unbalance voltage/current compensation for grid-connected converters, and active damping of system resonances/oscillations, etc.
- Input/output power control, which can be further decomposed into active and reactive power in the case of grid-connected converters. Moreover, the grid synchronization loop for grid-connected converters and the torque control of adjustable speed drives can also be implemented in this control layer. The bandwidth of this control layer is generally limited to the dynamics of the first two control layers, and hence it can result in subharmonic (below the fundamental frequency) oscillations. However, there is also another power control alternative, direct power/torque control, which similar to the hysteresis control, allows a fast dynamic response but also produces wideband harmonics.

Besides these commonly used control structures, there are some other nonlinear control schemes, such as sliding mode control, feedback linearization, and model predictive control. Those nonlinear control approaches generally present superior dynamic performance than traditional linear feedback or feedforward control options, but many cause more complicate power quality problems.

Traditionally, harmonic distortion studies only deal with lower order harmonics (< 2 kHz). The conventional PWM technique is aimed at reducing emission below 2 kHz. The same holds for alternative techniques like hysteresis control. Unfortunately, this leads to emission at PWM switching frequency and its multiples, in the RF range (10 kHz – 30 MHz). This is an important cause of "supraharmonic" or higher order harmonic emissions from PE converters with active switching [1]. If the switching function is non-deterministic then its frequency spectrum will be continuous because of non-periodicity of the signal. As a result, the average spectral power density of the broadband emission can be drastically reduced. This technique is used to overcome interference caused by the supraharmonics in the conventional PWM-controlled PE converters. Additionally, the low-frequency emission is minimal.

In addition to the steady-state harmonic distortions generated by the different switching patterns of converters, the controller interactions among multiple parallel- or cascade-connected converters can be the source of additional power quality and stability challenges. This problem will become more and more serious in the future electricity networks, due to the widespread use of power electronics technology in renewable power generation sources, flexible ac and/or dc transmission and/or distribution systems, microgrids, and energy-efficient loads.

2.1.3 Power quality impacts of the different topologies

Traditional SCR grid-commutated topologies can cause undesirable high levels of harmonic content and low power factor when they are connected to the power grid. Particularly 6-pulse rectifiers distort the supply system voltage with current harmonics of the order n = 5, 7, 11, 13, 17, 19, 23, 25 etc. (h=n*p +/-1, where h is harmonic numbers, n = 1, 2, 3…, p=number of pulses of the converter). In low voltage applications, this issue can be corrected in the PFC stage using passive components, such as inductors and capacitors, in a typical power filter arrangement; in the AC side prior to the semiconductor bridge, in the DC side after the bridge, or even in both places. Additionally, self-commutated converters produce supraharmonics (from 2 kHz to 150 kHz) due to the high switching frequency.

In medium and high voltage applications, the most common rectifier circuit is the six-pulse rectifier, but its input current harmonics are also a power quality problem. There have been significant efforts to improve the situation. When two individual six pulse bridge rectifiers are combined in a way such that each is fed from a separate transformer winding and each of these windings are phase shifted by 30 electrical degrees from each other (zig-zag transformer), these results in a 12-pulse rectifier. 12-pulse rectifiers produce approximately half of the current harmonics of 6-pulse rectifiers, i.e. only the orders n = 11, 13, 23, 25 etc. (p=12 in the aforementioned equation). The 18-pulse and 24-pulse rectifiers are formed similarly by connecting three or four six-pulse rectifiers, respectively. When three individual six pulse bridge rectifiers are combined in a way such that each is fed from a separate transformer winding and each of these windings are phase shifted by 20 electrical degrees from each other, then the 5th, 7th, 11th and 13th harmonics are cancelled. Finally, with a 24-pulse series-type rectifier the transformer should be arranged such that there is a 15° phase displacement between the voltages of any two adjacent secondary windings, so the 5th, 7th, 11th, 13th, 17th, and 19th harmonics are cancelled. The drawbacks are the special transformer and complicated cabling which add to the cost of the installation.

SCR grid-commutated topologies also produce non-characteristic harmonics in addition to the theoretically cancelled harmonics. These non-characteristic harmonics are depending on ripple in the D.C. current, harmonics in the AC voltage, unbalance in the AC voltage, tolerances in the main circuit component or imperfection of the control system, etc. [2].

With voltage source inverters employing pulse-width modulation (PWM) with switching frequencies in the kHz range, the desired output voltage can be obtained while reducing or eliminating discrete low order harmonics. In the past, high voltage applications of PE converter used a series connection of power-semiconductors only. Therefore, all semiconductors within one set per phase had to switch simultaneously at the mentioned frequencies. This results in high and steep voltage steps at the AC output, generating undesirable high level of EMI and switching losses. Harmonics performance of PWM-VSI can be improved by the use of modular multilevel converter (MMC) type configurations [3], while achieving the desired reduction from high frequencies and voltage switching. MMC generate a higher number of discrete voltage levels at the AC output to achieve a waveform close to a sinusoidal waveshape. The addition of several low voltage cells per series provides high scalability, leading to reduced cost and volume of the entire solution. Moreover, it allows a more creative use of these additional switches in novel modulation strategies, which enable to enhance the quality of output voltages and input currents [4]. The combination of using MMC VSC configuration and passive harmonic filters allows to mitigate many issues related to the harmonics generated from such converters.

Since their first appearance in the mid-nineties, MMCs have been gaining considerable popularity across all industries, mostly in the medium and high power applications. The recent applications of MMCs include: induction machine and motor drives, active rectifiers, power quality filters, interface of renewable energy sources, flexible AC transmission systems (FACTS), and high voltage direct current (HVDC). By 2015, the most common and established topologies include: the neutral point clamped (NPC) or diode clamped, the flying capacitor (FC) or capacitor clamped, and the cascaded H-bridge (CHB) or full bridge (mainly FACTS or possibly for HVDC) and half bridge (HVDC). A brief comparison among their characteristics is presented in the table 2 of reference [5].

2.1.4 Reasons for using PE

With the advancement of technology, as the cost of power electronics decreased significantly, size became smaller, and the performance improved. Power electronics applications are proliferating in industrial (aerospace, military, utility, and transportation), commerciall and residential systems [6]. In the past few decades, PE has emerged as an ubiquitous technology, with application in almost any areas [7], [8]. Key attributes to the success of applications using high power solid-state devices are those with high blocking voltages and operating frequencies (upwards of 5 kHz). High-voltage rated devices are required to simplify system configuration, size and reliability implications, which a large quantity of components imposes [9]. High switching frequency components are necessary to modulate the voltage waveforms at frequencies where flux saturation density is significantly reduced and smaller transformers can be used. Existing semiconductor power devices used for medium voltage applications up to 6.5 kV are limited to a maximum operating frequency of several hundred hertz due to the high switching losses that occur when operating at increased frequency levels. SiC power modules rated up to 3.3kV/1500A are available. The cuent rating limit for the SiC devices available as engineering samples (2016) is a MOSFET rated to 20 kV/10 A with an operating frequency in excess of 20 kHz.

2.2 THE USE OF POWER ELECTRONICS IN ELECTRICAL GENERATION AND STORAGE

Distributed energy, also known as district or decentralized energy, is generated or stored by a variety of grid-connected systems referred to as distributed energy resources (DER) or distributed energy resource systems. Megawatt scale PE converters are essential components in new distributed generation (DG) plants, such as wind turbines, photovoltaic systems and tidal generators, where they convert variable voltage inputs into fixed voltage outputs for connection to the grid.

2.2.1 PE interface for PV

There are a wide range of converter topologies that are available for use between a PV source and the distribution network. The circuits will include mechanisms for maximum power point tracking DC-DC converter, as well as a DC-AC converter system. A typical, transformer-less single-phase grid connected PV system is shown in Figure 2.1.

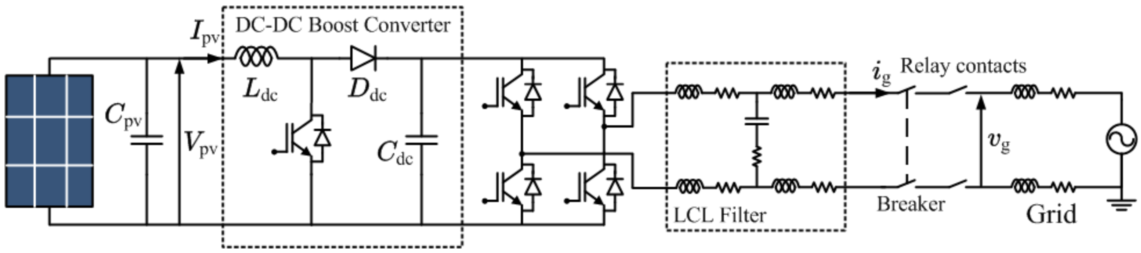


Figure 2.1 Typical Single-phase grid connected PV system

The DC-AC conversion stage as shown in Figure 2.1 is a single phase generic arrangement (including the DC-DC boost converter following by the inverter); many combinations of switches and other passive components exist. Conventional inverter technology uses a centralized topology, feed by several PV panels. Today central inverters are available for output ratings of up to several MWs. However, this development trend towards increasingly larger inverters is driving external costs higher. On the other hand, micro-inverter technology has been on the market since 2008. This technology uses a distributed inverter topology, with an inverter associated with each individual PV panel. Between them, string inverters offer the major advantages of central inverters, such as high DC system voltage range and three-phase output, while still maintaining the high efficiencies and flexibility.

From a PQ perspective, the control methodology used for the DC-DC converter and the inverter have a major influence on the performance of the PE. For example, the DC-DC converter, if not well designed, can influence the voltage fluctuation (flicker) at the point of common coupling (PCC) of the inverter system. The switching frequency of the inverter will influence the harmonic spectrum of the injected current. From a control perspective, strategies exist for active harmonic mitigation, particularly for the removal of low-order harmonics from the injected current waveforms.

In future networks, the PV PE will provide active power injection as well as reactive power support and active voltage regulation capabilities at their PCC. This introduces the possibility of control interactions between all active power electronic devices connected to the distribution network and control systems must be carefully designed with this in mind.

2.2.1.1 Harmonic interaction of PV inverters

PV inverters influence the distortion levels in the network in two ways. The first way is by acting as sources of harmonic currents because the current is not conducted over the entire power frequency cycle, even if the supply voltage would be perfectly sinusoidal. The second way is by altering the equivalent network impedance "seen" by other harmonic sources in the network.

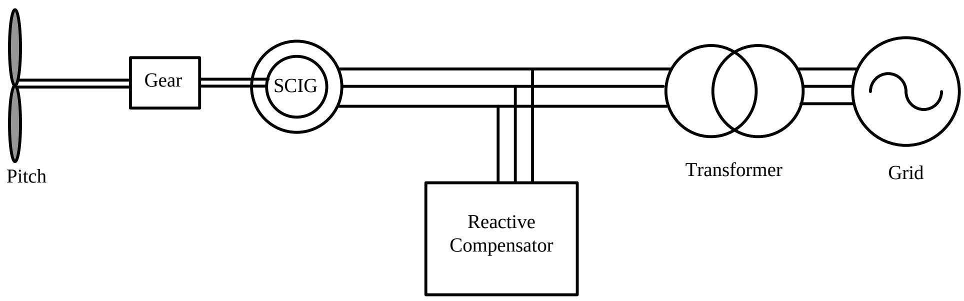
In the past, due to the lack of standards, PV inverters had output currents with a current THD typically in the range of 10 – 20 %. Presently, even the household units have an obligation to have a current THD less than 5 % at full load, e.g. in [1], which makes them one of the smaller sources of harmonic currents in the network. Examples of current waveforms and spectrums for domestic inverters can be found in APPENDIX A.

One of the methods for reducing the distortion of the current is using a passive filter (typically a LC or LCL filter) at the output of the inverter. The filter absorbs a significant part of the harmonic current generated by the bridge of the inverter. However, reactive elements of the filter – especially the capacitance, influence the frequency dependent impedance of the network. An increase of impedance magnitudes at frequencies at which current injection is present can lead to increased voltage distortion. In extreme cases, they can also cause a shift of resonant frequencies. More details on this topic can be found in APPENDIX B and references [11], [12], [13], [14], [15].

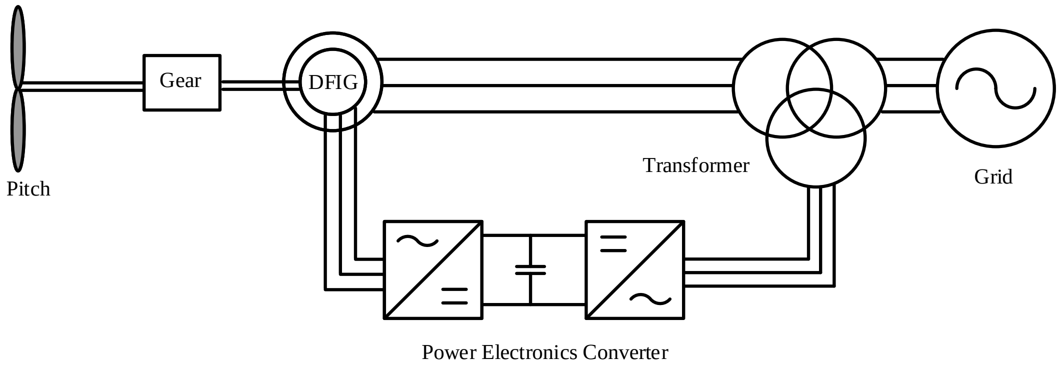
2.2.2 PE interface for Wind Power

Figure 2.2 shows three commonly used wind turbine systems to separately represent the two groups of DER units, including:

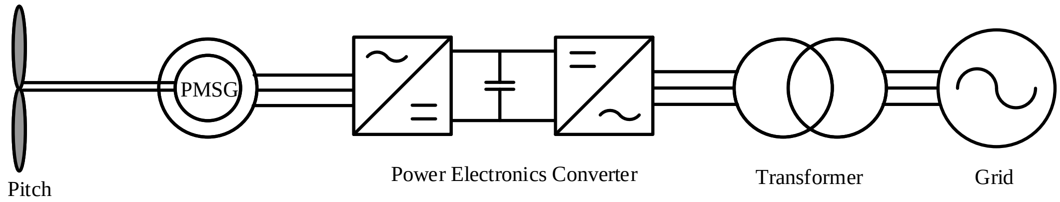
- Squirrel-Cage Induction Generator (SCIG) based fixed-speed wind turbines without using power electronics interfaces,
- Doubly-Fed Induction Generator (DFIG) based variable-speed wind turbines with partially rated power electronics interfaces,
- Permanent Magnet Synchronous Generator (PMSG) based variable-speed wind turbines with full-scale power electronics interfaces.



(a)



(b)



(c)

Figure 2.2 Three commonly used wind turbine systems. (a) Fixed-speed wind turbine system without PE interface; (b) Variable wind turbine system with partial-scale PE interface; (c) Variable wind turbine system with full-scale PE interface

Today, fixed speed wind turbines are only used for low power wind turbines, because the energy harvested with this kind of turbines is much smaller than with variable speed wind turbines. Fast wind velocity variation cannot be compensated and will result in fluctuating power into the grid. The power fed-in by this kind of turbines can only be controlled by blade angle control, which is relatively slow response.

The most common system used for medium size wind turbines (about 500 kW to 2000 kW) is the Doubly-Fed Induction Generator (DFIG) based variable-speed wind turbine [16]. This system can vary the turbine speed and thus achieve an optimal utilization of the available wind energy. The power electronic converter is typically sized for only about one third of the rated turbine power, which keeps the costs for power electronics at a low level. The converter can provide a certain amount of reactive power, which can help to increase power quality. One drawback of this system is the complicated generator with slip rings that require frequent maintenance. This system mainly reaches its power limit due to the decreasing nominal speed of the turbine rotor with higher turbine power. To maintain synchronization to the nominal frequency of the power grid, the required gear ratio of the transmission gearbox increases with power, leading to expensive gearboxes. Critical for this system is also the responses to grid disturbances, because the stator terminals of the generator are directly connected to the grid. Ride through requirements are difficult to meet in this system.

While used for some medium size turbines, the main application range of turbines with full scale converter and a permanent magnet synchronous generator (PMSG) are large turbines, especially for offshore applications. Main drawbacks of this system are high converter costs and high generator costs. On the other hand, due to fully decoupling of generator and grid, the rated frequency of the generator can be chosen to be much lower than grid frequency. Without increasing the pole number of the generator, a simple single-stage gear is sufficient, which is cheaper and much more robust than the multi-stage gear of 50/60 Hz generators. Besides being a cheaper, more rugged and less intensive maintenance mechanical system, the PMSG system with full scale converter also provides reactive power compensation capability and is able to meet the grid codes with respect to required ride-through performance.

Figure 2.3 depicts a wind turbine integrated with a battery energy storage system. The bidirectional converter controls the operation of the storage unit based on the dynamics of the prime energy source. The use of the intermediate storage energy system in the DC link allows programming virtual inertias and improving low voltage ride-through capabilities. Thus, the control system for grid-side inverter is decoupled from generator-side rectifier. Together with the droop functions for the grid-side inverter, virtual inertias can be integrated. Hence, the structures of wind turbines are not just determined by the types of prime energy sources, but also dependent on the load requirements, grid structures and associated operational scenarios. More details on this topic can be found in reference [17].

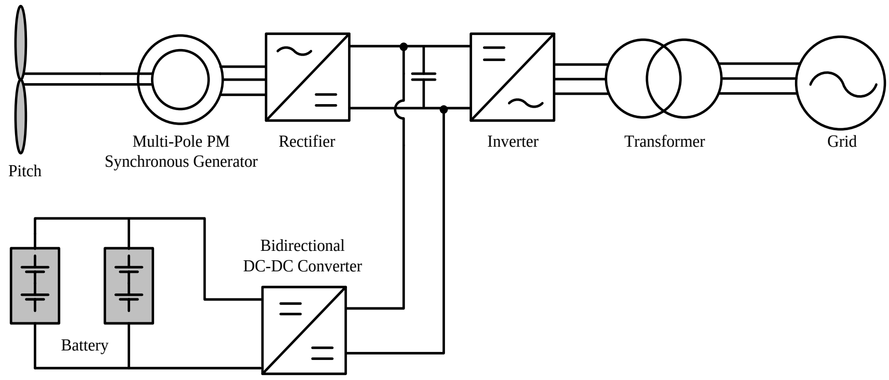


Figure 2.3 Typical structure of a wind turbine system integrated with a battery storage unit

2.3 PE FOR MICROTURBINES

As microturbines produce high frequency (typically 1500-2500Hz) AC power, the PE topology of microturbines has traditionally been AC-DC-AC. In this topology the AC power produced is rectified to DC power and then inverted to 50 Hz or 60 Hz, using a grid-commutated inverter, in the past, and most recently a self-commutated inverter

2.3.1 PE in large thermal and hydro power generation

For over 3 decades, PE in the MW range has been employed in traditional power generation, in particular, for the starting up of the power plants. This sub-chapter will concentrate on PE related to the starting-up of large gas turbines, a converter-based large thermal power plant, as well as a converter-based large hydro pump-storage power plant [18].

2.3.2 Start-up of a Gas Turbine

Modern day start-up of a gas turbine uses a static starting device based on static frequency converters (SFC) with atypical power rating range from 1MW to 20 MW. The SFC is a load commutated inverter, which drives a gas turbine generator like a synchronous motor, and accelerates up to the gas turbine's self-sustaining speed. The output of the SFC during start-up process varies with the speed of the synchronous machine. Depending on the size of the SFC and gas turbine, the start-up process continues until the unit reaches its self-sustaining speed. The SFC is an AC-AC "indirect" frequency converter. The rectifier and the inverter are a 12 or 18-pulse SCR converter, available for reducing harmonic influence both of the converter on the grid and on the ripple of the synchronous machine torque, respectively.

2.3.3 Converter interface of thermal generation to the power grid

In conventional power plants, turbines running at a different speed to the frequency of the power grid can be installed by using a mechanical gear-box with a fixed ratio to ensure that the turbine can be connected to a generator with the same frequency as the power grid. One of the drawbacks of the mechanical gear-box solution is a limitation on the MW size (> 80MW) of the turbine for this type of application due to safety concerns. As mentioned above, with the large scale integration of renewable variable energy resources into the energy supply systems, traditional power plants are called upon to provide flexible operational features to support system operability. In recent years, research and development have been invested in conventional thermal power plants to find an effective solution for the mechanical gear-box issue, to improve the operational flexibility as well as to allow new modes of operation. A new thermal power plant configuration that integrates a frequency converter between the generator and HV power grid is described. This PE converter can be seen as an "electronic gearbox" introduced between the generator and the grid allowing additional operation features for the plant as well as to support system operability of the grid. A typical power plant configuration is shown in Figure 2.4.

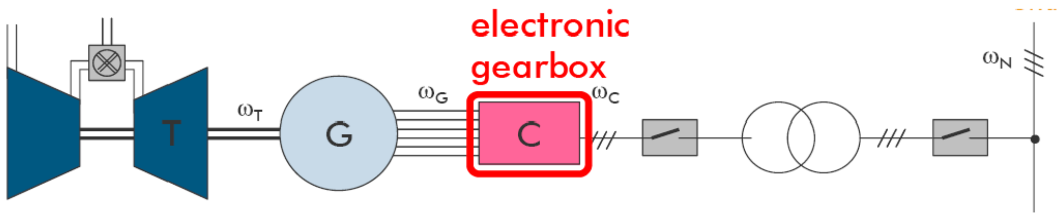


Figure 2.4 Typical power plant configuration

The generator has a polygonal stator winding with n phases, where n is a multiple of 3 and is greater than 3. To improve conversion efficiency, the generator is running at a higher frequency than the grid frequency. The generator functions are exactly the same as those of a conventional 3-phase synchronous unit. The first unit of the generator is in the range of 520 MVA. The converter has the following major functions:

- Act as a static frequency converter to start-up a gas turbine.
- Connect the poly-phase synchronous generator to a 3phase 50 or 60Hz electric power system.
- Act as a static excitation system for the poly-phase synchronous generator.

2.3.4 Converter application in advance pump storage hydro power plants

2.3.4.1 Doubly-fed induction machines

Traditional pumped-storage (PS) hydro power plant is a type of hydroelectric energy storage used by electric power systems for load balancing. This method of operation stores energy in the form of gravitational potential energy of water, pumped from a lower elevation reservoir to a higher elevation. Low-cost off-peak electric power is used to run the pumps. During periods of high electrical demand, the stored water is released through turbines to produce electric power. Although the losses of the pumping process make the plant a net consumer of energy overall, the system increases revenue by selling more electricity during periods of peak demand, when electricity prices are highest.

For most applications of pumped storage systems, only a limited controllable speed range is needed during normal operation. Taking this into consideration, variable-speed drive (VSD) operation can thus be achieved by using the concept of a doubly fed induction machine (DFIM) and a power electronic converter. Although cycloconverters have also been used, own to their drawbacks, self-commutation VSCs are preferred. This configuration has the advantage that the reactive power exchange with the grid can be controlled thus allowing voltage control in the grid and contributes to improving the stability as well as the operating conditions in the rest of the power system. As the required frequency for the rotor circuit in the doubly fed machine is given by the deviation from synchronous speed, its range of variation is usually limited. A typical power plant configuration is shown in Figure 2.5.

The latest technological evolution of VSD for pumped storage schemes is the multi-level VSC. Topologies based on back-to-back voltage source converters have become relevant for feeding the rotor windings of the DFIG when ratings of the VSCs are of the order of a few hundred MW.

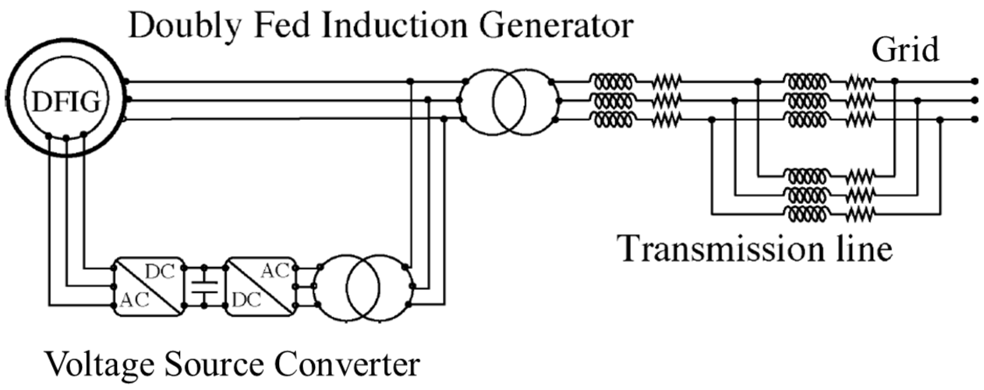


Figure 2.5 Typical VSD PS hydro plant configuration

2.4 CONVERTER-FED SYNCHRONOUS MACHINES

Recent technological progress on power electronic frequency converters has opened the door for a type of a variable speed pumped hydropower solution, referred to as the converter-fed synchronous machine (CFSM) [19], [20]. The concept of CFSM is to produce variable shaft speed by supplying the stator of a synchronous motor-generator with a variable excitation frequency. The latter is generated by a full-scale power electronic frequency converter, i.e., rated at essentially the full power of the motor-generator. The solution has become particularly attractive with the recent appearance of the MMC, which enables ultralow conversion losses and very high rated power (see Figure 2.6). Converter ratings of a few hundred MVA are possible.

Due to the reasonably high number of steps in the converter voltage, the voltage disturbances and as a consequence also the current disturbances created by the converter are considerably lower compared to designs based on two-level or three-level VSC.

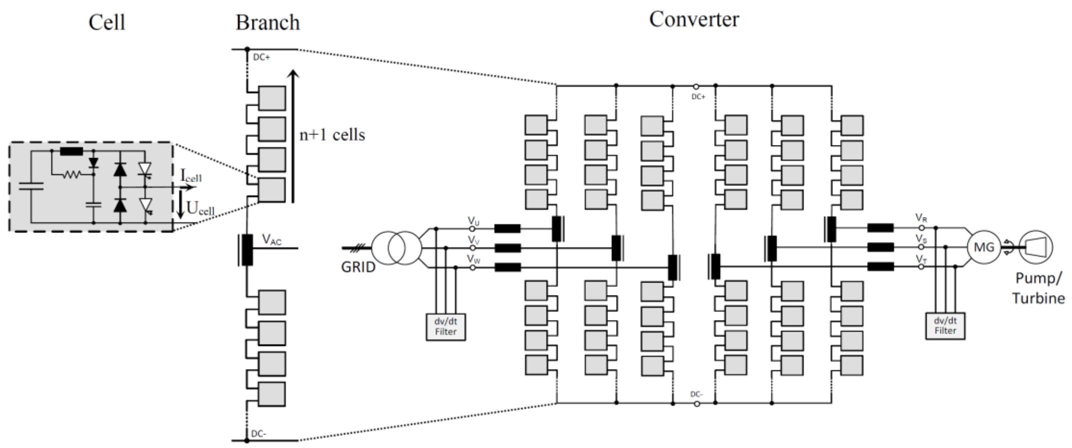


Figure 2.6 Possible topology of the Modular Multi-level VSC for CFSM

CFSM does not only increase the operational flexibility and efficiency of pumped hydropower plants; it can also provide a variety of ancillary services to the grid, making the solution to a valuable component of the overall system. However, it is also important to understand the distinct differences between conventional, directly grid-connected (fixed speed) generators and systems where the power plant is connected to the grid exclusively via a power electronic converter. The converter generally exhibits a very good capability in terms of its fault-ride-through (FRT) behaviour, which traditionally has been one of the main concerns of directly grid-connected synchronous machines and which is also challenging for DFIG with VSC connected to the rotor. The most critical aspect of the FRT for power converters is the initial drop of the voltage, in particular when the collapse is fast and deep. Furthermore, the converter can support grids with large penetration of renewable power sources with low inertia content due to shut down of large conventional generation units, typically thermal units. In particular, the converter fed machine can provide virtual inertia due to the very fast dynamic response to disturbances in the grid compared to response of conventional hydraulic controls.

Finally, an item that deserves close attention is the U-Q/Pmax requirement given in grid codes or requirements for generators (RFG) network code. In order to meet the customer requirements, a reasonable compromise between efficient converter design, supplementary methods to meet the code and clarification or negotiation of the ambition level may be needed.

2.5 PE IN TRANSMISSION SYSTEMS

The high voltage direct current (HVDC) has been employed for controlled transmission of bulk power over long distances, and interconnecting incompatible power grids, since 1954. Analogously, the pursuit of enhancing AC system controllability is achieved by the use of more recent flexible alternating current transmission system (FACTS).

2.5.1 HVDC transmission

HVDC systems convert power from AC to DC, transmit it as HVDC, and then reconvert it from DC to AC. However, in the case of conventional CSC HVDC, which uses SCRs, it also employs large filters. This drawback is avoided in latest HVDC technology, using modern devices, such as GTOs, IGBTs employing appropriate PWM techniques and latest generation of MMC type VSC .

HVDC applications are considered both technically and economically feasible options over traditional AC lines where large distances are involved. The DC circuits could be combinations of overhead lines, land and/or undersea cables providing asynchronous connections at both converter terminals. HVDCs have also been used as an option to transfer bulk power from offshore wind farms as distances and the amount of power to be exported to onshore substations is high. At transmission levels, HVDCs are considered at IEC as EHV/HV voltage levels (that is 275 kV, 400 kV, 1000 kV). In addition, HVDC applications are also used as an alternative option to expedite connection timescales using sea routes rather than land routes (e.g. West Coast HVDC between England and Scotland

2.5.1.1 Specific CSC-HVDC and VSC-HVDC configurations

The basic arrangements that are applicable for both CSC and VSC HVDCs are:

- Monopole with ground return or dedicated metallic return,
- Bipole with ground return, dedicated metallic return or without dedicated return path.

The choice of a monopole or bipole configuration depends on the level of power transfer, its availability and cost considerations of the HVDC scheme. Bipole are normal configurations for the HVDCs and driven by the level of power transfer and lower costs.

A CSC or VSC type HVDC installed on a transmission system asset typically consists of two converter bridges, DC-cables, converter transformers, reactive compensation devices and AC and DC filters for harmonic mitigation. However, the actual detailed equipment specification for a VSC type HVDC differs quite significantly from a CSC type HVDC due to the different valve devices (IGBTs currently being utilized for HVDCs) employed in the converter bridges resulting in different technical performance. The main technical differences of the VSC type HVDC is listed as below.

- Can operate to import and export reactive power – four quadrant operation;
- Allows black start for power restoration;
- Smaller power transfer capacity compared to CSC but gap is getting smaller;
- Due to reactive generation capability, no reactive compensation (that is normally as Mechanically Switched Capacitors, MSCs) are required unless to meet specific utility requirements;
- Power reversal by reversing current flow;
- Smaller filter requirements compared to CSC (extremely low level of harmonics for example in MMC converter) and as a consequence much smaller footprint for a VSC type HVDC.

2.5.1.2 Generic description of HVDC connections and equipment

The bipole configuration is the common configuration adopted for most HVDC planned installations with the main components for one converter station shown as in Figure 2.7 below at one of the HVDC converter terminals.

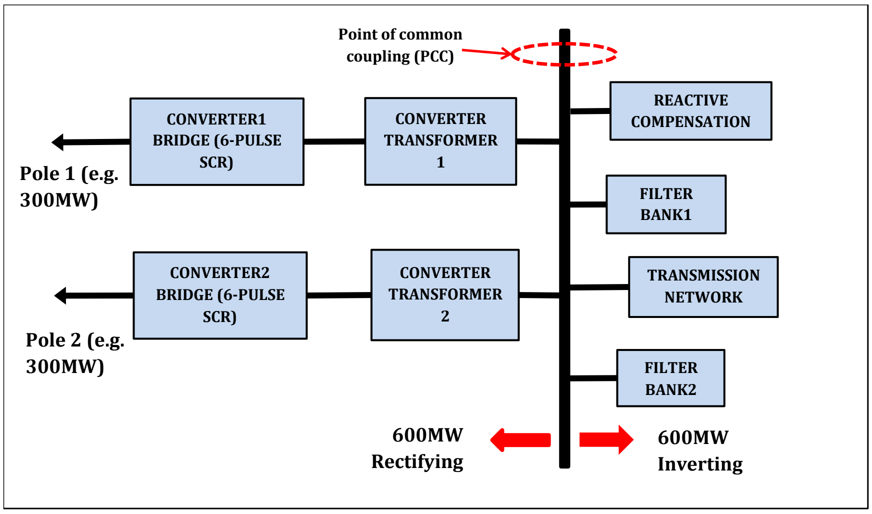


Figure 2.7 Bipole arrangement showing main components of a typical CSC station for one converter terminal

2.5.1.3 Converter bridge

This performs the AC-DC conversion (rectification) and DC-AC (inversion). In a classical CSC type HVDC, the bridge is assembled using thyristors devices into modules which are assembled as valves of the converter bridge. Alternatively, GTOs, IGBTs have been used in VSC. HVDCs installed with IGBTs being pre-dominantly used for planned HVDCs. Two-level, three-level converter bridge arrangements employing PWM switching strategies to minimize harmonics still require filters for mitigation as the AC voltage generated is still far from ideal (still contain rich harmonic spectrum depending on modulation techniques being used). Currently, the MMC approach with much lower harmonics and lower losses have been developed and installed for a VSC HVDC (e.g. 400MW Trans Bay Cable, USA HVDC).

2.5.1.4 Converter transformer

For a CSC type HVDC, the converter transformers are there to transform the utility AC connection voltage to the required AC voltage at the converter bridge. However, there are additional demands on the transformer due to the high harmonic contents of the converter AC current. The high characteristic harmonics generated from the 6-pulse bridge cause additional losses in the transformers which need to be included in its rating. As stated before, it is normal for the transformer windings on the valve side to have a star and delta configuration respectively to eliminate the triple harmonics. The VSC type HVDC can utilize conventional transformers with a series reactor at the converter bridge as the harmonics generated are lower or virtually eliminated compared to the CSC type HVDC.

2.5.1.5 Reactive compensation

It is necessary to provide reactive power support for a CSC type HVDC usually by installing shunt capacitor banks in addition to the filter banks required for harmonic mitigation. The number of capacitor banks and reactive power required are determined by the utility system reactive power exchange requirements and allowable voltage steps. However, a VSC type HVDC is able to operate in both reactive power generation and absorption, hence reactive compensation is only an additional requirement.

2.5.1.6 AC Filters

CSC type HVDC generate current harmonics according on the rectifier adopted. However, the filters installed are not only for dealing with these harmonics that are generated by the converters but additional filters are usually required to deal with the lower order odd harmonics due to the resonance conditions that could result in the amplification of these harmonics present in the utility system.

For the VSC type HVDC, there is filter requirement for the two or three level converter as harmonics are still generated whose harmonic profile is dependent on the PWM modulation strategy. The filter required is however more compact compared to the CSC type HVDC as there is no reactive compensation required resulting in lesser interaction with the utility system harmonics.

Due to the different HVDC available technologies and their continued development, the harmonics being generated and interaction with the utility system it is connecting will always require detailed studies [21]. The studies will identify the extent of the filter needs for the specific HVDC connection to ensure that harmonic levels comply with limits required by the utility at the point of common coupling.

2.5.2 FACTS devices

FACTS devices have been developed over the past two decades with three main objectives:

1. Increase the amount of power to be securely transmitted on existing lines;
2. Direct the power flow to the desired paths;
3. Enable an active and more flexible control of the whole transmission system [22][23].

IEEE and CIGRE Working Groups have produced guides and documents on various aspects of FACTS technology and applications including planning guide [24]. Several kinds of FACTS controllers have been commissioned in various parts of the world.

They can be divided in two families: the first one includes conventional thyristor-switched capacitors and reactors (without turn off capability), and quadrature tap-changing transformers; high-performance and cost-effective high-power GTO, IGCT or transistor (IGBT) based inverters are a prerequisite for the components of the second group. The first one has produced the thyristor-controlled series capacitor (TCSC), the static VAR compensator (SVC), and the thyristor-controlled phase shifter (TCPS). The second one has produced the unified power flow controller (UPFC), the static synchronous compensator (STATCOM), the static synchronous series compensator (SSSC) and the interline power flow controller (IPFC).

From an application's point of view, to control the end voltage, a SVC and a STATCOM are used; to change the line reactance, a TCSC and a SSSC are suitable to utilize; and finally, for a more powerful control over power flow, there are UPFC and IPFC.

Although the most widespread FACTS is the SVC, a STATCOM is much more compact than a SVC for similar rating and it can supply required reactive power even at low values of the bus voltage. The main drawback of SVCs is the injection of current harmonics into the line, as the firing angle. Also, different from a SVC, a STATCOM can supply active power if it is connected to an energy storage source based on batteries or ultra-capacitors.

The most versatile but costly FACTS device is the UPFC, which is able to independently and simultaneously control active power flow, reactive power flow and voltage magnitude and has been so far applied only in three installations worldwide.

The flexibility and adaptability of FACTS technology indicate that they might become part of the tools for solving power system problems in increasingly complex electrical environment resulting from both the variability and uncertainty of intermittent renewable generation sources. Especially FACTS with using multi-pulse and multilevel converters can help to alleviate transmission congestions but also aid in the improvement of power quality and other power system problems in a faster way.

Although existing studies met expectations, for widespread usage of FACTS devices by utilities, further advances must be achieved. In thinking through the consequences of the proliferation of power electronic based devices operating concurrently in power system, there is still more studies need to be done to investigate the possible interactions like induced circulated currents in one another, EMT, harmonic resonance, network resonance. A trend of developing more and more advanced FACTS controllers is evident to better utilize multiple converter systems tied to the grid in future power systems.

According to [25], in a short or midterm, shunt FACTS (SVC and STATCOM, the latter possibly combined with storage) are likely to be more and more integrated in transmission systems in Europe. In a longer term horizon (2020-2030), fast-adjusting devices (series and hybrid types of FACTS - SSSC, TCPST, UPFC) might be deployed in areas with high degree of congestion volatility.

2.6 PE IN DISTRIBUTION SYSTEMS

2.6.1 D-FACTS devices

FACTS have been typically applied to transmission lines, but they have also become important for large distributed generation applications, such as wind farms or large central solar systems, and it is expected that FACTS technology is to be further applied to distribution systems that will be redesigned in the near future for the SG.

2.6.2 Power Electronics Transformers (PET)

Existing zone substations, interfacing transmission and distribution systems, use conventional electromagnetic induction transformers for voltage and power conversion. These transformers, although highly reliable and efficient (98% - 99%), are physically large, require cooling systems, experience voltage drop when under load, cannot provide for reactive power compensation and do not provide a flexible distributed generation interface. Power Electronics Transformers (PET) or Solid-State Transformers (SST) are under investigation to replace conventional transformers for voltage conversion in the distribution level of electricity networks. Operating at medium to high frequencies [26], the distribution level sized SSTs are significantly smaller than equivalent conventional transformers, are comparably efficient (upwards of 95%) [27], have provision for both AC and DC outputs [28], require simplified cooling equipment, can correct power factor to unity and provide for reactive power compensation and flexible interfacing of distributed generation [29].

The idea of the SST is not new, but in terms of implementation, there are very little installations, see [30]. Much work needs to be done in terms of reliability, improved efficiency and required control strategies.

2.6.2.1 The SST Concept

The operation of the SST is (conceptually) similar to that of a switch mode power supply. Figure 2.8 illustrates the concept of the SST transformer.

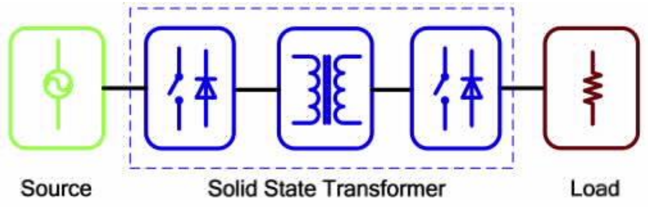


Figure 2.8 Solid State Transformer Block Diagram

2.6.2.2 Grid Applications of SST

The SST can provide additional functionality in distribution networks. They could allow for direct connection of renewable energy sources, energy storage systems and even provide DSTATCOM functionality as well as active harmonic filtering. Figure 2.9 illustrates the potential applications of the SST [31].

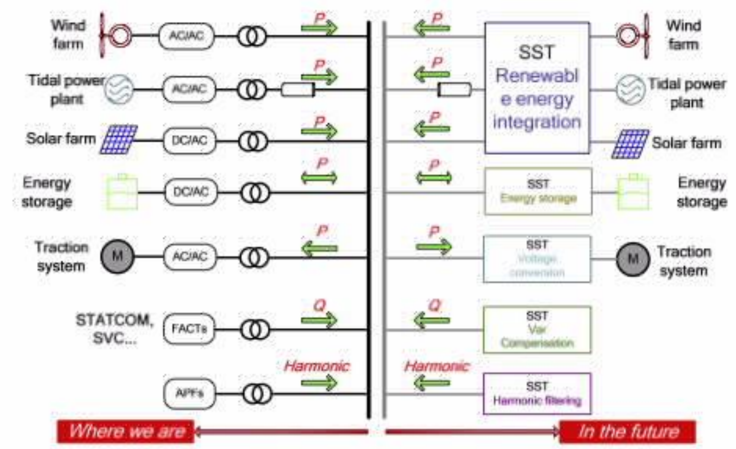


Figure 2.9 Potential Applications of SSTs in Distribution Networks

2.6.2.3 SST Topologies

If SST devices are to be used in distribution networks as a replacement for conventional transformers, they will need to have the capacity for bi-directional power flow as well as galvanic isolation between the primary and secondary connections. The bi-directional power flow capability permits energy exchange between the grid, the end users and distributed generation resources and storage facilities whilst galvanic isolation is a safety requirement. Direct AC-AC converters (without an intermediate transformer) are therefore not regarded as suitable for use in SST applications.

According to [31], there are four basic converter topologies suitable for satisfying the requirements of the SST concept;

1. Direct HVAC-LVAC,
2. 2-stage HVAC-LVDC-LVAC,
3. 2 stage HVAC-HVDC-LVAC,
4. 3-stage HVAC-HVDC-LVDC-LVAC converters.

These topologies are illustrated in Figure 2.10 (adapted from [32]).

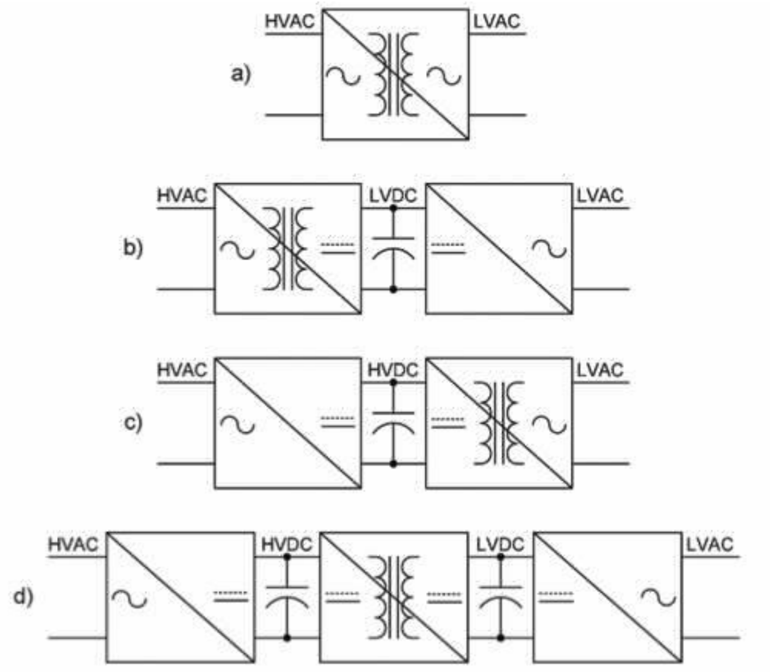


Figure 2.10: SST Converter Topologies

The 3-stage device, type (4), is the most widely used SST technology due to the large range of topologies that can be implemented for each stage. The first stage of these systems rectifies the high voltage AC low frequency input to a HVDC output. The second stage comprises three sections: the first section inverts the HVDC input to a HV high frequency AC input; the second section is a high frequency power transformer which steps the HV high frequency AC power down to an LV high frequency AC power; the third section rectifies the LV high frequency to a LV DC output. The third stage of the system inverts the LV DC input to the desired low voltage LV AC power output. The advantage three-stage converters possess over other topologies is the ability to provide a large number of additional beneficial functionalities.

2.6.2.4 SST Performance and Functionality

- Reactive Power Compensation: A conventional transformer will draw real and reactive power from the upstream grid, increasing line losses and causing voltage regulation problems. The SST can be designed so that it only draws real power from the HV (more likely MV) grid.
- Power Factor Correction: This ability of an SST to correct poor power factor would mean that the zone substation (sometimes referred to as a primary substation) would no longer require capacitor banks, eliminating associated PQ problems such as resonance, switching and oscillatory transients.
- Efficiency: To achieve a highly efficient SST with comparable efficiency to equivalent conventional transformers, a combination of highly efficient components (SiC MOSFETs and nanocrystalline alloy HF transformers) in a multi-stage converter topology with an advanced and accurate control system is required. SST devices are slightly less efficient than a modern, electromagnetic device by about 1%. However, a holistic approach is required for a deeper

understanding of the overall effect on the network and network loads by the use of SST technology.

- Reliability: The three-stage converter based solid-state transformer has a low voltage DC link between the high frequency rectifier and inverter on the secondary side. This DC link can be used to connect energy storage devices in addition to renewable energy sources. Energy storage devices including battery banks and supercapacitors offer the ability to ride through momentary interruptions.
- Power Quality: As with any PE interfaced device, well designed control provides the opportunity to mitigate power quality related problems, including harmonics, sag/swells, flicker. Any control strategy associated with the switching of the active devices in a SST should include active harmonic compensators ensuring the mitigation of low order harmonics, not solely from the SST itself, but also as a result of non-linear loads connected to the LV network.

2.7 PE IN CONSUMPTION: INDUSTRIAL, COMMERCIAL AND DOMESTIC

2.7.1 Large equipment

2.7.1.1 Drive systems

Cycloconverters are in use since many years for many industrial applications such as rolling mill main drives, mines hoist drives, cement mill drives, etc. One disadvantage of the cycloconverter is that it generates a wide band of interharmonics in addition to the characteristic harmonics. Cycloconverters were successively replaced by different configurations or assemblies of 2 or 3-level converters based on GTO/IGBT/IGCT technology. Recently, the introduction of MMC convertors resulted in less harmonic emission and lower demand for reactive power.

2.7.1.2 Electric arc furnaces

DC electric arc furnaces (DC-EAF) are usually based on 12-pulse bridge rectifier. DC-EAF requires an electrode current up to 120 kA. The electrode is fed through two six-pulse converters connected in parallel. Some other types of converters based on Thyristor technology are also used, such as 24-pulse converter. The main target of the rectifier control is to maintain the DC current of the electrode to a reference value while the control unit of the depth of the electrode maintains the impedance of the electrode circuit.

Submerge electric furnaces (SAF) comprise anti-parallel thyristor valve in series with the electrodes connected to each phase to control the electrode current. To equalize the heat of the melted material in the basket, the current in each of the electrodes is individually controlled causing unbalanced current and harmonics emission, mainly 3rd harmonic. In case of failure of an electrode, the SAF continues to operate with one or two electrodes resulting in a large amount of negative-sequence current and 3rd harmonic generation.

2.7.2 Small equipment

PE are widely used in various applications [33]. In industrial applications, PE are present in pumps, compressors, machine tools, induction furnaces [34], welding equipment, etc. In commercial applications, they are used in air conditioner, refrigeration, large computers and office equipment, uninterruptible power supplies (UPS) elevators, ventilation systems, etc. In domestic applications, PE can be found in cooking equipment, lighting, heating, air conditioners, refrigerators and freezers, personal computers, entertainment equipment, UPS.

2.7.3 PE in in Heating Ventilation and Air Conditioning Systems (HVAC)

In [35] the authors report some of the results of a study on harmonic characteristics and modelling of inverter air conditioners. Four categories of HVAC based on the type and control strategy of the PE interface of the ac motor that drives the unit’s compressor have been introduced:

- Type 0 (non inverter driven);
- Type 1 (low frequency switching rectifier with single and multi-pulse capacitor charging);
- Type 2 (high frequency switching rectifier with boost converter);
- Type 3 (high frequency switching rectifier with symmetrical semi-boost converter).

The authors also report the results of simulations and measurements taken on 5 inverter driven heat pumps. The main results were the following:

- Harmonic performance of 5 inverter-driven heat-pumps shows diversity of characteristics;
- Characteristics are predominantly due to rectifier circuit design and control scheme;
- PSCAD/EMTDC models provide accurate simulation of individual heat-pumps;
- Type 3 harmonic behaviour superior to others.

2.7.3.1 PE in lighting

Stricter requirements on lighting equipment regarding lumen per Watt has led to new types of lighting equipment that contain PE, for example compact fluorescent lamps (CFL), fluorescent tubes with electronic ballasts, LED lamps (including also street lighting). With the phasing out of the incandescent lamp more and more lamps with a PE interface will be on the market.

The PE topology used in CFLs is almost constant through different manufactures, and the basic topology of a modern energy saving lamp is described in [36]. As interface to the grid there is a diode rectifier bridge with a smoothing capacitor and behind that there are a filter and switching transistors.

The current drawn by these lamps is distorted and the harmonic emission as a percent of the fundamental is often high (current THD around 100 % is not uncommon). What matters to the grid is however the absolute value of the harmonics and for CFLs and LEDs the amplitude of the harmonics lies in the mA range as seen in Figure 2.11 where a measurement of a LED lamp is shown both in time and frequency domain. The current waveform drawn by the LED, which is shown in figure below, is similar to that of most CFLs. It is important to note that while the topology for most CFLs is similar this is not the case for LEDs. The harmonic emission associated with LEDs will vary depending to the topology used.

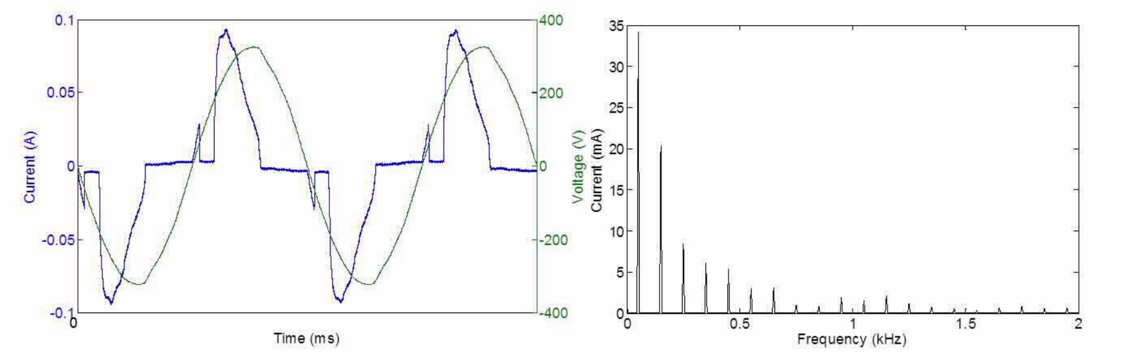


Figure 2.11 Measurements of an 8 W LED lamp in time domain (left side, voltage (Green curve) and current (blue curve)) and the result of the DFT of the current (right side)

Solid state light sources are now available and they offer viable alternatives to fluorescent and high intensity discharge (HID) lamps and far surpass incandescent lamps, regarding lumen per Watt. LEDs are driven with DC current, requiring an AC or DC power source. As shown in the Figure 2.12 [37], power supplies include PFC as a single state, integrated, or with a two-state arrangement where the first stage supplies a front-end DC voltage for a second stage that controls the LED array current.

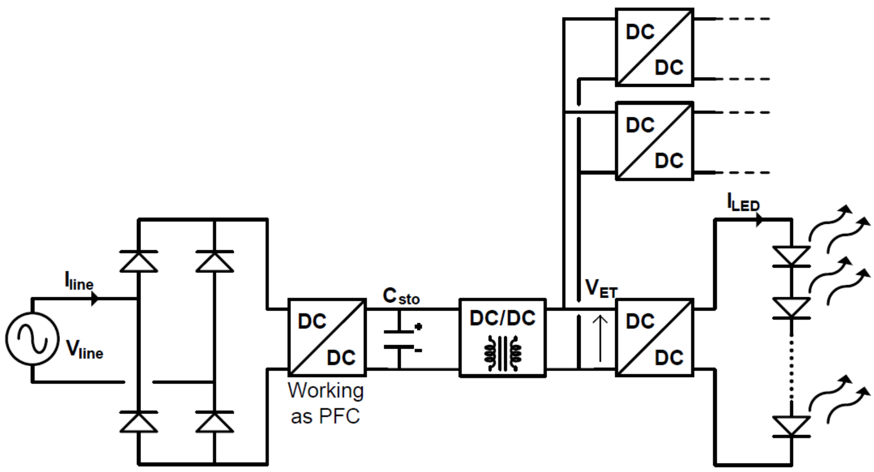


Figure 2.12 Typical three-stage off-line LED lighting driver topology with galvanic isolation

A DC/DC converter in constant current mode provides a constant output current to the LED over the entire supply voltage range. The power loss inside the LED control circuit is reduced to a minimum, because the configuration is optimized to the LED chain length.

In contrast with CFL, a uniquely topology characterizing all LEDs in the market is not found in the literature as mentioned earlier. Different topologies (Buck, Boost, Buck-boost, SEPIC, flyback, etc.) can be used to fulfill requirements regarding LED chain length and supply voltage range. The choice for a certain architecture and topology is driven by a number of criteria and requirements such us need for electrical isolation in the driver, need for dimming with phase cut dimmers, efficiency requirements, voltage and current requirements of the LED load, and stability over line voltage variations among others.

Furthermore, requirements on target lifetime, reliability/quality and certainly cost are driving choices into a certain direction. This makes it impossible to find a common PE topology through LEDs (for indoor and outdoor applications) available in the market.

Based on conducted emissions from the lamps up to 150 kHz, a classification of LEDs was made in [38]. From the measurements of a range of LED lamps, four typical lamps were selected:

1. Lamps with high levels of emission in the frequency range up to 2 kHz (low-frequency emission).
2. Lamps taking a mainly capacitive fundamental current (at 50 Hz).
3. Lamps with moderate levels of emission in the frequency range up to 2 kHz.
4. Lamps with high levels of emission in the frequency range above 2 kHz (high-frequency emission).

The difference in emissions measured at the terminal of the lamps can be traced back to the topology used.

Presently, there are no harmonic emission limits for LED with active power below 25 W, leading to a wide variety of emissions among LEDs found in the market. However, a new edition of IEC 61000-3-2 is expected where there will be requirements for LEDs above 5 W. Stricter requirements on low watt lamps (on harmonic emission or power factor) could lead to new topologies, which off course could lead to new power quality issues related to lighting equipment.

For lighting equipment with active power consumption above 25 W, the limits are stricter today (class C equipment as defined in IEC 61000-3-2). To comply with these limits some type of power factor correction (PFC) is needed. For fluorescent tubes driven by high frequency (HF) ballast, the most common way to handle these harmonic limitations is to use active power factor correction (PFC). One consequence of this solution is the introduction of conducted emissions in the frequency range above 2 kHz (supraharmonics 2-150 kHz) [39], where the limits on emissions are less strict. In [40] a PQ comparison study among LEDs used in street lighting was done. In this case, two LED street lamps were measured, showing different harmonic spectrum.

2.7.3.2 PE for charging EV

There are a wide variety of electrical vehicle (EV) chargers. They are characterized by their power output ranging from a few kilowatts to several tens of kilowatts. EV chargers can supply either DC or AC voltages, depending on the type of vehicle [41]. For high power devices, there are available charging schedulers that limit instantaneous power consumption to avoid expensive power grid upgrades and consequently avoid power quality issues. EV chargers can be connected to one phase or to three-phases of the supply network.

EV normally includes a AC-DC converter, whose simplest AC-DC topologies include a single-phase (4 pulse) or a three-phase (6 pulses) rectifier, which feeds a DC-DC converter controlling the DC output voltage and thus allowing to implement the battery charger algorithms [42]. An alternative to these non-controlled rectifiers are the controlled ones that allow to control the level of output voltage without other downstream control systems. Unfortunately, it presents a lower battery charge control level. Therefore, from the network viewpoint, the the supplied current is influenced by the topology of the charger, which consequently affects the level of harmonic distortion [43]. Recent developments of SiC devices for the AC-DC converters permit to reduce the level of harmonics injected into the power grid.

2.8 CONCLUSIONS

2.8.1 Findings

In our contemporary society, power electronics has now emerged as a large, complex and multi-disciplinary area in electrical engineering, being the linchpin in the efficient power handling when the treatment of data and communications. Power electronics is an enabling technology covering an enormous range of power levels, functions and applications. It offers numerous advantages in terms of lower cost, reliability, extension of functionality and high volume density. Their applications have recently expanded into industrial, power, consumer electronics, medical, automotive, aerospace and defense sector. The power electronics market is growing at a significant rate as increasing demand for use in portable devices, as well as applications such as renewable energies (such as wind, photovoltaic and fuel cells) and electric/hybrid vehicles.

Although power electronics development has been driven chiefly by the advances of semiconductors devices and converter topologies, it includes many constituent technologies, to follow [44]:

- Power switch (covering device technology, driving, snubbing, and protection technology);
- Converter (covering the switching methodology, such as hard switching, soft switching, resonant transition switching, and all the topological arrangements);
- Passive component (covering magnetic, capacitive, and conductive components);
- Packaging (covering materials technology, interconnection technology, layout technology, and mechanical construction technology);
- Electromagnetic environmental impact technology (covering harmonics and network distortion, EMI and EMC);
- Physical environmental impact technology (covering acoustic interaction, physical material interaction i.e., recycling, pollution);
- Cooling technology (cooling fluids, circulation, heat extraction and conduction, and heat exchanger construction);
- Manufacturing technology;
- Converter sensing and control technology. Among them, from the perspective of this chapter, the most important is the electromagnetic environmental impact technology.

2.8.2 Recommendations

Harmonic pollution generated by power electronics converters is one of the key problems of integrating them compatibly with the power grid. Traditional grid-commutated topologies cause undesirable high levels of harmonic content and low power factor when they are connected to the power grid. In VSI, through pulse-width modulation (PWM) with high switching frequencies (in the kHz range), the desired output voltage can be obtained, reducing or eliminating these discrete low order harmonics. However, this significantly increases harmonic emission spectrum towards higher frequencies, self-commutated converters produce supraharmonics (from 2 kHz to 150 kHz) due to the high switching frequency. Numerous problems related to current and voltage harmonic effects on power systems are commonly observed nowadays within this frequency range.

Any new converter should consider their EMI/EMC related impact since its early stage of design, even when the proposal is no more than one idea in the mind of the researcher. It is not enough to mitigate the problem in the final design, but to go to the root of the problem, trying that the harmful emission does not occur. New more complex converter topologies and new modulation schemes are being studied to solve control challenges [45], [46], such as: harmonics, voltage imbalances, etc., broadly speaking power quality issues.

2.8.3 Open issues

The trend in power management demonstrates the fundamental and increasing role of power electronics as an enabler for distributed energy integration, and for the future power system and smart grid. In next years will increase the number of research focused on solving compatibility challenges of supraharmonics. This issue has been conveniently reported in the literature and new standardization methods are being discussed at present. However, harmonic emission prevention in this frequency band requires new specific types of solution to be used. The recent emergence of artificial intelligence techniques into power electronics [47] has created an advanced frontier which could offer alternative solutions to the traditional power quality issues.

3. OVERVIEW OF SMART GRIDS AND POWER QUALITY

3.1 INTRODUCTION

The literature on electric power systems has been enriched the last five years by a large number of publications on "smart grids", including dedicated journals, dedicated conferences, technical and non-technical reports and a range of textbooks, e.g. [48], [49]. A transition from the traditional power grid to the new "smart grid" is envisioned by many and this vision is the driving force behind much of the research in electric power systems, which has been done in the last few years and continues at this moment.

In comparison to the "smart grid" the field of power quality is much older and the number of publications has remained constant and has even the tendency of decreasing. The question coming up is if there is still any research needed in power quality and is power quality still an issue in the future smart grid?

The following sub-chapters contains some observations on the relations between the two fields, "smart grids" and power quality and how future research on power quality plays a role in the transition to a future smart grid.

The term "smart grid" is briefly introduced in Section 3.2, following by a summary of the relations between power quality and smart grids in Section 3.3. Section 3.4 introduces power quality as an important performance indicator for the smart grid and Section 3.5 introduces new types of power-quality disturbances that may originate from new types of equipment connected to the grid. A final issue, the presence of large amounts of power-quality data, is mentioned briefly in Section 3.6.

3.2 THE SMART GRID

There are several definitions of the smart grid. The following one is used by the Swedish Energy regulator [50] and close to the one proposed by the European Energy regulators: "The set of technology, regulation and market rules that are required to address, in a cost-effective way, the challenges to which the electricity network is exposed".

The task force on smart grids that was set up by the European Commission uses a definition that is very strongly linked to one specific challenge: "Future grid that is needed for reaching efficiently the EU Energy and Climate Change targets for the year 2020".

Several other definitions are being used, either similar to the one above, or such that the kind of technology is being defined. The definition given by IEC is an example of such a definition:

Electric power system that utilizes information exchange and control technologies, distributed computing and associated sensors and actuators, for purposes such as:

- Integrate the behaviour and actions of the network users and other stakeholders;
- Efficiently deliver sustainable, economic and secure electricity supplies.

According to IEC, the terms "smart grid" and "intelligent grid" are synonyms.

The IEEE smart grid website gives the following description: "The "smart grid" has come to describe a next-generation electrical power system that is typified by the increased use of communications and information technology in the generation, delivery and consumption of electrical energy." This description is along the same lines as the one by IEC but it does not contain any of new challenges that are the driving forces to the shift towards a smart grid.

3.3 POWER QUALITY

A number of relations between the transition to the smart grid and power quality can be observed. These can be summarized as follows:

- The new technology, regulation and market rules can also be used to improve power quality. The main developments involve dedicated power-electronics controllers, once referred to by the term "custom power" [51]. But other developments, such as advanced voltage control (using data from multiple locations) and power-quality markets should not be forgotten or ruled out.
- Lately, the traditional grid was exposed to new challenges, including those related to power quality, and as a normal evolution the transition to the smart grid was needed. For example:
    - Solar panels connected to the low-voltage networks will result in overvoltages;

- The switching frequency of the converters in wind turbines causes high-frequency signals flowing into the grid;
- Harmonics are generated by EV chargers;
- The repeated starting of heat pumps can result in visible light flicker.

From a research viewpoint and also for practical applications, there is a potential for the occurrence of new types of disturbances due to the novel types of equipment connected to the grid just mentioned. Some examples are given in Section 3.5.

- When smart-grid solutions remove some of the other network limits, like overload or stability limits, power quality may become what sets the limits. Thus, even when power quality is not an issue now, it may become an issue in the future.

3.4 PERFORMANCE INDICATORS OF THE SMART GRID

What matters most to customers connected to the future electricity network (smart grid) are the following three issues:

- The price for using the network (the network tariff),
- The reliability,
- The power quality.

For some customers also safety and environmental issues also matter and one may argue that they should be added to this list as well. However, technical subjects like overload protection, operational security, power-system stability and insulation coordination are just internal technical issues that do not directly matter to the network users.

3.4.1 The Hosting Capacity Approach

Power quality and reliability become important when quantifying the performance of the future (smart) grid. This is part of the foundation of the so-called "hosting-capacity approach" [52], [53] that is illustrated in Figure 3.1.

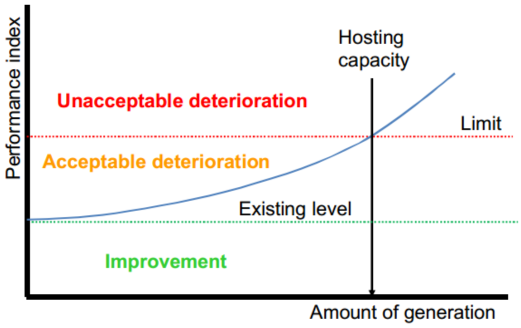


Figure 3.1 The hosting-capacity approach: comparing a performance index with a predefined limit gives the hosting capacity above which the reliability and quality of the supply can no longer be guaranteed

To determine how much new production can be connected to the grid (at a certain location, to a certain feeder or to the grid as a whole) a set of performance indices is compared with each index limit. Once any of those indices exceeds its limit, the hosting capacity is reached.

Connecting more generation than the hosting capacity will result in the grid no longer being able to provide acceptable reliability and power quality to its customers. This holds for the classical (existing) way of planning and operating the distribution grid. We will see below that there are alternatives under the smart-grid paradigm.

An overview of the development of the hosting capacity concept and its applications is given in Chapter 3 of [54].

The choice of performance index and limit can have a big impact on the hosting capacity. This has been shown by several studies [55], [56], [57] and an example is shown in the next section.

3.4.2 Overvoltages

When connecting renewable generation, one of the main power-quality issues is an increase in overvoltages occurrence.

The hosting capacity approach for this type of disturbance is shown in Figure 3.2 In this case, the performance index is the highest 10-min rms voltage for any customer at any moment in time. A range of performance indices is available but making a choice is one of the main issues in voltage-quality regulation [63].

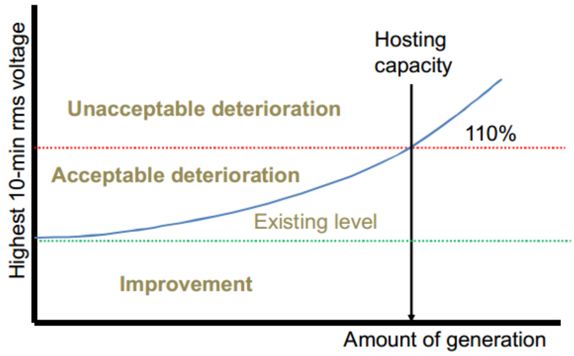


Figure 3.2 Hosting capacity approach for overvoltages

The impact of different indicators is illustrated in Figure 3.3 [61]. When the highest rms value is used, the hosting capacity is equal to 1 MW. If the 99% value is used, then the hosting capacity is increased to 2.3 MW. Thus by allowing the voltage to exceed the limit during 1% of the time, more than twice as much production can be connected. However, this comes at the expense of an increased risk of damage to end-user equipment because of overvoltages.

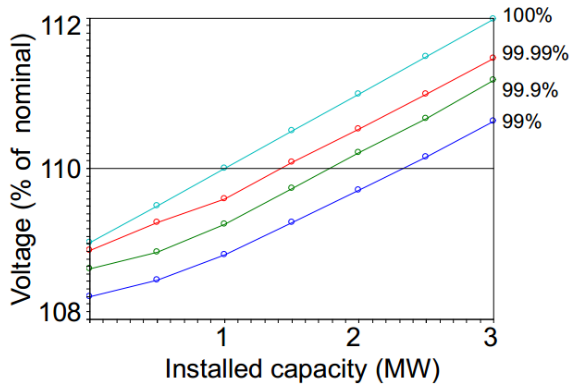


Figure 3.3 Four different performance indices with the same limit

3.4.3 Curtailment

Instead of allowing overvoltages to occur during a small percentage of time, the production can be curtailed whenever the voltage would otherwise exceed the limit. In this way the risk will not be carried by the network users with equipment sensitive to overvoltage, but by the owners of the generation units that will be curtailed.

With the increasing amount of local generation, there is no longer the risk of high overvoltages occurrence but the amount of energy that will be curtailed. Such example is illustrated in Figure 3.4 for three different locations [48][64]. A distinction has been made between hard curtailment and soft curtailment. For hard curtailment, the production unit is disconnected whenever the voltage would otherwise exceed the limit. For soft curtailment, the production is reduced such that the voltage remains equal to the limit.

Figure 3.4 also shows the annual electricity production as a function of the amount of installed production capacity. With hard curtailment, the annual energy production decreases after a certain amount of installed capacity. This reduction is dependent on the local voltage profile.

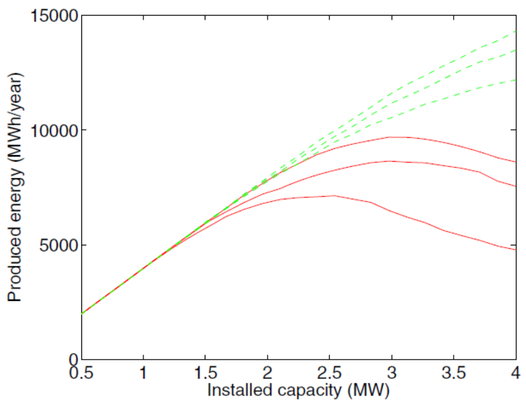


Figure 3.4 Produced energy, with curtailment to avoid overvoltages, for hard curtailment (red) and soft curtailment (green) at three different locations

3.4.4 Power Quality Knowledge

Power quality knowledge is needed to obtain suitable power quality indices and limits and to study their impact on the hosting capacity. However, this is not only a technical issue, also regulatory and political aspects will play a role here. When it concerns overvoltages, there is a balance to be made between limiting the amount of new generation that can be connected and the risk to damage to end-user equipment because of this type of disturbance.

Power quality knowledge is also needed to determine the technical and economic impact of connecting more distributed generation than the hosting capacity.

3.5 NEW TYPES OF POWER QUALITY DISTURBANCES

New technologies connected to the grid may introduce new types of power quality disturbances. What is urgently needed is a detailed study of the emissions from new types of equipment. This should not focus on "normal harmonic emissions" like 3, 5 and 7 order, but instead research efforts should be directed towards abnormal emissions. It is not possible to decide beforehand what kind of emissions will be of interest for a comprehensive study, and therefore, it is important not only to measure them according to standard methods as this will immediately limit the amount of new information that can be obtained.

3.5.1 Even harmonics

Modern wind turbines are equipped with power electronic converters and therefore are a source of harmonic emission.

The harmonic emissions from three modern wind turbines (2 and 2.5 MW size) is shown in Figure 3.5 (95% of time) [65], [66]. The highest magnitude values are below 1% of the nominal current and much lower than emissions from most of other equipment connected to the grid.

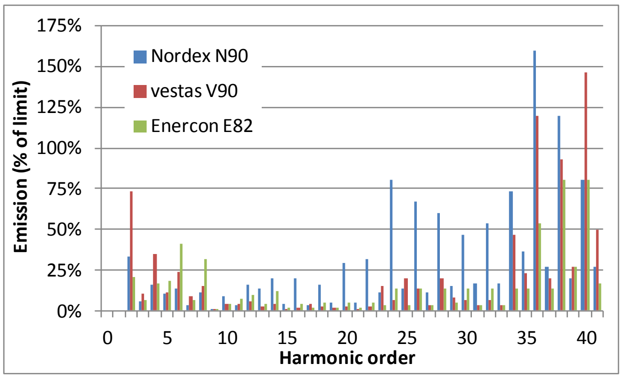


Figure 3.5 Comparison of emission from three modern wind turbines with the emission limits according to IEEE 519

Analysing the bar chart inFigure 3.5, where the 100% line corresponds to the emission limits set by IEEE 519, it can be noticed that the emissions are below the limits for most harmonics. The exceptions are the high-order even harmonics 36, 38 and 40 whose limits are set at 25% of the neighboring odd harmonics. It is not known what was the rationale behind the 25% value, but if 50% would been chosen, the limits do not have been exceeded.

3.5.2 Interharmonics

Besides harmonics, wind turbines also emit interharmonics [66], [67] as shown in Figure 3.6, for the same three wind turbines. Interharmonic levels are clearly higher than for other equipment. Most network operators do not use any limits for interharmonics, but when they are used they may be very low, thus imposing that the wind turbines to be connected using expensive filtering.

There is a need for a thorough evaluation of the emissions limits for “abnormal frequencies” like even harmonics and interharmonics, for voltages and as well for currents.

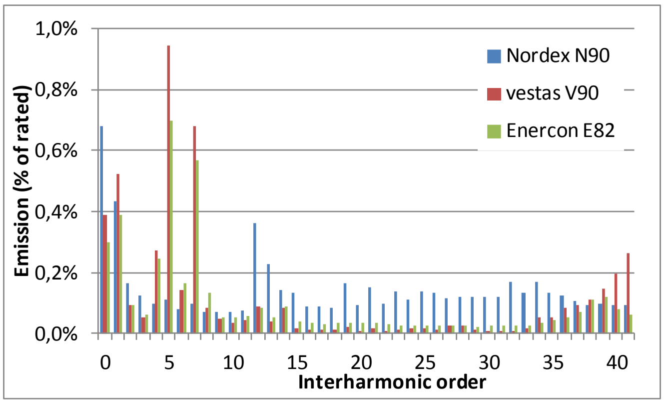


Figure 3.6 Interharmonics from three modern wind turbines

3.5.3 Medium-time-scale voltage variations

A new disturbance, without an index to quantify its severity, is illustrated in Figure 3.7 [61], [68], namely the fast variations in PV generation due to passing clouds.

When using standard methods for quantifying power quality, this disturbance will not be noticed. It is too fast to impact the 10-minute rms value; it is too slow to impact the flicker severity. New indices are needed to quantify how variations in voltage magnitude at this time scale are impacted by renewable electricity production.

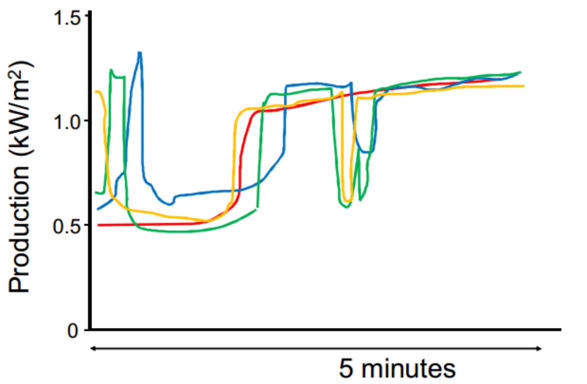


Figure 3.7 Variation in PV generation due to passing clouds; four solar panels located in the same street

3.5.4 Hosting Capacity for new Types of Disturbances

Calculating the hosting capacity for such new types of disturbances may be difficult (see Figure 3.8) the methods to calculate the value of the index as a function of the amount of new production. All these tasks require advanced power-quality knowledge.

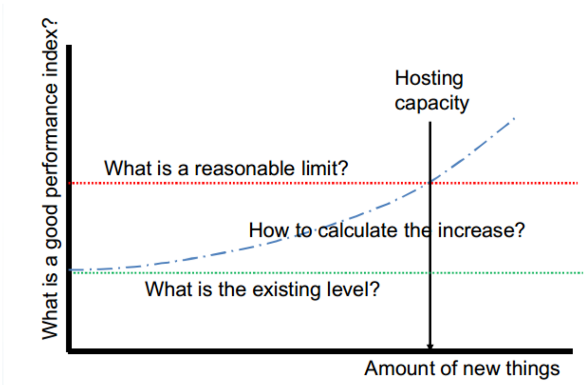


Figure 3.8 Uncertainties in calculating the hosting capacity for new types of disturbances

3.5.5 Supraharmonics

The term supraharmonics has recently been introduced to refer to the distortion of voltage or current in the frequency range from 2 to 150 kHz [70]. Such frequencies originate from the active power-electronic converters, which are present in many of the grid-connected equipment [70], [71]. There are some indications that a reduction in emissions of "normal harmonics" (lower-order odd harmonics) goes together with increased emissions of supraharmonics. This would make sense because active converters are commonly-used to reduce the level of harmonic emissions at lower frequencies.

The example shown in Figure 3.9 [71] presents the remnants of the switching frequency from a PV inverter. A 16 kHz signal is injected by the inverter regardless the generated power. When the PV system is switched off (rms current value close to zero) the 16 kHz signal disappears.

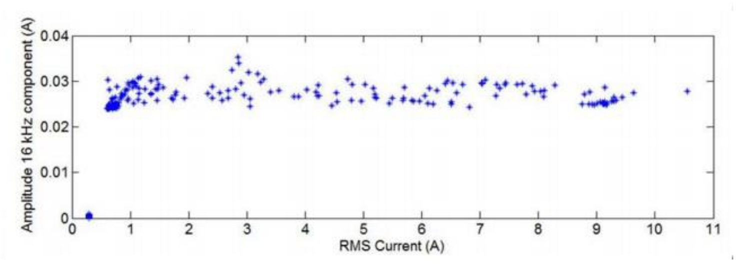


Figure 3.9 Supraharmonics from a 2.5 kW PV installation, as a function of the current magnitude

Another example is shown in Figure 3.10 [38] and it refers to the emissions from four types of LED lamps. The one on the bottom right is the one that is referred to as "low-power-factor". The other three do indeed have less emissions at low order harmonics, but they also have much more emissions in the supraharmonic range.

The work on this frequency range has just started and more research is needed to find suitable ways for quantifying this frequency range emissions. Also, another aspect to be studied is the spread of emissions and the impact on other neighboring devices.

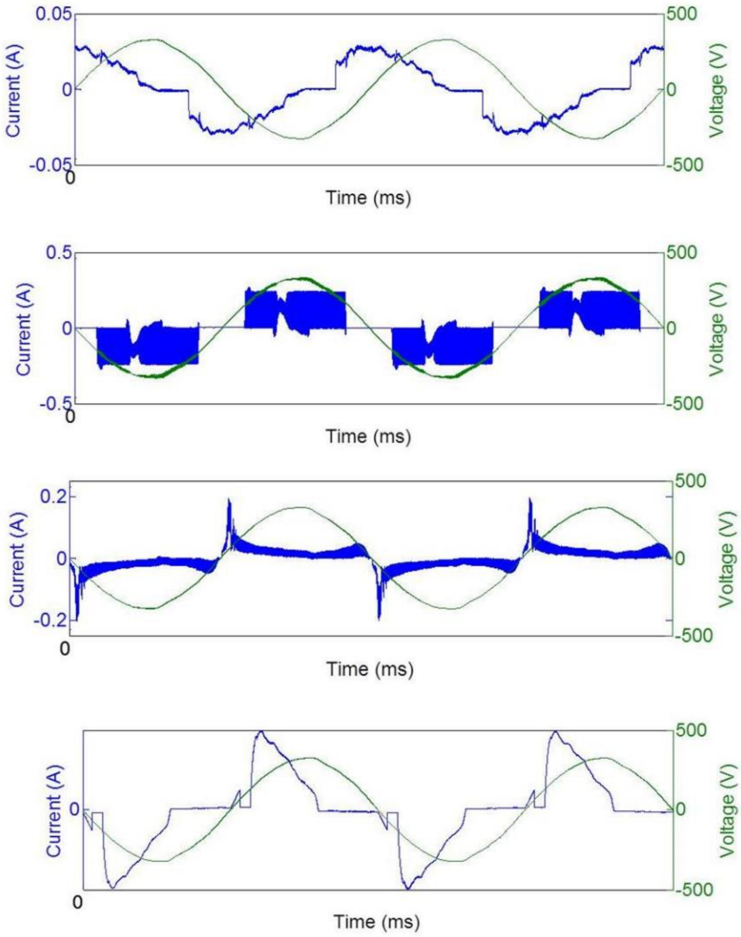


Figure 3.10 Waveform and spectrogram for four types of LED lamp

3.5.6 Interaction between end-user equipment and power-line communication

End-user equipment can interact with power-line-communication in several ways and an overview of the different ways of interaction is summarized in Table 3.1 [73].

Table 3.1 Different ways of interaction between end-user equipment and power-line communication (from [73])

	Disturbance	Interference
I	Voltage or current distortion due to end-user equipment at frequencies used for communication	The communication signal drowns in the disturbance and the communication does not succeed.
II	The end-user equipment creates a low-impedance path at the communication frequency.	Only a small amount of the communication signal arrives at the received and the communication does not succeed.
III	The communication signal results in large currents through the end-user equipment.	Reduction in life-length and incorrect operation of the equipment.
IV	Non-linear end-user equipment exposed to the communication signal results in currents at other frequencies.	Any possible adverse impact due to the new frequency components, including interference with communication.
V	Distortion of the voltage waveform due to the communication signal.	Incorrect operation of the end-user equipment.

3.5.7 Transmission Systems

The developments that go under the name "smart grids" will also impact the power quality at transmission level. The HVDC links, whose number is increasing fast, are a possible source of new types of emissions at transmission level.

HVDC is a known source of harmonics and many valuable studies on harmonics were in fact triggered by the introduction of HVDC. As HVDC links are normally equipped with harmonic filters, they also have the ability to filter harmonics from other sources but the same filters could also create resonances at other frequencies.

The shift has been from classical HVDC to new VSC based HVDC will introduce new types of harmonics, whose content is still unknown. Supraharmonics due to the switching of the valves are the first suspect. The active converters that are part of VSC-HVDC make that there is no longer a need for harmonic filtering. That also means that no new resonance frequencies will be introduced. The converters can even be used to filter low-order harmonics from other sources.

Another new type of transmission of power, ac cables, also have an important impact on the harmonic distortion levels by shifting resonances to lower frequencies [61], [72]. This might become worse due to the shift from large production units to renewable generation like wind and solar power that do not contribute to the short-circuit capacity. Their impact is not fully studied yet, but an early indication shows that it will result in higher distortion at lower frequencies and lower distortion at higher frequencies [61].

3.6 POWER QUALITY AND BIG DATA

At this moment there is thousands of power quality monitors connected to the grid that are all collecting data. In five to ten years from now, that number may increase significantly, which will result in a huge quantity of data stored in relational databases.

Strong automatic methods are required to analyse this big data, otherwise it won't be of any use and the growing size of databases may even become a barrier against further deployment of monitoring equipment and applications. Developing algorithms for such methods is another application of power quality knowledge.

To get an idea about the amount of data being involved in grid monitoring, let's consider a three-phase monitor that records 10-minute values for rms, harmonics (2 to 40th order) and interharmonics (0 to 39), for both voltage and current. That gives 25 million values per year. For a utility using one hundred of such monitors, it is a lot of data. The issue here is not so much the storage as the data processing and the difficulty in finding useful and valuable information.

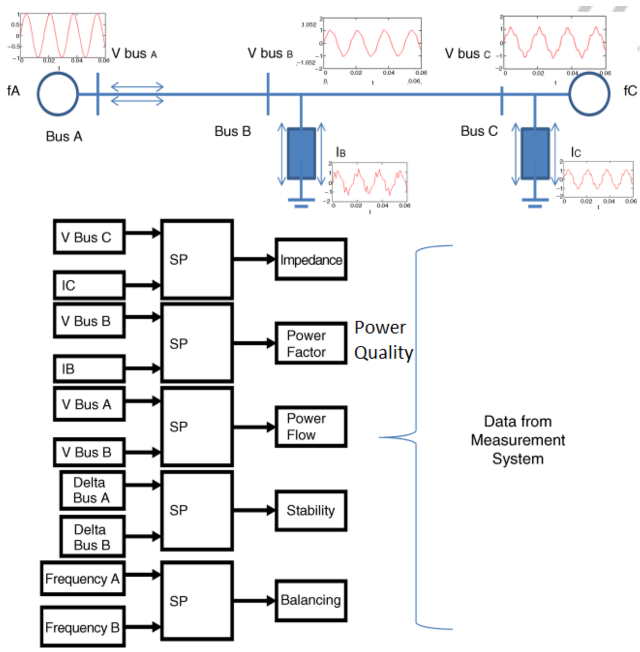


Figure 3.11 PQ System-Wide Signal Processing Analysis

As another example, let's consider a country with 5.2 million (mainly single-phase) customers where the rms voltage is measured every 10 minutes. That would give 270 billion data values per year.

The earlier-mentioned three-phase monitor continuously sampling three voltages and three currents at 256 samples per cycle will produce over a whole year 2.4 trillion samples. All this data is sampled but only a very small part of it is stored, in the form of a range of indices for variations and events. For some studies, like post-mortal analysis of equipment failures, one would like to have access to all the data. A balance between need for storage and need for information has to made continuously

What is needed is a way to get information out of this huge amount of data, without having to store all of it, and without having to search through all of it for every query. Figure 3.11 and Figure 3.12 (adapted from [74]) show a monitoring system which could help in dealing with the complexity of the power quality data to be processed.

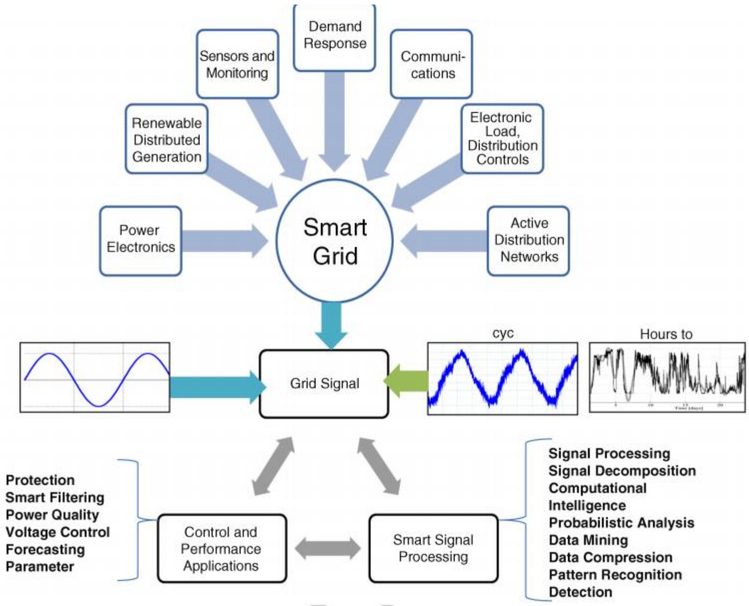


Figure 3.12: The New Context of PQ in SG [28]

3.7 CONCLUSIONS

3.7.1 Findings

Power quality will continue to play an important role in the power systems. The transition to the smart grid will sooner result in a higher demand for power quality knowledge. The future for power quality research may however be different from what we are used to from the past experience.

3.7.2 Recommendations

For power-quality research to contribute to the transition to the smart grid, two lines of future work are needed:

- Methods to determine suitable indicators and limits for power-quality disturbances: from long interruptions and slow voltage magnitude variations to interharmonics and transients.
- Detailed studies of any new sort of voltage and current disturbances that may be introduced to the grid by the presence of new types of equipment connected to the grid.

3.7.3 Open issues

It remains unclear what the future grid (the smart grid) will look like, which means that also the relations between power quality and smart grid will remain at least partly unclear.

The future direction of the hosting capacity approach remains unclear, especially how to include the range of power-quality phenomena that is potentially impacted by new production units. Developments are taking place outside of the scope of this working group.

Addressing the challenges due to complicated relations between power quality and smart grids require more people with power-quality knowledge than are currently available.

New power-quality phenomena, e.g. due to introduction of renewable electricity production, require new sets of indices and objectives.

Significant further research and development is needed on supraharmonics.

There remains a lack of methods and tools for automatic analysis of large amounts of power-quality data.

4. CHANGES IN PROBABILITY OF INTERFERENCE

4.1 INTRODUCTION

Within IEC, power quality is treated within the standards on electromagnetic compatibility (EMC). Within these standards, an important distinction is made between (electromagnetic) disturbances and (electromagnetic) interference. A disturbance is any deviation from the ideal voltage or current waveform, whereas interference refers to the case where a device does not operate as intended, gets damaged or experiences a reduction in life time due to high disturbance levels. For example, a voltage dip is a disturbance, whereas the tripping on a motor drive due to this dip is a case of interference. Most of the work on power quality concerns disturbances, but what actually matters in the end is limiting of avoiding interference. Electromagnetic compatibility is defined as the lack of interference, i.e. all equipment operates as intended. The aim of the EMC standards is to ensure a high probability of electromagnetic compatibility, hence a low probability that any interference occurs. Similar formulations, terminology and ultimate aims are present in other power-quality standards. Also are the terms "power quality disturbance" and "power quality interference" regularly used.

Note that the aim of EMC and power quality standards is not to avoid any interference. This only means that (a few) cases of interference do not imply that the standards are wrong. Allowing a few cases of interference is much more cost effecting than trying to prevent all possible cases.

The power system is undergoing changes similar to those of the society that it serves. These changes may significantly impact the power quality and reliability. That impact requires a thorough study to prevent serious deterioration of power system performance. Multiple changes are on-going in the electric power system: this includes changes in production, in storage, in consumption patterns, in equipment and in the electricity network. Some of the changes are aimed at improving the power quality. However the majority of these changes is due to other drivers.

The main aim of this chapter is to identify new potential cases of interference: due to increased levels of emission (Section 4.3), decreased immunity (Section 4.4) or by increased transfer to susceptible equipment (Section 4.5). The changes in production, consumption and in the grid that result in these changes are summarized in Section 4.2. An overview of findings, recommendations and open issues is given in Section 4.6.

4.2 RELEVANT CHANGES

The expected changes in the power system can be categorized into three different types, each having the potential to impact the probability of interference:

- Changes in production, where there is a shift from large conventional production units to small units connected to low-voltage (LV) and medium-voltage MV) networks; a shift to non-dispatchable renewable energy (solar and wind power); and a shift from synchronous machines to power-electronic interfaces. (Section 4.2.1)
- Changes in consumption: replacement of existing types of equipment with more energy-efficient alternatives; introduction of new types of equipment; the proliferation of small devices; and the almost complete shift to active power-electronic interfaces. (Section 4.2.2)
- Changes in the grid: underground cables; power-electronic equipment; the increased use of power-line communication; changes in protection and control. (Section 4.2.3)

4.2.1 Changes in production

A number of changes are taking place with electricity production, often at the same time:

- A shift from large production units to small production units connected to low and medium-voltage networks.
- A shift from dispatchable to non-dispatchable energy sources, mainly wind power and solar power.
- A shift from synchronous machines to power-electronic converters as interface with the grid.
- A shift to production units that do not or not always contribute to ancillary services like voltage and frequency control.

A related development is the possible wide-spread use of battery storage in the distribution grid and/or with network users.

When large production units mainly have a voltage-control function, the may be replaced by switchable capacitor banks.

The changes in production are discussed in detail in many other publications, including CIGRE reports, and are therefore not further discussed here.

4.2.2 Changes in consumption

Concerning changes in consumption, three major types of changes can be distinguished: the appearance of new types of consumption or new types of consuming equipment (Section 4.2.2.1); the replacement of existing equipment with modern (typically more energy efficient) versions (Section 4.2.2.2) and the proliferation of small equipment, e.g. in the form of chargers (Section 4.2.2.3).

4.2.2.1 New types of equipment

New types of equipment are being connected to the distribution grid. Major examples are heat pumps (in countries or regions with a shift to electric heating) and electric vehicle chargers. Almost all of these devices are connected to the grid through a power-electronic interface. The trend is towards active converters. These new devices are relatively-large loads on the low-voltage system, with sizes up to several kW. A comparison of heat-pumps for domestic use [75] gives a range from 2.6 to 10.7 kW. Heat pumps, for industrial use or for space heating of complete buildings, are available in sizes up to a few thousand kW.

Heat pumps are still rather uncommon in many countries, space heating being provided by non-electrical means (Natural gas in many European countries). Production surpluses due to wind and solar power may make electric heating more attractive than gas heating. Heat pumps have become so much more efficient that it should be assumed that they will dominate compared to resistive electric heating. This includes heat-pump-based water heaters and the use of heat pumps as part of district heating.

4.2.2.2 New versions of existing types of equipment

Equipment for heating, air-conditioning (HVAC: heating, ventilation and air conditioning), and cooling (refrigerators and freezers) is increasingly being equipped with adjustable-speed motors using active power-electronic converters. Such converters allow for the speed to be kept constant and adjusted to the need of the moment. This results in a big increase in energy-efficiency and has some other advantages as well.

In countries where electric heating has been common for much longer (like Sweden), a shift is taking place from direct electric heating (resistive heating) to heat pumps. Energy efficiency (less cost from the customer viewpoint) is also a driving force.

Other end-user equipment is also changing character: desktop computers are increasingly being replaced by laptop computers or tablets with a battery charger; CRT-based televisions are already to a large extent replaced by LED or plasma screens; incandescent lamps are in many countries being replaced very quickly by compact fluorescent lamps or LED lamps (see Figure 4.1).

The phasing out of the incandescent lamps started, among others, in the European Union in 2009. This led to a large number of energy saving lights being introduced on the market. The large reduction in price for LED lamps [76], [77] will further contribute to LED lamps becoming the major source of lighting in the not too distant future. Figure 1 shows the transition in use of light sources with domestic customers in the U.K. The phasing out of incandescent lamps is clearly visible starting in 2009. Instead, the number of energy saving light bulbs has increased a lot. By 2014 the incandescent lamp has nearly disappeared.

From a power-system viewpoint, a very important change is the increasing use of active-converters in the grid interface instead of the diode rectifier that was common in the past. No data is available on the extent to which active converters are taking over, but the impression is that the power supply for the majority of new equipment has some kind of active switching element instead of simply a diode rectifier.

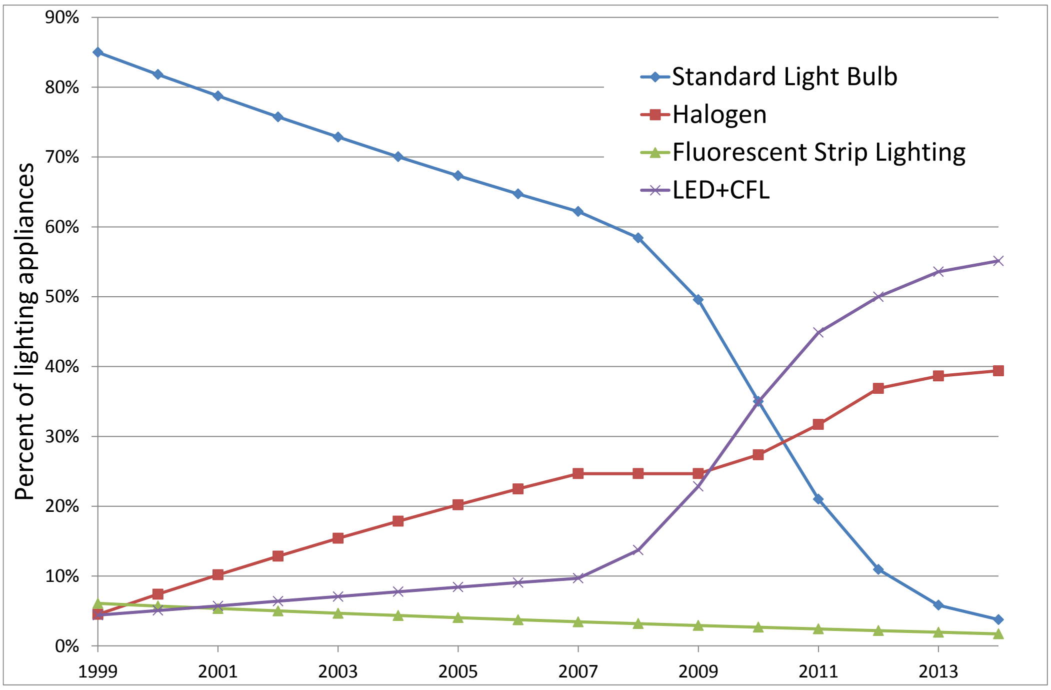


Figure 4.1 Replacement of incandescent lamps by other types of lighting in the UK, 1999 TO 2014 [79]

4.2.2.3 Proliferation of small equipment

The majority of devices with domestic and commercial customers connected to the power grid are nowadays small devices, each consuming a few watts of power. The main examples are LED lamps and battery chargers for all kind of hand-held devices, but also many larger devices consume a small amount of energy during most of the day (e.g. a television in stand-by or the clock on the microwave).

The increase in the number of electronic devices, including electronic lighting in UK households, is shown in Figure 4.2.

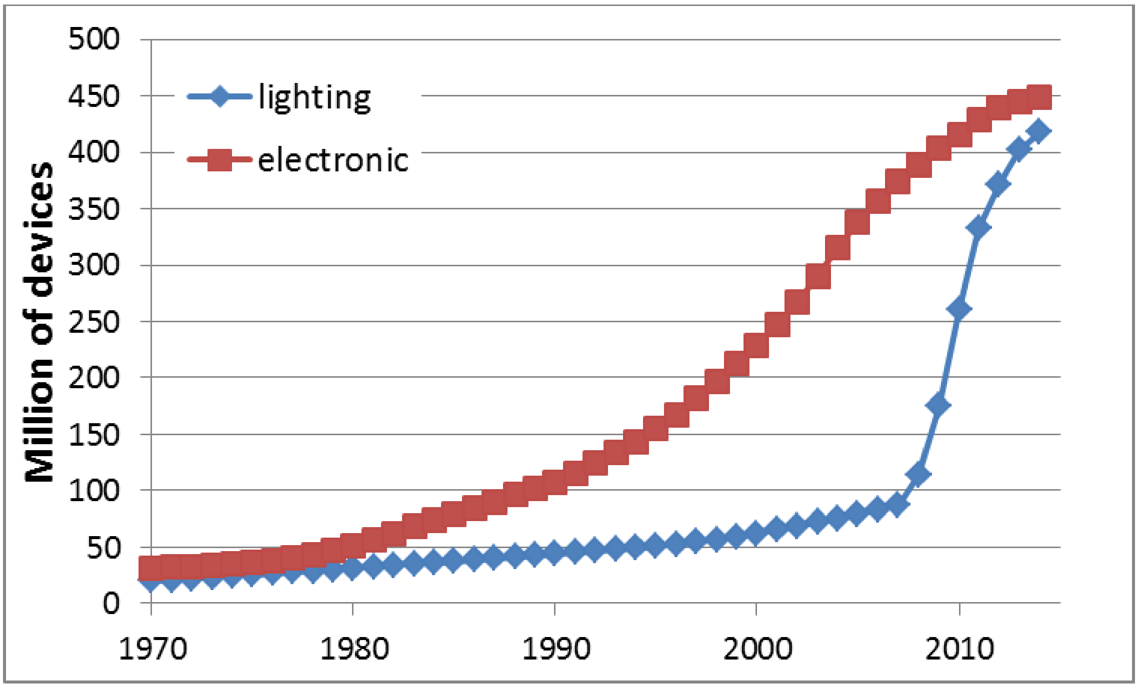


Figure 4.2 Number of domestic devices in the UK: electronic lighting (fluorescent, compact fluorescent and LED lamps) and other electronic devices (consumer electronics and computing)

4.2.3 Changes in the grid

Several changes are taking place in the grid as well: the replacement of overhead lines by underground cables (Section 4.2.3.1); the increased use of power-line communication (Section 4.2.3.2); the use of power electronics in the grid (Section 4.2.3.3); changes in protection and control (Section 4.2.3.4) and the expected increased use in smart-grid technology (Section 4.2.3.5).

4.2.3.1 Underground cables

Underground cables [1] at distribution level are common in many countries, although the level of cablification varies strongly between countries. According to [79], the percentage of underground cables is almost 90% in The Netherlands, but 10% or less in Lithuania, Ireland, and Finland. Figure 4.3 shows the trend of cablification in Sweden between 1998 and 2014 [79]. Both at low-voltage and medium-voltage, the percentage of cables shows a clear increasing trend. Note that in 2003 a new reporting method was introduced.Therefore the values before and after 2003 cannot be directly compared. However, the data show the same increasing trend.

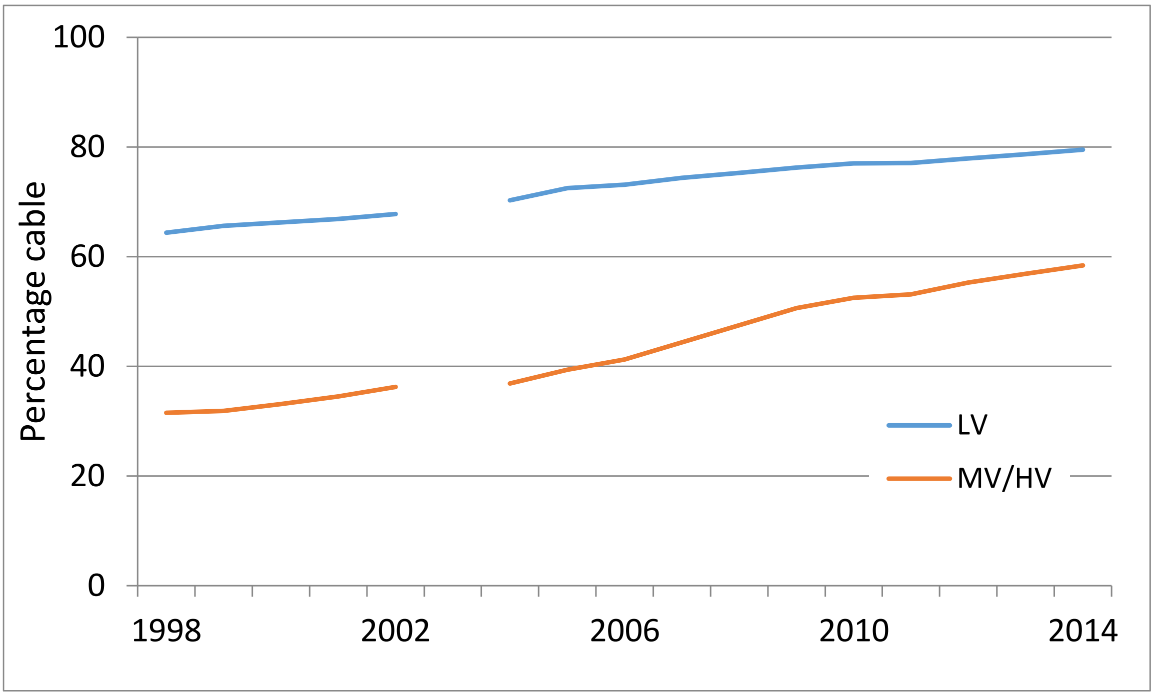


Figure 4.3 Increase of the percentage of underground cables in Swedish local networks [79]

4.2.3.2 Power-line communication

Smart meter technologies are being utilized in countries throughout the world. There are three main communication techniques for these low voltage connected meters: mobile communication networks, low-power radio, and power line communication (PLC). In Europe the frequency band (9 to 95 kHz) is used for power line communication by the network operators. In Japan and the United States frequencies up to 500 kHz are used. A good overview of power line communication used in different countries is presented in [80].

4.2.3.3 Power-electronic equipment in the grid

Power electronic converters are not only increasingly used for new production units and for new consuming equipment; they are also increasingly finding their place in the grid. The most visible examples are HVDC (mainly at the highest voltage levels) and SVC (more at medium voltage levels). Classically, these devices exclusively used thyristors ("grid-commutated converters"). Their modern equivalents (VSC-HVDC and Statcom) use active converters with IGBTs or GTOs ("self-commutated converters"). This has several advantages including a higher controllability. An overview of recent

[1] For completeness one should also consider cables at the bottom of a river bed or a lake or (in some exception cases) at the bottom of the sea. Electrically these have the same impact as underground cables, but there are differences in cables laying, failure rate and repair time. In the remainder of this report we will use the term "underground cables" or just "cables" to also include these other types.

publications on FACTS devices is presented in [81]. FACTS devices also have the ability to improve power quality; some recent publications are [82] - [86].

4.2.3.4 Changes in protection and control

Protection against abnormal and/or unwanted situations has been present in the grid from nearly the beginning. The developments are in the digitalization of protection equipment allowing for faster and more accurate detection of such situations, and in the increased amount of communication between individual relays. Another important trend is the appearance of anti-islanding protection with small production units connected to the distribution grid.

Modern protection and communication also allows for more advanced reclosing, restoration and reconfiguration schemes. The consequences of this are part of 7.

Power-system control, both manually and automatically, is finding its way to lower voltage levels. For example, distribution transformers with automatic tap-changers are now available from all major manufacturers. The consequences of this are part of 6.

Changes in protection and control have a significant impact on the number and duration of long and short interruptions. This will not be further discussed in this chapter.

4.2.3.5 Smart-grid technology

Several of the developments known under the term "smart grids" impact power quality: this can be intentional positive impacts; unintentional positive impacts (lesser probability of interference) or unintentional negative impacts (higher probability of interference). This is discussed in 5 for microgrids, in 6 for advanced voltage control, in 7 for feeder reconfiguration and in 8 for demand response. An overview of the impacts of smart-distributions technology on power quality, written by this working group and based on 7 through 9 is presented in [89].

4.3 CHANGES IN EMISSION

This section summarizes on-going or expected changes in emission for a number of disturbance types. Each section will address one type of disturbance; for some types, different changes are discussed in different subsections.

4.3.1 Voltage dips

Changes are expected in number of voltage dips as well as in characteristics of voltage dips.

4.3.1.1 Distribution cables

In distribution, the replacement of overhead lines by underground cables will result in fewer faults and thus in fewer voltage dips. However, faults still occur in cables as well. Since most cables at lower voltage levels are three phase, the number of three-phase voltage dips may actually increase. No data is available on this, so that it is not possible to make a quantitative assessment.

The number of voltage dips due to single-phase-to-ground faults is strongly dependent on the type of system grounding. For non-solidly-earthed systems, such faults will not cause any noticeable voltage dip. The overvoltages in the non-faulted phases could be a concern for cables at transmission levels and it may be decided to go over to solid-earthing together with increased cablification. This may lead to an overall increase in the number of dips.

The increased use of underground cables in distribution grids will result in more dips with a large phase-angle jump [90], [91]. However, as there are fewer faults in cables than in overhead lines, the total number of dips will be reduced. Note that what matters is the total number of faults (transient faults and permanent faults) as all of them cause dips. This is where cables very much outperform overhead lines.

The majority of dips, at most locations in the grid, are due to faults at transmission level. However, faults at distribution level often cause longer dips. Cablification at distribution level will thus result in less longer dips. As these are the most severe ones for equipment, it will constitute a significant improvement in quality of supply.

The kind of system earthing used in the medium-voltage distribution has a big impact here. When solid-earthing is used (as in common in North America), both single-phase and multi-phase faults cause a major dip for the end users and cablification at distribution level will have a major impact. When impedance-earthing is used at medium voltage (as is common in Europe), the situation is different. Single-phase faults will mainly result in a zero-sequence voltage, which will be removed by the delta-star-connected distribution transformer, and a low-voltage customer will at most experience a very minor voltage dip [91]. The result is that single-phase fault in the medium-voltage grids do not cause voltage dips for low-voltage customers and cablification will have less impact on the dip frequency. As cables have a higher percentage of two-phase and three-phase faults than most overhead lines, the number of dips experienced by end-users may even increase when cables start ageing.

4.3.1.2 Fault prevention

Improved methods for finding potential faults before they occur will result in fewer faults and therewith in fewer voltage dips. For overhead-line systems, the majority of faults might still be due to lightning strokes and those cannot be detected before they occur. It is however possible to anticipate weather-related faults and sensitive customers may be temporarily moved to a feeder with less expected faults or long exposed overhead lines may be temporarily taken out of operation. It is also possible to operate certain sensitive customers in island, assuming the proper on-side generation is available, during periods of high expected dip frequency.

Methods for early detection of incipient faults, e.g. through partial discharge detection [92] or detection or water treeing will further reduce the number of dips in cable systems [93].

4.3.1.3 Transmission cables

Cables at transmission level are being installed as well, but as a percentage of the total length it remains a negligible amount. The impact on voltage-dip statistics will therefore be negligible.

4.3.1.4 Equipment in the grid

Fault-current limiters will reduce the severity of the dips upstream of the limiter, but will make the dip deeper and possibly also longer downstream of the limiter. However, there is no indication that these devices will be used at a large scale within the near future. With some exceptions, there impact on dip statistics is therefore expected to be limited.

Dynamic voltage restorers will significantly reduce the severity of the dip downstream of the restorer. Some of these devices have been successfully in operation for several years already. However, their installation remains limited to one specific customer. Furthermore, there are no indications that any network operator plans to install them in the grid to create an overall reduction in number of dips experienced by the customers.

4.3.1.5 Distributed generation

The (increasing) presence of distributed generation in MV and LV distribution networks and their impacts on fault level, protection systems and strategies and voltage control will also influence the characteristics of dips experienced in those dips.

The presence of distributed generation will result in more shallow dips (for dips due to faults upstream of the generator and the customer downstream of the generator) [61], [94] but this may require additional steps in the protection coordination with slower fault clearing as a result. Slower fault clearing will cause longer dips.

The impact of distributed generation on the number of voltage dips will further be discussed in Section 4.5.1.

4.3.1.6 Equipment starting

The shift from using directly-connected induction motors to adjustable-speed drive (ASD) applications is expected to continue. According to the International Energy Agency, roughly 50% of all generated electrical power is consumed by Induction Motors (IM) [95], while recent studies in [96], [97], estimate that around 25% of the newly installed machines are supplied from ASDs. This means that less voltage dips due to motor starting can be expected. This will be most noticeable in industrial installations, but also in agricultural installations often connected to a weak rural network, which will experience fewer motor-starting dips.

Starting of drive-controlled motors is expected to lead to less severe dips than starting of induction motors, as ASDs typically allow controlled start-up conditions ("soft starting") and as a high starting current would require overrating of the ASD. However, the harmonic emission might be high during the starting of the motor, resulting in a new type of phenomenon, preliminary named as a "short-duration distortion due to device starting". Short periods with high levels of harmonics have been mentioned for several years in standards, e.g. IEEE Std. 519-1992 and Chinese standard GB/T 14549-1993.

It is stated in [98] that the number of "high-inrush-current devices" connected to the distribution grid increases. Such devices, like electric heat pumps or air-conditioning compressors, will cause voltage dips with starting. This assumes that such devices are equipped with direct-driven induction motors. The shift to power-electronics driven motors will again reduce the number of dips due to motor starting.

Note that dips due to device starting are of a different character than the dips due to faults, the ones normally studied. Equipment starting dips are of longer duration, more shallow, and more of local character than dips due to faults. These dips typically affect fewer customers than due to short-circuits, so the effect of ASDs on the numbe of voltage dips is expected to be very limited.

4.3.1.7 Single-phase short interruptions

Single-phase fault-clearing and reclosing will result in "single-phase short interruptions" or dips down to 50% in two phases behind a DYN-connected distribution transformer [91]. Single-phase short interruptions can have different (including more severe) impact on equipment than three-phase interruptions. IEC 61000-4-30 classifies such events as dips, but with zero residual voltage. However, in some countries these are classified as interruptions by the regulator. Additional characteristics are needed to get information that may be necessary to make the link with equipment performance. Possibly, a new type of event should be defined, somewhere in between a dip and a short interruption.

4.3.2 Voltage swells

Replacement of long overhead lines by underground cables in low-voltage networks will reduce the number of voltage swells in the healthy phases during single-phase faults. No information is available on the potential impact of this on voltage-swell statistics.

Underground cables have a much higher capacitance and somewhat lower inductance than overhead lines. The replacement will thus result in higher operating voltages for the customer, with the margin towards the overvoltage limit becoming smaller. A small rise in voltage magnitude will thus more often result in this limit being exceeded. This will result in more voltage swells, due to remote single-phase faults as well as due to load switching.

4.3.3 Harmonics

4.3.3.1 Power electronics in the grid

Until fairly recently, HVDC was considered as a serious source of harmonics at transmission level. Consequently, harmonic studies were performed standard with new HVDC connections. Also, all such links were equipped with harmonics filters, typically for harmonics 5, 7, 11 and 13.

The shift from line-commutated HVDC to self-commutated HVDC (from "passive converters" to "active converters") will impact the emission in two ways: the emission of low-order harmonics (5 and 7, 11 and 13, 17 and 19, etc) will become less. Meanwhile the emission at higher frequencies and possibly also at interharmonics will increase.

However, HVDC links are known as sources of harmonics and a harmonic study will be most likely be made with every new installation. Appropriate filters will be installed when needed. No surprises are expected here and no growth in voltage distortion due to these installations is expected.

FACTS devices are treated in a similar way as HVDC where it concerns their connection to the transmission grid. Harmonic requirements are part of the specification and harmonic studies a common part of the connection of the device. Connection of such devices is therefore also not likely to result in a large increase in harmonic levels. However, if power-electronic devices become more common at medium voltage levels, harmonic connection studies may become less common and harmonic voltage levels may increase. Harmonic emission in relation to FACTS devices are discussed in [99]. No reliable estimations are available of the expected amount of such devices in the future grid. Therefore, it is not possible to estimate how much this will impact future harmonic distortion levels. It is recommended to include harmonic distortion in research studies after the use of power-electronics in distribution grids.

4.3.3.2 Equipment connected to the grid

For the classical harmonic frequencies (low-order odd harmonics) the emission from most new types of production equipment is low. Measurements for PV inverters are presented in [100], [101]. Measurements for wind turbines are presented in [102], [103], [104]. An important issue related to the connection of renewable electricity production concerns its diversity. Electric consumption has a high level of diversity based on individual schedules. Consequently, equipment like electric water heaters, televisions, electric ovens do not typically operate at exactly the same time. However, distributed generation resources like photovoltaics have little diversity because the sun shines over a given area the exact same hours of the day.

Heat pumps and electric vehicle chargers may have a more classical spectrum with high levels of low-order odd harmonics. Information on harmonics from heat pumps is presented in APPENDIX E. A study on harmonics from EV changers [105] concluded that the harmonic emission from these chargers is small.

Some compact fluorescent and LED lamps show a heavily distorted current. It has therefore been a concern that the mass introduction of those lamps would result in large increases in voltage and current distortion. A number of studies have been carried out to investigate this [106], [107], [108], [109], [110], among others, with the main conclusion being that the increase in distortion is even in the worst case minor and in some cases the aggregation effects introduced by the lamps lead to a decrease in harmonic levels. After replacing 576 incandescent lamps with a combination of LEDs and CFLs in a hotel in Sweden, a slight increase could be observed for some individual harmonics in some phases while there was a decrease in other phases as seen in Figure 4.4 [108]. This trend was observed for harmonics up to harmonic order 40. Similar conclusions were drawn from measurements of the harmonic currents before and after the replacement with a group of 12 domestic customers [109]. The impact from other devices can hence not be ignored and even though the lamps add harmonics, the effect will, due to aggregation in the mixed-load environment, not be an overall increase in harmonic magnitude for the installation.

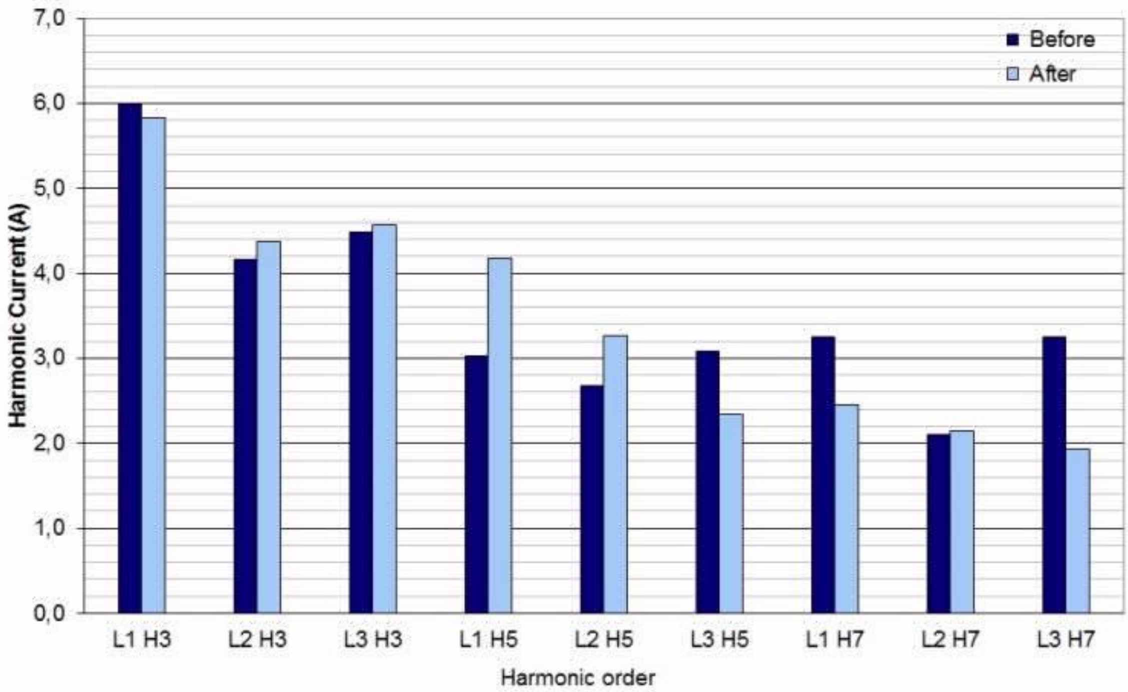


Figure 4.4 Harmonic current emission from a medium-size hotel before and after replacement of incandescent lamps by compact fluorescent and led lamps [110]

It is especially interesting to observe the small change in the third harmonic. It is this harmonic that is largely due to single-phase equipment and not much impacted by three-phase equipment. An increase in harmonics due to non-incandescent lamps would be expected to be visible especially for this harmonic. As the change in third harmonic is small, it is concluded that the replacement of lamps is not expected to result in any significant increase in harmonic distortion.

The situation will be different in new installations with a majority of or with only lamps. Those installations will supply many more lamps from the same cable or transformer than similar installations with incandescent lamps because of the lower energy consumption per lamp. There has been experience in this with large numbers of magnetic-ballast fluorescent or compact fluorescent lamps. This resulted in a higher cross-section of the neutral conductor. There is as yet no experience in installations with large amounts of LED lamps, where the number of lamps per cable or transformer would be even bigger than with fluorescent lamps. The resulting harmonic distortion is very much dependent on the cancellation between lamps in a large installation. No experience on this is available and studies on this are recommended, especially measurement-based studies as it remains unclear if the available models give sufficiently accurate results.

Measurements presented in [40] show that the harmonic emission from LED street lamps is similar to the harmonic emission from other common types of street lamps. Replacement of those other types by LED lamps will thus not result in an increase in harmonic levels; unless there is a resonance issue that is impacted by any difference in capacitance between the lamps (see Section 4.5.3.4).

However, the energy consumption of LED lamps is less, which means that more lamps can be supplied from the same transformer, with higher harmonic currents through the transformer as a result. No studies after this were found and no other experience on this subject was available in the working group.

In [111] the trend of harmonics from computers has been investigated during a number of years (2002-2008). Measurements have been taken during so called LAN parties where many people gather and play computer games. The conclusions from the measurements are that there is a clear trend of decreasing levels of harmonics (in relation to the fundamental component) from computers as seen in Figure 4.5. Newer computers may even have lower emission, but no data is available on that at the moment.

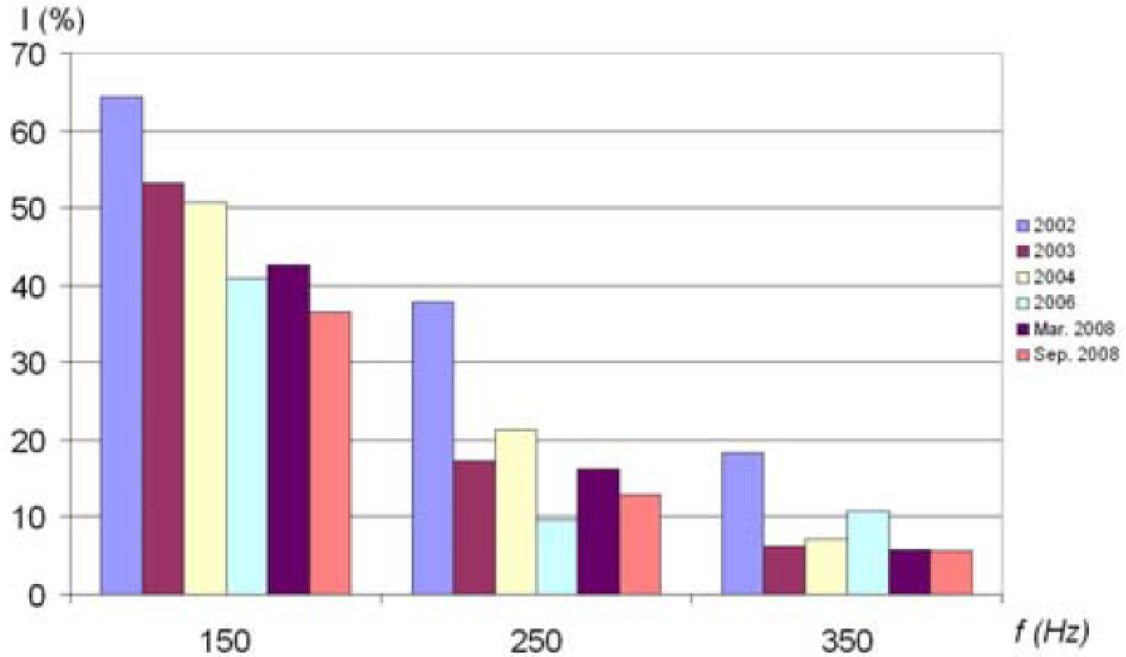


Figure 4.5 Change in harmonic currents 3, 5 and 7 (as a percentage of the fundamental) for large numbers of state-of-the-art computers, 2002 through 2008 [111]

Not only the change in magnitude of the current harmonic emission, but also possible changes in its phase angle should be considered for assessing its impact on the voltage distortion [110], [112]. In some cases, for an aggregate of devices the magnitude of harmonic current does not change but its phase angle does. That will change the aggregation with other equipment and its impact on the voltage distortion, which can be negative or positive. Even an increasing magnitude of harmonic current can have a positive impact on the corresponding voltage harmonic as long as the phase angle shift leads to a voltage drop over the network impedance that reduces the background harmonic voltage. It should be noted that the impact has to be studied individually for each harmonic order. While the harmonic current for one order can decrease the respective voltage distortion, another one can increase it [113].

A measurement has been performed at the terminals of a single family house. The results for the 5th harmonic are shown in Figure 4.6. In a first experiment, ten incandescent lamps, connected to one phase, were switched on and off. The green symbols show that no change in the harmonic current emission occurs, as these lamps emit only very small levels of harmonics. Afterwards all the incandescent lamps have been replaced by compact fluorescent ones and the experiment was repeated. Now the magnitude of the harmonic current did again not change significantly, but a closer look reveals that instead of magnitude the phase angle has shifted by about 180°. This shift indicates a dominance of the CFL emission. This can have a positive impact on the harmonic voltage as long as the dominance does not occur globally in the network.

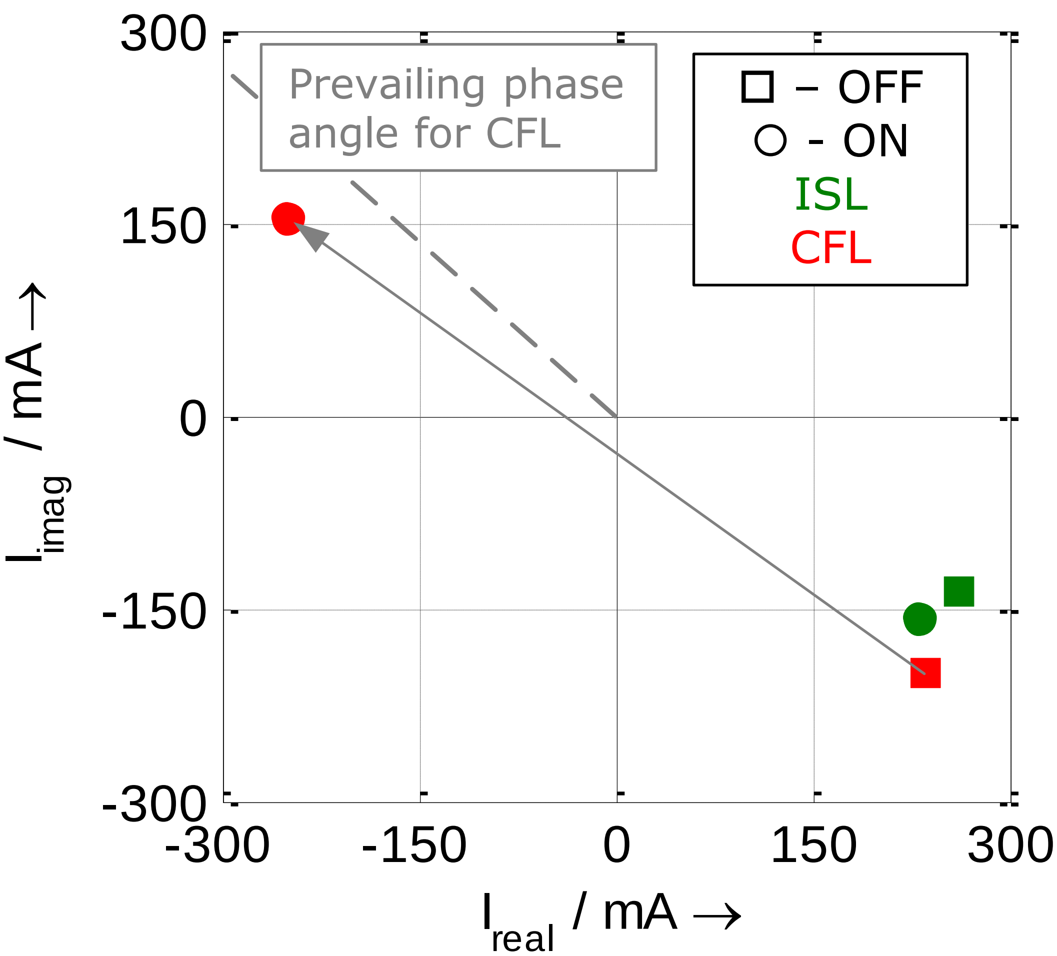


Figure 4.6: Fifth harmonic current at a customer's terminal

A field study with electric vehicle chargers has shown that even an increasing magnitude of current harmonics can have a positive impact on the voltage harmonics as long as the phase angle shifts in a suitable direction. Figure 4.7a shows the stepwise connection of nine electric vehicle charges to one phase of a feeder in a public LV network. The magnitude of fifth harmonic current increases by about 4 times, but it shifts from the 4th to the 3rd quadrant. The time characteristic of the voltage harmonic magnitude at the end of the feeder (Figure 4.7b) shows a reduction, which has a minimum value when all of the EV chargers are connected. This only happens when the background distortion is not already globally dominated by the harmonic emission of such chargers. More details can be found in [113]. However, it should be noted that the 3rd harmonic increased both in harmonic current and voltage during this field study.

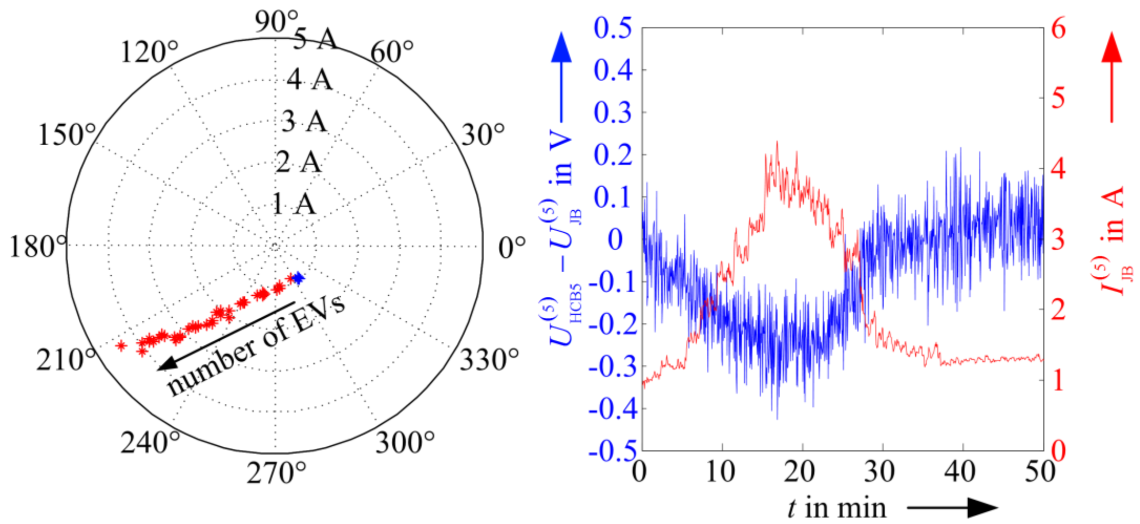


Figure 4.7 Fifth harmonic current at the beginning of a feeder (a) and 5th harmonic voltage at the end of a feeder (b) with consecutively connection and disconnection of nine electric vehicle chargers

A similar phase angle shift for the electric vehicle chargers in the example above can be seen for the 5th harmonic of small PV inverters. Figure 4.8 shows a measurement obtained from an LV grid with more than 50% solar power in relation to the rating of the distribution transformer. A significant phase angle shift, together with an increase of the harmonic current, can be identified for the 5th harmonic.

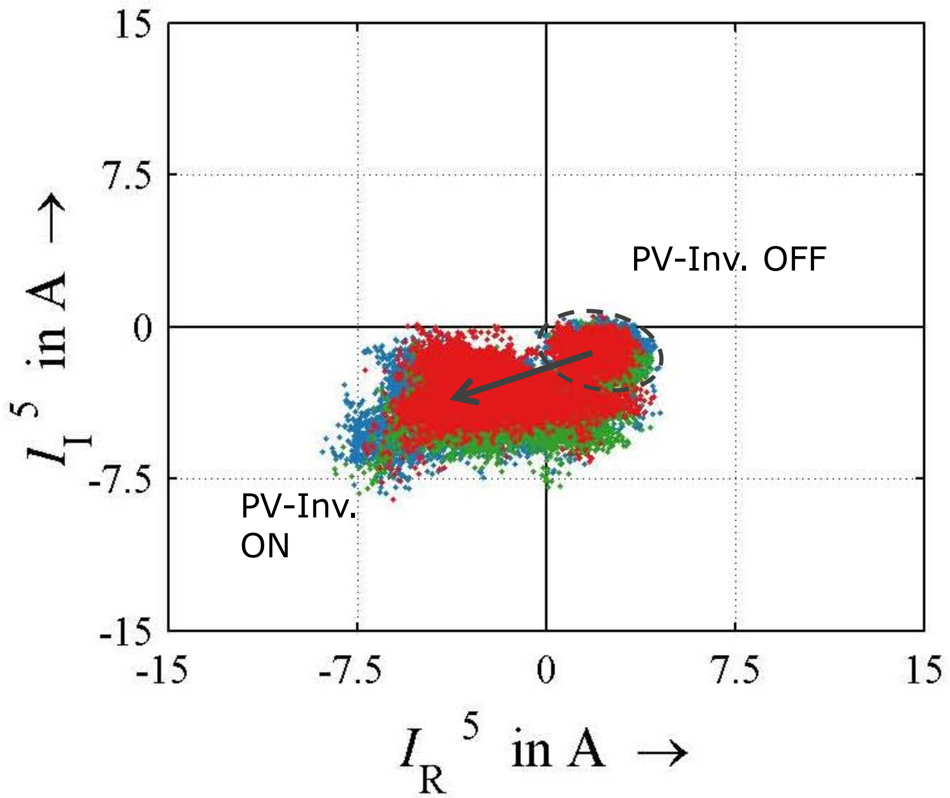


Figure 4.8 Changes in fifth harmonic current (magnitude and phase angle) due to the large-scale introduction of solar power in a distribution grid

These measurements show that large-scale integration of larger equipment (electric vehicle charges, photovoltaic inverters) could result in an increase in harmonic voltage distortion. Further studies on this are needed to quantify the impact and to estimate to which extent this results in an increase of the probability of interference.

4.3.3.3 Impact of the background voltage

Active converters react differently to voltage distortion than passive (diode or thyristor) converters. So-called "secondary emission" (driven by the background voltage distortion) will have to be considered. The role of the control system makes the interaction often unpredictable and even instability a possible outcome. The terms "*primary emission*" and "*secondary emission*" have been introduced to describe this [114], where primary emission originates in the device under study and secondary emission originates elsewhere. The secondary emission can also be a major contribution at the point of connection between a wind park and the grid [66], [102].

The differences between primary and secondary emission are explained in APPENDIX D, which also proposes a definition of the terms "primary emission", "secondary emission" and "*harmonic interaction*".

It has been known since long that the harmonic emission from a device depends on the background voltage distortion, e.g. [115]. For classical converters the relations were rather easily understood although often hard to model and quantify [116], [117]. If the voltage distortion due to the connection of a device results in a reduction of the current emission then there would be a negative feedback which would ensure stability.

With active power-electronic circuits finding their way into equipment, the impact of the background voltage distortion on the emission becomes much more complicated. Examples of this are shown in [118], [119].

4.3.3.4 Trends in harmonic voltage distortion

The harmonic voltage distortion has been recorded in several countries for a number of years (up to 20 years) at a large number of locations (hundreds or more in some countries). The available data is growing quickly and trends should become available soon. An overview of available data is summarised in APPENDIX G. A reducing trend is visible for some harmonics at some locations, but the available data is insufficient to draw any strong conclusions from this.

Changes in the voltage distortion have been observed in a number of countries.

An Austrian measurement campaign has shown a noticeable reduction in voltage distortion, at harmonic 5 [120] during the period 2000 through 2008. Harmonics 3 and 7 did not show any noticeable change, whereas harmonics 11 and 13 at LV appear to show a clear increasing trend but remain constant at MV. A measurement campaign in Switzerland [121] showed that voltage distortion for triplen harmonics (9, 15 and 21) is much higher compared to the limits than other harmonics. Especially harmonic 15 exceeds the limit at several locations. This harmonic also shows an increasing trend and the number of sites where the levels exceed the limits is increasing as well. A long-term power quality survey in Australia indicates a decreasing trend for voltage THD [122]. Measurements in the Netherlands, between 1998 and 2013, show a decrease in THD up to 2009, after which the levels remains about constant. A sudden, stepwise increase in 15th harmonic voltage was observed between 2007 and 2008 [123], [124]. In Brazil, HV measurements taken at the PCC of Wind Parks, between 2015 and 2016, have shown that the CP95 voltage harmonic levels also remain about constant.An overall increase in voltage distortion was reported with a recent power quality survey in the US [125]. No convincing explanation for any of the trends has yet been given.It is strongly recommended that more data is made available to the research community, to identify trends on harmonic voltage distortion. Any significant increase in levels would be a cause for concern and further studies.

4.3.4 Interharmonics

Interharmonics are spectral components at frequencies that are not integer multiple of the system fundamental frequency. Subharmonic are interharmonics with frequencies lower than fundamental frequency (60 or 50 Hz) [126], [127], [128].

Increased levels of interharmonics will be expected in future distribution and transmission grids. The increase is a result of new sources: distributed generation devices (experimental results on some types of wind turbines and PV inverters are reported in [66], [103], [129] and high efficiency industrial equipment [130] – [135], commercial (HVAC) and residential (Inverter air conditioning, washing machines, refrigerators, etc.) equipment.

4.3.5 Subharmonics

Several of the mechanisms that result in the emission of interharmonics, will also result in interharmonics with frequencies less than 50 of 60 Hz, i.e. subharmonics. Reference [66] shows such emission for modern wind turbines.

No information was found on the specific emission of subharmonics.

4.3.6 Supraharmonics

The term supraharmonics refers to all frequency components in the frequency range between 2 kHz and 150 kHz [136]. There are several sources that result in an increase of emission of supraharmonics; they will be briefly discussed in the forthcoming sections.

4.3.6.1 Power-line communication

Power-line communication (PLC) is an important source of supraharmonics and the highest levels are typically due to PLC. Other potential interference in which PLC is involved, is discussed elsewhere, here we only consider PLC as a source of emission [137].

Two important properties of the emission from PLC should be mentioned here:

- The resulting voltage distortion is according to EN 50065 allowed to be up to 134 dBμV (about 4 Volt) for frequencies up to 9 kHz and decreasing after that [136]. This is significantly higher than what is normally obtained due to emission from equipment connected to the grid (production or consumption).
- The emission is often intermittent; the highest levels are only obtained during a small fraction of the day. However, intermediate levels can occur during a substantial fraction of the day. An example is shown in Figure 4.9. Further, the use of hourly metering and other communication might increase the period during which high levels are present.

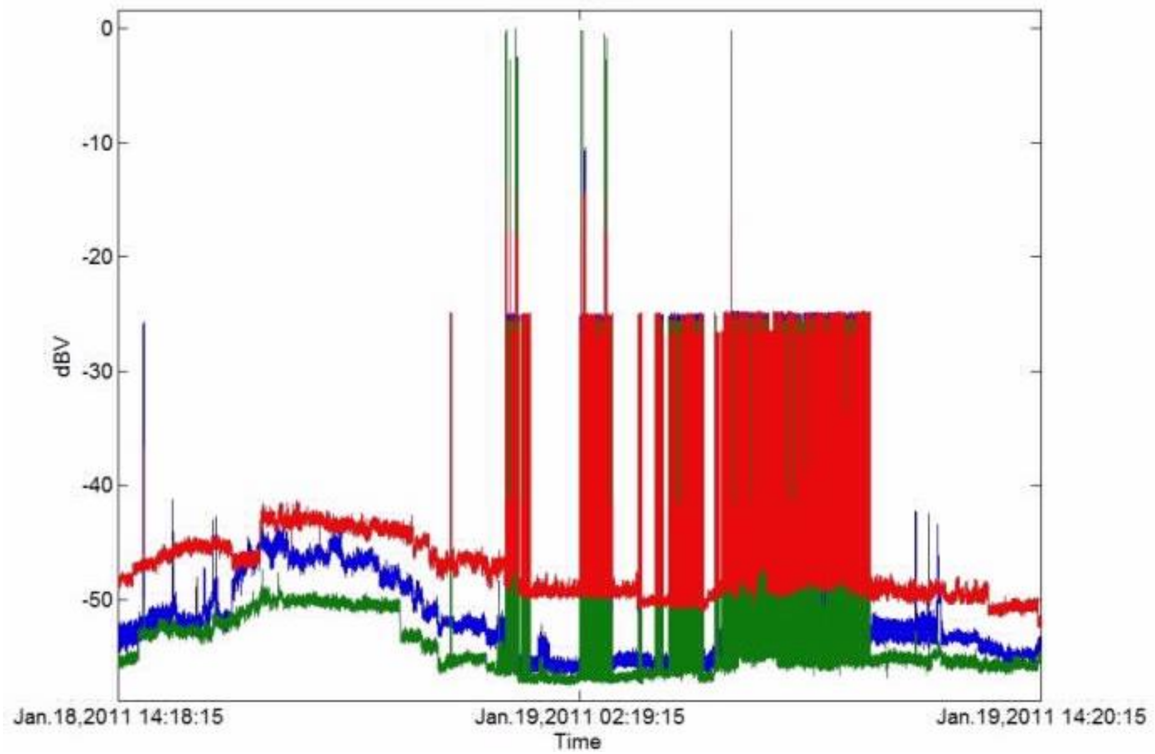


Figure 4.9 Voltage distortion at the communication frequency of a PLC device (in the supraharmonic frequency range) during a 24-hour period [70]

4.3.6.2 Equipment in the grid

VSC-HVDC and FACTS-based active converters emit supraharmonics at the switching frequency (typically a few kHz) and its integer multiples. The well-documented problems with cable terminations due to the Eagle-Pass installation occurred due to emission at a frequency of 12.4 kHz [138].

Grid-size battery storage is connected through an active converter and is also expected to be a source of supraharmonics. However, no measurements were found to confirm this suspicion.

4.3.6.3 Production units

Measurements of supraharmonic emissions from PV inverters are presented in [71], [100], [139]. PV is further discussed in the technical brochure by CIGRE JWG C4/C6.29 [140].

Wind power is expected to have emissions in this frequency range, but very limited measurements are available on this. Some of the measurements presented in [141] show significant emissions from wind turbines at frequencies somewhat above 2 kHz.

4.3.6.4 Consumption equipment

A large part of new devices result in increased emission of supraharmonics. This is discussed, among others, in Chapter 2 of this report.

The emission in this frequency range is shown for fluorescent lamps in [69], [142]; for LED lamps in [38], [143] and for EV chargers in [144], [145]. The propagation of supraharmonics is studied in [114], [146], [147]. The conclusion from both measurements and simulations is that the emission from devices mainly spreads to neighbouring devices and not to the grid. Additional study of the propagation of supraharmonics is needed. It will also require the development of new models for power-system components. For example, the coupling between primary and secondary side of transformers has to be considered.

The recent advances in solid state switching devices have provided an easy means to convert between ac and dc voltages for various applications. Small electronic devices in the past had to use small transformers in its charger to step the voltage down to a manageable level. This is no longer necessary because solid state technologies are able to convert to the lower voltage level without the heavy magnetic device. Similarly, it has become relatively easy to convert a dc voltage source to an ac voltage source by using solid state switches.

4.3.7 Slow voltage variations

New consumption (electric vehicles, electric heating) will increase the voltage variations and may cause undervoltages. At the same time, new production connected to the distribution grid will increase the risk of overvoltages. The latter issue is discussed in detail in the literature on distributed generation. This will not be further discussed here; however, an overview can be found in [61], [62].

4.3.8 Fast voltage variations

A distinction should be made between three types of fast voltage variations:

- Individual steps in voltages, taking place at a time scale well below one second, "individual rapid voltage changes"
- Continuous variations in voltage magnitude and phase angle at time scales below a few seconds, "continuous rapid voltage changes" or "flicker"
- Continuous variations at time scales between a few seconds and a few minutes. There is no standard term for this yet, but the term "very fast variations" has been proposed.

Flicker from wind turbines can be neglected. The tower shadow effect results in some level of flicker for induction machines, but these have become a minor fraction of the turbines. Other types of wind turbines do not show this effect. Variations in wind speed occur at a longer time scale and the resulting voltage magnitude variations do not cause any noticeable light flicker.

Flicker from PV can also in most cases be neglected. However, cloud movements and multiple panels connected to the same low-voltage feeder may cause some noticeable flicker. This is further discussed in the forthcoming report by CIGRE JWG C4/C6.29 [140].

Variations in wind speed and solar irradiation cause variations in production at timescale that is too slow to result in flicker but too fast to be considered in the slow voltage variations (with averaging periods of 1 minute or 10 minutes). These are called "very short variations" in [148], where it is shown that voltage variations in the range from 1 second to 10 minutes are expected to increase in magnitude and to change in character with massive introduction of wind and solar power in low and medium-voltage networks. It is recommended that these variations are further monitored and that suitable power-quality characteristics are developed to quantify the level of variations.

Also this is further discussed in the report by CIGRE JWG C4/C6.29 [140].

4.3.9 Transients

The use of synchronized breakers with capacitor banks will reduce the number of switching transients.

The shift from overhead lines to underground cables will reduce the number of lightning transients. However, the increased use of transmission cables could result in an increase of the number of switching transients due to cable energizing. Amplification of the switching transient can occur when cables are present at different voltage levels. For example: the switching of a cable at 400 kV could excite a resonance involving the cables at 130 kV, with a high amplitude switching transient as a result.

4.3.10 Voltage unbalance

Single-phase production units, mainly PV, will increase unbalance in the low-voltage network. This mainly involves solar panels. The main concern here is that a majority of them will be connected to the same phase low-voltage feeder. As all of them will be exposed to about the same insolation, there will only be limited aggregation effects. Several publications address the increase in unbalance due to the connection of solar power through single-phase inverters [105], [149] – [156], [263].

In European distribution networks there is the possibility to distribute the units over the phases, in North-American distribution networks (with single-phase laterals) there is no such possibility. A stochastic model is used in [263] to estimate the increase in voltage unbalance with random distribution of the inverters over the three phases. Results are presented for a sub-urban and for a rural network, both in Northern Sweden. High percentiles of the rise in unbalance are shown for the customers connected to the rural network in Figure 4.10 and for the suburban network in Figure 4.11 For a given number of customers with PV, a probability distribution function of the unbalance contribution from PV is obtained for each customer. From this distribution function, the expected value, 90th percentile and 95th percentile are obtained, for each customer (subscript "exp", "90" and "95" in the figure legend). Next the average and maximum values are taken over all customers (subscript "mean" and "max"), resulting in the six indicators shown in the figures.

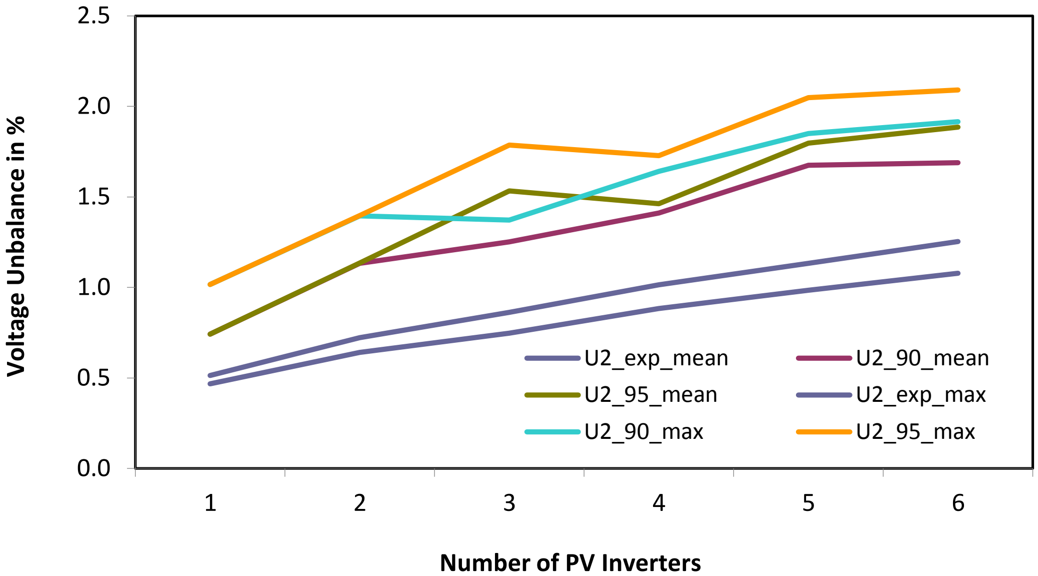


Figure 4.10 Stochastic voltage unbalance indicators for customers connected to a rural low-voltage network, as a function of the number of customers with PV [263]

The plots show a noticeable increase in voltage unbalance. However, the increase flattens of rather quickly for increasing number of customers with single-phase-connected solar power, when quantified as a high percentile.

Large single-phase loads (like electric vehicle chargers and heat pumps) will also increase the unbalance. There will be less similarity in time between the loads, compared to solar power. However, for the same reason, spreading them over the phases will have less impact on the worst-case unbalance.

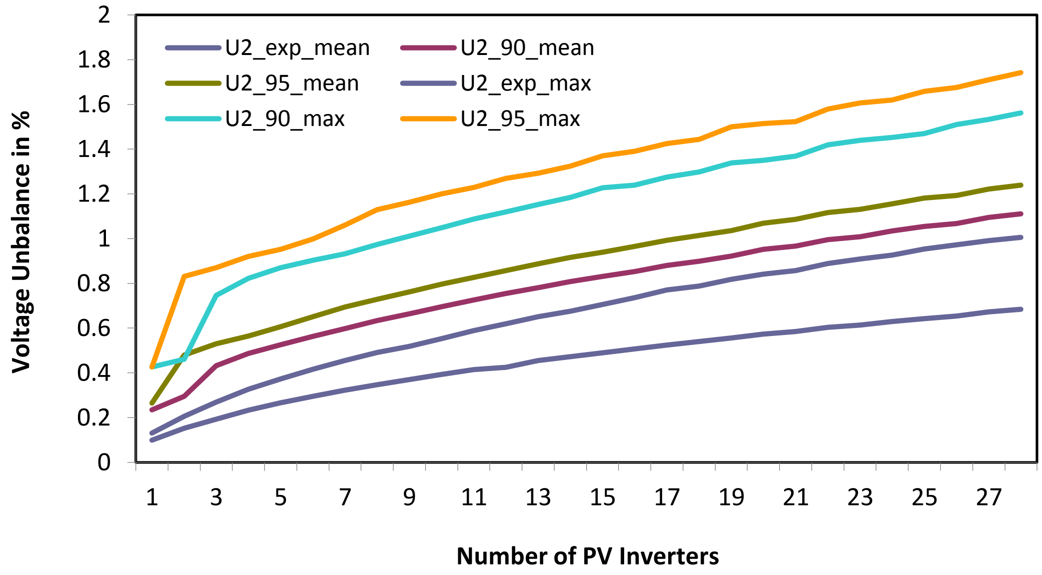


Figure 4.11 Stochastic voltage unbalance indicators for customers connected to a suburban low-voltage network, as a function of the number of customers with PV [263]

Moreover as firm generation plants are taken off line, changes in load flows may occur in the transmission system. Consider the case study in Figure 4.27, in Section 4.5.10.2, where firm generation is retired from substation F. The load doubles on the untransposed line between substations E and F. The result is an increase in the voltage unbalance to around 1.22% at station F.

Mitigation of voltage unbalance really needs to take place at the distribution and transmission planning levels to ensure that new generation sources are being placed in service in a balanced way. In addition, transmission system planners may need to verify that load flows don't cause voltage unbalance on long untransposed transmission lines.

4.3.11 Frequency variations

The large-scale use of wind and solar power, connected through power-electronic interface, will result in operational states where the total amount of inertia available to the system is small. This will cause larger variations in frequency during normal operation, but also larger drops in frequency when production units trip.

The rate of change of frequency due to an unbalance ΔP in an interconnected system is:

$$\frac{df}{dt} = \frac{f_0}{2} \times \frac{\Delta P}{E_{kin}}$$

Equation 4.1

where E_{kin} is the total kinetic energy in rotating mass accessible to the system and f_0 is the nominal frequency. The reduction in kinetic energy ("inertia") will result in faster changes in frequency and thus a wider spread of frequency around the nominal frequency.

The hourly-based electricity market results in large frequency shifts around the hour.

The increase in frequency variations is discussed widely as a concern for transmission system operation, but has not been discussed as a power-quality issue. The strong emphasis on this by the system operators will likely mean that frequency variations will not increase much. The existing variations are only in rare cases a concern for network users. Therefore even in the future, frequency variations in the interconnected grid do not have to be considered in power-quality studies.

Another possible development is an increased use of controlled island operation of small parts of the grid. This could give a significant increase in frequency variations, which is discussed in 5.

4.3.12 DC components

DC injection can be generally divided into *short-term injection* during events, e.g. during the inrush effect of transformer switching or during faults and *continuous injection*, e.g. caused by the operation of power electronics. This section is only focused on the continuous injection.

Further studies are needed on the dc injection during events, where one of the issues to be addressed is how to define the apparent paradox between events (being short duration) and dc components (remaining the same forever)

Up to now only little research exists about the topic. Papers [90] and [91] contain comprehensive discussions about causes and effects of DC currents. Typical mentioned effects are: saturation of network elements with magnetic cores (e.g. transformers), increasing corrosion and malfunctions of protection devices. DC injection from inverter-based equipment is mainly caused by asymmetries in manufacturing or faults inside the inverter. Particular attention has to be paid to devices with higher power rating and transformer-less topologies. Common examples for such devices are PV inverters, EV chargers, inverters in storage systems or active frontends for drives.

Consistent emission limits do not yet exist, but increasing attention is paid to continuous DC components by the standardization bodies. A comprehensive overview of emission limits for dispersed generation in LV networks, which are presently applied in different countries, is provided in [159]. The technical report also indicates the importance of limiting DC injection from inverter-based generation.

Most publications about measurements of DC currents are dedicated to PV inverters. In [160] the measured DC current of five different inverters with rated power between 2kW and 5kW varies between 2.4mA and 180mA. [161] has found for 12 inverters with power ratings between 2.3kW and 5kW a DC current in the range of 60mA and 225mA. At TU Dresden, the DC component resulting from spectrum analysis of three PV inverters (rated power between 5kW and 10kW) has been measured in the range between 40mA and 100mA. Furthermore, in the same laboratory the DC current of eight different EV chargers (single phase, 3.7kW) has been measured with magnitudes between 20mA and 200mA.

Further research in this field is strongly needed, particularly towards consistent measurement methods as well as propagation and aggregation of DC currents. As a result, reasonable and appropriate emission limits need to be developed.

4.3.13 Sub-synchronous resonances

Sub Synchronous Resonance (SSR) is related to the resonance conditions in an electric power system where the transmission system exchanges energy with turbine-generator units with shaft torsional mode natural resonance frequencies that are lower than the synchronous frequency [162]. Until recently, this phenomenon was mainly associated to steam turbine-generator units that are interconnected to transmission lines compensated by means of series-capacitor banks. The first SSR resulting in shaft failure of units at Mohave Plant in Southern California occurred in 1970 [163]. Different solutions that are proposed to mitigate SSR include Thyristor Controlled Series Capacitor (TCSC) [164] and physical damping filters [165].

With the introduction of power electronic converters in wind turbines, variable speed wind turbines of type DFIG are susceptible to SSR when radially connected to series-capacitor compensated transmission lines. In an electric power system, the wind turbine can be seen as an equivalent impedance which is depending on the modulation frequency [166]. Risk of SSR is present when the real part of the equivalent impedance becomes negative. In 2009 in Texas, a severe incident involving a wind farm and series-capacitor bank caused the failure of a crowbar circuit in the wind farm [167].

4.3.14 Geomagnetically-induced currents

No major change in emission of geomagnetically-induced currents is expected.

4.4 IMMUNITY TO DISTURBANCES

Changes are also expected in the immunity of equipment to voltage quality disturbances. Decreased immunity can, just like increased emission, give an increased probability of interference.

The structure of this section is the same as the previous section: each type of disturbance is discussed in a separate subsection. The relation between the equipment types and the disturbance types is given in Table 4.1.

Table 4.1 Types of equipment discussed under the different types of disturbances

Equipment	Voltage dips	Voltage swells	Harmonics	Interharmonics	Subharmonics	Supraharmonics	Slow voltage variations	Fast voltage variations	Transients	Voltage unbalance	Frequency variations	DC components
PV inverters	X											
Production units	X										X	
Active converters	X	X	X	X	X	X	X	X	X	X	X	X
LED lamps				X				X				
Power line communication						X			X			
Transformers						X			X			
Rotating machines						X			X			
Cable insulation						X						
Instrument transformers						X						
Three-phase converters										X		

4.4.1 Voltage dips

4.4.1.1 Fault-ride-through

This is a special case of dip immunity, where the aim is to avoid mass tripping of production units after a dip originating in the transmission system. Pure technically, there is no difference between dip immunity and fault-ride-through. There are, however, big differences from a regulatory viewpoint. The transmission-system operator, being concerned about system stability, puts requirements on the immunity of production units against voltage dips.

Those requirements are given in terms of residual voltage and duration, thereby neglecting the impact of other characteristics, like phase-angle jump and voltage unbalance on the production unit. For large synchronous machines and their auxiliary supply, the impact of dips is rather well understood. But for smaller units, especially with a power-electronics interface, the impact is less well understood and other characteristics should be considered as well. The check-list for equipment manufacturers that was proposed by an earlier CIGRE group could serve this purpose [168].

Reference [169] showed that a photovoltaic inverter is very sensitive to phase-angle jump. A large phase-angle jump associated with a voltage dip also has a significant detrimental impact on the transient response of DFIG-based wind turbines. The overshoots in the rotor current and DC-link voltage will significantly increase and exceed the safety limits of the DFIG system if the dip is associated with a large phase-angle jump, [170], [171].

The behaviour of the power electronic interface of grid coupled inverters up to 10kW will have a major impact on inverter stability with respect to voltage dips and other disturbances [172], [173], [174], [175], [176].

Most grid codes give the fault-ride-through for production units, including for renewable energy production. Most modern renewable-energy production is connected by means of a power-electronic inverter. The fault-ride through requirements cover mainly low voltage ride-through during balanced voltage dips (caused by three-phase faults) as these were the most severe events for conventional production units (large synchronous machines). However, only some of the gird codes specify how the production unit shall behave under unbalanced voltage dips.

4.4.1.2 Active converters

Active converters will react differently to dips that passive (diode and thyristor) converters. The impact of multiple dips shortly after each other has never been fully investigated and may reappear with new equipment based on active converters.

Equipment manufacturers are reasonably aware of the need to make their equipment more immune to voltage dips. However, standardization is still incomplete and IEC 61000-4-11/34 defines the test methods and propose the test levels (non-mandatory) with moderate requirements (equipment is allowed to trip, but should not be damaged). Future equipment may also be immune to other characteristics than residual voltage and duration (the ones mentioned in the standard) and equipment may actually be damaged when exposed to more severe dips than the ones in the standard. This concern is especially relevant for low-power equipment, where the power-quality knowledge of the manufacturer may be limited to what is required according to product standards.

The number of manufacturers of small end-user equipment is increasing and there is a higher diversity in used power-electronic interfaces than in the past. Effectively, this reduces the risk of mass-tripping of end-user equipment.

Equipment manufacturers should be made aware of the voltage dip check list created by CIGRE/CIRED/UIE WG C4.110 [168]. The dip immunity tests that were done 10 to 20 years ago should be repeated for modern equipment to assess their voltage-dip immunity. Not only residual voltage and duration should be considered, but also other relevant dip characteristics. Additionally, as a reference, some of the existing national voltage-dip limits (e.g. Sweden, France, and South Africa), with a division of areas of responsibility in terms of duration and residual voltage magnitude, can be used as a reference for manufacturers.

For effective immunity coordination of three-phase users, the tolerance curves of equipment need to be defined per dip type (number of affected phases), as both their occurrence rates and effects are different. Propositions for the improvement of the dip-immunity testing procedure are given in [177], [178], to include the effect of unsymmetrical dips and phase-angle jumps. Immunity classes for equipment are also proposed in [178], to allow easier coordination of expected dips and immunity of an installation.

Regarding the immunity to different types of dips, an experimental study on a VSD and contactor for different types of dips is presented in [179]. It is shown that depending on the loading conditions of the VSD, the drive tolerates deeper single-phase dips in comparison to two or three-phase dips. Near 0 % mechanical loading, single-phase dips may also lead to no effect. For other types of equipment there is a need for further testing. For aggregated loads – complete feeders of substations, effects of dips measured in MV networks on the loading before and after the event is examined based on field measurements in [180], also showing the minor effects of single-phase dips (on the load power before/after the dip). Additional results of immunity testing of motor drives, lighting equipment and personal computers can be found in [181], [182], [183].

When the dip statistics are available at the MV or HV levels, the dip type seen by the users might be altered, depending on the transformer connection. As an example, single-phase dips observed in isolated MV networks are normally not seen on the LV terminals of users. Regarding the statistics of dips per type, a global overview of dips per type is given [184] for more than a 1000 locations. It was shown that globally 20 to 30 % of dips are of Type I (single-phase) in MV and HV networks (in particular countries even a higher percent). At the LV level, 54 to 69 % of the dips are seen as Type I, which should be taken into account when defining the immunity of an installation with three-phase equipment.

Regarding generation, system voltages during network fault conditions and fault clearing were traditionally controlled by rotating machines. Synchronous machines support system voltage (positive-sequence voltage) and in the same time naturally decrease the voltage unsymmetrical (negative-sequence) during unsymmetrical fault conditions.

4.4.1.3 Multiple dips

Due to increased use of automatic reclosing and feeder reconfiguration schemes, multiple dips and short interruptions are expected to occur more often. There is still a lack of knowledge on how these multiple events impact end-user equipment.

During an earlier working group (CIGRE/CIRED/UIE JWG C4.110), the issue of possible damage due to multiple events was discussed, but did not result in any conclusion. A thorough study of this is still very much needed.

4.4.2 Voltage swells

Voltage swells can result in the tripping of production units connected to the distribution system. Therefore, the "high-voltage ride-through capability" is becoming part of grid codes [185]. Severe voltage swells (due to single-phase faults) are a local phenomenon and there is no risk for mass tripping.

The impact of voltage swells on modern equipment with active converters is unknown. Further study is needed on the impact of swells on the control algorithm and on possible component damage.

4.4.3 Harmonics

Active converters are expected to have a different immunity to background voltage distortion than passive converters. No information is available on this, it is recommended to keep following the developments and to initiate new research where needed.

Active converters generally require an inner closed-loop control with a wider frequency range than conventional passive converters [61]. A particular concern with active converters is the growth of harmonics at certain frequencies due to critical grid resonances. Grid impedance in combination with the converter impedance seen by the grid may destabilize a grid resonance. This destabilization is due to the behaviour of the active converter which actively contributes to the resonance. Active converters can be represented by their equivalent conductance and resonance conditions occur when the real part of the conductance becomes negative [186]. These conditions may give rise to overvoltages caused by harmonics with the consequence of equipment damages. Reference [187] shows grid resonance caused by a wind park with DFIG based wind turbines.

Experience gained in various traction systems has led to a new standard EN 50388-2 [122] in order to propose measures to mitigate resonance stability. IEC standards [188], [189], [190] recommend procedures to test immunity of control equipment to disturbances up to 150 kHz but no concrete requirements are formulated to mitigate destabilization of grid resonances.

Secondary emission at the device terminals is driven by the background voltage (i.e. the voltage at the point of connection before the connection). See APPENDIX D with this chapter for more about secondary emission. The secondary emission is often associated with a current through a filter impedance (like a capacitor). A high secondary emission can result in accelerated gain of this filter and is thus strongly related to the immunity of the device. Increasing secondary emission implies an increased current through the device (typically involving the EMC filter). This current could induce interfering currents through the sensitive electronics or result in overheating of device components.

There is a testing standard (IEC 61000-4-13) for immunity against harmonics and interharmonics. However the limits set in this standard do only apply to equipment when referred to in a product standard. To avoid unexpected problems with immunity to harmonics, it is recommended to include these limits in the product standards, included in the generic immunity standards IEC 61000-6-1 and IEC 61000-6-2.

4.4.4 Interharmonics

Traditionally, interharmonics voltage levels were low, which has resulted in low emission limits, but interharmonic voltages of less than 1% are able to produce serious light flicker in compact fluorescent and LED lamps (models, numerical and experimental results are reported in [191], [192], [193]), PLL systems malfunctioning; models, numerical simulations; and experimental results are reported in [194], [195], [196], [197], [198].

One of the main issues that have to be addressed is the accuracy of the metric introduced by the IEC Standard 61000-4-7 for interharmonic measurement and assessment that has also been included in the new version of the IEEE Standard 519. Spectral leakage due to desynchronization problems can produce totally misleading results even from Class A commercial PQ instruments [199], [200], [201].

4.4.4.1 Active converters

The impact of interharmonics on active converters is unknown and without details of the control algorithm used it is difficult to make any estimation of the impact. As there is a wide range of control algorithms, the impact may show a large variation among different devices.

It is recommended to start setting up immunity standards that cover a wide range of voltage disturbances, including interharmonics.

4.4.4.2 Light flicker with non-incandescent lamps

It is well known that IEC compliant Flickermeters are capable of detecting Light Flicker only due to low-frequency voltage interharmonics below the double of the system frequency as higher order interharmonics do not cause much RMS variation in incandescent lamps [202]. As a result, the existing version of commercial flickermeters is suitable only for incandescent lamps and is not able to detect the effects of high-frequency interharmonics on different lamp technologies. On the other hand, different studies in the recent literature have demonstrated the sensitivity of the new lamps (CFL and LED) both to lower and higher frequencies interharmonics in terms of Light Flicker [202], [191], [193], [203], [204], [205]. Moreover, two of the main activities of the CIGRE WG C4.111 [206] were to review additional available research regarding lamp sensitivities (to voltage fluctuations) and to make recommendations for possible future ways to manage voltage fluctuations. Finally, the IEEE Standard 1453 [207], contains APPENDIX D (informative) titled "Impact of interharmonics on flicker related to non-incandescent lamps".

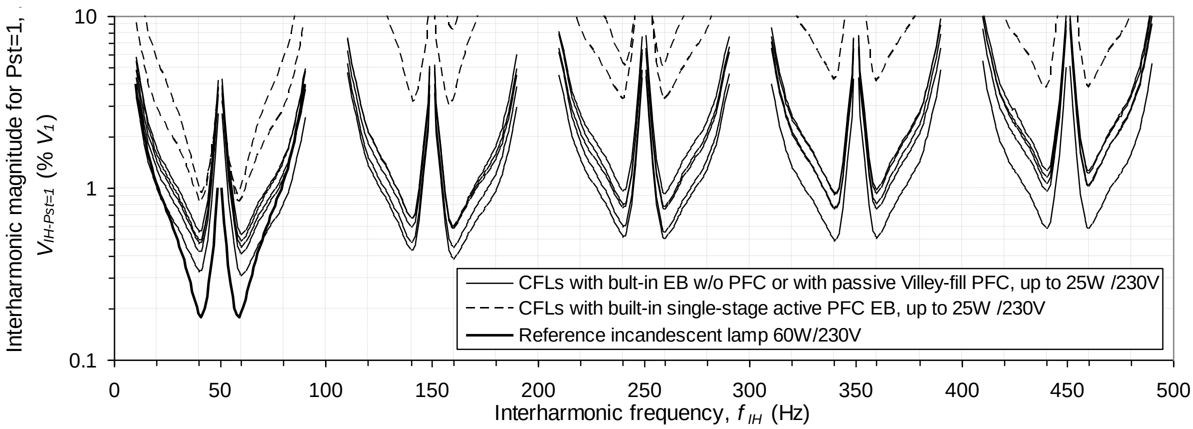


Figure 4.12 Interharmonic-flicker curves of compact fluorescent lamps with built-in electronic ballasts (input power up to 25W)

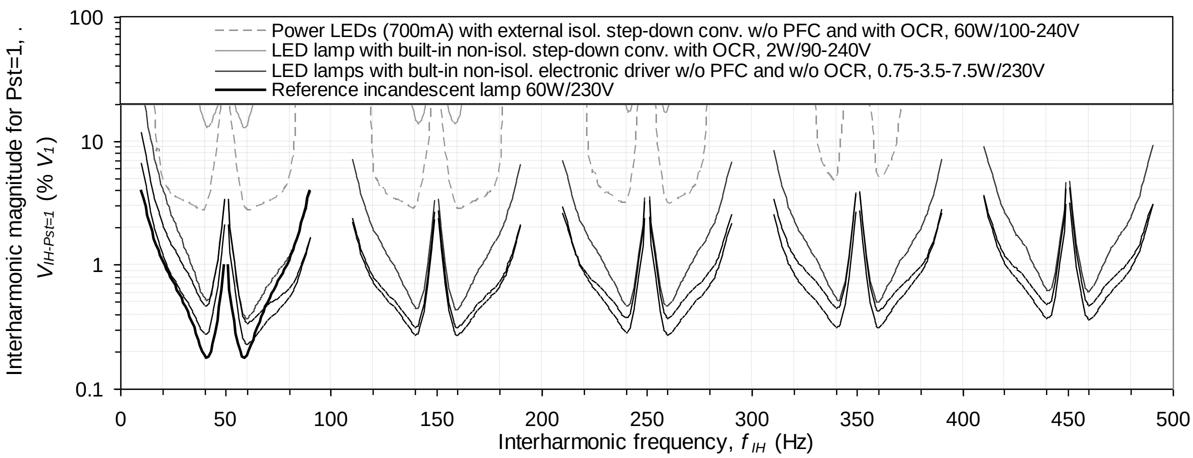


Figure 4.13 Interharmonic-flicker curves of various LED lamps

Experimental results [191], [201], [207] (see Figure 4.12 and Figure 4.13) indicate that the flicker performance of compact fluorescent and LED lamps is similar to that of incandescent lamps for interharmonics below the 2nd harmonic. These lamps continue to be sensitive to interharmonics around higher order harmonics (e.g. 3rd and 5th) where flicker is not an issue for incandescent lamps. This may be attributed to the use of diode bridge rectifier in LED lamps and CFLs.

4.4.5 Subharmonics

Subharmonics are prone to cause reduction of life of AC motors (models, numerical and experimental results are reported in [208], [209]), due to significant additional power loss in the stator winding, and power transformers due to core saturation phenomena (models, numerical models, and experimental results are reported in [210], [211], [212]), mechanical torque resonances [213], [214]. No change in this immunity of expected however.

The impact of subharmonics on power-electronic converters is unknown.

4.4.6 Supraharmonics

4.4.6.1 End-user equipment

Supraharmonics started to become a concern just a few years ago and immunity requirements, in particular for differential mode disturbances have been published quite recently [215]. This emission has not been considered in the design process for the majority of today's power electronics. An increase in the number of malfunctions and non-intentional equipment behavior due to the presence of supraharmonics has been reported during the last years [216]. Examples include clocks running too fast, non-intentional switching of hair dryers, significant errors in energy metering and flickering lights. In addition, a device subjected to frequencies below 20 kHz can produce audible noise due to stimulation of a mechanical resonance [145].

Supraharmonic currents can cause an additional temperature increase, especially in devices with passive cooling. Beside the capacitors in grid side EMC-filters especially the electrolytic DC-link capacitors are affected [70], [217]. Figure 4.14 illustrates the current waveform drawn by a compact fluorescent lamp with and without a supraharmonic component present in the supply voltage. Figure 4.15 exemplarily presents the increase of temperature depending on the increase of supraharmonic voltage for three different lamps [217].

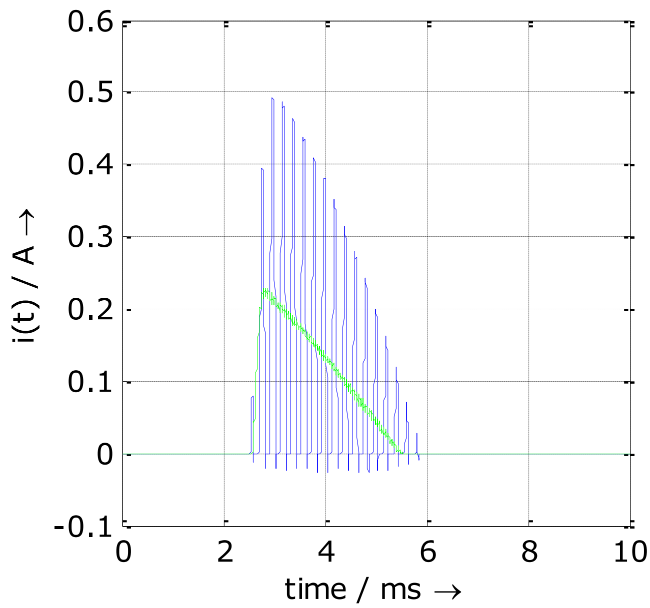


Figure 4.14 Current waveform of a compact fluorescent lamp without (green) and with (blue) supraharmonic content in the supply voltage [217]

The temperature increase is not limited to the capacitors, but can also affect other circuit components like rectifier bridges (see the higher number of switching in case of the current including the supraharmonic component in Figure 4.15). In contrast to the obvious interferences mentioned above, the temperature increase does not generally affect the functional behaviour of the device for the end-user, but could reduce the lifetime of the equipment considerably.

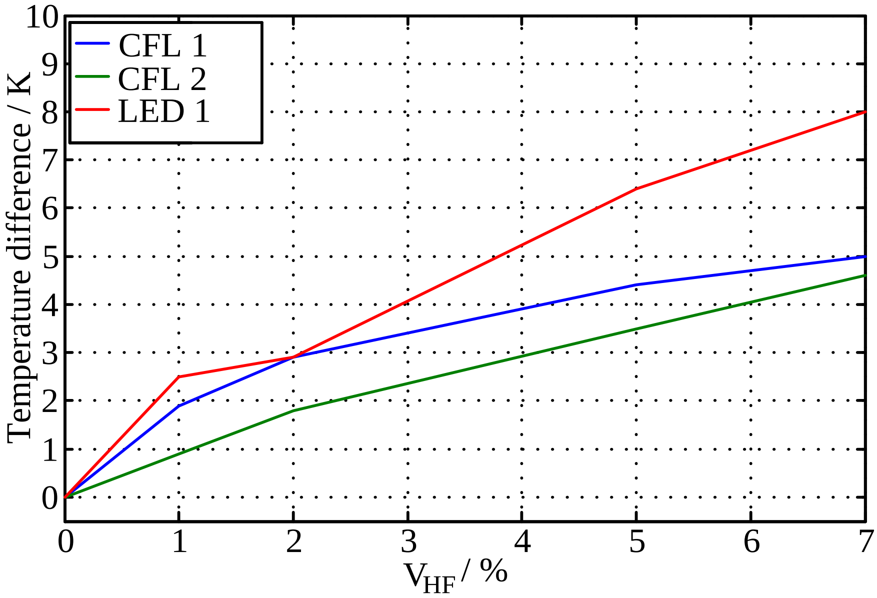


Figure 4.15 Temperature difference between sinusoidal and distorted supply voltage (DC-link capacitor) [217]

An issue associated with touch dimming lamps changing states when high frequency content is present in the power system has been discovered. It was appropriate to determine how sensitive the touch dimmers are to the high frequency content. There were two touch dimmer lamps selected for the test and each lamp was tested individually. A lamp was connected to one of the phases of an artificial mains network device and then high frequency signals were injected with a signal generator. The injection was accomplished by connecting a 2.04 μF capacitor to the phase conductor and in series with the signal generator that is in parallel with a 50 Ω resistance which is then connected to the neutral conductor. The injected signal was repeated every 600 ms where there was no signal output for 500 ms and then a sinusoidal waveform output for 100 ms. The frequency of the injected signal was varied from 50 kHz to 200 kHz in steps of 10 kHz and the magnitude of the signal was varied for each test point to determine when the lamp changes state. It was found that the voltage level for the first lamp needed to be an average of 113 dBμV for the first light to change lighting states and 104.8 dBμV for the second light to change states. The average voltage level to step through the lighting states for the first lamp is 115.9 dBμV and 106.1 dBμV for the second lamp [218].

Several examples of supraharmonics impacting end-user equipment are also presented also in two CENELEC reports, where the second one has been made publicly available [216]. Examples are also presented in a range of conference papers, with [219], [220] just being two random examples. The highest levels of supraharmonics occur due to power-line communication. The impact of power-line communication on end-user equipment is therefore an important issue to study. There is however lack of information also on this, for example the difference between immunity to short-duration emission (from power-line communication) and to long-duration emission (from end-user equipment).

PLC in the frequency range 9 to 95 kHz has been used extensively in Sweden and Italy since about 2010. No large-scale equipment damage or mal-operation has been reported in association with the use of PLC. But that of course does not mean that there is no such impact and further studies remain needed.

4.4.6.2 Power line communication

Emission from end-user equipment in the communication band (9 to 95 kHz) may deteriorate the communication, e.g. between smart meters and the network operator. High emission from end-user equipment in the communication band is shown regularly and is often mentioned as a possible cause for communication problems. There are some reports of PLC interfering with customer devices [221]. There are however limited documented cases and as stated in [73], the main cause of communication problems is elsewhere.

4.4.6.3 Cable insulation stress

There are indications that the presence of high-frequency components in the voltage makes cable insulation ages faster than normally [138], [222]. The main case study is the failure of cable terminals after the connection of a VSC HVDC installation at Eagle Pass on the border between Mexico and the United States. The measured voltage and its spectrum are shown in [138].

The failures occurred in "compact type cable terminations rated 24 kV with resistive/refractive stress grading". The problem was resolved by installing another type of cable terminations, "generally called geometric type, which has an insulation characteristic expected not to be dependent on frequency".

Several studies have been done on the impact of harmonics, especially high-frequency harmonics, on the insulation of cables. According to [222], high harmonic contents may results in higher temperature of the dielectric material which in turn increases ageing processes. The impact on capacitors is treated in [223].

A large number of publications have also been published on the impact of high harmonic contents on motor insulation. That work is however mainly aimed at studying the repetitive pulses produced by PWM inverters in adjustable-speed drives [224], [225], [226]. The levels of harmonics and repetitive pulses are a completely different order of magnitude than in the public grid and those studies have no value for the immunity of equipment connected to the grid.

The overall conclusion at this stage is that there is no indication that long-term exposure of insulation to relatively low levels of supraharmonics noticeably impacts the ageing of insulation.

4.4.6.4 Transformers

The presence of higher frequencies in the current through a transformer is expected to reduce the life of its insulation due to increased heat development in the core and the forming of hot spots.

Where it concerns transformer insulation failures, the main concern is their exposure to extremely fast rises in voltage from zero to 100%. There have been several cases of such transformer and motor failures when vacuum breakers are used together with cable networks with limited amount of other load connected [227], [228].

Another failure mechanism of transformers is the excitation of internal winding resonances by switching actions in the transmission grid [229]. Transformer protection due to transformer resonance being excited by high frequency harmonics generated by PE can cause resonant overvoltages in the transformer windings which present a problem for the transformer designer.

As high levels of supraharmonics can deteriorate the insulation of cables (Section 4.4.6.3) it may also impact the insulation of transformers. However, no information on this was found and it is not clear at which levels of supraharmonic voltages this deterioration may become noticeable.

It is necessary to determine if there are any resonant points in the transformer because harmonic content at the resonant points can be problematic. Work has been done to test transformers to determine the driving point impedance for each transformer. It was found that the highest resonant point frequency was 80 kHz (low voltage terminal excitation) and that the transformer excitation terminals that are chosen will change the driving point impedance. If the chosen excitation terminals are high voltage terminals, then the resonant point is going to be a lower frequency than if the low voltage terminals were excited. High voltage excitation for single phase transformers will have the first resonant point around 10 kHz; low voltage excitation for the same transformers will have the first resonant point in the range of 15 kHz to 80 kHz. Also, there are typically a few additional resonant points that follow the large first resonant point. The resonant frequencies are found to be a function of the rated voltage, power, and terminal connection scheme [230].

4.4.6.5 Rotating machines

As high levels of supraharmonics can deteriorate the insulation of cables (Section 4.4.6.3), it may also impact the insulation of rotating machines. However, no information on this was found and it is not clear at which levels of supraharmonic voltages this deterioration may become noticeable.

4.4.6.6 Instrument transformers

As high levels of supraharmonics can deteriorate the insulation of cables (Section 4.4.6.3) it may also impact the insulation of instrument transformers. However, no information on this was found and it is not clear at which levels of supraharmonic voltages this deterioration may become noticeable.

4.4.7 Slow voltage variations

Active converters may be more sensitive to slow voltage variations, but there is no documented evidence. In general, there is very little knowledge on the impact of slow voltage variations (specifically undervoltages and overvoltages) on end-user equipment. A thorough study on this would be a useful contribution to the discussion.

It is also important to mention the lack of standardization on immunity against slow voltage variations. The only standard test that is relevant is the one for voltage fluctuations where a device is exposed to voltages that vary between 92 and 100% or between 100 and 108% of the nominal voltage. There is however no test that exposed equipment for a longer period to voltages of 110% or higher or to voltage of 90% of lower.

It is important the appropriate immunity tests are developed.

4.4.8 Fast voltage variations

The societal transition from incandescent lamps to other types of lamps has resulted in a challenge to the validity of the basis of the flickermeter standard. Consequently, it has been suggested to change or even abolish the flickermeter standard [231]. Working group C4.108 concluded that new types of lighting are significantly less sensitive to fast voltage variations than incandescent lamps [231]. However, later studies indicated that this is not necessarily the case [232], [233]. Flicker with non-incandescent lamps is also studied in CIGRE Working Group C4.111 [206].

4.4.8.1 Non-incandescent lamps

Recent years, many of the exporters committed to study the characteristics of flicker for different kinds of lamps. The Lamp Gain Factor variations, for incandescent and fluorescent lamps, depending on voltage fluctuations are shown in Figure 4.16 [234]. Lamp Gain Factor is defined as the ratio of percentage of relative light fluctuation to the percentage of voltage fluctuation. It was observed during these tests that the lamp's amplifying characteristic, or gain factor, is the important consideration for flicker due to voltage fluctuations. If the gain factor is greater than unity, the lamp is said to have an amplifying effect. Additional tests also show how inter-harmonics (non-integer harmonics) and phase-shifting harmonics on the power line can cause fluorescent lamps to flicker, despite having low gain factors when compared to incandescent lamps.

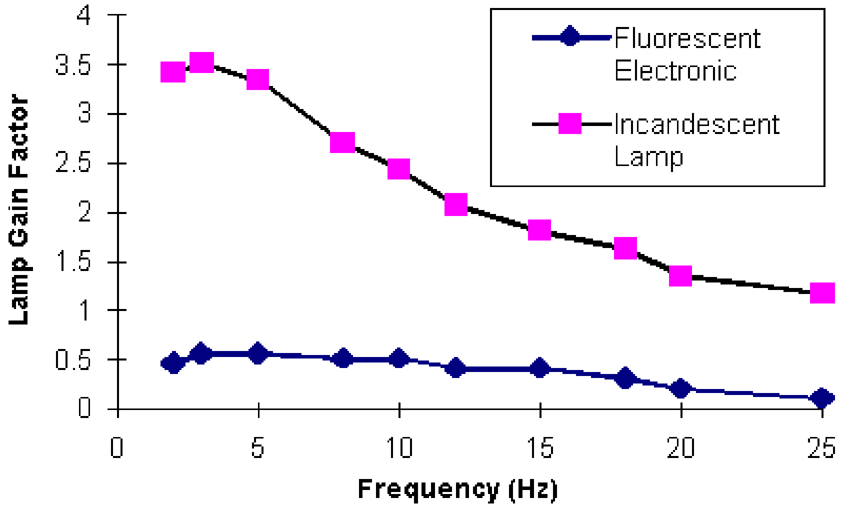


Figure 4.16 Gain Factor Variations for Different Lamps [234]

Another paper [235] shows the test approach and results for getting flicker response of different types of lamps. The relative luminance L_r is used to evaluate the luminance flux variation for different types of lamps, here L_r is defined as expression:

$$L_r = \frac{L_{f_m}}{L_{av}} \times 100$$

Equation 4.2

L_r is relative value per unit of f_m (f_m: voltage modulation frequency) amplitude (p.u.). L_{fm} is the absolute luminance of f_m component. L_{av} is the average luminance of this type of lamp. It is obtained by a luxmeter and selected as base value in this calculation.

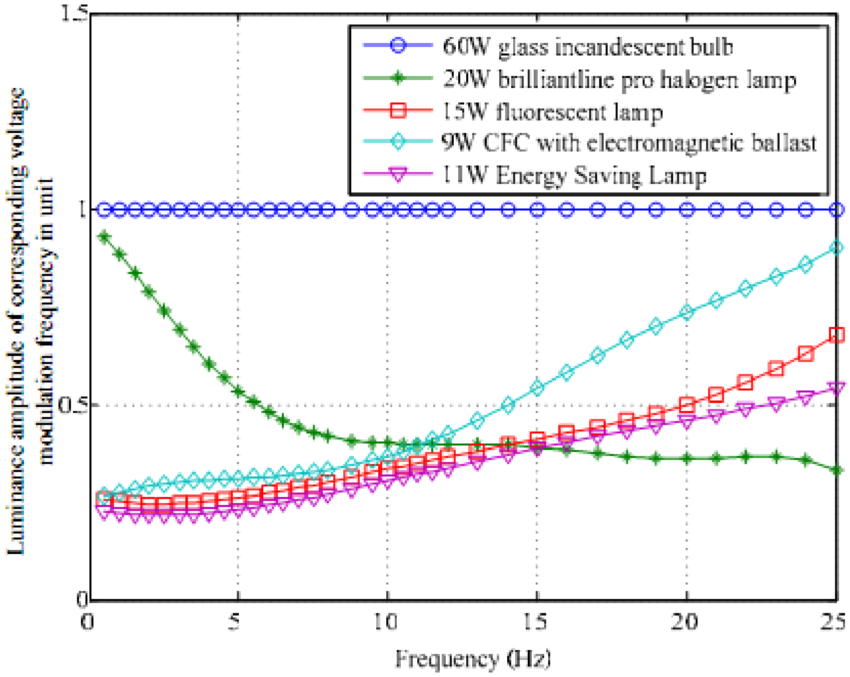


Figure 4.17 The flicker responses of different type of lamps versus voltage modulation frequency with modulation voltage amplitude is Pst=1 [235]

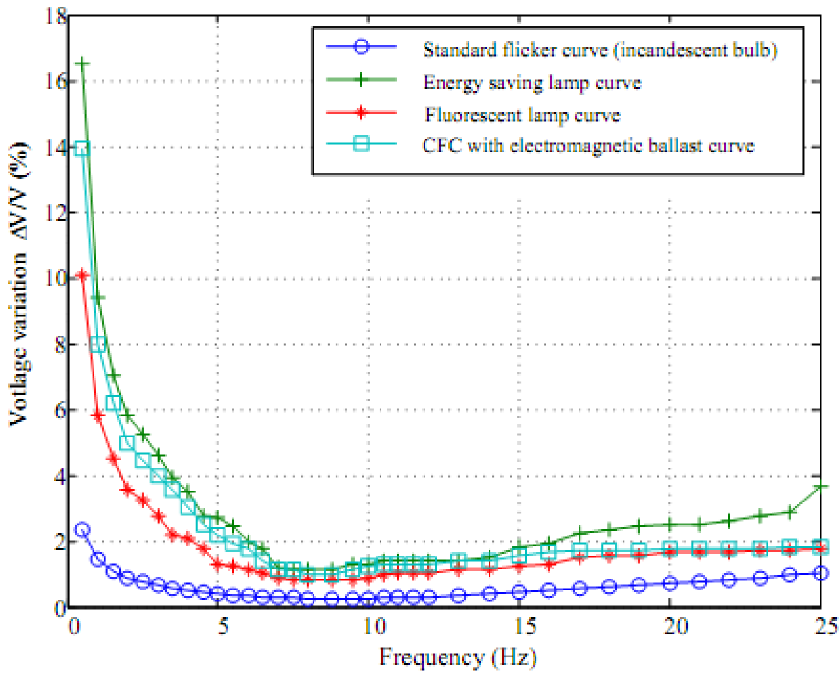


Figure 4.18 Flicker curves for different types of lamps [235]

The variation of the relative luminance shows clearly the different flicker responses (see Figure 4.17). In Figure 4.17, the luminance of the incandescent lamp for different modulation frequency is selected as base value Lb, then Lr per unit can be calculated by: Lunit=Lr/Lb). The flicker curves (modulation voltage amplitude versus voltage modulation frequency when Pst=1) for different types of lamps are also presented in Figure 4.18.

In [233] the impact of fast voltage variations on light flicker with 24 different LED lamps is presented. For the same lamps also the harmonic distortion has been measured. The results for both flicker and harmonic distortion are shown in Figure 4.19.

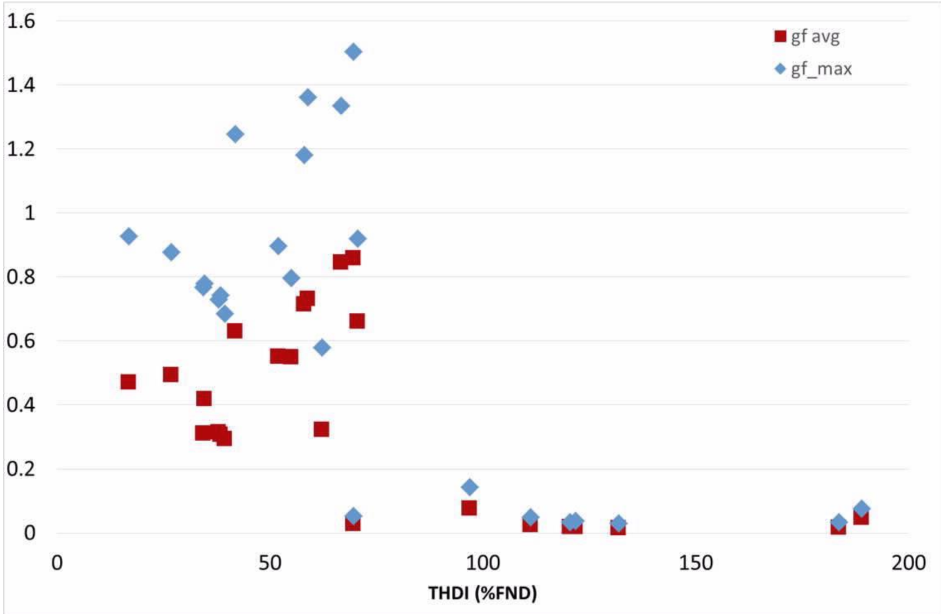


Figure 4.19: Normalized gain factor (vertical scale, with flicker for incandescent lamps equal to unity) versus current THD (horizontal scale, in % of fundamental) for 24 different LED lamps: maximum normalized gain factor (blue squares) and average normalized gain factor (red squares) [233]

4.4.8.2 Voltage-magnitude variations and non-lighting equipment

However, the potential detrimental effects caused by voltage fluctuations on electrical equipment should also be considered prior to any changes to the flicker limits adopted by utilities. Recent work investigating the effect on equipment of various levels of flicker has indicated that common items of electrical equipment will experience uncharacteristic currents when the equipment is subjected to high levels (as defined by the power quality index known as the short term flicker index, P_{st}) of fast voltage variations [236]. The common devices investigated included single-phase rectifier plus capacitor circuits, mains connected squirrel cage induction motors, and adjustable speed drives. These unusual currents increase the overall RMS current in the device, leading to increased losses, and potentially, premature loss of life.

When the flicker index was originally conceived, it reflected the physiological effects on humans without consideration of the effect on electrical equipment. A consequence of this lack of consideration is that there is a disconnect between what is acceptable from a human perspective and that which is acceptable from an equipment perspective.

As an example, consider a simple single-phase rectifier circuit with a capacitor filter at the output. This circuit is then subjected to a AC voltage with regular, sinusoidal fluctuations with a modulating frequency f_m and variations in magnitude of ΔV. Figure 4.20 illustrates the change in the capacitor RMS current and the modulation frequency and voltage variation magnitude changes. The voltage fluctuations used in Figure 4.20 are seldom found in operational practice, but illustrate the phenomena under investigation.

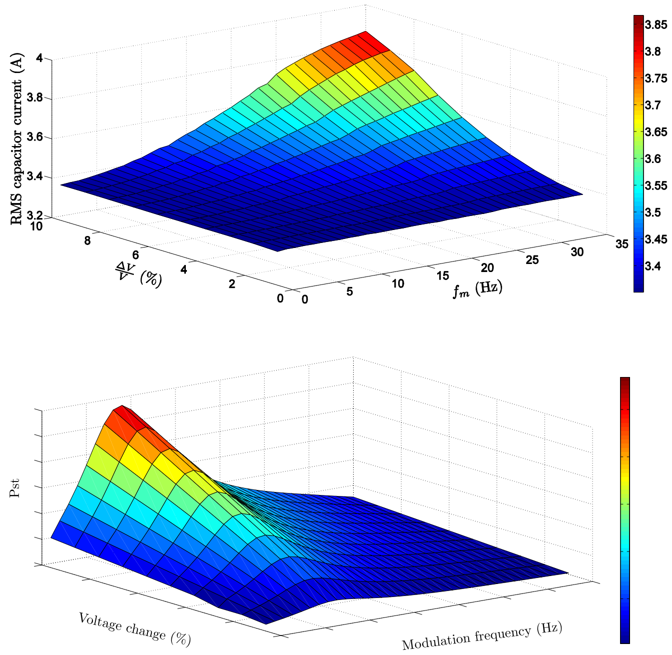


Figure 4.20 (a) Variation of capacitor RMS current with fm and ∆V/V (b) Variation of Pst with fm and ∆V/V [237]

Figure 4.20a indicates that the capacitor RMS current increases quickly under higher voltage change rates and higher modulation frequencies. Therefore, a higher voltage change and higher modulation frequency will increase the rectifier capacitor losses and potentially induce premature loss of life. This situation cannot be represented by using the flicker level index P_{st}. As noted in Figure 4.20b, how modulating frequencies and voltage variations do not necessarily result in high values of P_{st}. The unusual current increase noted in this application has been observed to occur in direct-connected 3-phase, squirrel cage induction motors [237] as well as adjustable speed drive systems [238].

There is a body of work required to determine whether or not the presence of other rapid voltage changes in combination with regular voltage fluctuations can contribute to uncharacteristic currents in components directly connected to the power distribution network.

Presently, P_{st} is the only indicator used for fast voltage variations in determining power system EMC levels and planning levels. However, some standards also additionally specify limits on rapid voltage change. A comprehensive index or method should be proposed the alleviate the limitation of P_{st} and be used to assess the voltage fluctuation effects on other sensitive equipment.

4.4.9 Transients

4.4.9.1 Active converters

The power-electronic components in active converters are expected to be more susceptible to overvoltages than the ones in passive converters. The immunity of active converters to overvoltage transients is discussed in E.7.

In [239] a case is shown where a transient current in a power line is inductively coupled to a nearby metallic telephone wire causing damage to modems connected to this wire. The metallic wire and modem were used for communication as part of a smart-grid demonstration project.

4.4.9.2 Transformers

Sharp wavefronts, e.g. due to switching on a cable or due to re-strikes with vacuum breakers, can result in insulation failures with transformers. There are no changes in immunity expected from transformers, with the exception of transformers specifically designed to withstand such wavefronts.

4.4.9.3 Rotating machines

Sharp wavefronts, e.g. due to switching on a cable or due to re-strikes with vacuum breakers, can result in insulation failures with rotating machines.

4.4.10 Voltage unbalance

For three-phase converters a small difference in the magnitude of the line-to-line voltages can result in a large unbalance in current. The negative-sequence voltage is no longer a suitable characteristic to quantify the severity of the unbalance; other characteristics need to be developed.

The immunity of voltage unbalance on three-phase converters will likely be strongly device dependent. No further information on this was found.

The difference in magnitude between the phase-to-neutral voltages will limit the possibilities for conservative voltage reduction.

4.4.11 Frequency variations

Equipment connected to the grid is rarely inherently sensitive to frequency variations. Those variations are too small (rarely exceeding 1%) to have any impact on the performance of equipment.

An increasing amount of equipment is however equipped with protection using frequency and/or rate-of-change-of-frequency as input parameters. The massive tripping of equipment because of large deviations or fast changes in frequency has become a concern for system operators. It is discussed in detail elsewhere and will not be further treated in this report.

It was mentioned by a group representing the paper industry, that frequencies below 49 Hz could impact the performance of the paper machines.

Regular frequency drops below 49.9 Hz are reported as being a problem for hydropower installations in Sweden. This is the frequency where the fast primary frequency control is activated.

It can however not be ruled out that even relatively minor frequency variations might adversely impact the control algorithms in certain active power-electronic converters. No such immunity issues are known to the working-group members however.

4.4.12 DC components

The impact of dc components on transformers and motors is well known; no changes are expected in this immunity.

No information is available on the immunity of modern equipment to dc components.

4.4.13 Geomagnetically-induced currents

Electric fields produced by magnetic field variations during geomagnetic disturbances cause Geomagnetically Induced Current (GIC). The adverse effect of GIC is a current flowing through the power system with a path through the grounding of the transformers. The frequency of the induced current is very low and it appears as a slow-varying DC current [230], [231]. The magnetic core of the transformers may saturate with the consequence of an increase of harmonics. Power electronic converters and their protection systems may be affected by the abnormally high level of harmonics. One major effect of GIC occurred in Quebec in 1989, where capacitor banks become overloaded due to high harmonic distortion and tripped, causing a total blackout of the power system [232].

Immunity of PE converters and their protection systems against GIC and its effects is actually not standardized but guidelines are proposed for some converter types [170]. WG C4.32, "Understanding of the Geomagnetic Storm Environment for High Voltage Power Grids", evaluates the measured geomagnetic data over 30 years to develop an understanding of the nature of these storms relative to their potential impacts on high voltage power grids.

4.5 TRANSFER OF DISTURBANCES THROUGH THE GRID

Even when emission remains the same, several developments make that disturbance levels at equipment terminals may increase. Also, this can result in an increase in the probability of interference.

There are also developments that have the opposite effect: the transfer decreases and therewith the probability of interference. Both will be discussed in this section.

An important quantity in this context is the "transfer impedance": it is the ratio between the voltage at a certain location and the current at another location causing this voltage.

4.5.1 Voltage dips

4.5.1.1 Reduced amount of conventional production

Reduced amount of conventional production at transmission level results in a reduction in fault level with increased number of voltage dips as a result.

Studies on the impact of this replacement on voltage dip indices are presented in [244], [245] especially for increasing amounts of wind power in the UK grid. It is shown that the number of dips during periods with high amounts of wind power is clearly increasing. However, a simplified model of the variation in wind power production during the year resulted in a relatively small increase in the number of dips per customer per year. The highest increases were expected for those locations that had small dip frequencies before, whereas locations that already had a high number of dips, did not see much increase. The latter is illustrated in Figure 4.21 [245]. This study is however based on a simplified model of the wind-power production. This study further only considered voltage dips due to three-phase faults.

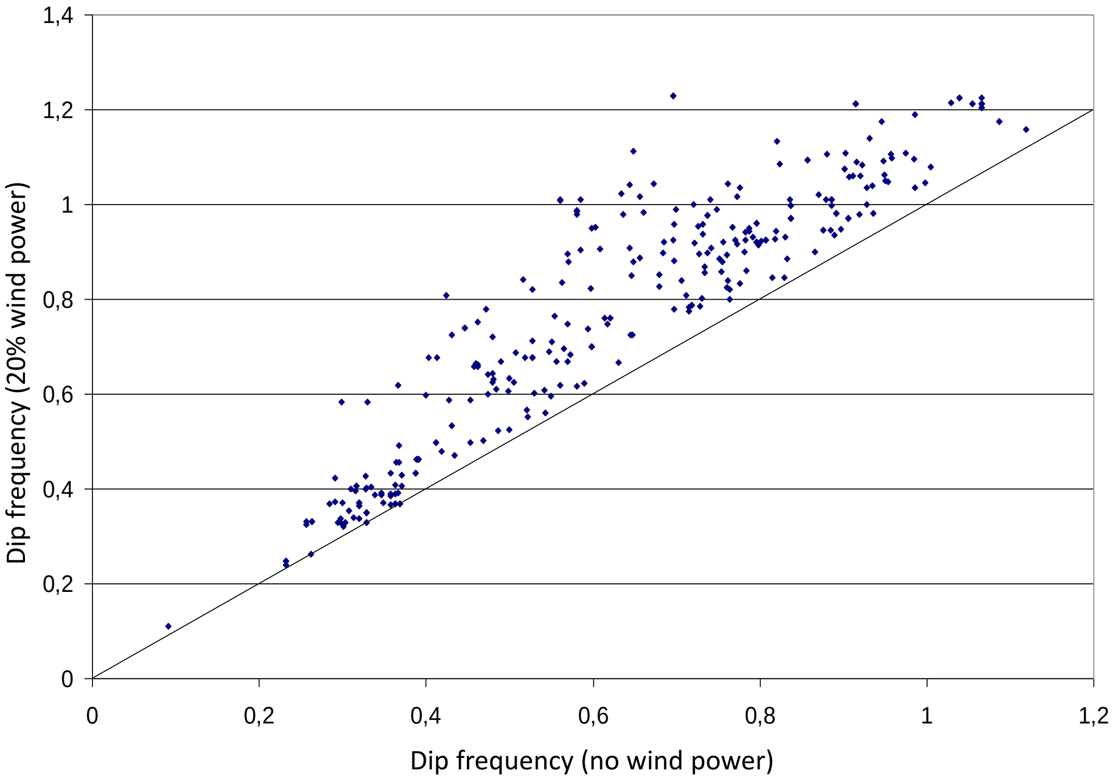


Figure 4.21 Change in voltage-dip frequency (normalized values) for individual nodes, no wind versus 20% wind [245]

An example of the increased spread of voltage dips is shown in Figure 4.22. More customers will be impacted by a fault that occurs during a low-wind, low-consumption state, as area of the grid experiencing a voltage dip (the "area of vulnerability") increases. From the viewpoint of an individual customer, the "exposed area" increases, resulting in more dips. The impact of this on dip statistics has however not been quantified.

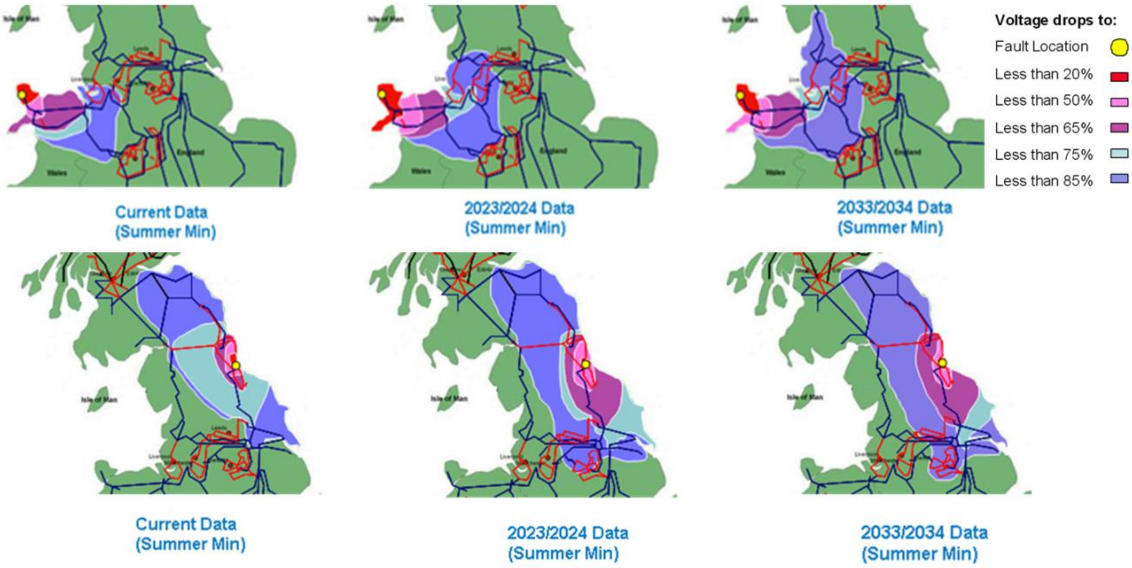


Figure 4.22 Spread of voltage dip due to fault at two different locations in the UK transmission grid, for the summer minimum production, existing situation (left), situation in 10 years (center), situation in 20 years (right)

A study of the spread of voltage dips in the German transmission system is presented in [246]. In future, the average number of customers experiencing a dip due to a transmission-system fault, will somewhat increase. However during certain operational states, with low amounts of conventional production in operation, the number of customers affected will increase a lot.

4.5.1.2 Increased amount of distributed generation

The impact of distributed generation on voltage dips depends strongly on the behaviour of the generation during the dip. The more the generator contributes to the fault, the more it supports the voltage with a less severe dip as a result.

The impact of synchronous production units having the biggest contribution to the fault, and induction machines on the number and characteristics of voltage dips is presented in [61], Section 6.6. It is shown that distributed generation can result in a significant reduction of the number of dips below a certain voltage threshold. Synchronous machines can reduce the number of both balanced and unbalanced voltage dips; induction machines only reduce the number of unbalanced dips.

4.5.2 Voltage swells

Voltage swells due to single-phase faults are a zero-sequence phenomenon and the zero-sequence impedance is not likely to be impacted by three-phase-connected production units. Single-phase units connected phase-to-neutral at low voltage may however impact the zero-sequence source impedance and therewith the maximum swell voltage. This depends strongly on the way in which the single-phase production units react to the undervoltage and overvoltage during a single-phase fault.

4.5.3 Harmonics

4.5.3.1 Cables in the distribution grid

Underground cables are getting more common. They add shunt capacitance to the network resulting in resonances at lower frequencies.

The resonance frequency for low-voltage cable network is rather high and not expected to be of concern. Also, the damping in low-voltage networks is rather high. Consider the following example of a range of typical networks:

- 400 Volt nominal voltage
- 50 kVA to 800 kVA distribution transformer, 4% impedance; neglect the contribution of the medium-voltage network to the source impedance. The inductive part of the source impedance is between 32 and 510 ·H.
- Between 1 and 10 km of cable, with 0.1 ·F/km capacitance. The total capacitance is between 0.1 and 1 ·F.

- The resonance between capacitance and inductance gives a resonance frequency between 7 and 89 kHz.
- In medium-voltage networks, the resonance frequency is lower and amplification of higher order harmonics can be expected. Again an example of a range of typical networks is given.
- 10 kV nominal voltage
- 10 to 50 MVA transformer, 20 to 30% impedance; neglect the contribution of high-voltage network to the source impedance. The inductive part of the source impedance is between 1.9 and 6.4 mH
- Between 10 and 50 km of cable, with 0.2 ·F/km capacitance. The total capacitance is between 2 and 10 ·F.
- The resonance between capacitance and inductance gives a resonance frequency between 630 Hz and 2.6 kHz.

4.5.3.2 Cables in the transmission grid

Long ac cables at transmission level result even faster in low resonant frequencies than cables at lower voltage levels. The consequences of the lower resonant frequencies include higher harmonic voltage levels and higher-amplitude lower-frequency switching transients. Some examples are shown in [247] - [252].

The combination of cables at different voltage levels could result in amplification of harmonic voltage levels when resonance frequencies at the two voltage levels are similar. The mechanism is similar to the occurrence of high overvoltages at the terminal of a low-voltage capacitor bank when switching a medium-voltage capacitor bank [252].

An overview of resonances frequencies that can be expected for different cable lengths, nominal voltages, and fault levels is given in Table 4.2 [248]The fault levels are the 95% range of actual fault levels for those voltage levels in the UK transmission grid. Resonances at low-order harmonics can be expected. Note that the length in the table is not the distance between the two cable terminals, but the total length of cable circuits that are connected to one transmission substation. For example: 3 parallel circuits of 20 km length and four circuits of 15 km length, originating from the same 400-kV bus, would result in 120 km of cable.

Table 4.2 Resonant frequencies (Hz) for the combination cable – grid: distributed cable model [248]

Length	132 kV		275 kV		400 kV	
	1 GVA	4.1 GVA	6 GVA	15 GVA	9 GVA	32 GVA
5 km	773 Hz	1526 Hz	906 Hz	1409 Hz	765 Hz	1414 Hz
15 km	438 Hz	826 Hz	511 Hz	770 Hz	434 Hz	772 Hz
50 km	226 Hz	376 Hz	258 Hz	358 Hz	224 Hz	359 Hz
100 km	-	-	166 Hz	212 Hz	146 Hz	213 Hz

The study presented in [253], for a 220-kV cable of 100 km length connecting an off-shore wind park to the on-shore transmission grid, shows resonance frequencies between 100 and 150 Hz.

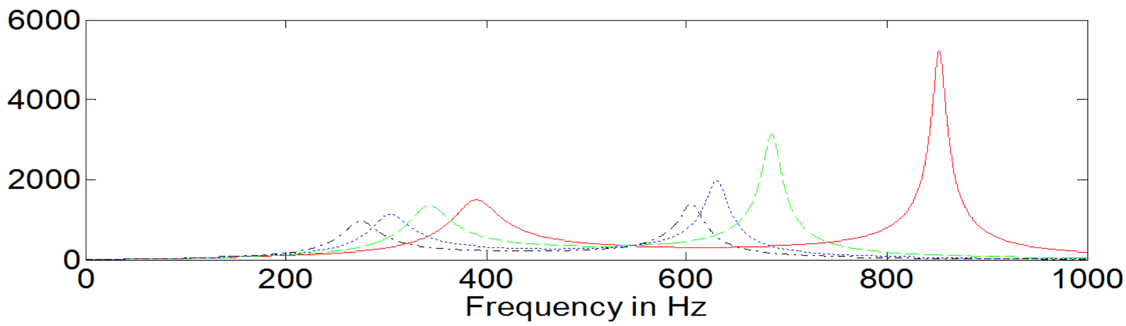


Figure 4.23 Transfer impedance (in Ohm) from the sending end of a 15-km 400-kV cable to the secondary side of a 400/132-kV transformer on the receiving end of that cable [248] The different colors refer to different lengths of cable of 132-kV side.

4.5.3.3 Reduction in damping

The amount of linear load providing damping at resonance frequencies (known as "resistive load") is decreasing fast. This might result in very high distortion when resonance frequencies come close to harmonic frequencies. This is partly compensated by a lower emission of certain types of devices, and mainly driven by the equipment requirements.

There is a general trend of replacement of non-electronic loads by electronic loads. This takes away a source of damping at resonance frequencies. Together with the before-mentioned shift of resonances to lower frequencies, it could result in a local or global increase in harmonic voltage levels.

It is not known how much of the damping is provided by low-voltage equipment and how big part of this is provided by lamps. So we don't how much the removal of incandescent lamps will matter, but it is a fact that network operators are concerned. Also, other types of "resistive load" are being replaced by "electronic load"(e.g. resistive electric heating by heat pumps and directly-driven motors in refrigerators and air-conditioners with adjustable-speed drives).

As there are no available comparative network impedance measurements which could indicate the reduction of damping due to changing types of equipment. Simulation results can be used as a reference as presented in [13], [254],. The results shown present changes with assumed changes of load parameters, and presently there are no results which could indicate what would be a suitable range for varying parameters.

This has been observed in field measurements. In a case study conducted during the 2010 FIFA World Cup, measured distortion levels in the HV and MV networks were presented in [255]. During the games, sharp increases of non-zero sequence harmonic voltages due to TV sets were observed. However, there were significant decreases during the half-times of the games which were attributed to the use of non-TV loads such as food heating devices. The exact portion and effect cannot be distinguished from the change in emission.

This issue needs a serious research emphasis: to quantify the damping so that changes can be quantified and also to study the impact of any reduction in damping on the transfer and harmonic voltage distortion at different voltage levels.

4.5.3.4 Increased amount of capacitive equipment

Nowadays, the dominating share of electrical appliances are equipped with power electronics, which use different kinds of shunt capacitors in their circuits (grid-side EMC filters, DC link). While the amount of equipment with capacitances is likely to increase further, the number of "classical" devices with resistive or inductive behavior is expected to continuously reduce. Few examples are the introduction of frequency-inverters in refrigerators, air conditioning systems, or circulation pumps (e.g. in house water installations). According to this trend, a considerable increase of distributed capacitances (e.g. on the first resonance) has to be expected in LV networks [256].

This is also an issue for harmonic simulations in LV networks, where the loads are mostly represented as ohmic-inductive equivalent circuit. In this case, the first resonance is only determined by the cable capacitance and usually located at frequencies in the kHz – range, even in case of larger cable networks. Therefore LV networks are traditionally assumed to be free of resonances. For example, a rural grid in Sweden (six customers, 755 meter cable, 100 kVA transformer) was found to have a resonant frequency equal to 22 kHz.

Exemplarily a recent measurement of network harmonic impedance in a newly built German LV network with about 400 customers has shown a distinctive resonance already at a frequency of 500 Hz (see Figure 4.24). This is far too low to be caused by the cable capacitance only. In a detailed simulation, the measured resonance in the frequency range between 200 Hz and 900 Hz could only be modelled by replacing the standard load model of each household by an extended model including an additional capacitance of about 12µF. First experiences have shown that the element parameters of the model are not constant, but have to be varied for different frequency range. More research is required to obtain a more general model for such studies.

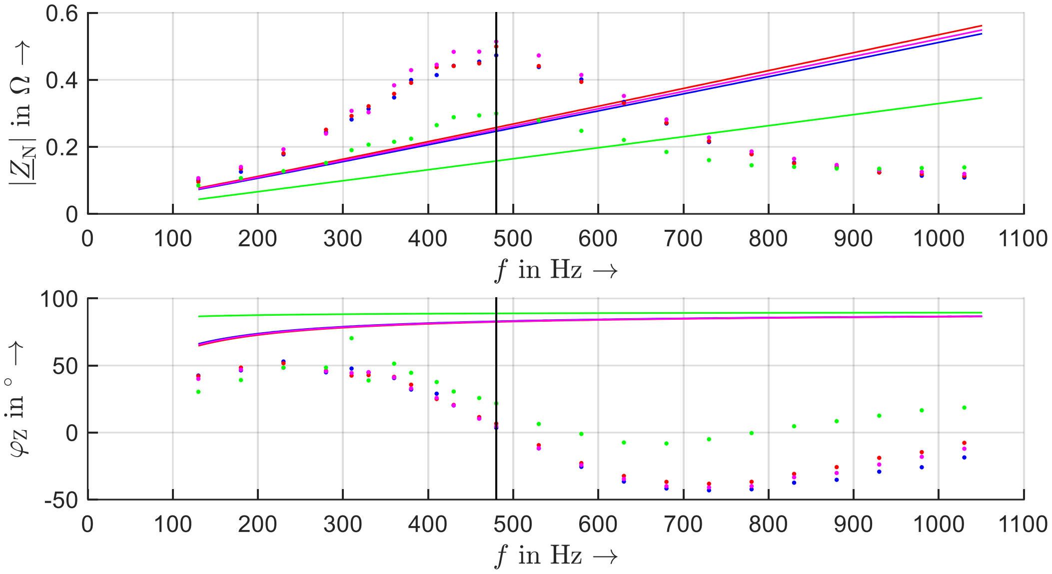


Figure 4.24 Network harmonic impedance at four different locations in a residential LV grid (Dots – measurement values; lines – simulation with ohmic-inductive loads; colors represent different locations)

The impact of capacitance in PV inverters on the resonance frequency is shown in Figure 4.25, where the dotted horizontal lines indicate the low-order odd harmonics, order 5 through 15. The resonant frequency is close to harmonic 15 for the network without PV and harmonic 7 could be reached for large amounts of PV. The capacitance per customer, without PV, was assumed equal to 6 μF.

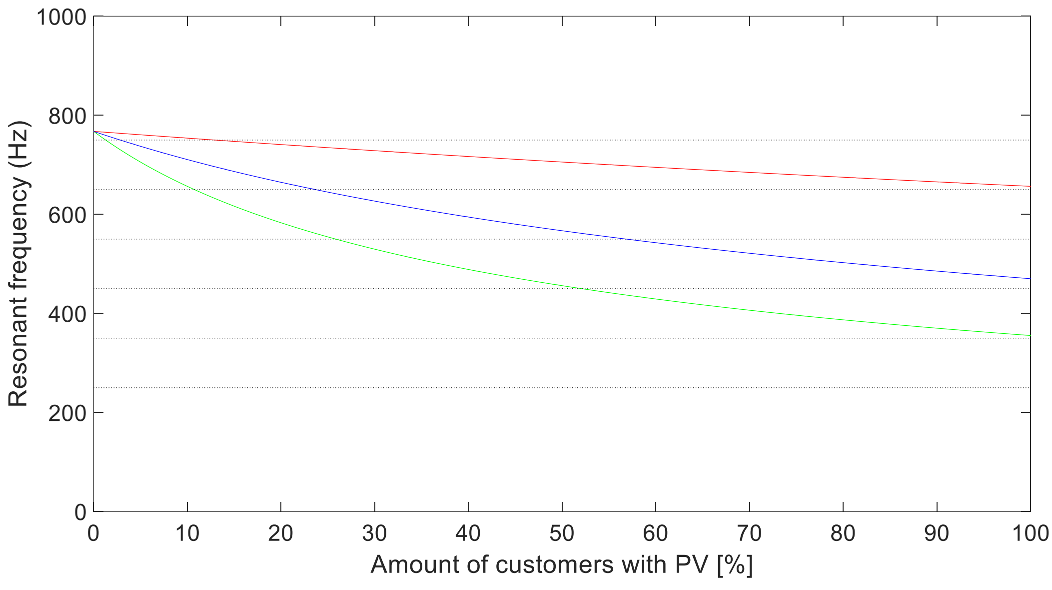


Figure 4.25 Resonant frequency in a low-voltage distribution grid with 225 customers as a function of the amount of customers with PV, inverter capacitance equal to 2.2 ·F (red), 10 ·F (blue) and 22 ·F (green)

This increase of distributed capacitance should be taken into account(e.g. when assessing possibly required reactive compensation capacity during network planning). Furthermore, LV networks, especially newly built ones with electronic equipment of the last generation should not in general be treated as resonance-free. Both the possible series resonance seen from the upstream MV network as well as the parallel resonance seen from the LV grid has to be considered. Further discussion is also needed about the measurement and interpretation of network harmonic impedance in the presence of electronic equipment utilising semiconductor switching. The network harmonic impedance varies more or less significantly within a fundamental cycle as shown in [257]. The characteristic and level of this variation can also provide useful information about the consumer characteristic at a measurement site.

4.5.3.5 Passive harmonic filters.

HVDC installations are equipped with passive harmonic filters. These filters typically also filter emissions originating elsewhere. The installation of more HVDC links may result in a decrease in the harmonic voltage levels for those frequencies at which the link is a major emitting source.

When replacing line-commutated by self-commutated HVDC [258], there is no longer a need for harmonic filters to remove the lower-order harmonics. Those filters were known, but rarely acknowledged, to also remove lower-order harmonics from other sources. The lower emission of modern HVDC at lower frequencies may therefore, paradoxically, result in an increase in voltage distortion at those frequencies.

4.5.3.6 Less conventional production

This will result in a shift of resonances to lower frequencies. Harmonics below and around the resonance frequency will be amplified; but harmonics somewhat above the resonance frequency may actually be reduced. This is illustrated in Figure 4.26 [61]. The weaker grid (red) shows a lower resonant frequency than the strong grid (green). For lower frequencies, weakening of the grid will result in an increase of voltage distortion; but for higher frequencies, the voltage distortion will increase.

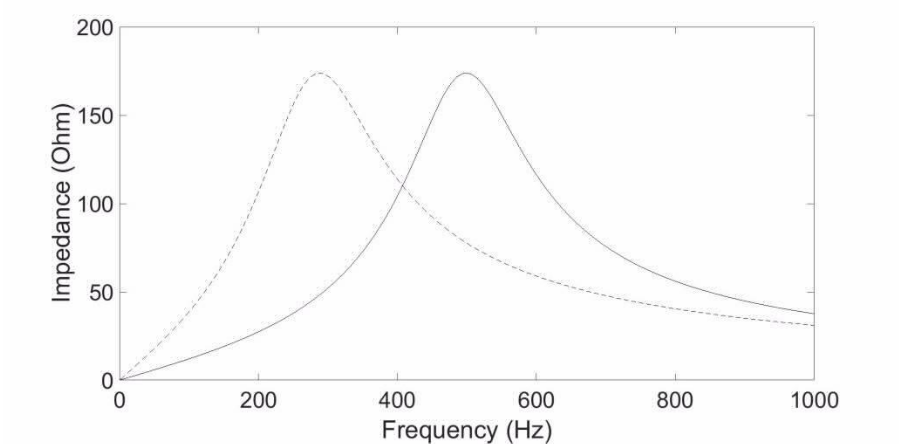


Figure 4.26: Source impedance versus frequency in a transmission system for a strong grid (green) and for a weak grid (red) [61]

At least one network operator reports to compensate for the loss of conventional production by adding capacitor banks. This will reduce the resonance frequency even further.

4.5.4 Interharmonics

The impact on the transfer of interharmonics is very similar to the impact on the transfer for harmonics.

4.5.4.1 Resonances at transmission level

Passive filters with HVDC links will have series resonances at interharmonic frequencies. More such links may result in increased amplification of interharmonics.

Also resonances due to transmission cables and/or wind park collection grids may result in amplification of interharmonics.

4.5.4.2 Less conventional production

This will result in a shift of resonances to lower frequencies. Interharmonics below and around the resonance frequency will be amplified; but interharmonics somewhat above the resonance frequency may actually be reduced in amplitude.

4.5.5 Subharmonics

There is no indication that the transfer for subharmonics will be impacted by any of the discussed changes.

4.5.6 Supraharmonics

The spread of supraharmonics is strongly impacted by the presence of other devices nearby. Changes in the impedance of those devices or adding new devices can have a strong impact on the spread of supraharmonics. Due to different cable length and many devices often each with their own filter, resonances are likely to occur. The consequences of this are not known yet.

Power-line communication can be hindered because of the creation of low-impedance paths by equipment connected to the grid [73].

4.5.7 Slow voltage variations

No known impacts.

4.5.8 Fast voltage variations

Less conventional production at transmission level will result in an increase in the source impedance at power-system frequency (50/60 Hz) at transmission level, with a wider spread of flicker as a result.

Production at lower voltage levels may, however, provide some voltage support in the time scale up to a few seconds. This will cause of reduction of flicker, especially when coming from the transmission grid. The support will typically be passive, not active support through a control algorithm, although the latter is certainly possible.

The deregulation of the electricity market has resulted in the scheduling of power stations no longer being under the control of the network operator. Also this can result in locally reduced fault levels and thus in increased levels of voltage disturbances. A case of an arc-furnace in Norway has been intensively studied and discussed. The flicker level used to be reduced by a nearby hydro-power station. However the market mechanisms made that this power station was no longer always running when the arc furnace was producing [259].

Power-electronic converters have the ability to control the voltage magnitude very fast. This makes it possible to reduce also fast voltage variations.

4.5.9 Transients

The presence of long cables in the transmission system can result in low resonance frequencies that amplify switching frequencies. In [253] a case is shown where a 100-km long 220-kV cable amplifies the second harmonic in voltage due to transformer energizing.

It is shown in [260] that unbalance loading could increase the overvoltage transient due to energizing of local production units. The overvoltages in a lightly loaded phase could be significantly higher than in the other phases.

Another example is the occurrence of harmonic overvoltages when energizing a transformer in the neighborhood of an underground cable. An overvoltage issue can occur on the low-voltage side that is due to resonance from the power cable and the transformer. This issue is magnified when the low-voltage side of the transformer is unloaded. Four power system configurations have been identified that, if present, could result in overvoltage on the transformer low-voltage terminal: a ground fault at the opposite end of cable from transformer, energizing a transformer through a cable that is connected to a bus bar with several other cables, energizing a transformer through a cable that is in parallel with another transformer with a matching cable, and energizing a capacitor bank that is connected to a bus bar that is supplying a transformer through a cable [261].

4.5.10 Voltage unbalance

4.5.10.1 Reduction in conventional production

Less conventional production at transmission level will result in an increase of the 50 or 60-Hz source impedance at transmission level, with a wider spread of unbalance as a result. While unbalance at transmission levels is rarely an issue, high-speed railways and some steel-industry processes are the exception.

Three-phase production units at lower voltage levels will however often provide a low-impedance negative-sequence path. This reduces the voltage unbalance.

4.5.10.2 Untransposed lines resulting in more voltage unbalance

Voltage unbalance is a source of concern for 3 phase loads connected to the system. Though multiple methods exist to compute voltage unbalance, they all attempt to quantify impact to loads. As load shape changes due to distributed generation new operational challenges may emerge.

IEC 61000-3-13 defines voltage unbalance in a polyphase system, as a condition in which the magnitudes of the phase voltages or the phase angles between consecutive phases are not all equal. The two primary measures of voltage imbalance are the ANSI C84.1 definition which is expressed in percent as the maximum deviation from the three phase average. Alternatively, the IEC uses the ratio of negative sequence components to the positive sequence components.

Disturbing loads, single phase loads and untransposed lines are the leading sources of voltage unbalance on the transmission system. Since most distributed generation is connected to the distribution system, the potential for unbalanced voltages exists as new generation sources could end up being on single feeders in the distribution system.

Moreover as firm generation plants are taken off line, changes in load flows may occur in the transmission system. Consider the case study in Figure 4.27, below, where firm generation is retired from substation F. The load doubles on the untransposed line between substations E and F.The result is an increase in the voltage unbalance to around 1.22% at station F.

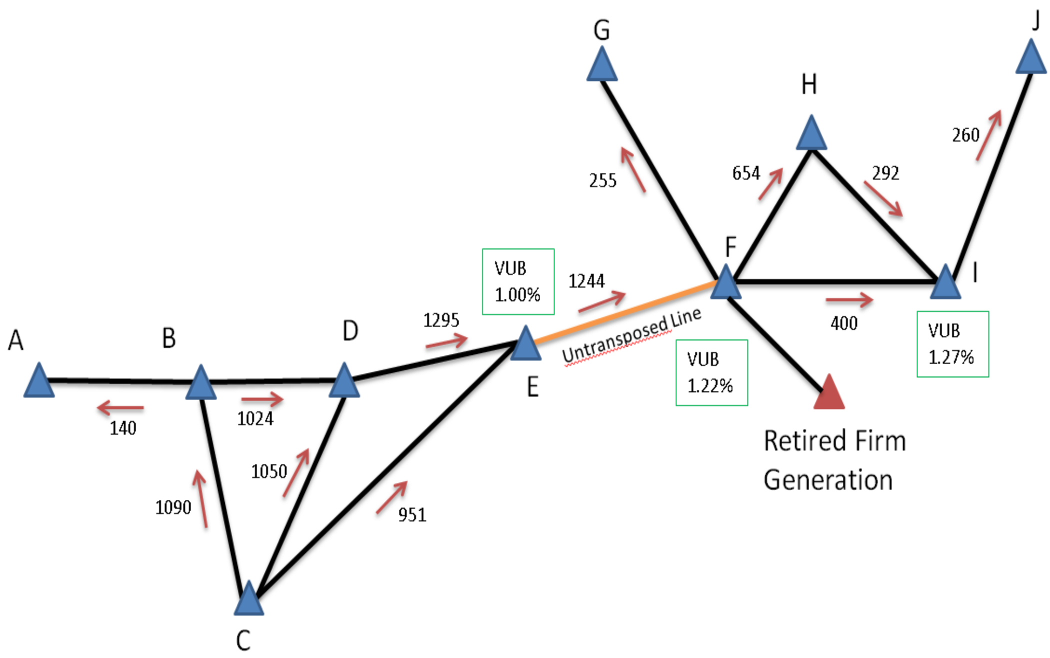


Figure 4.27 Voltage Unbalance Case Study

Mitigation of voltage unbalance really needs to take place at the distribution and transmission planning levels to ensure that new generation sources are being placed in service in a balanced way. In addition, transmission system planners may need to verify that load flows don't cause voltage unbalance on long untransposed transmission lines.

Voltage unbalance due to untransposed transmission and distribution lines is also discussed in [262].

4.5.11 Frequency variations

No known impacts.

4.5.12 DC components

No known impacts, but dc components in ac networks are not very well understood anyway.

4.6 CONCLUSIONS

4.6.1 General

4.6.1.1 Findings

- The on-going changes in the power system have impacts on emission, immunity, and the transfer of disturbances. All this impacts the probability of electromagnetic interference. A detailed review of knowledge is presented for four on-going changes: new types of electricity production; increasing amounts of power electronics; replacement of overhead lines by cables; and replacement of incandescent lamps by compact fluorescent and LED lamps.

- The review presented in this chapter did not show any situation where an immediate large increase in probability of electromagnetic interference is expected. However, several changes in emission, immunity and transfer require further studies and serious monitoring of the developments.
- Several of the changes are expected to result in a shift of resonances to lower frequencies. This will impact harmonics and switching transients. The increased emission at higher frequencies may be (partly) compensated by the shift in resonance to lower frequencies. But at the same time, the transfer of disturbances will become less predictable.
- The immunity of modern equipment with active power-electronic interfaces against all kinds of voltage disturbances is unknown.

4.6.1.2 Recommendations

- Further studies, including fundamental research, are needed for several types of disturbances that were almost not present in the grid before the large-scale introduction of active power electronics. This concerns especially: interharmonics; DC components and low-frequency subharmonics ("quasi-DC"); components above one or two kHz ("supraharmonics").
- The shift of resonances to lower frequencies requires a new look at harmonic propagation studies and voltage quality limits.
- The immunity of new devices against all types of voltage disturbances requires studies and may require new standards. Especially flicker with LED lamps needs to be studied.
- Studies are needed to explain the discrepancy between simulations and measurements where it concerns the impact of large numbers of compact fluorescent and LED lamps on the harmonic distortion.
- Research and studies are needed after the immunity of modern equipment with active power-electronic interfaces against all kinds of voltage disturbances. Such research and studies should result in recommendation for equipment manufacturers to avoid lack of immunity.
- Work is needed towards improved immunity tests for equipment, without having to put any additional requirements in product standards.
- Spread of knowledge and case studies are needed on the changes in capacitance of the grid at different voltage levels and for different kind of grids.

4.6.1.3 Open issues

- It remains unclear how knowledge on actual voltage disturbances and their importance for immunity, should be disseminated to the equipment manufacturers. This should preferably be done without any additional compulsory requirements of equipment immunity.

4.6.2 Voltage dips

4.6.2.1 Findings

- Power-electronic driven equipment is able to start without high currents being taken from the grid. This will lead in a reduction of the number of dips, especially those due to motor starting.
- The replacement of large production units by small ones will change the spread of voltage dips through the grid. Somewhat simplified: dips will spread further through the transmission system, but will be damped in distribution systems with production units embedded.

4.6.2.2 Recommendations

- The immunity of equipment against multiple voltage dips, occurring short after each other, requires further research.
- To be able to study immunity of power-electronics equipment against voltage dips, a better understanding is needed of the characteristics of voltage dips.

4.6.2.3 Open issues

- The need for standard methods for calculating additional characteristics of voltage dips remains not clear. This will enable additional statistics on voltage-dip characteristics but may also lead to unnecessary complication of voltage-dip statistics.

4.6.3 Voltage swells

4.6.3.1 Findings

- Replacing of overhead distribution lines by cables will result in a significant reduction in the number of voltage swells.

4.6.3.2 Recommendations

- Case studies are needed to quantify the reduction of the number of voltage swells due to the replacement of overhead distribution lines by cables.

4.6.3.3 Open issues

- None.

4.6.4 Harmonics

4.6.4.1 Findings

- The harmonic emission from new production units is small, especially for the low-order odd harmonics. But as such production units are additional equipment that doesn't require an increase in transformer or cable size, some increase in harmonic emission may still be expected.
- The use of more advanced power-electronic interfaces with equipment results in less emission for the low-order odd harmonics.
- Active converters react differently to voltage distortion than passive ones. Not only secondary emission but also interaction (see APPENDIX E) can play an important role.
- The massive replacement of incandescent lamps by compact fluorescent and LED lamps did and will not result in a significant increase in harmonic distortion.
- The change in capacitance of the grid and equipment connected to it will impact the spread of harmonics.
- The replacement of large production units by small ones will change the spread of harmonics through the grid.

4.6.4.2 Recommendations

- The emphasis in research and standardization on low-order odd harmonics should be reduced. Instead more attention should be given to high-order odd harmonics, even harmonics, interharmonics and supraharmonics.
- Not only changes in harmonic magnitude but also phase angle of harmonics should be considered in harmonic studies and measurements.
- There is a need for further fundamental research on secondary emission and interaction. Both simulations and measurements are needed.
- The impact of large numbers of small devices on the harmonic voltage and current distortion should be studied.
- Further research is needed on the impact of secondary emission (and thus of the voltage distortion) on the immunity of equipment against harmonics, interharmonics and supraharmonics.
- More case studies are needed on the impact of changing capacitance on the spread of harmonics at different voltage levels and for different kinds of networks.
- Fundamental research is needed on the damping of harmonics provided by end-user equipment, the way in which this changes with the introduction of active power-electronic converters, and the way in which this change is expected to impact harmonic distortion levels are different voltage levels and for different kind of networks.
- Harmonic studies should become standard practice with network operators and not just be performed with the connection of large new installations. The network operators should take more responsibility in knowing and understanding harmonic distortion in their networks.
- Fundamental research is needed after the consequences of resonances in transmission grids close to low-order harmonic frequencies, especially harmonics 2, 3, 5 and 7. The damping needs to be quantified and possible non-linear phenomena with transformers and HVDC links should be studied.

- Wide-scale mapping is needed of the trends in harmonic distortion, at all voltage levels. As much details as possible should be made available to the general research community to allow interpretation of the results.

4.6.4.3 Open issues

- It remains unclear how important secondary emission and interaction are at different locations in the grid. There are strong indications of their importance at the equipment terminals, but the importance at other locations remains unclear.
- It remains unclear if there is a need for setting more strict emission requirements of small devices with a large penetration.
- It remains unclear if there really will be a significant reduction in damping of harmonic resonances due to the introduction of active power-electronic interfaces with equipment.

4.6.5 Interharmonics

4.6.5.1 Findings

- Increased levels of interharmonics are expected in future grids.
- Several studies have shown the sensitivity of compact fluorescent and LED lamps to interharmonics in terms of light flicker.
- The change in capacitance of the grid and equipment connected to it will impact the spread of interharmonics.
- The replacement of large production units by small ones will change the spread of interharmonics through the grid.

4.6.5.2 Recommendations

- Interharmonics should become an integral part of research and studies on harmonics. The emphasis in research and standardization on low-order odd harmonics should be reduced. Instead more attention should be given to high-order odd harmonics, even harmonics, interharmonics and supraharmonics.
- Wide-scale mapping is needed of the trends in interharmonic distortion, at all voltage levels. As much details as possible should be made available to the general research community to allow interpretation of the results.
- Further research is needed on the impact of secondary emission (and thus of the voltage distortion) on the immunity of equipment against harmonics, interharmonics and supraharmonics.
- Further research is needed on the impact of interharmonics on light flicker. The results of this research should be included in future standardization on light flicker.
- More case studies are needed on the impact of changing capacitance on the spread of interharmonics at different voltage levels and for different kinds of networks.

4.6.5.3 Open issues

- The need for additional standardization on interharmonics remains unclear.

4.6.6 Subharmonics

4.6.6.1 Findings

- With the increase in interharmonics, also an increase in subharmonic distortion is expected.
- There are no indications of an increase of subharmonics not related to interharmonics.

4.6.6.2 Recommendations

- Wide-scale mapping is needed of the trends in subharmonic distortion, at all voltage levels. As much details as possible should be made available to the general research community to allow interpretation of the results.
- More studies are needed after the impact of subharmonics on power-electronic equipment.

4.6.6.3 Open issues

- The need for additional standardization on interharmonics remains unclear.

4.6.7 Supraharmonics

4.6.7.1 Findings

- An increasing amount of equipment emits non-negligible levels of supraharmonics in the grid. Voltage distortion in this frequency range has shown to be non-negligible at certain locations. No overall information is available on the existing levels.
- The impact of supraharmonics on cables depends on the type of cable terminals used.
- The change in capacitance of the grid and equipment connected to it will impact the spread of supraharmonics.
- Wide-scale mapping is needed of the trends in supraharmonic distortion, at all voltage levels. As much details as possible should be made available to the general research community to allow interpretation of the results.

4.6.7.2 Recommendations

- Fundamental research on supraharmonics is needed among others to provide input to standardization.
- Supraharmonics should become an integral part of research and studies on harmonics. The emphasis in research and standardization on low-order odd harmonics should be reduced. Instead more attention should be given to high-order odd harmonics, even harmonics, interharmonics and supraharmonics.
- Measurement campaigns are needed to provide information on existing levels of supraharmonics.
- Further research is needed on the impact of secondary emission (and thus of the voltage distortion) on the immunity of equipment against harmonics, interharmonics and supraharmonics.
- The impact of the type of cable terminals on their immunity against supraharmonics needs to be mapped and disseminated to network operators and cable manufacturers.
- More case studies are needed on the impact of changing capacitance on the spread of supraharmonics at different voltage levels and for different kinds of networks.

4.6.7.3 Open issues

- There remains disagreement on whether supraharmonics are a concern leading to an increased probability of interference. Further research is certainly needed, as well as certain standards. However, standards should not become an unnecessary barrier against the introduction of certain types of equipment.

4.6.8 Slow voltage variations

4.6.8.1 Findings

- New production units connected to the distribution network will increase the risk of overvoltages. This is a well-known phenomenon; no further basic research is needed.
- The introduction of new types of consumption, like electric heating and electric vehicles, will increase the risk of undervoltages. The introduction of more energy-efficient equipment (like LED lamps) will reduce the risk of undervoltages.
- Compact fluorescent and LED lamps are less sensitive to overvoltages than compact fluorescent lamps.

4.6.8.2 Recommendations

- Case studies, preferably using a stochastic approach, are needed of the impact on large but unknown amounts of small production units on slow voltage variations.
- Measurement campaigns are needed to obtain a detailed mapping of the existing slow voltage magnitude variations as a function of time-of-day and time-of-year.

4.6.8.3 Open issues

- Would an increase of the overvoltage limit be appropriate now that lamps are less sensitive to overvoltages where at the same time the connection of solar power is made more difficult because of those overvoltage limits?

4.6.9 Fast voltage variations

4.6.9.1 Findings

- The introduction of wind and solar power will result in additional variations in voltage at the time scale between 1 second and 10 minutes.
- No change is expected in the variations at time scales less than 1 second, which are the main cause of (classical) light flicker.
- The impact of fast voltage variations on flicker with compact fluorescent and LED lamps is completely different from the impact for incandescent lamps.
- The replacement of large production units by small ones will change the spread of fast voltage variations through the grid.

4.6.9.2 Recommendations

- Further studies are needed to understand and map voltage variations at the time scale between 1 second and 10 minutes.
- Changes are needed with regards to standardization on light flicker.

4.6.9.3 Open issues

- The importance of voltage variations at the time scale between 1 second and 10 minutes remains unclear. Further studies are needed, but there is as yet no need for standardization or regulation covering the range.
- It remains unclear if short-term flicker severity (Pst) should be kept as a voltage-quality index.

4.6.10 Transients

4.6.10.1 Findings

- The replacement of large production units by small ones will change the spread of transients through the grid.
- The change in capacitance of the grid and equipment connected to it will impact the spread of transients.
- The increasing amount of cables and equipment with a capacitive interface will increase the number of switching transients.

4.6.10.2 Recommendations

- Studies are needed on the impact of transient, like capacitor energizing transients, on power-electronic equipment.

4.6.10.3 Open issues

- It is not clear if overvoltage transients are a significant concern for LED street lamps or whether the reported cases are due to bad installation practices.

4.6.11 Voltage unbalance

4.6.11.1 Findings

- Single-phase production units, which in practice will almost exclusively be solar power, increase the voltage unbalance in the distribution network.
- The replacement of large production units by small ones will change the spread of unbalance e through the grid.

4.6.11.2 Recommendations

- Further studies, especially stochastic ones, are needed to quantify the impact of single-phase production units on the voltage unbalance.
- Measurements are needed of the existing voltage unbalance in low-voltage networks, both magnitude and phase angle, and its variation with time-of-day and time-of-year.

4.6.11.3 Open issues

- It remains unclear if single-phase inverters should be forbidden or restricted as has been suggested in some countries. The actual impact of such inverters on the unbalance and the impact of high levels of unbalance on three-phase equipment should be investigated first.

4.6.12 Frequency variations

4.6.12.1 Findings

- A wide-scale penetration of wind and solar power is expected to result in an increase in frequency variations.

4.6.12.2 Recommendations

- The increase in frequency variations should be monitored but there is no need for any mitigation actions from a power-quality viewpoint.

4.6.12.3 Open issues

- For which level of frequency variations does it become a power-quality issue? This may become a relevant question in future microgrids.

4.6.13 DC components

4.6.13.1 Findings

- There are indications of increased emission of DC components by active converters, but no clear information is available. At this moment there is no indication that this will result in increased probability of interference.

4.6.13.2 Recommendations

- Further research is needed after the emission and spread of DC components.
- Further research is needed on the impact of DC components on power-electronic converters.

4.6.13.3 Open issues

- None

4.6.14 Subsynchronous resonance

4.6.14.1 Findings

- Subsynchronous resonance may become an issue with wind parks under certain circumstances.
- With the replacement of large production units by small ones, subsynchronous resonance may become less of an issue that before.

4.6.14.2 Recommendations

- Further studies on subsynchronous resonances are, at this moment, not needed from a power-quality viewpoint.

4.6.14.3 Open issues

- To which extent are there relations between subharmonics and sub-synchronous resonance.

4.6.15 Geomagnetically induced currents

4.6.15.1 Findings

- The emission of geomagnetically induced currents is not expected to change, but the sensitivity of equipment and society to the consequences has increased.
- An important consequence of geomagnetically induced currents is the presence of high harmonic voltage distortion in the transmission grid.

4.6.15.2 Recommendations

- The immunity of power-electronic converters to high levels of harmonic voltage distortion should be studied, this holds especially for transmission-grid-connected equipment like HVDC and FACTS

4.6.15.3 Open issues

- Is there a need for standardized tests against the high levels of harmonic voltage distortion that can be expected due to geomagnetically induced currents.

5. MICROGRIDS

5.1 INTRODUCTION

This chapter introduces the concept of microgrids in the context of power quality and power quality management. At this point in time, the widespread use of microgrids has yet to be realised. There is a great deal of research activity, attracting interest from universities and utilities. The islanded operation of microgrids brings with it a considerable number of issues: frequency and voltage control, load management, reactive power control, and disconnection/reconnection (to the main grid) strategies to name a few. In addition, the concept of PQ management in a microgrid network also brings many challenges to the table.This chapter attempts to capture the issues surrounding power quality in microgrids.

5.2 WHAT IS A MICROGRID?

The CIGRE WG6.22 definition of a microgrid is given as [286]:

"Microgrids are electricity distribution systems containing loads and distributed energy resources, (such as distributed generators, storage devices, or controllable loads) that can be operated in a controlled, coordinated way either while connected to the main power network or while islanded."

The Microgrid group at Berkeley Lab define a microgrid as:

"A microgrid is a localized grouping of electricity sources and loads that normally operates connected to and synchronous with the traditional centralized grid (macrogrid), but can disconnect and function autonomously as physical and/or economic conditions dictate."

The U.S. Department of Energy Microgrid Exchange Group also have their own definition a microgrid. In all cases, there is a focus on the requirement for localised control as well as the ability to operate whilst connected to the main grid (traditional operation) or as an island.

The literature suggests [287] that Microgrids will be able to offer advantages to both utilities and customers. These benefits include improved energy efficiency and reliability of supply, a reduction in overall energy consumption through Distribution Management System (DMS) principles, loss reduction and reduced environmental impact. The microgrid is seen as the preferred distribution network architecture to be used with the so-called 'smart grid' concept in order to optimally exploit the benefits arising from integrating large numbers of small to medium sized DER units (less than approximately 1 MW) into LV and MV distribution networks.

There are three major objectives/benefits of microgrids [288]:

1. to present a controlled profile to the wider power system, e.g. to dampen the variability of a local renewable resource and buffer the grid from it;
2. to use local assets unlikely to be chosen or difficult to operate by the centralised grid, e.g. small-scale renewable resources, or interconnected plug-in electric vehicle batteries used for ancillary service;
3. to provide power quality and/or reliability (PQR) different from the local standard of service, e.g. to serve particularly sensitive loads such as emergency services, and potentially provide heterogeneous service to its internal loads.

Within the context of a microgrid, distributed energy resources (DERs) cover all possible sources at the scales suitable for managing the generation of electrical power for the loads of the microgrid. For example, generators include fossil or biomass-fired small-scale combined heat and power (CHP) devices, photovoltaic modules (PV), small wind turbines, mini-hydro, etc. Non-renewable sources can also be included, such as diesel driven generation.

Storage devices include all electrical (e.g. superconducting magnetic energy storage (SMES)), electrochemical (e.g. batteries), mechanical (e.g. flywheel) and heat storage technologies. Collectively, such devices are referred to as energy storage systems (ESS). While the microgrid concept focuses on a power system, thermal storage can be relevant to its operation whenever its existence affects operation of the microgrid. For example, the availability of heat storage will alter the desirable operating schedule of a CHP system as the electrical and heat loads are decoupled. Similarly, the precooling or heating of buildings will alter the load shape of heating ventilation and air conditioning (HVAC) system, and therefore the requirement faced by electricity supply resources.

Controllable loads such as lighting, pump systems and air conditioning, have a vital role to play in the operation and control of a microgrid, particularly when operating in islanded mode. The ratio of load relative to generation capacity is much smaller in a microgrid. The variability of load will therefore have a much greater effect in small-scale systems such as a microgrid.

Microgrids can operate in grid-connected or grid-disconnected (islanded) modes.

When the microgrid is connected to the main grid, the strength of the main grid provides a reference for both system voltage and frequency. Although within the microgrid, PQ issues may arise as a consequence of the level of DER, the problem is no different compared to the issue presented in Chaper 4 .

However, when the microgrid is operating in islanded mode, frequency and voltage stability becomes a localised problem. In addition to these key parameters, the change in the short circuit capacity at the POC of large polluting loads means that the agreed emissions no longer are applicable. Alongside the change in short circuit capacity at the POC of large polluting loads and the microgrid-to-main-grid junction, the characteristic impedances of the microgrid will also change. This can lead to system resonances that simply do not exist in grid-connected mode.

Microgrids can be classified according to the type of power distribution: Line-Frequency 50/60 Hz AC (LFAC) microgrids, DC microgrids, High-Frequency AC (HFAC) microgrids, and hybrid DC and AC-coupled microgrids [289] The LFAC type is the most common, while the DC concept has been applied in telecommunication systems and EV charging stations, and HFAC is used for marine and aircraft power distribution systems (e.g. 400 Hz).

In this chapter, only LFAC and the DC microgrids will be discussed.

5.3 OVERVIEW OF PQ PHENOMENA ASSOCIATED TO MICROGRIDS

5.3.1 Main PQ phenomena

The main PQ phenomena associated to microgrids are (see Chapter 4):

- Harmonics, Interharmonics and Supraharmonics;
- Slow voltage variations;
- Fast voltage variations;
- Voltage unbalance;
- Frequency variations;
- DC components.

Some of them will be briefly discussed in the following of this chapter.

5.3.2 PQ Phenomena related to connection and disconnection

This sub-section describes how connection and disconnection of a Microgrid (from the main grid) is likely to impact loads.

Microgrid mode transition can be classified into two types; GCM to IM and IM to GCM. Each transition needs to be carefully designed to ensure that no abnormal operating conditions are imposed in the microgrid. The mode transfer from grid connected to islanded mode has been identified as the most challenging since the microgrid will be subjected to large voltage magnitude and angle variations, creating undesirable operating conditions for connected loads [290]. Furthermore, the grid connected to islanded mode transition can be classified into two additional types; planned and unplanned islanding.

The planned disconnection are determined based on the grid-side ancillary service requirements and planned network outage conditions, such as service outages for distribution feeders. Therefore, the mode transition strategy must be prudently planned based on the forecasted generation surplus/deficit in the microgrid system.

Unplanned islanding conditions mainly occur due to undesirable network conditions (i.e. during large voltage or frequency variations), hence microgrid must be designed to continuously monitor these variations and subsequently switch to the islanded mode to maintain uninterruptible supply to the microgrid loads. During such undesirable network conditions, voltage and frequency variations create adverse operating conditions for loads operating in the microgrid system. For a successful mode transition, the microgrid generation must be matched with the load demand in order to alleviate transient phenomena in the microgrid.

One active area of discussion is the control strategy for power-electronic interfaced DG during the transition from GCM to IM and back again. In general, during GCM operation, the strategy of the VSI is to operate in current control or power factor control modes, using the measured grid voltage and frequency as a reference. However, in IM operation, the VSI operates in voltage control mode because of the lack of a utility voltage for the formation of the reference. Thus, it is clear that 'the fit-and-forget strategy for integrating DG is not a sustainable option and a co-ordinated approach with active control of these units will be required' [291].

Loads that are sensitive to variations in supply voltage quality require careful consideration when mode transition occur, especially in the case of a planned transition. The control system responsible for planning the transition needs to carefully assess the load and generation requirement prior to transitioning from GCM to IM. If, when the transition occurs, sensitive loads disconnect from the grid (which has now become the IM microgrid) as a consequence of frequency, phase or voltage transients (rapid frequency changes, phase jumps leading to commutation failure in power electronic circuits, voltage sags or swells, etc.), then the change in load requirements will potentially create a load/generation unbalance that could potentially be difficult to manage unless there is adequate energy storage.

A summary of likely PQ disturbances during mode transition from GCM to IM and vice versa are:

1. Phase angle jumps in supply voltage; more likely during unplanned transitions.
2. Voltage sags or swells; as a consequence of load/generation unbalance and unplanned disconnection of sensitive loads.
3. Frequency variations; as a consequence of load/generation unbalance.

The transition strategies, the ratio of machine interfaced generation to power electronic interfaced generation and the control scheme of these units will have a significant influence on the level of the PQ disturbances that will take place during mode transition.

5.4 PQ IN LINE-FREQUENCY AC (LFAC) MICROGRIDS

In LFAC microgrids, whose generic simplified block diagram is shown in Figure 5.1, the DER devices are typically interfaced to the grid via a power electronics interface, with the exception of conventional rotating machines. In such cases, it is possible to have both directly connected, as well as power electronic interfaced devices. In some microgrid design philosophies, regardless of the type of DER, all devices are connected via power electronics for improved control of fault current, droop response, etc. The Consortium for Electric Reliability Technology Solutions (CERTS) microgrid, for example, is an "all power electronic interface", whose potential applications include industrial parks, commercial and institutional campuses and other locations that require uninterrupted and high power quality electricity supply [292].

From a PQ perspective, LFAC microgrids are operated in two distinctive modes: grid-connected and islanded. The adverse impacts on PQ are expected during islanded operation, but also during the transitions between islanded and grid- connected operations as discussed earlier. These transitions may make some DER units to switch from voltage controlled mode (during islanded operation) to current controlled mode (during grid-connected operation), causing voltage stability problems due to the delay in detection of non-intentional islanding [291].

In islanded mode, higher dynamics and wider ranges of interactions between microgrid loads and available small or medium-scale DERs will result in more pronounced, more frequent and longer voltage and frequency variations. This will be further augmented by the reduced short circuit power and inertia of microgrids.

The power electronics interfaces of DER connected to the microgrid include traditional grid-commutated topologies, which might cause undesirably high levels of harmonics when they are connected to the power grid. Self-commutated PWM (Pulse-Width-Modulation) controlled inverters typically produce supraharmonics (waveform distortion in the range from 2 kHz to 150 kHz) [136].

For the static performance of microgrids, the low X/R ratio of distribution line impedance might affect the load sharing accuracy of inverters, typically resulting in unbalances. Furthermore, harmonics and unbalances are poorly compensated with the connection of nonlinear and unbalanced loads. For the dynamic behavior of microgrids, the voltage and frequency dependencies of load responses have to be taken into account when choosing droop characteristics for DER units, otherwise controllers may fail to ensure a proper sharing and lead to instability [288].

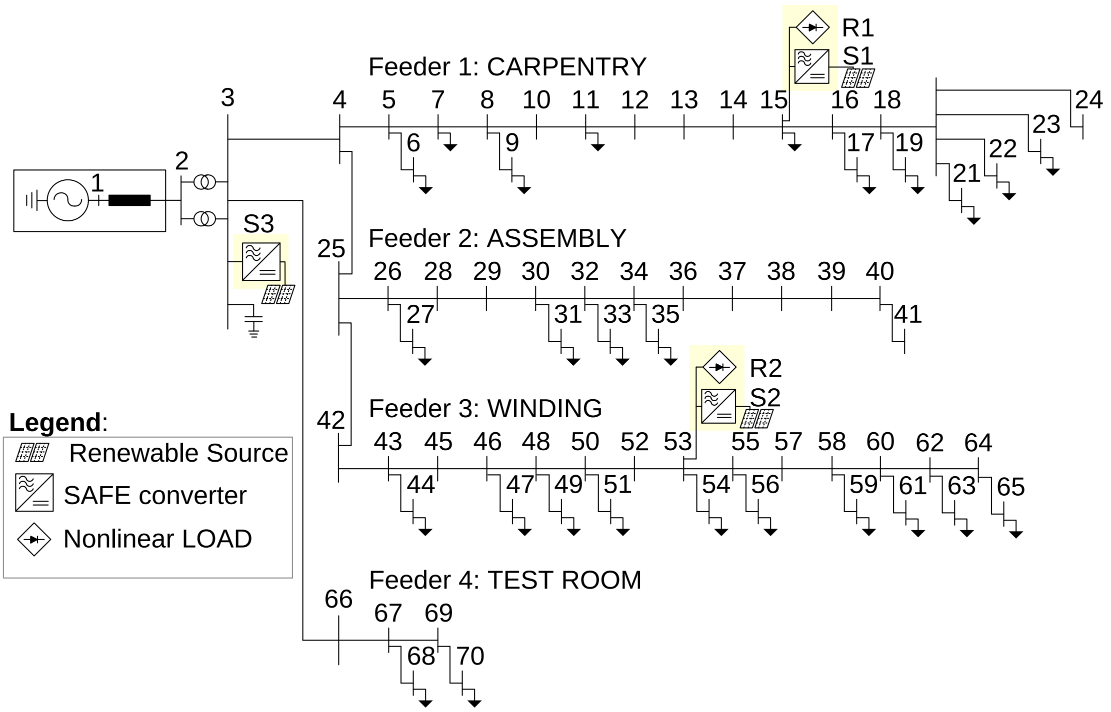


Figure 5.1 Simplified diagram of generic AC MG with renewable sources, Synchronous Active Front-end (SAFE) and nonlinear loads

5.4.1 Main PQ Phenomena

There are two key issues associated with harmonic disturbances in microgrid context; an increase in the level of distortion (current and voltage) and the change in the resonance that may be observed in the microgrid.

An increase in the level of THD (both current and voltage) arises as a consequence of the high number of inverter-based generating devices located in the microgrid and the disconnection of machine-based devices from the PCC during islanded mode of operation [292].

Several papers have highlighted the change in the frequencies under which resonance may be excited in microgrids as a consequence of their diverse electrical characteristics [293]. The authors indicate that microgrids are likely to have a wider range of frequencies under which resonance may occur compared to those of a conventional distribution network. Both the topology and components within the microgrid contribute to this problem. Resonance normally occurs at frequencies less than 20 times the fundamental frequency in conventional distribution networks, but in microgrids, this rule-of-thumb is unlikely to hold true. In [294], the authors describe how the multiple, parallel-inverter-based grid-interactive microgrid presents a challenging environment with regard to inverter interactions that can potentially excite multiple resonances. These interactions take place as a consequence of the output filter stages and grid impedances rather than at a control level. The authors identify resonances that can take place; internal resonance (in the inverter itself), parallel resonance between inverters, and series resonance between the main grid and the microgrid. The third scenario requires the microgrid to be operating in grid-connected mode. However, all is not lost. The authors also describe control techniques that can be easily employed in both voltage and current controlled devices in order to dampen the occurrences of said resonances. In [295], the authors also indicate that the presence of passive harmonic filter devices and capacitor banks can exacerbate the resonance problem when in islanded mode.

The authors of [296] have identified that voltage THD cannot be determined from current THD for inverters whilst connected to the grid (grid-connected mode) due to the presence of background distortions and particular grid-side impedances. When a transfer to islanded mode occurs, there is a risk that higher order harmonics will resonate with local loads or changed system impedances, causing much higher harmonic voltages.

A simulation-based study of harmonics impact within an AC microgrid is investigated in [295], as well as mitigation solutions like passive filters and active filtering. The study, based on an experimental microgrid consisting of both machine and power electronics interfaced sources, as well as a variety of linear and non-linear loads, describes how replacing a capacitor bank with a harmonic filter and the introduction of active harmonic filtering can improve the THD within a microgrid.

Analysis of grid-interfacing converter systems with enhanced voltage quality for microgrid applications is investigated in [297], experimental validations of microgrid operation under unbalanced/nonlinear loads revealing the frequency spectrums and the total harmonic distortion, under distorted grid conditions, and unbalanced voltage dips were conducted.

The experimental harmonic analysis of microgrids operating in grid connected mode (GCM) or standalone mode is conducted in [298]. The authors utilise a so-called 'harmonic compensator unit' that is able to compensate for the distortion arising as a consequence of the background distortion when in grid-connected mode and the inherent distortion from the interaction between the load current and grid impedance when in islanded mode (IM).

Analysis of the harmonic distortion levels and reduction methods with increased penetration levels of the PVs is carried on in [299]. The investigation revealed that the worst voltage distortion may be found to be outside the acceptable level of the IEEE Standard 519.

The most vexing problem is understanding how the microgrid paradigm will evolve in the future grid. Many of the solutions offered with regard to resonance minimisation and harmonic mitigation are costly and require utility-wide approaches, or involve complex inverter control strategies and configurations that are not utilised in the current technology. As microgrids evolve, there will likely be a mix of old and new technologies and there will be a need for new devices to be able to compensate for a wide range of old technologies, unless the management of the microgrid is prepared to make appropriate investment. In this case, the problem could be regarded as an economic one rather than a technology-based issue.

A nonlinear three-phase load with one phase disconnected is connected to a microgrid to generate fundamental voltage unbalance as well as negative and positive sequences of harmonics is considered in [300]. The voltage distortion is mitigated by selective insertion of capacitive virtual impedances for negative sequence of fundamental component as well as positive and negative sequences of main harmonics. The method employed uses advanced inverter control strategies to compensate for the uncharacteristic harmonics as well as the unbalance introduced as a consequence of the two-phase connection. Whilst the method indicates that such a strategy is able to provide the required compensation, how this system might be employed in a microgrid situation is yet to be investigated.

The detection of harmonics and voltage fluctuations, and unbalance in an AC real practice microgrid was conducted in [301]. The operation of distributed energy resources and nonlinear loads affecting the power quality was investigated. An interface platform for PQ analysis and data table lists at selected nodes, measured at different time intervals, was created.

Power quality analysis of low voltage microgrids, regarding unbalance and harmonics, and application of storage units for compensating the electromagnetic disturbances is conducted in [302], simulations and experimental tests were carried out to demonstrate the effectiveness of the storage inverter control to compensate the current harmonics and unbalance.

5.4.2 Mitigation

A key enabler to the mitigation of PQ related phenomena in microgrids is the use of advanced inverter control strategies for power electronics interfaced DERs. These inverters will require the use of virtual impedances, advanced voltage and current control strategies and, quite possibly, a communications infrastructure to permit a coordinated approach to the mitigation of PQ related problems.

5.4.2.1 Single or multi-purpose devices

This sub-section addresses devices that one would connect to the Microgrid to mitigate PQ problems.

The application of D-FACTS (D-STATCOM, SMES, DVR-dynamic voltage restorer, APF-active power filter, OPQC-unified power quality conditioner) in microgrid is presented in [303]. The use of active power filters and static VAr compensators to improve to improve the power quality for a three-phase-three-line microgrid is investigated in [304]. Active power filters to mitigate voltage harmonics and voltage fluctuations in microgrids, by implementing a control system that implements harmonic damping and voltage regulation, is investigated in [305]. The use of multiple active-filter units, instead of a large central unit, for reducing the harmonic distortion of power systems and to improve the power quality is presented in [306]. The use of a D-STATCOM to reduce voltage fluctuations in high-level penetration of DG systems is analysed in [307].

An integrated power quality controller based on a variable reactor mitigating the harmonic penetration, limiting the fault current and compensating the voltage fluctuation is proposed and verified through simulations and experiments in [308].

5.4.2.2 Operation of inverters

Many sources in a Microgrid will be connected via an inverter interface. The operation of this interface can have significant impact on the PQ as well as other services in the Microgrid. e.g. frequency and voltage regulation, reactive power support, active harmonic compensation, high frequency harmonics etc. When the Microgrid is grid-connected, their operational characteristics may be different. An in-depth review of power sharing control principles in AC microgrids is conducted in [309], illustrating the control schemes and comparing the various methods in term of advantages and disadvantages.

The power quality behaviour of DC/AC inverter connected devices in microgrids is function the choice and implementation of the control algorithms, realizing a compromise between DC bus ripple and AC power quality. Different control strategies are applied for reducing the levels of voltage unbalance and harmonics at the PCC in [310].

A converter control system based on harmonic power versus voltage loop bandwidth droop to share the harmonic current among multiple inverters when sharing nonlinear loads is investigated in [311]. A control system composed of harmonic compensator, fundamental power controllers, voltage and current proportional-resonant controller and virtual impedance loop, for selective compensation of main voltage harmonics in a grid-connected microgrid is proposed in [312].

5.5 PQ IN DC MICROGRIDS

The DC Microgrid, whose generic simplified block diagram is shown in Figure 5.2, is not without PQ phenomenon. The variances for 230 V rms 50 Hz systems, for example, have counterparts in DC systems; voltage regulation, ripple, ripple frequency, sag, swell, average value etc.

In the existing AC networks, in order to achieve a high degree of voltage continuity, many customers have installed uninterruptible power supplies (UPS), which includes AC input, DC link and DC/AC conversion stages with a battery interposed. Other customers are employing DG units and storage energy systems for improving the supply reliability. Some of the distributed generation technologies like photovoltaic cells, fuel cells and storage systems (batteries, super-capacitors) generate DC power while other distributed energy sources (like micro-turbines, Stirling engines, wind turbines) and some storage systems (flywheels), require a DC intermediate conversion stage for transforming the high-frequency electrical energy into suitable 50 Hz energy [286] - [314].

The ensuring of a proper supply continuity level and the achieved stage of development by the distributed generators, have determined the consideration of realizing a low voltage DC distribution system. Proposals for DC networks for commercial facilities, buildings, for critical customers requiring high power quality degree have been considered in [315], [316], [317]. The low voltage DC distribution system has to ensure that loads are supplied with a high degree of power quality and supply continuity, and to facilitate an easier interconnection of the distributed generation sources.

Different configurations of low voltage distribution system were proposed in [318], [319], [320], [321], [322], composed of small capacity distributed resources (photovoltaic and fuel cells, small capacity micro-turbines), storage systems (super-capacitors, electrochemical batteries, super-magneting energy storage, flywheels) for supply continuity during short time interruptions, emergency units (Diesel power system) for sustained interruptions, and various high power quality requirement degree loads (AC and/or DC loads).

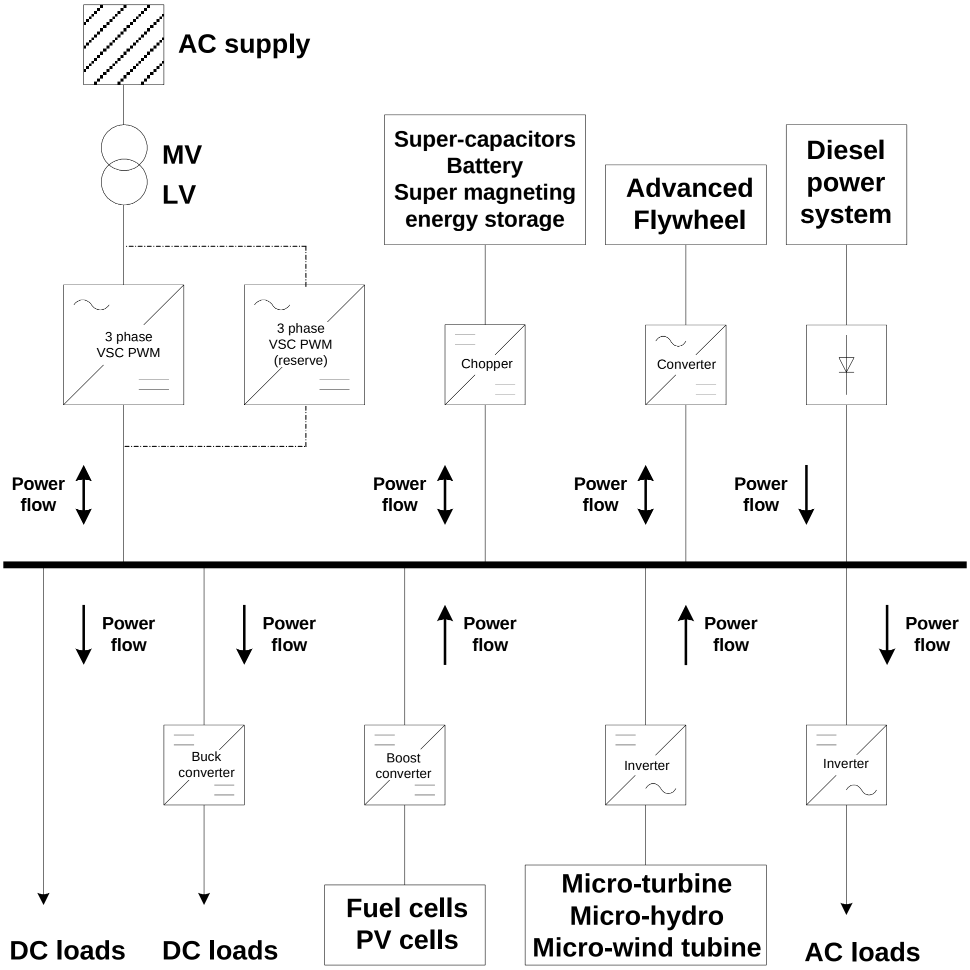


Figure 5.2: Simplified diagram of generic DC MG

The DC/AC interface should ensure that the harmonic distortion injected in the AC network is reduced, such that to not exceed the limits stipulated by standards. To guarantee the supply continuity of the customers during short-duration interruptions, storage power systems are interconnected to the low voltage DC distribution system. The Diesel power system is designated to supply the loads during sustained interruptions in the AC network.

Experimental implementations of small scale DC grids and transient tests with load variations, reverse flow occurrence, transients in AC and DC grids can be found in [323], [324], [325], [326]. Faults and interruptions can occur in the AC network but without DC side customer end interruptions and complaints. In case od DC faults, the grid can be planned such that to isolate the fault line and to continue the operation of the not-affected loads.

5.5.1 Main PQ Phenomena

An adaptive DC link voltage control method during the low voltage ride-through operation period of photovoltaic installations is implemented to mitigate the high frequency harmonics injected into the mains is implemented in [327]. In addition this control method, during unbalanced faults within the main grid, can attenuate the 100 Hz DC link voltage ripple occurring in this case.

An harmonic mitigation strategy to reduce current harmonics induced by the front-end rectifiers in multi-drive systems consisting of diode rectifiers, silicon controlled rectifiers (SCR), and boost converters in the DC-link is implemented in [328]. The method is tested through simulations and experiments, showing good reduction results of the current total harmonic distortion.

The harmonic analysis of isolated/nonisolated DC microgrid, with hybrid energy sources with various loading regimes, is investigated in [329]. The considered loads were pulsed type, drawing high currents during short periods of time, causing voltage and frequency fluctuation.

The harmonic currents absorbed by a converter or the voltage ripple produced by a source converter, are controlled through filters whose capacitance can draw substantial inrush current [330], [331], [332], [333], [334], [335].

A control method to mitigate the second-order harmonic ripple in a boost inverter-based single-phase grid-connected ESS is implemented in [336]. The method was experimentally tested on a grid-connected storage systems, the results revealing that this method does not increase other frequency harmonic components in both steady-state and transient operation.

An inductive filtering method to an industrial DC microgrid to attenuate the effects of both the harmonic and the reactive power on both the public power network and the industrial custom power system was applied in [337].

A review of possible configurations for DC grids, as well as prominent hardware topologies, is conducted in [338]. In addition, discussion on the several newly proposed protection systems is carried on.

5.6 CONCLUSIONS

5.6.1 Findings

When an LFAC microgrid is connected to the main grid, the strength of the main grid provides a reference for both system voltage and frequency. Although within the microgrid, PQ issues may arise as a consequence of the level of DER. However, when the microgrid is operating in islanded mode, frequency and voltage stability become a localised problem. Alongside the change in short circuit capacity at the PCC of large polluting loads and the microgrid-to-main-grid junction, the characteristic impedances of the microgrid will also change. This can lead to system resonances that simply do not exist in grid-connected mode. In islanded mode, higher dynamics and wider ranges of interactions between microgrid loads and available small or medium-scale DERs will result in more pronounced, more frequent and longer voltage and frequency variations. An increase in the total harmonic distortion (both current and voltage) arises as a consequence of the high number of inverter-based generating devices and the disconnection of machine-based devices from the PCC during islanded mode of operation.

A key enabler to the mitigation of PQ related phenomena in microgrids is the use of advanced inverter control strategies for PE interfaced DERs. These inverters will require the use of virtual impedances, advanced voltage and current control strategies and, quite possibly, a communications infrastructure to permit a coordinated approach to the mitigation of PQ related problems.

The DC microgrid is not without PQ phenomena. Disturbances in the main AC grid, for example, have counterparts in DC systems: voltage regulation, harmonics, frequency variations, sag, swell, etc.

5.6.2 Recommendations

Further studies on LFAC and DC microgrids are required. They should answer to questions such as which of them are easier to implement, if they can efficiently co-exist facilitating symbiosis like DC smart home within a LFAC smart city.

5.6.3 On-going discussions

The most vexing problem is to understand how the microgrid paradigm will evolve in future grids. Many of the solutions offered with regard to resonance minimization and harmonic mitigation are costly and require utility-wide approaches, or involve complex inverter control strategies and configurations that are not used with the current technology. As microgrids evolve, there will likely be a mix of old and new technologies and there will be a need for new devices to be able to compensate for a wide range of old technologies, unless the management of the microgrid is prepared to make appropriate investment. In this case, the problem could be regarded as an economic one rather than a technology-based issue. In addition to these key parameters, the change in the short circuit capacity at the PCC of large polluting loads means that the agreed emission levels no longer can be applicable.

Voltage quality in microgrids is currently under investigation within IEC SC 8B.

6. ADVANCED VOLTAGE CONTROL AND POWER QUALITY

6.1 INTRODUCTION

An IEEE task force on volt/var control[2] [264] has been started in 2010. The scope of this working group was to understand how new technologies such as distributed resources, renewables, plug-in hybrids and their increased penetration in the distribution system will impact the volt/var control and how it needs to change in the future. Also, the smart grid can benefit from technologies such as smart inverters that can not only provide active power but also non-active power control and thus provide volt/var control. Along with technology issues, it is also important to drive how the standards need to evolve or shift to account for needed technology and system changes.

In this chapter are summarized the trends that are expected in the volt-var control of distribution systems (Section 6.2) and is given an overview of the way in which this smart distribution application will or might impact the power quality (Section 6.3). Findings, recommendations and several issues that remain under discussion, are summarized in Section 6.4.

The voltage control or volt-var control (VVC) [3] in the future grid is expected to be significantly different than it is today. The main driving force behind this, especially in Europe, is the ongoing or expected large-scale introduction of solar power in the distribution network. Changes on demand side will also contribute to the changes in voltage control, e.g. the introduction of electric heat pumps replacing gas heating; plug-in electric vehicles, participation of load in short-term (one hour and less) electricity markets and distribution customers providing reactive-power support to higher voltage level.

6.2 FUTURE VOLT-VAR CONTROL

6.2.1 Voltage control

The conventional voltage control in distribution grids [265], [266], [267], [268] is based on:

- Automatic on-load tap-changers (OLTC) of HV/MV transformers;
- Off-load or on-load tap-changers on MV/MV voltage regulators;
- Off-load tap-changers of MV/LV transformers
- Capacitor banks and voltage boosters along some MV and LV feeders.

This is expected to change in the future grid in a number of ways, partly due to new challenges, partly due to the availability of new technologies, in most cases due to a combination of the two.

6.2.2 Distribution networks

At this stage it might be important to emphasize the difference between two types of distribution networks, which will be referred to here for simplicity as "European grids" and "American grids". The difference is in the role of the low-voltage networks (also referred to as "secondary distribution"). Low-voltage networks are small in American grids, supplying just a few customers and the voltage drop is limited. All voltage control takes place in the medium-voltage (MV) network ("primary distribution"). In European grids, the low-voltage (LV) networks are substantial, with 800-kVA distribution transformers being no exception. Voltage control therefore takes place at LV as well as at MV.

6.2.3 Solar power

The very fast growth of solar power connected to the low-voltage distribution in some countries is causing large supply voltage variations in LV distribution systems, which require the building of additional cables and transformers or improved voltage control. Future shifts from direct use of fossil fuel to energy-efficient use of electricity (electric cars, heat pumps) will further increase the demand for improved voltage control.

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2 In this chapter we use the term volt-var-control (VVC) even to include more advanced methods known for example as volt-var optimization (VVO) or conservation voltage reduction (CVR)

3 There was a discussion about terminology, VVC or VVO? In Google VVC is used about twice as much as VVO. But in Google Scholar VVC is used 10 times as much. Therefore VVC was selected.

6.2.4 New technology

The availability of new technology enables a holistic view of the system to address supply voltage variations together with minimizing losses, reducing losses on consumption side and avoiding component overload. This is achieved by employing state-of-the-art monitoring, communication and control technologies, which assist the voltage control along multiple feeders over a wide area, while focusing on global optimization rather than individual feeders used for traditional VVC [35]. Such control systems are also referred to as "Volt-Var Optimization" [270], [271], [272], [360], [361], [365], [366].

This is achieved by employing state-of-the-art monitoring, communication and control technologies, which assist the voltage control along multiple feeders over a wide area, while focusing on global optimization rather than individual feeders used for traditional VVC [35]

Depending on network topology the hosting capacity of LV networks for PV installations can also be increased by introducing voltage regulated MV/LV distribution transformers [273], [274], [285], [287], [342], [349], [352], [353], [354], [355], [356], [357]. The voltage control can be realized by on-load tap changers or electronic switches. The latter will allow more switching actions without an increased risk of ageing, an increased need for maintenance, or both. It is shown in [357]that, for a typical German low-voltage grid, the use of an OLTC is considerably cheaper than the change of all cables within the grid.

Also grid-size battery storage [30] and the inverter of distributed generators [350], [358], [364], [365] have been proposed in several publications for voltage control of the distribution grid. Battery storage has the advantage that it can control both active and reactive power. In distribution networks, with a low X/R ratio, controlling active power is more affective for controlling the voltage than controlling reactive power.

The subject of distribution-system control is an important part of the scope of our sister group C6.25 [351]. That group will among others map the developments on this field.

Distribution transformers with OLTC are considered by several European network operators to cope with the high amount of solar power and future increase of heat pumps and EVs [274], [287], [342], [357].

Although there is no indication yet of network operators implementing some of the very advanced optimization schemes discussed in recent literature [270], [271], [272], [349], [360] the availability of modern monitoring, control and communication equipment makes such schemes within reach of existing technology. Practical implementations will likely include customer-side inverters and grid-based power electronics in the control.

6.2.5 Ancillary services

Future distribution systems will have a growing number of production units connected to the ac grid through power electronic interfaces. Some of these units will be able to provide network and system ancillary services, including contribution to voltage control and reactive power. Even if such ancillary services may be more efficient with tools like SVCs or STATCOMS, production units equipped with inverters are already present in the system, making the marginal costs small or even zero. The effectiveness of reactive power injection for voltage control is influenced by both location of the unit and properties of the network. It is therefore likely that coordinated control of inverters and the existing utility equipment is required [280].

Some European countries (i.e. Italy) are studying the necessary to define a multi-level process involving TSOs and DSOs, in which small production units actively participate in energy markets and provide ancillary services such as frequency regulation, voltage control, spinning reserves, standby reserve, backup reserve, load following, real-time balancing, reactive power service, etc.[281].

There is a general concern by network operators about letting part of all of the voltage control being taken care of by customers or customer equipment. The responsibility for the voltage being within an acceptable range remains with the network operator, but the network operator will have to rely on equipment on customer-side of the meter to achieve this. Very good rules and responsibility sharing is needed here.

6.2.6 Transmission-system support

The shift from large conventional power stations to renewable energy and smaller non-conventional production units will result in operational states with a shortage of reactive power at the transmission level. The reactive power may instead be supplied by customers or production units connected to the distribution grid.

Several solutions are under discussion [363], with either compulsory requirements or some market-based solution. In either case, operational states will occur with a large flow of reactive power from the distribution to the transmission grid. This could interfere with the voltage control in the distribution system and a coordinated approach is needed. The other way around, a situation may occur where the voltage limits in the distribution grid may limit the ability of the distribution grid to fulfill the reactive power demand at transmission level. Some reactive power control on the transmission level would likely still exist, as it would allow the transmission-system operator more control and reduce the losses associated with the transport of the reactive power from the distribution to the transmission grid.

As is shown in [343] the use of distributed generation for voltage control at distribution level will result in uncontrolled reactive power flows at higher voltage levels. The higher X/R ratio at higher voltage levels may make that the (uncontrolled) impact at transmission level may be of a similar magnitude as the (controlled) impact at distribution level. This could in turn be one of the driving forces behind the involvement of distributed generation in transmission-system support, which in turn could make voltage control of distribution network more complicated [359], [362].

Another opinion held in the group was that this should not be the case in a properly designed power system. The discussion on this was not continued, as the reasons for changes in voltage control and/or reactive-power support are beyond the scope of this group. This group only covers potential power-quality impacts of such changes.

6.2.7 Conservation Voltage Reduction

The Conservation Voltage Reduction (CVR) approach has been used by US electric utilities for many years to decrease demand by reducing the voltage delivered to the load, especially during the peak load periods [269], [341]. The allowable voltage range of 114-126 Volts (±5% of 120V) must be maintained during normal system operation. CVR was implemented initially by reducing voltage at the substation using on-load tap changers. The technique was subsequently complemented using switchable capacitor banks along the feeders in addition to voltage regulators, which also allows for minimized losses. The main driver behind recent application of CVR is in reducing the total consumption with end-users [284], [341], [348].

CVR aims at reducing electricity consumption of low-voltage customers by reducing supply voltage. A range of North American utilities have such schemes in operation, whereas many others are planning the implementation. With CVR the voltage in the distribution network is kept as low as possible without exceeding the lower limit of the allowed voltage variations. The implementation typically involves on-load tap changers (OLTCs), voltage boosters and capacitor banks, but future schemes will likely involve DER as well. The term "volt-var-optimization (VVO)" is often used in this context, especially when loss minimization is one of the objectives.

6.2.8 Discrete versus continuous control

A distinction is made here between "discrete VVC" (based on switching, like transformer tap-changers or capacitor banks) and "continuous VVC" (based on a controllable source of reactive power like the voltage-source converter in a solar panel). Although both methods will maintain the voltage within the regulatory limits, their additional impact on PQ is rather different.

6.3 IMPACT ON POWER QUALITY

The introduction of new methods for VVC will have a positive impact on the supply voltage variations; both undervoltages and overvoltages will diminish. Very fast methods for voltage control may even improve voltage flicker and reduce the number of severe voltage dips and swells.

Next to this, some other types of disturbances may be adversely impacted by VVC. The latter is the main point of discussion within the working group and some of the early results, including several points or on-going discussions, are summarized in the forthcoming sub-sections.

6.3.1 Slow voltage-magnitude variations

When the voltage control is based on HV/MV OLTC transformer, the voltage behind individual distribution transformers may be out of the acceptable range. This could especially be a concern with CVR, where the voltage is maintained close to the lower voltage limit [345], [346], [347].

A study based on 57 low-voltage feeders in the UK [345] investigated the probability that the customer voltage is outside of the regulatory limits. To maintain this probability below 1%, the voltage on the MV side of every LV transformer should be maintained between 0.94 and 1.1 pu. However, if a value of 5% non-compliant customers is acceptable, a wider voltage range from 0.91 to 1.1 pu could be considered. This sets limits to the use of CVR without active voltage control in the distribution system.

6.3.2 Short-duration undervoltages

The CVR might result in an increase of the number of short-duration undervoltages. Taken over one to ten minute windows, the voltage magnitude will be acceptable, but closer to the lower limit. However, at shorter time scales, the voltage magnitude might exhibit deeper and more frequent excursions across the undervoltage limit.

Very limited actual data on this is available and a study [277] showed that the risk of undervoltages is very low when using CVR. The measurement also showed that there would be at most a small increase in number of equipment trips related to voltage sags. It is unclear if this is valid for other locations and for longer monitoring periods.

Here it is also important to consider both the criterion used when controlling the voltage magnitude and the speed with which the control system reacts to changes in voltage magnitude. When, for example, a 10-minute average is used (as the voltage quality requirements are based on 10-minute values) and this value is kept close to the undervoltage limit, the number of short-duration events dropping below this limit may increase a lot. When instead a 1-second average would be used to control the voltage, the number of such events would be much lower. The latter will however be unlikely to be achieved by discrete VVC, as the number of rapid voltage changes (see next subchapter) would become unacceptable. Very short averaging times will also require fast control algorithms and with multiple controllers acting closely together, such fast control may result in control instabilities. Finally, it is worthwhile noting that new voltage "medium speed" variations (i.e. variations related to the clouds movement for small LV PV systems) with dynamics lower than 10 minutes but higher than some seconds are expected to appear in distribution systems.

Sudden events like voltage dips due to faults or equipment starting cannot be predicted by most control systems and will still result in about the same drop in voltage as with conventional voltage control. As the voltage will be close to the undervoltage limit more often, the number of events dropping below a certain threshold (like 80 or 90% of nominal voltage) is likely to increase [148], [275], [276].

However, very limited actual data on this is available and a study done by Hydro Quebec in 2010 [277] showed that the risk of undervoltage is very low when using CVR. It also showed that there would be at most a small increase in number of equipment trips related to voltage dips.

Very fast controllers, reacting within some tens of milliseconds, will be able to limit duration of voltage dips, but the above-mentioned stability issues with multiple controllers will be even bigger.

When multiple controllers (capacitor banks, boosters, tap-changers, but also power-electronic converters) are present in the distribution network, short-duration undervoltages and even short-duration overvoltages can occur because of differences in reaction time between different controllers.

6.3.3 Rapid voltage changes

When using discrete VVC, step changes in voltage magnitude will occur every time the controller takes an action. Such step changes are referred to as "individual rapid voltage changes", typically abbreviated as "rapid voltage changes" (RVC). The more strict the voltage band, e.g. for conservation voltage reduction, the higher the number of rapid voltage changes that are expected. This is only a concern for discrete VVC, not for continuous VVC. Studies presented in [340], [342], [352] show that the number of tap changes can vary a lot depending on the control algorithm used. The study presented in [342] predicts between 136 and 467 switching actions per year, i.e. on average 0.4 to 1.3 per day. The number may however show a strong day to day variation. The risk of increasing ageing due to a high number of tap changer operations was mentioned in [353], [358], but not in relation to power quality. Whereas the average number of operation over a longer period is what matters for ageing, it is the highest number during a one-day period that matters for power quality. In [352] the number of tap changes is calculated, for a day in July with changing cloud cover. Three different values are compared for the averaging period over which the rms voltage is calculated. With increasing amounts of PV penetration and 1-min averaging, up to 80 rapid voltage changes can occur on one single day. However, using 30-min averaging will bring this down to 10 events per day. Some of the results are shown in Figure 6.1.

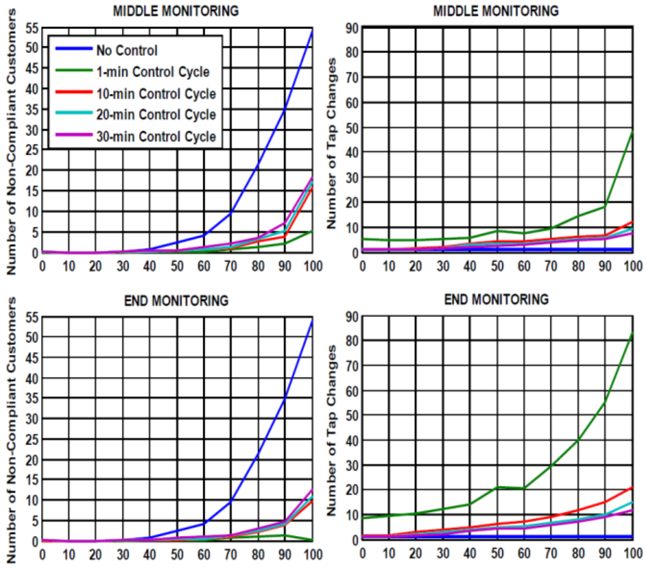

Figure 6.1 Number of non-compliant customers (left) and number of tap-changer operations (right) as a function of the percentage of homes with PV, for different values of the control cycle over which the rms voltage is calculated. Upper and lower curves refer to d

The magnitude of the rapid voltage changes will be determined by the steps in the tap-changer. Different manufacturers and publications give different values. The value of 2.5% has been traditionally used for the off-load tap changers and this vale is used for example in [342]. But values of 2% are mentioned in [340], [352]. The higher steps and shorter switching intervals also increase the risk that Pst limits are exceeded.

In Germany an increased use of voltage regulated distribution transformers is expected and therefore respective limits are recommended for planning purposes. In case the transformer switches only a few times a day (less than one switching per 100 minutes) flicker is no issue, but the maximum voltage change must not exceed 6 %. In case of more frequent switching operations, the resulting flicker severity must satisfy Pst ≤ 0.35; Plt ≤ 0.25. Moreover the maximum voltage change should be less than 3%. These values are likely to be taken over by the branch organization of network operators in Germany, Austria, Switzerland and Czech Republic for the next revision of the "Technical Rules for Assessment of Network Disturbances".

Here it should be strongly emphasized that these limits for maximum voltage change apply for distribution transformers with automatic tap changers. When capacitors are used for voltage control, voltage steps of 3% or higher should be avoided, as will be discussed in the next section.

With the expected increase in number of (individual) RVC it is important to have a generally accepted standardized method for measuring them. Such a method will be part of IEC 61000-4-30 [278]. More experience with the use of these measurement methods is needed.

Many countries and network operators currently have the requirement that a production unit connected to the distribution network shall not result in a voltage rise exceeding 3% [340]. This is partly due to avoid rapid voltage changes, but also a means to avoid high risk of overvoltages without the need for detailed studies with each connection. The use of advanced voltage control in distribution networks, could result in the 3%-rule being removed. The connection and disconnection of small production units could then however result in higher value of rapid voltage changes. The frequency of such events will however be low and be limited to failures in the unit or its production during periods of high production.

Distributed generation in Germany has to disconnect from the grid when the 10-minute average voltage at the point-of-common coupling with other customers exceeds 110% of the nominal voltage [357]. With high PV penetration this can result in a large number of rapid voltage changes during sunny days. Should the abovementioned 3% limit be abolished, this can even result in large magnitude rapid voltage changes occurring often during such days.

6.3.4 Resonances

The presence of a capacitor bank as part of VVC schemes will introduce new resonances to the system. In most of the advanced schemes, regular switching of the capacitor bank is necessary, which will result in regular changes in resonance conditions, with large variations and less predictability in harmonic levels as a result. Changing resonance frequencies is only a concern for discrete VVC not for continuous VVC.

The presence of resonances is not a concern by itself. Only when those resonances are excited by harmonic emission and when the damping is low, with high harmonic distortion result. Damping is typically lower at medium voltage than at low voltage, so that the first concern would be for capacitor banks connected to medium voltage. Voltage control schemes at low voltage are not expected to appear in North America, but they may occur in rural grids in Europe. The main emission reaching the medium voltage network is at harmonic orders 5, 7, 11 and 13. For single-phase feeders also harmonic orders 3 and 9 will be present. Resonance frequencies around these harmonic orders should be avoided as much as possible. Resonance frequencies around the second harmonic could result in instabilities with power-electronic converters.

There is a strong relation between the resonance frequency f_{res} and the voltage step ΔV due to switching the capacitor, assuming that the switched capacitor is the main source of capacitance at the switching location [117]:

$$f_{res} = \frac{f_0}{\sqrt{\Delta V}}$$

Equation 6.1

where f_0 is the power-system frequency (50 or 60 Hz). A resonance frequency at harmonic 7 corresponds to a voltage step of about 2%, harmonic 5 to 4%; and a step of 6% corresponds to a resonance frequency around harmonic 4. As harmonics 5 and 7 are the dominating ones at distribution level, any voltage step of 2% or higher due to capacitor bank switching introduces a serious risk of high distortion due to resonance.

Conventionally, when harmonic resonances were a concern, the capacitor banks would be combined with a reactance either by tuning the resonance frequency to short-circuit the harmonic currents or by detuning the resonance frequency so that it would always stay away from the harmonics being emitted. Neither of this appears practical in case of multiple resonance frequencies that change regularly. Adding damping either in the form of resistances part of passive filters or by means of active filters is a possible solution that should be further investigated [282], [282].

When using harmonic filters to mitigate or avoid resonances it should be considered that including passive harmonic filters will introduce new resonance frequencies that in turn change with every change in the grid. In some countries, the use of harmonic filters is prohibited as they may interact with other equipment in the system.

6.3.5 Harmonic distortion

Continuous VVC could use existing devices or additional devices. In the latter case, this new device is continuously being connected to the distribution grid. Next to reactive power at fundamental frequency there will also be exchange at higher frequencies (so-called "harmonic distortion"). The amount and frequency of the distortion will depend on the kind of technology used for the control of reactive power. Most of the modern applications are based on voltage-source converters using active control. The result is a rather low distortion for lower-order harmonics but higher distortion than normal at higher frequencies, so-called "supraharmonics". The origin, spread and properties of supraharmonics is discussed in other chapters of this report. Most of the continuous control methods use power-electronic converters that introduce harmonics into the grid. Especially an increase in the emission of supraharmonics is expected [283].

There are also indications, but no confirmed cases, that certain switching and control schemes for the voltage-source converters will result in higher levels of interharmonics and even harmonics.

When already existing converters like those in PV installations will be used to control voltage or reactive power, the impact on harmonic levels depends on the implemented control algorithms. While some inverters result in no change of harmonic levels, others can show differences in the harmonic currents up to 30% for selected harmonic orders.

Using switched capacitor banks will introduce harmonic resonances that will change whenever a capacitor is switched. Using many small banks will introduce a large number of possible resonance frequencies, resulting in a likely amplification of harmonic emission over a wide range of frequencies.

There is a strong relation between the resonant frequency and voltage step due to switching the capacitor, assuming that the switched capacitor is the main source of capacitance at the switching location. A resonance frequency at 7th order harmonic corresponds to a voltage step of about 2%, for 5th harmonic to 4%; and a step of 6% corresponds to a resonance frequency around 4th harmonic. As 5th and 7th harmonics are the dominating ones at distribution level, any voltage step of 2% or higher due to capacitor bank switching introduces a serious risk of high distortion due to resonance.

6.3.6 Switching transients

Switching of capacitor banks will result in switching transients, which can have detrimental effect on the operation of end-user equipment. This is only a concern for discrete VVC, not for continuous VVC.

Using switched capacitor banks will introduce switching transients; using multiple banks will also introduce back-to-back switching transients that have a much higher oscillation frequency and where amplification of the oscillations may occur. The magnitude of the capacitor energizing transient depends strongly on the amount of damping present in the network. Earlier measurements have shown overvoltages up to 1.5 to 1.8 times the pre-event voltage magnitude during the switching of individual capacitor banks [367]. For certain combinations of resonance frequencies in systems with multiple capacitors, the magnitude of the energizing transient can be much higher than normal and values up to 4 p.u. have been measured [367]. But those measurements did not concern volt-var control schemes, so it is not known if those high overvoltages can also occur there.

However, recent measurements [277], specifically related to energizing of capacitors part of a VVC scheme, showed overvoltage up to only 1.2 times the pre-event voltage magnitude. Further studies are needed to decide to which extend capacitor energizing transients could be a concern. More information on damping of switching transients in distribution networks is needed.

The magnitude of the capacitor energizing transient depends strongly on the amount of damping present in the network. Earlier measurements have shown overvoltages up to 1.5 to 1.8 times the pre-event voltage magnitude. However, recent measurements by Hydro Quebec, specifically related to energizing of capacitors part of a VVC scheme, showed overvoltage up to only 1.2 times the pre-event voltage magnitude. Further studies are needed here to decide to which extend capacitor energizing transients could be a concern. More information on damping of switching transients in distribution networks is needed.

The presence of multiple capacitors introduces two additional potential problems:

- The occurrence of high-frequency transients with back-to-back capacitor switching. The impact of repeated occurrence of high-frequency transients on end-user equipment is not known and needs to be investigated.
- When energizing a capacitor in a system where already capacitors are present, multiple resonance frequencies occur. For certain combinations of frequencies, the magnitude of the energizing transient can be much higher than normal and values up 4 per unit have been measured. But those measurements did not concern VVC schemes, so it is not known if those high overvoltages can also occur there.

Doing measurements in advanced VVC schemes is certainly encouraged but as the number of schemes remains limited, and because very high overvoltage values may only occur in very specific situations, simulations studies should be done in parallel with those measurements.

Possible methods to avoid high energizing overvoltages are the use of synchronized switching and the use of a damping resistor.

6.3.7 Unbalance

Voltage unbalance will be reduced by some of the optimization schemes, mainly those were individual voltage control is used in the three phases. For three-phase control schemes, like three-phase capacitor banks of three-phase distribution transformers with automatic tap-changers, only the positive-sequence voltage can be controlled. Both zero-sequence and negative-sequence voltages will remain the same.

6.4 CONCLUSIONS

6.4.1 Findings

Volt-var control will likely be different in the future from what it is today. This will be partly driven by necessity, partly by the availability of new technology. Whereas overall this will have a positive impact on the voltage variations in the distribution network, there are also a number of potential negative impacts.

Some of the potential negative impacts include:

- Increased number of short-duration undervoltages including shallow voltage dips.
- An increased number of (individual) rapid voltage changes and the associated increase in flicker severity.
- Additional resonances with the risk of high levels of harmonic distortion.
- The emission of harmonics and supraharmonics by some of the devices used for VVC.
- A higher number of switching transients, including higher frequencies due to back-to-back switching and higher overvoltages due to multiple resonance frequencies being excited.

The actual impact will depend strongly on the aim and implementation of the VVC.

6.4.2 Recommendations

Many of the potential impacts are ill-understood, in part because the details of the future control algorithms are often not known yet. Studies are needed towards quantifying the adverse impact on power quality of different control algorithms.

Guidelines are needed on what are acceptable sizes and numbers of voltage steps in distribution networks. Experience is needed on standardized methods to measure and analyse rapid voltage changes.

The use of power-electronic converters, which is a part of end-user equipment, to introduce damping at harmonic frequencies should be seriously investigated.

Studies are needed, both simulations and measurements after damping provided by the low and medium-voltage networks and by equipment connected to it. Information on damping is needed for estimating the amplification of harmonic levels due to resonances and also to estimate the overvoltages due to capacitor energizing.

The impact of repeated switching transients on end-user equipment should be investigated.

6.4.3 On-going discussions

An essential question that should be asked, before any implementation of a VVC scheme, is whether there are cases where the negative impacts of VVC are more than the positive impacts. It is important that these cases are identified and be the base for recommendations to network operators that want to introduce new ways of VVC.

New types of disturbances, or types of disturbances occurring more often than in the past, may require additional indices, to be properly tracked and studied. There is on the other hand a need for simplified reporting on power quality, where the use of a small number of indices would be the desired situation. A discussion is on-going on this dilemma and as yet no consensus has been reached on this.

Using power-electronic controllers, like the ones present in more and more equipment that is anyway already connected to the distribution network, allows for very fast and accurate voltage control. The results would include a very smooth and constant voltage and an improvement of voltage quality over a range of phenomena and timescales. This will however require a complete overhaul of the existing VVC philosophies and will also require that the network operator relies on equipment beyond its control. The issue of adverse interactions between many fast controllers will also have to be solved.

A related point of discussion is if additional requirements should be placed on VVC to improve voltage quality. Here one may think of averaging times less than 10 minutes and even algorithms mitigating dips, swells and severe voltage flicker as part of the overall control system.

Limits on maximum size of rapid voltage changes do not consider the high risk of resonances when capacitor banks are used for voltage control. The higher the voltage step due to the switching a capacitor bank the lower the resonance frequency. Either separate recommendations are needed for voltage control using capacitor banks or alternatively, all voltage steps are to be limited such that no resonances will occur at low-order harmonics. No consensus has been reached within the group on which way to go.

7. FEEDER RECONFIGURATION AND POWER QUALITY

7.1 INTRODUCTION

Growth of electric power systems over the last century has resulted in a large increase in the number of distribution feeders in the world. These feeders experience faults that must be repaired before the services are returned to normal. The restoration of power supply can be expedited if the location of a fault is either known or can be estimated with reasonable accuracy.

Radial distribution system design has evolved as the most efficient, inexpensive way to serve many loads from a single source. The need for greater reliability has driven a transition to a “mesh” or “loop” design - actually a hybrid of existing radial feeders and new ties between substations and feeders—that can carry out the work of advanced distribution system applications. The hybrid or mesh design provides a means to isolate faults and reroute power around the troubled section, keeping as many customers as possible in service while the faulted section is repaired [368].

The process of altering the topological structure of the distribution network is known as feeder reconfiguration. Automatic feeder reconfiguration is a feature for improved service to the customers following a fault or a system disturbance. Reconfiguration of feeders, automatic or manual, are also required during other situations like load balancing, load isolation etc. Feeder reconfiguration is an integral component of advanced distribution automation (ADA) strategy, also called smart distribution strategy, of a load serving entity.

While automatic feeder reconfiguration has a larger impact on PQ parameters like short interruptions, manual reconfiguration can also affect PQ parameters like long interruptions. It is always desirable that PQ is preserved during feeder reconfiguration except under faulted conditions. However, following a fault, PQ parameters may be allowed to deviate for a short period of time.

This chapter presents a range of scenarios under which PQ parameters will be affected. The scenarios include feeder reconfigurations as a result of network faults as well as normal network operation.

A distinction will thereby be made between feeder reconfiguration following a fault and feeder reconfiguration not associated with a fault. For feeder reconfigurations following a fault, the short period during the fault or the way in which the operation of the protection (which is automatic after all) impact the PQ are not considered.

For feeder reconfiguration not following a fault, the following types will be considered

- Feeder reconfiguration as part of the preparations for preventive maintenance, as far as this is done automatically.
- Feeder reconfiguration to enable to maximum penetration of distributed energy resources (DERs) without violating voltage limits. (i.e. scenarios not dissimilar to load balancing; generation balancing, or rather reconfigurations to ensure maximum local generation at the distribution network level).

Short term fluctuations (leading to flicker) and the voltage variations recognised as changes to the RMS voltage over 3 minute (for example) interval are discussed in this chapter for feeder reconfiguration conditions. The possibility of over- or under-voltage conditions for extended periods (i.e. outside the accepted +10%, -6% limit for example) is considered as a PQ issue and needs to be addressed by possible feeder reconfiguration schemes.

7.2 FEEDER RECONFIGURATION FOLLOWING A FAULT

It is important to determine the location of a fault when it occurs so that the utility may restore electric service to the affected customers as soon as possible. In the past, restoration of the system following a disturbance would have required a human response based on the operation of protective devices, which is often local. Expectations for quicker restoration times have led, for example, to the development and installation of fault circuit indicators (FCIs) or fault passage indicators (FPIs) to more selectively identify and isolate the faulted part of the system [369]. With the introduction of communication technologies in the distribution system, and the installation of automated switches and reclosers in recent years, it is now possible to identify and isolate the faulty part or section of the network very quickly. An automated process for restoration contributes to improved reliability indices.

Fault location, isolation, and service restoration (FLISR) system is an important aspect of system operation to improve network reliability. In some cases, it is also known as fault detection, isolation, and restoration (FDIR). Considered as one, FLISR/FDIR is designed to detect a fault on a feeder, isolate the faulted section, and restore service to unfaulted sections, reducing restoration time for the faulted section while maintaining service to unaffected customers. Although FLISR and FDIR are used synonymously, a subtle distinction can be made between the two systems. Precise fault location may not be an integral part of a FDIR system and depends on other external systems like outage management system (OMS) and geographic information system (GIS) – in some cases, customer information system (CIS) data may even be used to locate the fault and resourcing the repair crew accordingly. FLISR/FDIR logic can be centralized at the operation centre or distributed over substation-based or peer-to-peer switches residing in feeders) [368].

ADA technologies can positively impact traditional reliability indices such as system average interruption duration index (SAIDI), system average interruption frequency index (SAIFI), customer average interruption duration index (CAIDI), and momentary average interruption frequency index (MAIFI). The application of ADA technologies offers utilities the capability of restoring service to customers on the healthy portions of a feeder in under 5 min. This capability improves SAIDI, SAIFI, and CAIDI scores while the momentary service interruption does impact MAIFI. US utilities gladly accept this compromise because of fines and/or regulatory good standing focus more on SAIDI, SAIFI, and CAIDI scores [368].

However, the application of ADA technologies to improve reliability indices by automatic feeder reconfiguration also brings in additional PQ issues [370], [371], [278]. PQ parameters of a network require continuous evaluation, especially after reconfiguration following a fault. Next section focuses on specific parameters that require attention following a network reconfiguration affecting the type of sources and loads connected to a feeder.

7.3 EFFECT OF FEEDER RECONFIGURATION ON PQ DISTURBANCES

During network fault situations, a number of feeder reconfiguration scenarios can happen depending on the type of fault that has occurred and the related protection scheme that has been enacted. Sound engineering practice should ensure that basic power system protection should not be compromised or affected by any feeder reconfiguration strategy associated with the MV network.

7.3.1 Effect on Harmonic Distortion

The possibility of a change in the ITHD and VTHD of the MV and LV network exists, for a number of reasons, following a reconfiguration. Variation in fault level as a result of switching arrangements is unlikely to be a major contributor, especially at the MV level. It is more likely that reconfiguration may introduce a different mix of loads that could either improve or worsen the THD (both ITHD and subsequent VTHD).

7.3.2 Effect on Rapid Voltage Changes

The transition from one switching arrangement to a different one may yield rapid changes in the RMS voltage in the MV and LV networks. Recloser schemes as well as advanced distribution automation strategies will significantly change the number of rapid voltage changes. While IEC 61000-4-30, Ed. 3 [278] may provide further insight in to the rapid voltage change phenomena, it is important to note that improved reliability and rapid voltage changes are interrelated.

7.3.3 Effect on Flicker

In situations where there are high numbers of sectionalisers or reclosers, significant step changes may occur in voltage values as the network recovers from the fault. This would most definitely impact the short term flicker perceptibility value (Pst) of an MV and LV section of the network. The rapid voltage change phenomena will affect flicker indices.

7.3.4 Effect on Steady State RMS Voltage

Transitions in switching arrangement, in particular with momentary interruptions, may cause the RMS voltage to change over a wide range in a relatively short period of time. This could result in changing voltage unbalance as well. In a network with high DER penetration (which includes storage systems as well as generation resources), there is a likelihood that some of the DER may have been disconnected from the network following a fault. During periods of high generation, these multiple connect and subsequent reconnect operations may cause fluctuations in the RMS voltage levels beyond the normal regulation ranges. In systems with VVC/VVO or other active voltage regulation devices, there may be a period of time where the voltage level and the voltage unbalance could be quite dynamic in nature.

Faults or reconfigurations may also cause the disconnection of major loads, significantly affecting the voltage regulation in both MV and LV networks.

In a future grid, disconnections may not be a problem, in particular if DER requirements change in order to provide higher levels of fault ride-through tolerance, which are addressed in [373].

7.3.5 Effect on System Frequency

In a network with high DER penetration, there is a possibility that some of the DER to be disconnected from the network following a fault. During periods of high generation, this might result in local variation in system frequency. This is an evolving issue as present distribution systems are not equipped with means for controlling system frequency and depends on bulk-power transmission system for load-generation balance. Future distribution management systems (DMS) and microgrid management systems are expected to have effective means for controlling system frequency to accommodate high penetration of DER [368], [374]. However, DER systems default response to abnormal frequencies as addressed in [373] may help in the interim period.

7.3.6 Other Effects

Other effects that may manifest after a fault include:

1. A change in current and voltage unbalance as a consequence of load re-arrangement.
2. A change in current unbalance as a consequence of single-phase circuit tripping or reclosing operations.
3. A change in the resonant frequency of the MV and LV networks. For example, the relative positions of power factor correction (PFC) capacitors may be altered following a reconfiguration. The reader should refer to Chapter 8 of this report for commentary on Volt-VAr control (VVC) and Volt-VAr optimization (VVO) issues.
4. Loss of visibility of PQ performance as a consequence of reconfigurations that also changes the relative position of sensors in the distribution network.
5. Reconfiguration can lead to an excessive number of transformer energisations which should be avoided. The likelihood of ferroresonance is low since the energisations will likely be on loaded rather than unloaded transformers. What is more likely is that transients will occur and will last for longer periods since the changing nature of the network load is one with lesser resistance. There will also be an increase in the level of second harmonic distortion, which should be managed by limiting the number of transformers energised simultaneously following system restoration/reconfiguration after a fault.
6. FLISR/FDIR typically achieves either reducing frequency of Long Interruptions (LIs), or by speeding up service restoration and thus significantly reducing duration of LIs. With particular reference to LI, Short Interruptions (SI) and Voltage Dips (VD), very often the event originating those kinds of disturbances is the same. Moreover, sequences of events are frequently generated; for example, an unsuccessful autoreclosure will lead to two VDs separated in time by the autoreclosing interval, but, more generally and according to the specific automation technique adopted and type of the fault, a higher number of consecutive VDs can occur [371], [372]. More research on aggregation techniques [375], [117] is needed.

Future networks may permit islanding of feeder sections of the distribution network if sufficient generation exists to sustain the local loads. In essence, the formation of a micro-grid might be permitted for short periods of time in order to improve reliability. In this case, the PQ of the island will be significantly different to that of the non-island (grid-connected DERs) case. The reader should refer to 5 of this report for details involving microgrid issues.

7.4 FEEDER RECONFIGURATION DURING NON-FAULT SITUATIONS

One of the main focuses of feeder reconfiguration during non-fault situations is to balance load and reduce network losses [376]. The reduction of network losses and load balancing has become more complicated with the addition of large amount of DERs and research work is being conducted to optimize these operation parameters [377]. The stochastic nature of photovoltaic (PV) systems at distribution level requires attention to control the active and reactive power flow in the network so that PQ parameters are managed within limits.

PQ parameters of a network require continuous evaluation, even after reconfiguration of a feeder without any fault for loss optimization and maintaining voltage profile along the feeder.

7.5 POWER QUALITY AND RELIABILITY INDICES

The advantage of having feeder reconfiguration capability is to improve reliability and to provide distribution network service providers with operational options. However, the overall goal of network operation must include minimising the number of disturbances that a customer will experience over a certain time window. To this end, indices are used as a metric for monitoring the power quality and reliability (PQR) of distribution networks.

In a feeder network with advanced automation capabilities to improve reliability indices, new/modified power quality indices other than those in [375], are required to be addressed:

1. Multiple voltage dips over short or long periods of time,
2. Excessive current unbalance,
3. Excessive second harmonics associated with transformer energisation,
4. Steady state voltage fluctuation resulting from reconfiguration operations,
5. Small duration frequency variation due to disconnection of large amount of DER.

7.6 CONCLUSIONS

This chapter discusses the impact of feeder reconfigurations on power quality. Based on the discussion, the impact of feeder reconfiguration on power quality can be summarized as follows.

7.6.1 Findings

This chapter discusses a range of scenarios for feeder reconfiguration under which PQ parameters will be affected. The scenarios include feeder reconfigurations as a result of network faults as well as normal network operation. Following PQ parameters are affected due to feeder reconfiguration following a fault:

7.6.1.1 Harmonic distortion

A change in the level of ITHD and VTHD of the MV and LV network is possible.

7.6.1.2 Rapid voltage changes

Recloser schemes as well as advanced distribution automation strategies will significantly change the number of rapid voltage changes.

7.6.1.3 Flicker

Short term flicker perceptibility value (Pst), of a network with high numbers of sectionalisers or reclosers, can be higher. Rapid voltage change phenomena will also affect flicker indices.

7.6.1.4 Steady state voltage

Transitions in switching arrangement, in particular with momentary interruptions, may cause the RMS voltage to change over a wide range in a relatively short period of time. This could result in changing voltage unbalance as well. In systems with VVC/VVO or other active voltage regulation devices, there may be a period of time where the voltage level and the voltage unbalance could be quite dynamic in nature.

7.6.1.5 System frequency

In a network with high DER penetration, some of the DER may be disconnected from the network following a fault. During periods of high generation, this might result in local variation in system frequency.

7.6.1.6 Other effects

- Change in current unbalance,
- Change in the resonant frequency of the MV and LV networks,
- Loss of visibility of PQ performance as a result of reconfigurations,
- Possibility of long duration transients and excessive amount of second harmonic due to large number of transformer energisations,
- Higher number of consecutive voltage dips.

PQ parameters of a network require continuous evaluation, even after reconfiguration of a feeder without any fault for loss optimization and maintaining voltage profile along the feeder, which has become more complicated with the addition of large amount of DERs.

7.6.2 Recommendations

Following recommendations are made to mitigate or minimize the impact of feeder reconfiguration on power quality:

7.6.2.1 Planning for an active distribution system

It is important to plan for an active distribution system, wherever possible, to minimize the impact of feeder reconfiguration on power quality. This planning for an active distribution system includes the placement and sizing of DERs, capacitor banks, switching equipment like reclosers and sectionalisers, as well as protection and control system. The planning should complement the traditional approach for loss optimization and voltage profile management.

State estimation and frequency control at the distribution system is important to address the impact of DER on power quality. One approach to mitigate the impact of DER on frequency is to adopt a distributed frequency control approach by creating microgrids wherever large amounts of DERs are integrated. These microgrids can be connected to the main grid with back-to-back dc, like those traditionally used for bulk power system, to create frequency islands. This will provide an opportunity to define power quality parameters of asynchronous microgrids in a manner conducive to the realities of such systems [374].

7.6.2.2 Operation strategy for an active distribution system

It is required to adopt proper operation strategy for an active distribution system. One aspect of it is to have a dynamic switching strategy, following a fault, to minimize the impact of feeder reconfiguration on power quality parameters as discussed above. This will be possible with a better designed active distribution system. However, it is also possible to minimize the impact in some cases even if the system is not designed for an active distribution system but has evolved into such system.

7.6.3 Open issues

Reliability indices are used as a metric for monitoring the power quality and reliability (PQR) of distribution networks. In a feeder network with advanced automation capabilities to improve reliability indices, new/modified power quality indices, other than those in [9], are required to be addressed:

- Multiple voltage dips over short or long periods of time,
- Excessive current unbalance,
- Excessive second harmonics associated with transformer energisation,
- Steady state voltage fluctuation resulting from reconfiguration operations,
- Small duration frequency variation due to disconnection of large amount of DER.

8. DEMAND SIDE MANAGEMENT AND POWER QUALITY

8.1 INTRODUCTION

Successful transformation of existing electricity networks into the future "smart grids" essentially relies on the correct assessment and understanding of complex supply-demand interactions. In the context of "smart grids", the primary determinants of these interactions are the changes in the actual amount and form of power flows and energy exchanges between the "supply side" and "demand side". On both sides, the changes in the basic principles of operation, which are already taking place in existing networks and will be only more pronounced in the future, are characterised by a shift from unidirectional flows of powers and energy exchanges at only fundamental supply system frequency, to bi-directional power flows and exchanges of energy in both direct current (dc) form and alternate current (ac) form in much wider frequency ranges. Power Quality remains to be important for the analysis of all these interactions and changes, as it offers key indicators and metrics for describing and quantifying electromagnetic compatibility between the grid, i.e. "supply side", and end-users'[4] equipment, i.e. "demand side".

8.2 GENERAL DEFINITION AND TYPES OF DEMAND SIDE MANAGEMENT

Demand Side Management (DSM) denotes various functionalities, services, measures and actions on the "demand side" of power supply systems, which are generally aimed at changing the amount of power demands in terms of related spatial and/or temporal consumption patterns through the control of loads. There are various forms of DSM, which range from:

- Improving energy efficiency by replacing older, power-intensive types of loads with the new types of modern equipment, through
- Introduction of time-of-use tariffs and price-based incentives, promoting use of specific loads at certain times, to
- Sophisticated management and balancing demand control schemes, deployed either in (close to) real-time, or within the specific time period (e.g. hour-ahead, or day-ahead scheduling), as a part of system support and ancillary services, or in coordination with the operation of distributed energy resources, or other loads.

Accordingly, the following two general types of DSM could be distinguished:

1. **DSM-T1**: Energy Efficiency and Energy Conservation DSM programs, when less-efficient types of equipment are being (systematically) replaced, or declared "obsolete", or even banned for sale, in order to allow for a wider scale implementation of a more efficient, or lower-power consuming equipment (e.g. banning of incandescent lamps and their replacement with CFLs and LED lamps, or recent EU "Eco Design Directive"5). DSM-T1 schemes also include technical or technology improvements and developments of various types of electrical equipment, typically occurring over the longer time-scales (e.g. replacement of CRT TVs with LCD TVs);6
2. **DSM-T2**: Direct DSM control of (specific types of) electrical equipment, either by, or on behalf of end-users, or by network operators, or by a third party, typically aimed at reducing system peak load, or as a part of network balancing mechanism, or to realise certain system support capabilities, or to provide different types of system reserve (primary/secondary, frequency response, etc.). Although DSM-T2 schemes are generally directed towards improving network performance (including PQ), there are specific DSM applications which are using DSM for other purpose (e.g. as a part of microgrid control).

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[4] Increased deployment of distributed generation units within the end-users' installations (i.e. on the "customer side" of the meter) might influence that specific end-users change their consumption pattern from being net importers (i.e. consumers), to being net exporters (i.e. producers) of active power, due to variations in demands, or distributed generation outputs, or both. Sometimes, this situation is described using the term "prosumer" (**pro**ducer + con**sumer**), while this report uses term "network user" as a more suitable than the term "end-user".

[5] http://ec.europa.eu/enterprise/policies/sustainable-business/ecodesign/

[6] PQ issues related to introduction of new types of loads are discussed in Chapter 2.

Table 8.1 gives a brief overview of the above discussed types of DSM, including a short description of different DSM schemes applied, or encountered in practice, which is also accompanied by a general definition of DSM in Index of Terms and Definitions of this report.[7]

Table 8.1 Types of DSM, including short descriptions of DSM schemes

<table>
<tr><th colspan="2">DSM Type</th><th>Description</th><th>Examples</th></tr>
<tr><td rowspan="2">DSM-T1</td><td>Energy Efficiency and Energy Conservation Measures</td><td>Changes happen gradually, over the longer time periods, or in stages</td><td>▪ Phasing-out of incandescent lamps and switching to CFL and LED lamps
▪ Use of ASDs instead of directly-connected motors</td></tr>
<tr><td>Technical or Technology Improvements Resulting in Adoption of New Types of Loads</td><td>Changes are typically manifested over the longer time-scales, depending on the new equipment adoption rate</td><td>▪ Replacement of CRT TVs with LCD TVs
▪ Electric Vehicle Chargers (electrification of transport)
▪ Heat Pumps (electrification of heating)</td></tr>
<tr><td rowspan="3">DSM-T2</td><td>Time-of-Use Tariffs</td><td>Changes in demands are scheduled and initiated during specific time periods (typically day-ahead or longer), e.g. for reducing system peak load</td><td>▪ Switching-on of specific loads (e.g. electrical heating loads) during the night, when system demand is low (e.g. so called "economy 7/12" tariffs)</td></tr>
<tr><td>Demand Response and short-term electricity market</td><td>Changes in demands are initiated within shorter time periods (typically sub-hourly, or hour-ahead), as a part of network balancing mechanisms</td><td>▪ On/Off switching of specific loads (e.g. electrical heating loads) to balance generation from renewable (e.g. wind-based) systems.</td></tr>
<tr><td>Provision of System Support and Ancillary Services</td><td>Changes are initiated much faster (in order of seconds or minutes) and controlled in real-time to provide primary or secondary system reserve (frequency response)</td><td>▪ Switching-off of non-critical loads to support system during contingencies and faults (controlled load shedding at customer side)</td></tr>
</table>

8.3 IMPACT OF DSM ON PQ

A wider-scale implementation of various DSM schemes will potentially result in significant changes of aggregate system load, regarding both the load structure (introduction of new, or significantly different types of loads) and the load compositions (variations in demand profiles and in end-use patterns/mixes of end-users' loads, as determined by the participation of specific types of load in the aggregate demand). The corresponding changes in the electrical characteristics of the aggregate system load will have an impact both on:

- The network (i.e. impact on the "supply side", requiring actions from network operators), which from the PQ point of view can be generally categorised and described in terms of "emission", and
- The network users (i.e. impact on the "demand side", including on-site generation), which from the PQ point of view can be generally categorised and described in terms of "immunity".

Additional issues, such as "***electromagnetic interference***"[8] between some new types of loads (or the ways in which they are operated or controlled, e.g. switched) and some of the DSM control schemes

[7] DSM definition is adopted from CIGRE TB566, "Modelling and Aggregation of Loads in Flexible Power Networks", 2014.

[8] In IEC 60050, Section 161-01, "electromagnetic interference" (EMI) is defined as: "Degradation of the performance of an equipment, transmission channel or system caused by an electromagnetic disturbance", while "electromagnetic disturbance" is defined as: "Any electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter". Two notes are provided: *Note 1:* In English, the terms "electromagnetic disturbance" and "electromagnetic interference" designate respectively the cause and the effect, but they are often used indiscriminately. *Note 2:* In French, the terms "electromagnetic disturbance" ("perturbation électromagnétique") and electromagnetic interference" ("brouillage électromagnétique") designate respectively the cause and the effect, and should not be used indiscriminately.

(implemented using specific control signals), as well as network equipment and communication systems, should be also considered.

The further text provide some general information and discussion of PQ-related “emission”, “immunity” and “interference” issues due to the implementation of various DSM schemes.

8.3.1 Network-related PQ-DSM effects (PQ emission issues)

Any larger-scale implementation of direct DSM, i.e. controlled connecting, disconnecting or shifting of specific type(s) of load(s) within the aggregate demand, will change network characteristics and impact system performance at bulk load supply points (BLSPs), or at points of common coupling (PCCs), which then may impact wider network, or “propagate” further through the other parts of the network. This is typically manifested by, e.g. noticeable changes in harmonic emissions, load power factors, or dynamic characteristics of the aggregate loads (e.g. contribution to system inertia and damping), as well as in further interactions with the network and grid impedance. This impact will be as stronger as the more loads, i.e. the higher amounts of powers, are switched (connected or disconnected) by the specific DSM schemes.

A more frequent on/off switching of blocks, or groups of specific loads in various DSM scenarios might also lead to the more pronounced (i.e. too deep and/or too frequent) system voltage variations, i.e. step changes in voltage, which would then require implementation of more complex voltage control actions. Some even higher requirements for the changes in system voltage regulation and control are possible, e.g. in cases with (very) frequent starting of motor-based DSM loads. The load recovery period after specific DSM scheme is implemented and all shifted/disconnected loads should be reconnected, will be typically associated with a higher than usual consumption, resulting in lower supply voltages and possibly higher levels of harmonic emission (depending on the switched load types). Finally, a closer coordination of the devised DSM schemes with the implemented reactive power compensation and power factor controls, as well as active or passive filtering in the network might be necessary. All these issues generally belong within the scope of PQ analysis.

As discussed previously in Chapter 4, introduction of a new generation of modern power electronic equipment, which offer improved controllability, increased efficiency and higher energy savings, may impact the harmonic emissions (or more generally, current and voltage waveform distortions) and also result in electromagnetic interference. Here, of particular importance are new types of emission (e.g. increased emission in frequency range above 2 kHz, due to a high-frequency switching of modern power electronic loads).

8.3.2 End-user-related PQ-DSM effects (PQ immunity issues)

Improved energy-efficiency of modern equipment is often made possible by use of active power electronic converters (utilising “active power factor control” circuits), forming a part of the grid interface for connection of the equipment. As discussed in previous section, a drawback of the use of power electronic interfaces is possible increase of waveform distortion levels and introduction of new electromagnetic interferences. Although it is possible to make modern power electronic loads to tolerate a wide range of disturbances, they are in practice often more sensitive to PQ disturbances than older (non-power-electronic) equipment—even a very brief voltage sag or a short interruption can lead to their tripping or malfunction [378], [379]. Such tripping or malfunctioning may have further negative impact on the grid, or on the nearby equipment. However, there are also examples of a lower equipment sensitivity, as, for example, CFLs are generally less sensitive to flicker than incandescent lamps [380].

The replacement of resistive and linear loads with non-linear power electronic loads (i.e. application of DSM-T1) will not just impact an increase of low-frequency emission, or occurrence of new types of emission, but it will also influence dynamic system behaviour and responses to faults, i.e. reduced system damping, causing possible harmonic resonance problems, when capacitors that are often present on the grid side of the converters might introduce new resonances. It is further not clear whether the reduced amount of resistive load will result in a higher amplification at existing and new resonance frequencies. It should be noted that the possible reduction of the system damping is a separate issue, which is neither emission, nor immunity-related, and it also does not belong specifically to DSM. However, this is one of the possible effects of implementation of DSM measures that might impact PQ performance and is, therefore, mentioned here.

One characteristic example of a large-scale change in the structure and types of system-connected loads is replacement of directly-connected motors with drive-controlled ones (also known as “variable-speed” motors). The shift from using directly-connected induction motors to adjustable-speed drive (ASD) applications is evidenced in recent studies (e.g. [381]), which estimate that around 25% of newly installed motors are ASD-controlled, which is illustrated in Figure 8.1 [382]. This means that a lower number of voltage dips due to motor starting can be expected, which will be most noticeable in industrial installations, but also in agricultural installations, which are often connected to a weak rural network, where the effects of motor-starting dips are typically more pronounced. However, harmonic emission from ASDs will increase, as they replace directly connected motors.

Starting of drive-controlled motors is expected to lead to less severe dips than starting of induction motors, as ASDs typically allow control of start-up conditions (“soft starting”) and as a high starting current would otherwise require overrating of the ASD. However, the harmonic emission might be high during the starting of the motor, resulting in a new type of phenomenon, preliminary named as a “short-duration distortion due to device starting”.

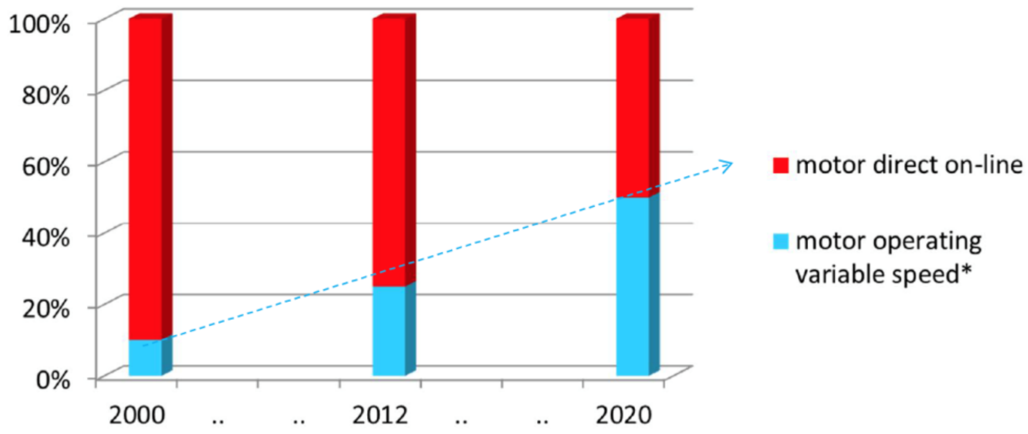

Figure 8.1 Estimated contributions of directly-connected and drive-controlled motors [396]

Further impact on the “demand side” will come from the anticipated near-future electrification of the road transportation sector, which will introduce a large-scale deployment of electric vehicle battery chargers, which are also non-linear power electronic loads with possible impact on PQ and also one of the likely targets of DSM actions and schemes, due to relatively large power demands of electric vehicle battery chargers.

An example of the potential impact is illustrated in Figure 8.2, showing impact of group-connection/disconnection of EV chargers on a negative sequence voltage unbalance, measured in a German LV network [383]. The connection of single-phase chargers to three-phase power supply systems can cause significant unbalance in terms of fundamental voltages and currents. Even if the charging points are equally distributed on all three phases, an impact on unbalance is possible due to the different charging behaviour of customers and differences in actually connected EV chargers. This field study has shown that a connection of 10 EVs in the same phase, each drawing a charging current of around 16 A, can result in the unbalance values exceeding the currently prescribed compatibility level (2% in EN 50160). Even if charging points are uniformly distributed on all three phases, the impact of the 10 EVs on unbalance is visible. Especially during the evening hours, measured negative sequence unbalance values can double to up to 1.6% (see Figure 8.2).

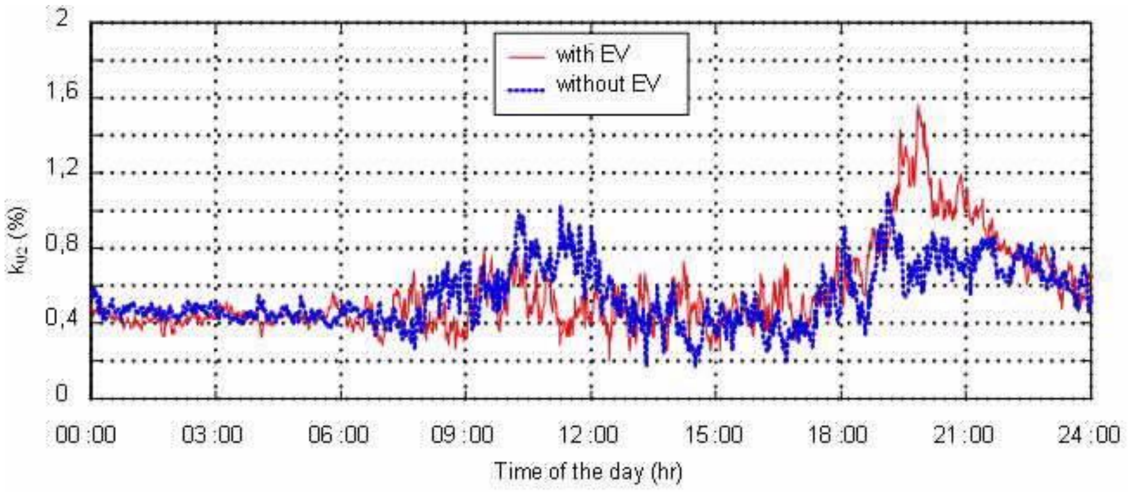

Figure 8.2: Impact of group-connected EV chargers on negative sequence voltage unbalance

Finally, connection of inverter-interfaced distributed generation and microgeneration systems (with or without energy storage), which could be either operated as a part of the DSM, or implemented/coordinated in the networks in which DSM is applied, might also have an impact on PQ. Regardless whether included in the specific DSM scheme or not, these sensitive modern power electronic equipment might trip, malfunction or further interact with the network and/or other types of equipment, which then may have strong impact on the implemented DSM scheme.

8.3.3 Direct vs. Indirect PQ-DSM impact (EMI issues, DSM for PQ improvement)

Considerations should be given to the assessment of DSM on PQ regarding "***reactive***" vs. "***preventive***" DSM schemes, where the former might implicitly, but fully put PQ out of focus (e.g. when DSM is implemented as part of system support schemes, to preserve system stability, or to prevent system collapse). Reactive schemes might be needed to "save the system" and during their activation PQ requirements may become secondary. Care should be taken to avoid damage to end-user equipment or wide-scale equipment malfunction, especially when reactive schemes are activated more often than what is current practice. In this context, implementation of DSM schemes will allow network operators to disconnect larger amounts of system loads not as a part of emergency load shedding schemes, but as a part of the contracted operating reserve [384].

8.3.4 EMI issues:

It is anticipated that a large number of wired and wireless communication and monitoring/metering systems (e.g. "smart meters", advanced metering infrastructure (AMI), DSM infrastructure, etc.) will be applied in future electricity networks for capturing, processing and exchanging information on the actual state of the network and conditions of all network components. Consequently, there will be an increased possibility for electromagnetic interference (e.g. with power line carrier signals, but also with other (tele)communication systems), or delays in two-way communication, as well as possible problems in sharing monitoring, metering and communication infrastructures for implementing hierarchical or prioritised network control. It is already reported that specific PQ disturbances (e.g. harmonics coming from end-user electronic loads) may interact with the DSM control signals (e.g. interference with power line carrier signals) [73], [385]. Of particular importance is possible interference with power line communication signals used for DSM, including weakening of the signal due to input capacitance of the connected devices, and supply voltage variations – both slow and rapid. As previously mentioned, this might establish a potentially complex framework of EMI interactions, between individual or groups of equipment, between DSM-dedicated signals and other network control communication systems, as well as an additional influence on supply voltage variations.

Previous research has shown that EMI originating in LV network can travel to MV network through the transformer's parasitic couplings [386]. As these disturbances can have relatively strong impact despite originating in remote locations, their origin is rarely easily pinpointed. Techniques to shield wires from EMI have been developed over the years for specific applications, such as substations, but they might not be appropriate to prevent the harmful effects of EMI caused by transients [387]. In addition, EMI caused by radio frequency phenomena (specifically in the range of power line communication signals of 35 kHz– 95 kHz, CENELEC A band in EN50065-1), as well as directly or indirectly related emission of harmonics, needs to be further evaluated.

8.3.4.1 PQ-driven DSM:

DSM may be applied for the sole purpose of improving PQ performance, or improving PQ performance may be one of the targeted DSM functionalities [388].

Frequency control is one example of DSM-T2 schemes. By aggregating a large number of energy, rather than power-reliant loads [389], [390], [391], the grid frequency support could be realised by controlling the usage cycle of heating/cooling loads (space/water heaters, or freezers/refrigerators). More recent research in [392] also suggests incorporating wind farms in the DSM control loop to improve the overall efficiency and effects of implemented schemes.

Frequency control is in general not aimed at improving the power quality, but at maintaining the global balance between production and consumption. Similar methods may however be developed for improving other PQ performance characteristics. Examples include methods to optimize the voltage profile of the network, while simultaneously taking into account the load priority [393], or smoothing the power consumption curve [394]. Further similar control methods are developed for incorporating battery energy storage systems, which are capable of feeding both active and reactive power to the grid [395].

8.3.4.2 Additional “smart grid” considerations

There are specific applications which are using DSM for other purpose, e.g. as a part of microgrid controls, discussed in Chapter 5. Particularly when the microgrid is operated in islanded mode, higher dynamics and wider ranges of interactions between microgrid loads and available small or medium-scale generation/storage resources will result in more pronounced, more frequent and longer voltage and frequency variations, This will be further augmented by the reduced short circuit power and inertia of microgrids. This indirectly relates implemented DSM controls to their effects on PQ, which will be different for different balancing and management schemes, as these might vary in the context of virtual power plants and microgrids. In any case, implementation of virtual power plant (VPP) and microgrid concepts will heavily rely on DSM to enable optimum, or maximum use of all network/user resources. Accordingly, these anticipated functionalities of future networks, and their relation to DSM, should be also considered with respect to the improvement/deterioration of system-user PQ performance. In addition to the research on using VPP to improve PQ by frequency control, [396], [397], recent work suggest incorporating VPP in voltage control [398] by, e.g., finding the optimal placement and control of distributed generation, while similar approaches also used for distributed energy storage systems within the VPP [399].

Some of the expected future network functionalities, e.g. increased automation and reconfiguration schemes, or wider implementation of automatic reclosing operation, will results in more frequent or longer voltage sags and short interruptions, which, in connection with some of applied DSM schemes, may result in additional PQ equipment immunity issues.

Network transients may also increase, due to e.g. high-speed switching to alternative supply points, or a more frequent switching of capacitor banks, while an ability to operate in off-grid conditions, such as in microgrids, will significantly improve reliability, but may result in the lower PQ levels within the microgrids, or elsewhere [400].

8.4 CONCLUSIONS

Generally, any wider-scale implementation of DSM, for any reason or purpose, will change the structure and composition of the aggregate system load, in which certain types of equipment will be wholly or partially connected and/or disconnected to/from the network. This will have potentially strong impact on the changes in the PQ performance of both the aggregate load and local network, primarily at the PCC where the aggregate DSM-enabled load is connected. Based on the amounts/types of involved DSM loads and local network characteristics, these changes and impact may propagate further through the network. As a consequence of applied DSM actions and schemes, there may be additional network interactions, with e.g. VVC, capacitor switching and active/passive filtering, which then may impact PQ network performance in a complex and not easily quantifiable ways. The following text gives summary and concluding remarks on some PQ aspects of a wider implementation of various DSM schemes in future electricity networks.

8.4.1 Findings

- Connecting and disconnecting large amounts of same or similar types of loads in various DSM schemes might change network characteristics and impact grid PQ performance, for example through the higher levels of waveform distortions, unbalances, or more pronounced voltage variations.
- The load recovery period after DSM-based load reconnection will be associated with a higher than usual demands, resulting in lower supply voltages and possibly higher harmonic emission levels (depending on the switched load types).
- Disconnecting specific types of load in large groups might remove certain harmonic cancellation effects, again causing temporary increase of harmonic emission. For example, disconnecting a large resistive electric heating load may significantly reduce system damping and result in considerably higher distortion levels, if resonance frequencies are close to harmonic frequencies.
- The replacement of (older) resistive and linear loads with non-linear power electronic loads might not result only in an increase of existing and occurrence of new types of waveform distortions, but it might also influence dynamic system behaviour and responses to faults.
- Modern power electronic loads are typically (but not always) more sensitive to PQ disturbances than older (non-power-electronic) equipment. This might have further negative impact on the grid and/or nearby equipment, as well as result in the unexpected outcomes of the implemented DSM control schemes.
- More frequent switching of DSM-enabled groups of loads will lead to a higher number of voltage step changes, requiring additional voltage control actions and possibly resulting in a more frequent unintentional tripping of sensitive equipment. However, opposite effects might also occur, e.g. the increased use of ASDs will result in a lower number of voltage dips due to a motor starting.
- Some of the expected future network functionalities, e.g. increased automation and reconfiguration schemes, or wider implementation of automatic reclosing operation, will results in the more frequent or longer voltage sags and short interruptions, which, in connection with some of the applied DSM schemes, may result in the additional PQ equipment immunity issues.
- Network transients may also increase in "smart grids", due to e.g. high-speed switching to alternative supply points, or a more frequent switching of capacitor banks, while an ability to operate in off-grid "islanded" conditions, such as in microgrids, will significantly improve reliability, but may result in the lower PQ levels within the microgrids, or elsewhere.
- A large number of wired and wireless communication/monitoring/metering systems in "smart grids" will increase possibility for EMI with power line carrier signals, but also with other (tele)communication systems. Harmonics from end-user electronic loads may interact with the DSM control signals (e.g. power line carrier signals), including weakening of the signal due to input capacitances of the connected devices. Both slow and rapid supply voltage variations might occur.
- Economic incentives in the form of short-term (e.g. hourly) markets can result in the simultaneous switching of large numbers of devices. For example, in a network with small combined-heat-and-power plants (μCHPs), these units may switch-on almost at the same time, if the electricity price exceeds a certain threshold.

8.4.2 Recommendations

- In cases of too deep and/or too frequent system voltage variations due to the switching of DSM-enabled loads, a more complex VVC actions would be required for maintaining PQ levels within the specified limits.
- Introduction of new types of power electronic-based loads may impact the current and voltage waveform distortions, where of particular importance are new types of emission (e.g. increased emission in frequency range above 2 kHz, due to a high-frequency switching of modern power electronic loads), requiring further work and analysis on their impact and propagation.

- A closer coordination of the devised DSM schemes with the implemented reactive power compensation and power factor controls, as well as active or passive filtering in the network might be necessary in cases when PQ levels deteriorate.
- DSM will be used as a part of microgrid controls. In islanded mode, higher dynamics will result in more pronounced, more frequent and longer voltage and frequency variations, further augmented by the reduced short circuit power and inertia of microgrids. This indirectly relates implemented DSM controls to their effects on PQ, which should be carefully evaluated during both design of DSM schemes and microgrid controls.
- EMI originating in LV network can travel to MV network through the transformer's parasitic couplings and relatively strong impact from sources at remote locations might occur due to DSM-based larger changes in system load composition. In addition, EMI caused by radio frequency phenomena (in the range of power line communication signals), as well as direct/indirect harmonic emission, needs to be further evaluated.
- The uncontrolled connection/disconnection of single-phase power-intensive electronic loads (e.g. EV chargers) to weaker three-phase power supply systems can cause significant unbalances in terms of the fundamental voltages and currents, and equal phase-distribution of the controlled loads should be included in the design of the optimal DSM schemes.

8.4.3 Open Issues

9. NEW MEASUREMENTS TECHNIQUES

9.1 INTRODUCTION

Future electricity networks will be more efficiently operated and will offer better reliability and sometimes improved power quality. They will offer more flexibility due to architecture reconfiguration (see feeder reconfiguration in Chapter 7) and capability of islanding operation (see microgrids in Chapter 5). The panel of these characteristics is completed by another characteristic of the smart grid, namely the continuous measurement and monitoring of fundamental electric parameters such as voltage and current and also some environmental parameters such as temperature, humidity, water level, presence of gas.

Continuous evolution of hardware and software technologies, which are quantified by better performing measurement chains (see Figure 9.1), including sensors and Intelligent Electronic Devices IEDs (doing acquisition, analysis and evaluation), makes possible in smart grid to perform permanent voltage and current measurement or monitoring at a grade of accuracy compatible with PQ grade.

The monitoring process will detect all kinds of waveform distorting phenomena, which may require eventually new indices for new types of distortion, e.g. supraharmonics. In addition, other PQ phenomena as voltage sags, harmonics and unbalance might require the development of more complex and more comprehensive indices based on statistics calculated from recorded data and waveforms captured from the grid itself.

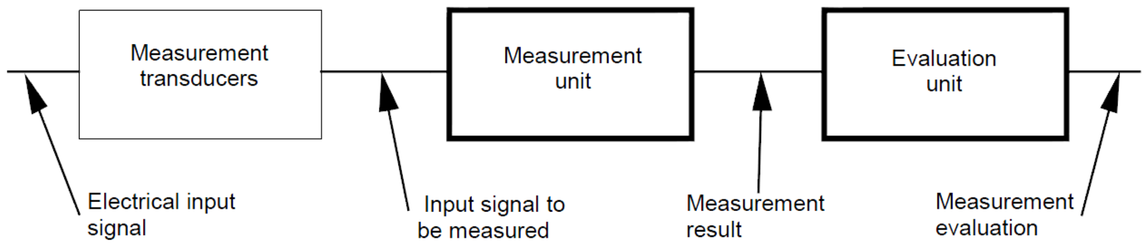

Figure 9.1 Measurement chain (source [291])

The new measurement techniques depend on the complexity of the disturbing phenomena and on the configuration of the smart grid. The following aspects should be emphasized:

- Location of the PQ monitoring
- Hardware for monitoring PQ including:
  - Transducers/sensors
  - IED complying with new requirements (maybe not yet in standards)
  - Communication interface
- Measurement unit
  - Measurement techniques
  - Indices
- Evaluation unit (analysis of measured data)

The following sections discusse each of these aspects.

9.2 MEASUREMENT LOCATION

Present practices used by utilities (TSO and DSO) include monitoring in substations and at customer/user's POC or PCC. Future practices will add monitoring at the point of connection of distributed generation and storage and along distribution feeders.

The trend at higher voltage levels is obviously towards measurements everywhere. The Guidelines of Good Practice by the European Energy Regulators (www.ceer.eu) recommend measurements in all HV and EHV substations. This recommendation was later taken over by CIGRE JWG C4.112.

Also at lower voltage levels the trend is towards measurements at all locations, both in protection relays and controllers and also in revenue meters (advanced metering infrastructure (AMI)). Most of these devices do not store much data, but the potential is clearly there. The issue to be resolved is now no longer where to measure, but what to measure, how to store the measurements data, how to use that data, etc.

More detailed information on monitoring location can be found in the CIGRÉ Technical Brochure TB 596 produced by CIGRÉ/CIRED JWG C4.112.

9.3 HARDWARE FOR MONITORING PQ

The monitoring process requires transducers, which sense voltage, current, temperature, humidity, etc., and IED that analyze the signals provided by transducers.

9.3.1 Transducers

The transducers can be devided into three categories:

- Current
- Voltage
- Combined current and voltage measurements (current and voltage elements are integrated in the same compact cast)

Classic transducers as instrument transformers are very well performing at fundamental frequency and less performing at higher frequencies. The chart in Figure 9.2 indicates the percentage of over 40 voltage transformers with levels from 6 kV to 400 kV that maintained an accuracy of 5% for ratio and 5º for phase angle over a frequency range up to 10 kHz [401].

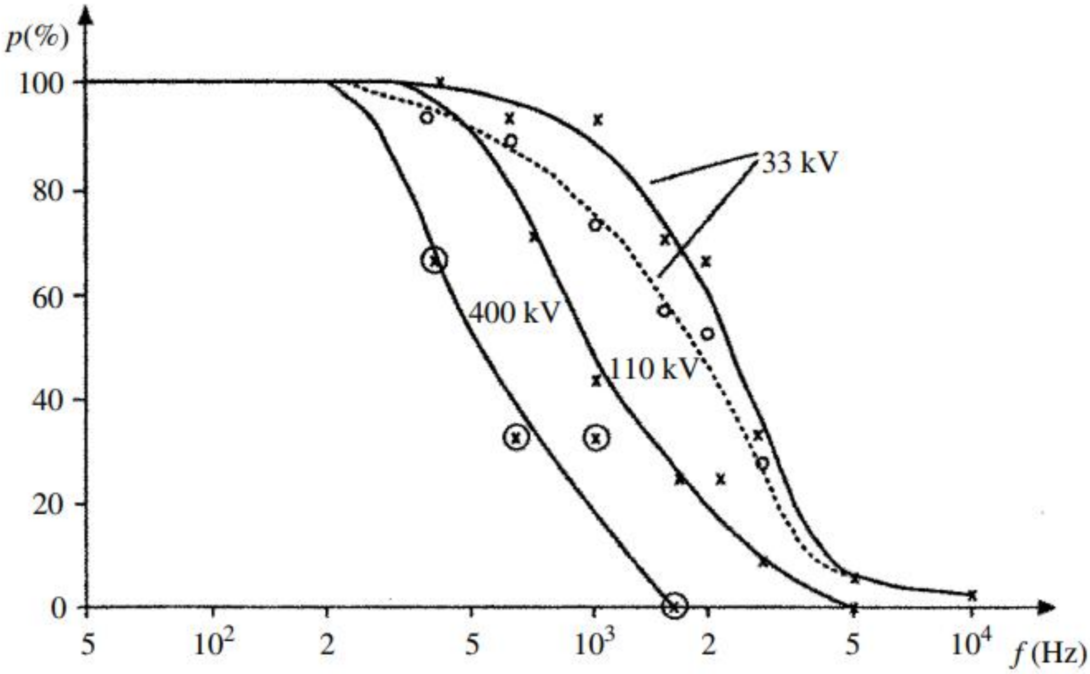

Figure 9.2 Percentage of voltage transformers, the transfer ratio of which has a maximum deviation (from the nominal value) of less than 5% or 5º up to the frequency f . [401]

Sensors represent a new solution for current and voltage measurement in HV, MV and LV power systems, providing information required for protection, fault location, PQ monitoring, network monitoring and operation. They are based on different phenomena or effects [401], [402]:

- Current:
  - Passive systems
    - Optical systems (Faraday effect)
    - Microwave systems
  - Active systems

        - Rogowski-coils
        - Search coils.
        - Hall effect
        - Proprietary electrical field sensing technology
    - Voltage
        - Capacitive voltage transformers (CVT)
        - Optical systems :
            - Pockels effect
            - Kerr effect
        - Impedance voltage dividers:
            - Resistive
            - Capacitive
            - Resistive-Capacitive
        - Proprietary electrical field sensing technology

Another example of comparison test between MV transducers is given in [403]. It included both phase and amplitude response and it was shown that VT's response on frequencies higher than 2 KHz isn't linear. To resolve this problem the use of a divider was suggested. As the divider itself lacks galvanic insulation, equipment including optical insulations has been developed to use for voltages up to MV[404], [405]. For the measurement of current, a transducer using a Rogowski coil combined with phase and amplitude correcting electronics has been presented [406]. For low voltage applications that do not need high power capacity but instead prioritize cost matters, an Arduino based combined voltage and current transducer was put together.[407].

Besides published results and conclusions from international tests performed by laboratories, transducer manufacturers should provide additional information on the frequency response of their devices and when required even calibration factors for magnitude, phase angle and temperature corrections corresponding to different applications bandwidths.

As resonances in voltage instrument transformers are sensitive to many impact factors (e.g. temperature, burden, etc.), only an application bandwidth as recommended in [408] should be requested from the manufacturers. Using full calibration curves measured in the laboratory can result in significant errors in field measurements, particular at frequencies around the resonance frequencies of the instrument transformer.

More detailed information on transducers can be found in the CIGRÉ Technical Brochure TB 596 produced by CIGRÉ/CIRED JWG C4.112.

9.3.2 Intelligent Electronic Devices (IED)

For a long period of time, dedicated devices such as PQ analyzers, scopes, etc. were used to monitor the quality of the power supplied by utilities (TSO and DSO).

In recent years, utilities started exploring possibilities to leverage the monitoring potential (data acquisition, analysis, storage and transfer to the power system control centre) of IEDs already connected to the grid such as [409]:

- RTUs,
- Controllers,
- Relays,
- Meters/AMI.

These IEDs are capable to measure:

- Line currents,
- Line to ground voltages,
- Capacitor current,
- Neutral current.

Some of them comply with IEC 61000-4-30 and measure accordingly:

- Harmonics

- Interharmonics
- Unbalance
- Voltage flicker
- Dip, swell and interruptions
- RVC

9.3.3 Combination of transducer and IED (Line monitor)

Several manufacturers have to date proposed a combination of transducer and IED, such as line monitors (see Figure 9.3). Sometimes, line monitors may be a better solution than using separate devices, for monitoring the distribution and transmission overhead lines.

Line monitors are capable to:

- Monitor the current, the electric field, the voltage when a connection to neutral/ground is provided,
- Perform local signal treatment,
- Communicate wireless the information acquired.

Figure 9.3 Medium voltage overhead line monitors

9.4 MEASUREMENT UNIT

The Measurement unit (c.f. Figure 9.1) measures the input signals (current and voltage) and process them in order to calculate several indices that characterize the different power quality phenomena. Present measurement units cover traditional disturbing phenomena. For example, they measure harmonics up to 50st order, and calculate the traditional THD (Total harmonic distortion) factor. It might not cover new phenomena such as supraharmonics, which should be integrated in future practice firmware.

The PQ indices that are used today have been introduced several decades ago. The main documents defining PQ indices are IEC 61000-4-30 and IEEE 1159. As the network evolves, the PQ indices should evolve with it. Since the distributed generation becomes more prolific, so do the challenges associated with it [411]. For example, a new set of indices [412] was proposed to better understand the unbalance caused by the shading in PV.

There is a new trend or approach in disturbance based versus non-disturbance-based processing, which has stimulated the development and use of monitors that would be able to record continuously 3-phase waveforms. One such device is already available on the market and it performs some advance data compression. As a consequence of this trend, in the future, besides the option to store information on a pre-defined number of disturbances/indices (dips, harmonics, etc), the user will have higher flexibility in repocessing the data (complete waveforms) and extracting aditional information on top of that pre-defined. So far, the research has been driven mostly by standardization towards the evaluation of standardised PQ indices. Now that "the gate was opened", new possibilities and new ways of treating, analysing and evaluating the data may appear and that will cosiderably help the development and validation of new PQ indices.

Next subsections presents some of the measurement issues associated to the different PQ phenomena and some new indices proposed in the literature to better characterize each of the disturbances. Future practices don't exclude current practices, they may include them in total or partial.

9.4.1 Harmonics

9.4.1.1 Magnitude

Harmonic magnitudes are well defined by international standards regarding indices and limits. The standard IEC 61000-4-7 establishes the requirements of the measurement instrumentation intended to measure harmonic currents and voltages using a sine-based Fourier transform. For further analysis the spectra of each measurement interval (10 cycles in a 50 Hz system, and 12 cycles in a 60 Hz system) is usually aggregated in time and frequency.

In the frequency domain analysis, different methods of grouping the spectral components are defined in order to cover the whole energy of the signal referred to as grouping and subgrouping [428]. This is e.g. of importance in case of leakage effects caused by a variation of harmonic current/voltage within the measurement interval. Measurement equipment complying with IEC 61000-4-30 class A or S devices provides harmonic sub-groups as specified in this standard [278].

Aggregation in time is usually required when signals are monitored for long periods of time. Regarding magnitudes, different methods are applied to aggregate the data like minimum, mean, root mean square (RMS) or maximum. The most common aggregation interval is 10 min, however 1 min or 30 min are also used. Longer aggregation intervals usually result in a less dynamic time series with a smaller variation range. According to IEC 61000-4-30 magnitudes must be aggregated (e.g. to obtain a 10-minute value from 10-cycle values) using the RMS. When comparing measurements taken with different instruments, which do not have the aggregation mathod implemented according to IEC 61000-4-30, the results from similar aggregation methods should be carefully verified. For example for wind turbines, the emission measurements done according to IEC 61400-21 often use the arithmetic mean.

Assessment of harmonic magnitudes not only depends on the aggregation interval and method, but also the assessment percentile (95%, 99%) and the assessment interval (typically one week).

Single measurements have shown differences between different aggregation intervals and respective bodies were concerned about the adequateness of the calculation parameters as provided in present standards (e.g. 10-minute-interval). Therefore, a different aggregation intervals and assessment percentiles have been seriously discussed during the last years. In order to contribute to the dicussion in [433] the impact of the aggregation interval, aggregation method and assessment quantile on voltage harmonic analysis is studied in detail based on a set of measurements. At least based on the results of this study, the choice of 95-%-quantile and 10-minute-mean values seems to be adequate for voltage harmonic assessment. The aggregation method based in maximum values is less suitable for assessing long-term effect, but can rather be used for troubleshooting and investigation of equipment malfuncation.

9.4.1.2 Phase angle

Although harmonic magnitudes are defined by almost all standards in terms of indices and limits, up to now only little importance has been given to the harmonic phase angles. Due to the lack in the standardization most instruments do not provide harmonic phase angles at all or manufacturers use individual implementations based on different references or even own interpretations and the results are consequently not comparable.

In general, "relative" harmonic phase angle (phase angle between current harmonic and voltage harmonic) and "absolute" harmonic phase angle (phase angle between current harmonic and voltage fundamental) must be distinguished.

Regarding grid measurements, there is still a gap in the phase angle definition [70] in the standards IEC 61000-4-7 and IEC 61000-4-30. While measurement for a single time instant is well defined, there is a lack of definition on methods to aggregate the harmonic phase angles in frequency and in time. Different "time-zero" references can be selected as reference for the phase angles. In power system analysis, the measurement interval is usually synchronized to the voltage fundamental and consequently its positive zero-crossing is selected as the time-zero reference.

Another important issue that must be taken into account in the phase angle calculation is the definition of the Fourier transform. While the Fourier transform mathematical derivation is based on cosine signals, measurement instruments usually implement a sine-based Fourier transform as this corresponds to the measurement interval based on positive zero-crossing and is required according to IEC 61000-3-12 for current harmonic assessment of equipment [436]. Cosine-based vs. sine-based calculation results in a 90° phase angle rotation. In order to ensure comparable phase angle values and to avoid ambiguties, either exact knowledge about the implementation of the Fourier transform or a respective standard implementation is required.

For the frequency aggregation, grouping of harmonic phase angles is not possible from a mathematical point of view and has practically no meaning. Therefore, no phase angle information can be provided for grouped or subgrouped values as is required for harmonic magnitudes according to IEC 61000-4-

30, but only for individual spectral components. A solution to that is presented in [436]. It is proposed that the phase angle of the main spectral component of each harmonic subgroup is reported as the phase angle of the harmonic subgroup if the main spectral component clearly dominates the subgroup value.

For long term measurements, a time aggregation is also needed for harmonic phase angles. In recent publications it has been proposed the use of the prevailing harmonic phasor, as a suitable method for time aggregation of harmonic phasors [70], [437]. The prevailing harmonic phasor is composed by a prevailing magnitude and a prevailing phase angle:

$$\underline{Y}_{prv}^{(h)} = Y_{prv}^{(h)} \angle \varphi_{prv}^{(h)}$$

Equation 9.1

Where Y_{prv} can be replaced by U or I for harmonics voltages and currents respectively, and h is the harmonic order. The prevailing magnitude $\mathrm{Y}_{\mathrm{prv}}^{(\mathrm{h})}$ represents the central tendency of the magnitudes of the harmonic phasors . It is calculated as the RMS of the current harmonic magnitudes inside the considered evaluation interval, as described in the IEC 61000-4-30.

The prevailing phase angle $\varphi_{\mathrm{prv}}^{(\mathrm{h})}$ represents the central tendency of the harmonic phase angles. It is the phase angle resulting from the phasor sum of the harmonic phasors in the aggregation interval. However, if the harmonic phasors have a wide variation in the complex plane, the prevailing phase angle loses its meaning. The prevailing phase angle can be reported only if the harmonic phase angles have a low variation. The variation of harmonic phase angles is evaluated with the prevailing ratio, which is calculated as:

$$PR^{(h)} = \frac{\left|\sum_{i=1}^{m} \underline{Y}_{prv}^{(h)}\right|}{\sum_{i=1}^{m} \left|\underline{Y}_{prv}^{(h)}\right|}$$

Equation 9.2

This factor compares the difference between the phasor sum and the arithmetic sum of the measurements. *PR* varies between 0 (complete dispersion of the phasors in the complex plane) and 1 (all phasors are in the same direction). A *PR*=0.8 is selected as a threshold to decide if the prevailing phasor should be reported.

9.4.2 Indices for Harmonics

Harmonic emissions open a discussion based on discriminating between polluters increasing the harmonic level and cleaners reducing the harmonic level. In particular this approach requires very accurate measurements of the harmonic phase angle. A state of the art of harmonic indices and a proposal for a novel harmonic severity index is available in [419].

The calculation process of the severity index includes eight steps

1. Calculate over 10-min interval during one week harmonic and interharmonic groups (IEC 61000-4- 30 and IEC 61000-4-7). The calculation of the phase angle of harmonic currents would be useful to determine the origin of the distortion, either the customer or the system. It should be noted that harmonic phase angles are mathematically only defined for spectral components but not for grouped values. However, if the spectral harmonic component dominates the group value, the respective phase angle can be reported (see section 9.4.1.2 for more details).
2. Calculate weekly 95% values for each harmonic and interharmonic group to build a "weekly spectrum."
3. Compare the "weekly spectrum" with limits and give a "weekly harmonic severity" value to each harmonic and interharmonic subgroup using Figure 9.4.
4. For values between those indicated, use linear interpolation.

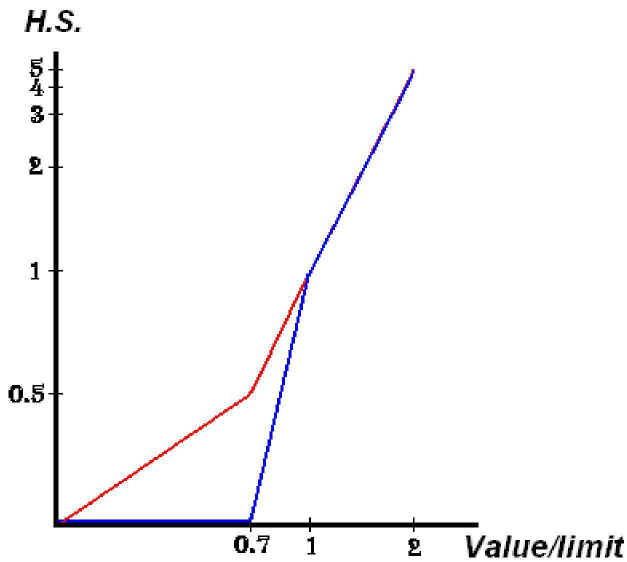

Figure 9.4 Harmonic Severity Scale

5. The resulting 80 weekly subgroup severity values are used to build the "weekly harmonic severity" spectrum. The weekly harmonic severity (WHS) of the site is the sum of these values.
6. The yearly harmonic severity (YHS) of the site is the sum of the weekly value over one year.
7. The 3-phase severity index is obtained by adding each phase values.
8. When available, the origin of the harmonics should be included in the index evaluation.

Two scenarios are possible:

1. The customer is a polluter, when the harmonic originates from customer
2. The customer is a cleaner, when the harmonic originates from grid.

The polluter contributes to the harmonic distortion severity, and the cleaner reduces it. In the second case, the "weekly harmonic severity" in steps 3 and 4 is multiplied by (–1) and the process continues with steps 5, 6, and 7.

To decide wether a customer pollutes or cleans harmonics, several methods can be applied. A commonly used method is the direction of active power flow, which however can provide wrong results under specific circumstances. A summary of different methods can be found in [435]. CIRED/CIGRE working group C4.42 is actively working on the development of a reliable method than can be easily implemented into power quality monitors. Consequently, the harmonic contribution of a customer installation will also be a novel index that will become important in the future. It is expected that similar methodologies can also be developed for unbalance and flicker.

9.4.3 Interharmonics

Concerning interharmonic measurements, in [438] it was proven that also a small error in synchronization causes severe spectral leakage problems in the IEC framework. It was also proven that it possible to improve accuracy by means of Hanning windowing or advanced signal processing techniques compatible with IEC 61000-4-7 (i.e. based on DFT [439] or on Prony-based advanced methods [440]) that can be implemented in IED. There is a great interest in the academic, industrial and standard communities about the need of fixing limits for interharmonic voltages once accepted the IEC Standard 61000-4-7 protocol for their measurement. However, the abovementioned errors due to spectral leakage [438] even for Standard IEC 61000-4-7 Class A instruments can be of the same order of quantity of amplitudes of limits under discussion ranging from 0.1% to 0.5% for interharmonic voltages.

9.4.4 Indices for Interharmonics

The most common indices used for interharmonics are those based on the Interharmonic sub-group concept introduced in IEC 61000-4-7. In that standard, there is no reference explicitly made to the Subgroup Total Interharmonic Distortion (*TIHDS*) factor, but in existing literature and in some commercial PQ instruments, complying with Class A requirements, a reference is made to the following $TIHDS_{YLF}$ formula:

$$TIHDS_{YLF} = \sqrt{\sum_{h=2}^{h=40} \left(\frac{Y_{isg,h}}{Y_{sg,1}}\right)^2}$$

Equation 9.3

where $Y_{isg,h}$ are the RMS magnitudes of the interharmonic subgroups in the low-frequency range, from 0 - 2 kHz. $Y_{isg,1}$ can be considered a compact and practical index for sub-harmonics.

9.4.5 Supraharmonics

Measurement techniques and description of instruments in the supraharmonic range is covered by two standards: IEC 61000-4-7 [428] and CISPR 16 [429]. IEC 61000-4-7 covers the lower range (2-9 kHz) in informative APPENDIX B and the proposed method is to be seen as a guideline. Frequencies between 9 and 150 kHz are not discussed. The proposed method is the use of a time-domain sampling instrument with a high-pass filter starting at 2 kHz to suppress the power system frequency as well as the more dominating lower order harmonics. The recommendation is that the attenuation of the fundamental frequency exceeds 55 dB. IEC 61000-4-7 further recommends taking a rectangular data acquisition window of 200 ms of the signal which is then post-processed to determine the frequency components. This will result in a frequency separation of 5 Hz that are then grouped into 200 Hz bands to harmonize with the lower CISPR 16 frequency band, starting at 9 kHz.

The CISPR 16 standard takes a different approach than IEC 61000-4-7 and recommends measurements with a measuring receiver. Measurement above 9 kHz according to the CISPR standards are mainly performed for standardized laboratory test of the emission levels from equipment. These types of measurement are done in a controlled environment with known source impedance. An example is communicating devices that have to be tested according to CISPR 16 with a quasipeak detector over a duration of 1 minute at a specified point on a CISPR artificial network. This approach to measuring supraharmonics has some drawbacks; only limited information about the time-domain can be achieved and scanning the frequency range will in practice increase the risk of missing valuable information since the signals in this range are often non-stationary both in time and frequency. A more detailed description of measurements in the supraharmonic range can be found in [430], [431]. Another method for measuring supraharmonics in the frequency range between 9 kHz and 150 kHz is proposed in the informative annex of IEC 61000-4-30 Ed.3. However, this method does only cover about 8% of the signal and provides 2 kHz bands instead of 200 Hz bands. A comparison of the DFT based methods is provided in [431].

Measurements of supraharmonics can normally not be done using a standard power quality meter. The instrument used has to ensure a high enough amplitude resolution and sample rate. An oscilloscope with anti-aliasing filter and appropriate additional filters as described above is recommended for time-domain measurements. The frequency response of the current probes has to be considered to ensure that they are appropriate for frequencies up to 150 kHz. In MV networks, special care has to be taken regarding the accuracy of the IVT's (Inductive voltage transformers). As described in [432], there are several factors that influence the frequency response and the possible error tends to increase with frequency. In networks with nominal voltages of 20 kV and above the accuracy of the IVT's is not acceptable for frequencies above 2 kHz as concluded in [432].

9.4.6 Indices for Supraharmonics

At this time, there are no defined indices for supraharmonics. A first approach in defining new indices would be to evaluate, if the indices for harmonics could be extended also to the frequency range corrsponding to supraharmonics. In [421], a set of indices is proposed based on the behaviour of supraharmonic emissions generated by a number of household appliances. The proposal is partly based on existing indices for harmonics.

The analysis of supraharmonics can be performed either in time or in frequency domain. The reference [421] proposes indices for three different ways of representation of supraharmonic emission:

- Frequency representation by using Fast Fourier Transform
- Cycle based time-frequency representation by using Short Time Fourier Transform
- Time representation after extracting the supraharmonic content by using filtering

Three different ways of representing the emission from a device are illustrated in Figure 9.5. To gain the understanding on how a specific device injects supraharmonics into the grid, an analysis using all three representations is strongly recommended. It's worth noticing that Figure 9.5 shows a sample of a particular device, and different devices can show similar or completely different behaviours.

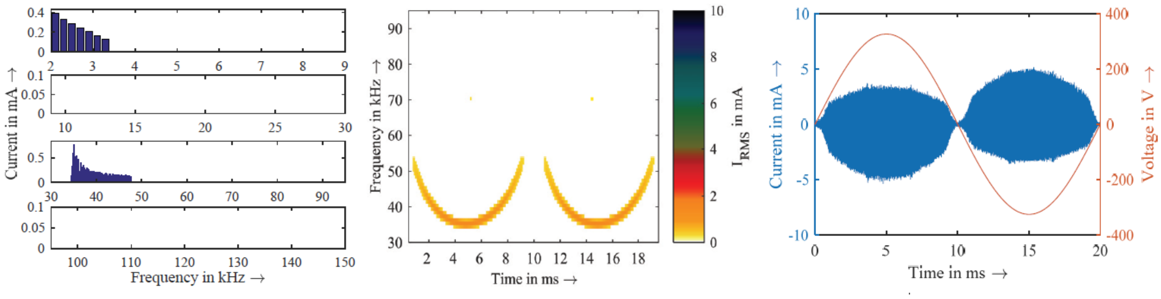

Figure 9.5 Example of frequency (left), time-frequency (middle) and time (right) representation of the supraharmonic emission [421]

An overview of the indices proposed in [421] can be seen in Table 9.1.

Table 9.1 Indices for supraharmonics frequency representation

Indices for frequency representation	
Index	*Description*
Total Supraharmonic Current, TSHC	Total emission in absolute value. The index can also be given as a percentage value of the fundamental or rated current (similar to the THD defined for the harmonic range).
Weighted Supraharmonic Current, WSHC	Total emission in absolute value including a frequency-dependent weighting factor. This indexcan also related to fundamental or rated current.
Cycle-by-cycle variation, CCV	Fluctuation of emission between consecutive power cycles
Indices for time-frequency representation	
Emission scattering, ES	Variation of magnitude and frequency of supraharmonic emission within power cycle
Indices for time representation	
Half cycle symmetry, HCS	Comparison of positive and negative half cycle
Duration, t_{SH}	Duration of the emission relative to the power cycle
Location, x_{SH}	Point on wave of the begining of dominant emission related to the power cycle
Point on Wave, PoW	Point on wave of the peak value related to the power cycle
Crest factor, C_{SH}	Level of constancy of the emission

The list of indices presented in Table 9.1is not complete and it should be seen as a first approach towards potential and appropriate indices for the frequency range between 2 and 150 kHz. More research is needed for example on how suitable the indices are for field measurements and for devices with changing operating states.

Aditionnal information on supraharmonics measurement, analysis and evaluation is available in APPENDIX H.

9.4.7 Slow voltage variations

Measurement of voltage magnitude is presently defined by the standard IEC 61000-4-30 [278] as the time 10 or 12 cycle RMS values (for 50 Hz and 60 Hz systems, respectively), aggregated over several possible longer time periods – typically 150/180 cycles, 10 minutes or 2 hours. For most regulatory purposes the 10 minute value is used for slow voltage variations, as it gives a fair representation of their thermal effects [117]. In some countries the 1 minute time aggregation is also used [444]. A comprehensive discussion on the measurement method (e.g. the choice of RMS as representative for the magnitude) and choice of data window and sampling frequency can be found in [117], with examples of signal conditions which lead to differences when measured with different parameters which can still satisfy the requirements of [278].

Unlike the measurement of rapid voltage variations and voltage dips and swells which led to a number of publications and discussions in the recent year, the measurement of slow voltage variations did not raise significant attention in the recent years, and is therefore not expected to be changed in the future due to the predicted changes in networks.

9.4.8 Indices for Slow voltage variations

The RMS voltage is used as a basis for quantifying the severity of slow voltage variations. Three characteristics versus time are defined in IEC 61000-4-30: 10/12-cycle values, 150/180-cycle values, 10-minute values. Next to the 10-minute value, the standard also allows the calculation of the RMS value over other time windows, typically 1 minute.

The following additional indices require to be defined:

- The highest 1-cycle or 1-second value during a 10-minute window
- The lowest 1-cycle of 1-second value during a 10-minute window
- The RMS value over one day or one week.

The first two indices are calculated by several instruments, but no standard definition exists at this time. They are also calculated for other parameters such as harmonics or unbalance. The later one is used in the regulation in at least one country.

9.4.9 Dips and swells

The standard IEC 61000-4-30 recommends that the basic measurement U_{rms} of a voltage dip and swell shall be the $U_{rms(½)}$ on each measurement channel. Refreshing every half cycle was a condition imposed by the computing power of older IEDs. Recent IEDs based on newer technologies aren’t anymore ruled by the same restriction, so updating the 1-cycle RMS value as many times as the number of samples available for each cycle will allow a more precise identification of the beginning and end of the voltage dip or swell.

Proposal for new dip and swell indices (see section 9.4.10) are built on single-event characteristics and one of them is the phase angle at which a voltage dip begins, also called point-on-wave. The measurement of the phase angle and phase shift of the voltage dip shoud become a practice.

Better understanding of simultaneous dips and swells on different phases require the analysis of zero, negative and positive sequences of the fundamental frequency during an unbalanced dip. This analysis can also explain how the dip propagates through the network.

Measuring the signal distortion during a dip, as the RMS value of the non-fundamental components, whaich is a non-traditional method, may help to understand the effect of the dip on electronic devices.

9.4.10 Indices for voltage dips and swells

The standard IEEE 1564 introduces a single-event voltage sag severity index S_e, which is calculated from the retained voltage in per unit and the duration of a voltage sag in combination with a reference curve. Use of the SEMI F47 curve as a reference is recommended, but the method works equally well with other methods. The index is calculated using the equation:

$$S_e = \frac{1-V}{1-V_{curve}(d)}$$

Equation 9.4

where V is the voltage sag magnitude, d is the event duration, $V_{curve}(d)$ is the magnitude value of the reference curve for the same duration, V(t) is the RMS voltage during the event and Vnom is the nominal voltage.

IEEE P1564 standard also defines a voltage sag energy index, EVS, from the RMS voltage versus time.

$$E_{VS} = \int_0^T \left[1 - \left\{ \frac{V(t)}{V_{nom}} \right\}^2 \right] dt$$

Equation 9.5

where $V(t)$ is the RMS voltage during the event and V_{nom} is the nominal voltage. The integration is taken over the duration of the event, which is, for all values of the RMS voltage below the threshold. The voltage sag energy has the unit of time and it can be expressed in cycles, milliseconds, or seconds.

A new weighted *SSI* (WS_e) is proposed in [419], which considers the S_e, such as defined in equation (4), as the main term of the index, and the E_{VS}, such as defined in equation (5), as a weighting factor.

$$WS_e = S_e \times E_{VS}$$

Equation 9.6

In case only retained voltage and duration of an event are available, equation 9.6 becomes

$$WS_e = \frac{1-V}{1-V_{curve}(d)} \times \left[1 - \left(\frac{V}{V_{nom}} \right)^2 \right] \times d$$

Equation 9.7

If the waveforms are available, WS_e can be calculated using one-cycle RMS voltage values updated every half-cycle, as in the following expression:

$$WS_e = \frac{1-V}{1-V_{curve}(d)} \times \frac{1}{2f_0} \sum_{k=1}^{N} \left[1 - \left\{ \frac{V_{rms(1/2)}(k)}{V_{nom}} \right\}^2 \right] \times d$$

Equation 9.8

Equation 9.7 gives a global result, useful not only for the customer but also for the utility. The first term in this expression, which indicates the impact of the sag on customer equipment, and in case of unbalanced sags, is overevaluated, is weighted with the energy loss. When the waveform is available, the use of equation 9.8 for the calculation of WS_e is recommended, because the energy loss is calculated more accurately.

In addition to *SSI* (WS_e), [419] proposes an interesting potential impact factor (PIF) for voltage dips or swells, which can be used for benchmarking feeders, substations, areas or entire networks.

Some new developments in dip characterization, which are used for a number of additional single-event indices are presented in [171], [420]. Several methods, based on earlier proposed algorithms for extracting three-phase characteristics (dip type, characteristic voltage, and so-called "PN factor"), are compared. The difference is in the way in which the time variation of those characteristics is treated to result in single-event characteristics. The proposed indices include:

- Phase-angle jump for each voltage channel.
- Phase-angle jump for a multi-channel dip.
- Characteristic phase-angle jump for a dip in a three-phase system.
- Dip type, characteristic voltage and PN Factor calculated using the symmetrical component algorithm.
- Dip type, characteristic voltage and PN Factor calculated using the six-phase algorithm.

Two of them have shown a good potential to be used as future dip indices.

9.4.11 Rapid voltage changes RVC

The measurement method given in standard IEC 61000-4-30 uses a detection method based on the difference between the $U_{rms(½)}$ on each measurement channel and the Rapid Sliding Reference Voltage U_{rsr} calculated for that same channell.

U_{rsr} is calculated for each channel using equations (9) or (10):

$$U_{rsr(n)} = 0{,}996\,667 \times U_{rsr(n-1)} + 0{,}003\,333 \times U_{rms(½)} \text{ (50 Hz)}$$

Equation 9.9

$$U_{fsr(n)} = 0{,}997\ 223 \times U_{fsr(n-1)} + 0{,}002\ 777 \times U_{rms(½)}\ (60\ \text{Hz})$$

Equation 9.10

9.4.12 Indices for RVC

Three different indices are defined in standard documents to quantify variations in the magnitude of the voltage:

- The short-term and long-term flicker severity index, quantifying the impact of voltage variations at time scales of a few seconds and less by their potential impact on a standard incandescent lamp.
- The magnitude of rapid voltage changes ("voltage steps").

Presently, there is a need for two sets of new indices. The first one would include alternatives, to the short and long-term flicker severity, that are more relevant to modern types of lighting (CFL and LED lightning, which appears to become the dominant type). Interharmonics have long been considered as a phenomenon that should be included in the flickermeter. A proposal including interharmonics in a general lamp model is proposed in [422]. One of the important barriers against the introduction of such an alternative index is that there is a wide range of lamps technology showing rather dissimilar behaviour during fast voltage variations [423].

The second need is in the time scale between 1 second and 10 minutes, where no indices exist. This may be partly solved by a higher time resolution (e.g. 1 second instead of 10 minutes), but that would merely result in large data volumes without additional information. A proposal for quantifying voltage magnitude variations in this time scale, referred to as "very-short variations" or VSV, was presented in 2005 [275] and applied on a few occasions, especially with wind and solar power integration. The proposal is a step forward but some further development is required. One of the limitations of the VSV method is that its values are dominated by large step changes in voltage.

9.4.13 Flicker

Concerning Light Flicker (LF) measurements, the IED used for monitoring should overcome the limitations of the IEC Flickermeter Standard, which is based on the reference incandescent bulb [422]. It is well known that IEC compliant Flickermeters (FM) are capable of measuring fast voltage fluctuations in terms of P_{st}, which is a good indicator of the amount of LF with a standard incandescent lamp. In particular, the demodulator present in the block 2 and the band pass filter of block 3 of the standard IEC FM block diagram cut away voltage fluctuations of the fundamental component caused by interharmonics over the double of the system frequency. This is because they do not cause much RMS variation in incandescent lamps. Interharmonics over the double of the system frequency are taken into account by the IEC FM only when they produce modulation of harmonics. So, the existing FM, which was designed specifically for 60 W reference incandescent bulb, is not able to detect LF produced by different lamp technologies. Recent literature have demonstrated the sensitivity of the new lamps (CFL and LED) in terms of Light Flicker to interharmonic frequencies lower and higher than the double of the system frequency even in absence of harmonics. Moreover, the CIGRE WG C4.111 has recently reviewed additional available research regarding lamp sensitivities to make recommendations for possible future ways to manage voltage fluctuations. Finally, the IEEE Standard P1453 "Recommended Practice for the Analysis of Fluctuating Installations on Power Systems, contains the Annex A (informative) titled "Impact of interharmonics on flicker related to non-incandescent lamps".

There is a need to introduce a new FM to cope with the abovementioned limitations. In the relevant literature, recent examples of new FM are reported. Some authors replace the demodulator block of the IEC FM, using different approaches, with a block detecting peak fluctuations. In other papers changes are introduced in the FM demodulator utilizing multiple pass-band filters or artificial injection of odd harmonics and adjusting also the Weighting Function (WF) to approximate the response of lamps different from incandescent. However, the majority of the proposals have not given satisfying and general results. Finally, other proposals remove the demodulator and modify WF in order to evaluate LF directly from fluctuations of lamp light flux (Optical Flickermeters). Theese FMs evaluate temporal flicker severity of any lamp at any voltage condition very accurately but are not practical, since the measurement methodology needs laboratory tests with real lamp placed in opportune test chambers.

A new proposal is contained in [422] where a tunable flickermeter based on a generalized lamp model able to account for lamp technologies different from incandescent is presented. Compliance with the

Standard IEEE 1453 (IEC 61000-4-15: 2010) is proven and performances for different lamp technologies are demonstrated by means of numerical and laboratory experiments showing the almost perfect equivalence with an optical flickermeter.

9.4.14 Indices for voltage flicker

Flicker is evaluated with the short-term and long-term flicker evaluation indices (P_{st} and P_{lt}) as defined in the IEC 610000-4-15. Both indices are well accepted, and the focus of recent research has been put on the Flickermeter and the compatibility levels, and not on the indices.

9.4.15 Transient voltage

The transient measurement depends on the transient type and the characteristics configured on the monitoring instrument and reported by it.

The standard IEC 61000-4-30 formulates several detection methods:

- *Comparative* - based on exceeding an absolute threshold
- *Envelope* - method: similar to comparative method, but with the fundamental removed prior to analysis
- *Sliding-window* - where instantaneous values are compared to the corresponding values on the previous cycle
- *dV/dt* - when an absolute threshold of dV/dt is exceeded
- *RMS value* - using very rapid sampling, RMS value calculation over subcycle intervals and comparison to a threshold
- *Other method* - including frequency versus amplitude

9.4.16 Indices for Transients

Voltage and current transients are mentioned in IEC 61000-4-30 and a number of possible single-event indices are mentioned in that document:

- Peak voltage
- Overshoot voltage
- Rate of rise of the leading edge
- Frequency parameters
- Duration
- Damping coefficient
- Energy and power

However, no definitions are given in that document, nor in any other standard document. The result is that different power-quality monitors calculate the single-event indices in different ways. This makes, among others, benchmarking and exchange of knowledge more difficult.

If voltage and current transients are to be seen as a serious power-quality phenomenon, it is essential that commonly agreed definitions become available for single-event indices. A detailed discussion of such indices and pitfalls in their calculation are presented in [117], [426].

9.4.17 Unbalance

Measurement of voltage unbalance is covered by the standards IEC 61000-4-30 and IEEE 1159. In both cases, the unbalance of the fundamental is assessed using the ratio of the magnitude of the negative sequence component to the magnitude of the positive sequence component. This method is globally accepted and implemented in all PQ measurement devices.

Another useful, but up to now rarely used index is the zero sequence unbalance of fundamental. In particular the zero sequence unbalance of current in LV networks is an indicator for the neutral conductor loading.

In the last years also the unbalance of harmonics have been discussed in several papers [424]. Harmonic current unbalance can be useful to decide if a balanced or unbalanced harmonic load flow is required in a simulation or to study how harmonics propagate via transformers with a delta winding, where only the positive and negative sequence component are transferred. It is important to note that the prevailing or dominant sequence of harmonics depends on the harmonic order. Assuming an approximately balanced distribution of harmonics to the phases, the prevailing system for 3rd harmonic is the zero sequence, for the 5th harmonic the negative sequence, for the 7th harmonic the positive sequence and so on. The prevailing sequence component can be also defined as balanced component, the remaining towo components as first and second unbalanced component [425]. The three components can be calculated as follows:

$$\begin{pmatrix} \underline{I}_{b}^{(h)} \\ \underline{I}_{u1}^{(h)} \\ \underline{I}_{u2}^{(h)} \end{pmatrix} = \frac{1}{3} \cdot \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}^{(h-1)} \cdot \begin{bmatrix} 1 & \underline{a} & \underline{a}^2 \\ 1 & \underline{a}^2 & \underline{a} \\ 1 & 1 & 1 \end{bmatrix} \cdot \begin{pmatrix} \underline{I}_{a}^{(h)} \\ \underline{I}_{b}^{(h)} \\ \underline{I}_{c}^{(h)} \end{pmatrix}$$

Equation 9.11

Table 9.2 provides a translation schema of the original Fortesque sequences to the three components in equation (11).

Table 9.2 Fortescue sequences for first and second unbalance component

	Harmonic order h						
	3	***5***	***7***	***9***	***11***	***13***	***15***
$\underline{I}_{b}^{(h)}$	0	-	+	0	-	+	0
$\underline{I}_{u1}^{(h)}$	-	0	-	-	0	-	-
$\underline{I}_{u2}^{(h)}$	+	+	0	+	+	0	+

Fortescue sequences: + Positive, - Negative, 0 Zero

Recently several methods requiring the assessment of the phase angle of an unbalanced component have been developed and applied. This includes e.g. the study of superposition of multiple unbalance sources as well as techniques for reducing unbalance by active filters or efficient distribution of unsymmetrical devices to the phase conductors in three phase systems (see section 10.4.2. For the implementation of such methods, the measurement of the complex unbalance components (magnitude and phase angle) is essential.

9.4.18 Indices for Voltage unbalance

The impact of voltage unbalance has traditionally been mainly on rotating machines, especially on induction motors. The negative-sequence voltage causes a negative-sequence current; which heats up the machine, including the formation of hot spots. Besides an increase in losses, it reduces the lifetime of the machine.

IEC and Cenelec use the negative-sequence voltage to quantify unbalance, with 10-minute averages and weekly 95, 99 or 100% values used as performance requirements by the regulators in different European countries. The impact of short-periods in which the limit is exceeded on losses and loss-of-life is limited, so that a 95% time appears most appropriate.

IEEE and ANSI also use the difference between phase-to-phase or phase-to-neutral voltages as an index [427]. The difference between phase-to-phase voltages is more appropriate for predicting the impact on three-phase inverters and rectifiers. Large unbalances between the phase-to-phase voltages result in unbalances between the currents with tripping of the protection as a result. Short-duration indices (3-seconds) and strict (100%) thresholds are more appropriate in this case. However, the limit may be placed higher than a value, which is the equivalent to 2% negative sequence.

Unbalanced voltages also result in voltages at equipment terminals being exceeded faster; this gives in turn a smaller margin in distribution planning. Both differences, between phase-to-phase voltages and between phase-to-neutral voltages, are appropriate indices. Either 10-min or 1-min averages can be used, depending on which one is used for supply voltage variations. There is no need for a regulatory or standardized limit for this, as requirements on supply voltage variations are taking care of that. Sometimes, network operators may want to set their own internal planning levels.

Regarding new proposals for unbalance indices, it is worth mentioning a global unbalance severity index (*GSVUF*), defined in [419] as a combination of *VUF*, the three-phase index as the main term, and three indices V_aUF, V_bUF, and V_cUF, representing the contribution to unbalance of each phase, as weighting factors. These individual indices can be instantly used not only when the evaluation of each phase unbalance is necessary but also when determining the rate of phase voltage fluctuation over and under the voltage reference threshold is necessary, because of the variation of connected one-phase loads, nonsymmetrical three-phase loads, or other reasons.

The individual phase unbalance index has two components, a counter $C_{ph10minV+}$ for 10-min periods when the RMS phase voltage is over the reference value V_{ref} and a second one $C_{ph10minV-}$ for 10-min periods with the RMS voltage level below the reference value V_{ref}. The average value of the three phase-to-neutral voltages V_{ph} can be chosen as a reference value. When the phase-to-neutral voltages are replaced by line-to-line voltages V_{l-l}, the average value of the three line-to-line voltages is recommended as a reference value. Then the index can be expressed as a complex number with $C_{ph10minV+}$ as the real term and $C_{ph10minV-}$ as the imaginary term.

$$V_{ph}UF = C_{ph10\min V+} + jC_{ph10\min V-}$$

Equation 9.12

Where:

- $V_{ph}UF$ = individual phase unbalance index (i.e., V_aUF, V_bUF, V_cUF),
- $C_{ph10\min V+}$ = counter for 10-min periods when the RMS phase voltage > V_{ref}, and
- $C_{ph10\min V-}$ = counter for 10-min periods when the RMS phase voltage < V_{ref}.
- j = complex operator ($j = \sqrt{-1}$)

Equation 9.10 can be rewritten in "polar" form:

$$V_{ph}UF = \left|C_{ph10\min V}\right|\left(\cos\theta_{ph} + i\sin\theta_{ph}\right) = \left|C_{ph10\min V}\right| e^{j\theta_{ph}}$$

Equation 9.13

Where:

$|C_{ph10minV}|$ = *complex modulus* ($\left|C_{ph10\min V}\right| = \sqrt{C_{ph10\min V+}{}^2 + C_{ph10\min V-}{}^2}$),

θ_{ph} = *complex argument* ($\theta_{ph} = \tan^{-1}\left(\dfrac{C_{ph10\min V-}}{C_{ph10\min V+}}\right)\theta$).

The new global unbalance severity index *GVUF* is given by the equation:

$$GVUF = VUF \times \left(V_aUF + V_bUF + V_cUF\right)$$

Equation 9.14

Where:

- VUF = system unbalance index,
- V_aUF = phase An unbalance index,
- V_bUF = phase Bn unbalance index,
- V_cUF = phase Cn unbalance index.

If V_aUF, V_bUF, V_cUF are written in polar coordinates, the equation (12) changes to:

$$GVUF = VUF \times \left(\left|C_{pha10\min V}\right| e^{j\theta_{pha}} + \left|C_{phb10\min V}\right| e^{j\theta_{phb}} + \left|C_{phc10\min V}\right| e^{j\theta_{phc}}\right)$$

Equation 9.15

An example of graphical representation of the global unbalance severity index, as a chart of incremented values shown in stacked columns, is illustrated in Figure 9.6. It indicates which phase is more or less unbalanced and in what manner, if an undervoltage or an overvoltage is predominant,

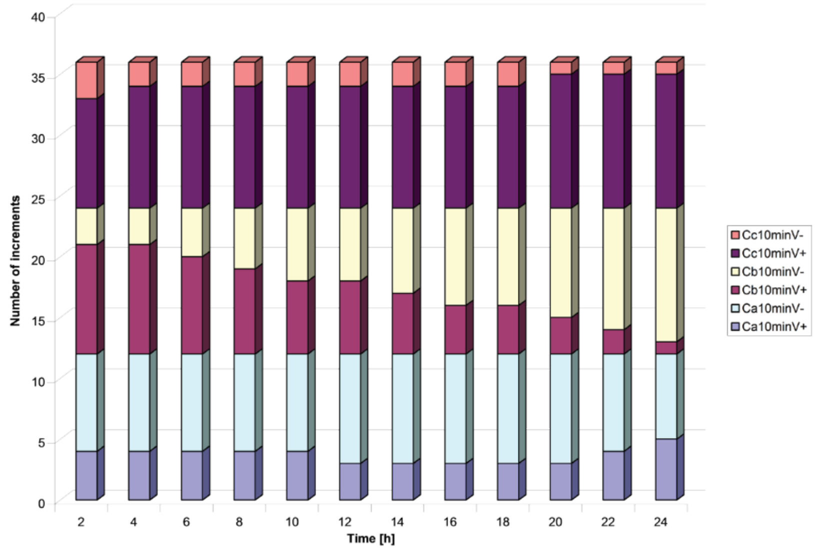

Figure 9.6 Daily distribution of 2 h cumulative phase unbalances VaUF, VbUF, and VcUF (incremental plot) [419]

If the NEMA LVUR or IEEE PVUR unbalance index are chosen to characterize the system unbalance, equation 9.15 can be written as:

$$GLVUR = LVUR \times \left(V_{ab}UF + V_{bc}UF + V_{ca}UF\right)$$

Equation 9.16

or

$$GPVUR = PVUR \times \left(V_{a}UF + V_{b}UF + V_{c}UF\right)$$

Equation 9.17

9.5 EVALUATION UNIT

Because there are more and more measuring points at transmission and distribution levels, the data gathered becomes ubiquitous and there is need for methods to further refine it. The software required to perform this process asociated with present practices is listed below:

- Software to extract data from the monitors, to further process it, and to store it in a database (e.g. analytic platform database).
- Software for manual searches in the database.

The software that supposedly will be required for future practices includes:

- Software for database management including the generation of reports, which can be periodic reports but also triggered reports (e.g. providing important information to the control room or to the planning department).
- Software based on specific algorithms to treat data in the database in order to calculate statistics.

In the future, so-called agents could continuously screen the data for specific events (like the steep change in a harmonic level) and send an alert to the user. In a second step, these agents could be furthermore developed to give assistance to the system, providing to the user not only the information related to the event, but also the possible causes and suggestions for mitigation.

Different PQ indices for the aggregation and analysis of the measured data have been proposed in the last years, in order to reduce the amount of data and also to identify sections of the network with the worst and the best PQ issues [413]. For example, in [414], [415] and [416] global PQ indices have been proposed, which are able to assess different PQ phenomena on different sites. By using other new indices, the value of unbalance can be aggregated into a single figure, for easy implementation [417] and without using the symmetrical components or alternatively concentrate on the deviation of the measured signals from the reference values [418].

9.6 CONCLUSIONS

9.6.1 Findings

The late technological developments allow the new PQ monitoring devices to sample the voltage and current waveforms at higher frequencies, analyse them faster, timestamp the events more accurately using GPS technology, save data in standardised formats (PQDIF/IEEE Std. 1159.3 and COMTRADE/ IEEE Std C37.111) and transfer data using wireless communication.

The shifting to higher frequency, up to 150 kHz, will require new types of transducers, namely new sensors, which will replace the traditional instrument transformers. The instrument transformers already in operation should be carefully characterised up to this frequency range in order to take into account systematic errors encountered during PQ monitoring campaign. These accuracy errors can be diminished by frequency calibration on voltage and current for magnitude and phase angle.

The changes in the network require a critical revision of the usefulness of existing indices, their possible update and the development of novel indices. Some examples include harmonic phase angles, indices for supraharmonic emission or unbalance. With respect to measurement methods, the optical flicker meter will become more and more important with the increasing use of energy-efficient lighting.

Regarding the continuously increasing amount of measurement data new, automatic software agents are required to extract as much as possible useful information for the system operator. The "health status" of the system should be visualized by easy-to-interpet and flexible to aggregate indices..

9.6.2 Recommendations

In future systems a balance should be found between power quality monitoring with traditional PQ analyzers and with non-traditional devices such as relays and controllers, which are used for daily network operation, and Advanced Metering Infrastructure including meters with power quality measurement capabilities. This will allow to keep PQ related investments and costs at acceptable levels.

Distortion measurements require novel and suitable sensors, especially in MV, HV and EHV networkss. This should already be considered in the planning stage of a new substation.

Standardized measurement methods as well as a set of indices are urgently needed for the frequency range of 2 to150 kHz. Due to the specific signal characteristic in this frequency range, these indices should not only consider frequency domain but also time domain and time/frequency domain.

The assessment of customer emission, which at this time uses methods based on currents, should be based on methods continuously monitoring the "true" contribution of a customer installation to the voltage quality.

9.6.3 On-going discussions

New types of disturbances, or types of disturbances occurring more often than in the past, may require additional indices (e.g. based on aggregation) in order to be properly tracked and studied. There is on the other hand a need for simplified reporting on power quality, where a small number of indices is the desired situation. A discussion is on-going within the group on this dilemma.

There might also be a need for new indices for unbalance, flicker, and voltage dips. A discussion on this subject has already started within the working group.

10. NEW MITIGATION METHODS

10.1 Introduction

In future smart grids mitigation methods will still be required to ensure Electromagnetic Compatibility. Beside well-known classical methods, also novel methods are needed in order to address the developments indicated in the previous chapters.

In general, mitigation means reducing the probability that an electromagnetic disturbance produced by a source in the network affects a customer or an equipment. Three different types of mitigation can be distinguished, which are based on:

- Reducing emissions generated by customer's installations
- Decreasing the transfer in the network
- Improving the immunity of customer's installations

Improving the performance of a customer installation with respect to emission and/or immunity (types a) and c)) can be done either with external mitigation equipment or by improving the installation itself or a component of it (e.g. EMI-filters). The later issue is discussed in detail in 2 and is not further considered in this chapter.

A strict discrimination between the types of mitigation is not always possible. Some measures may involve more than one of mitigation types aforementioned. For example, a passive harmonic filter will reduce the harmonic emission of a customer installation mainly by changing the transfer impedance.

The mitigation can be applied either to customer side (installation) or to network side. Different methods of mitigation can be distinguished and classified as follows:

- Methods requiring additional mitigation equipment:
  - Network side:
    - Additional mitigation equipment with impact on multiple customers
  - Customer side:
    - Additional mitigation equipment with impact on a single customer installation or individual components of that installation
- Methods not requiring additional mitigation equipment:
  - Network side:
    - Network modifications (e.g. feeder reconfiguration, reinforcement or splitting of the busbar)
  - Customer side:
    - Methods directly related to customer's devices

In this chapter, all mitigation methods are discussed focusing on their technical impact only. Different options with similar results can have significantly different costs. Further discussion of cost issues can be found in Chapter 11.

The chapter starts with a short review of well-established mitigation methods, which will still be used in the future. The following sections summarize new mitigation methods that might become important for future grids and discusses some of them in more detail, based on the mitigation classification criteria aforementioned.

10.2 Review of existing mitigation methods

This section provides an overview of major mitigation methods that are used today as current practices or are more frequently addressed by on-going research activities.

10.2.1 Harmonics

The harmonic mitigation methods in the power system can be divided roughly into three categories:

- Passive filtering
- Active filtering
- Converter based strategies

The passive filters can often be a cost effective solution [422] to mitigate the harmonic content. They offer a wide array of different topologies [442] and can be used in various applications. The high-speed railway in China is one good example [443]. While being relatively inexpensive and simple to design, locally installed passive filters change the impedance of the system, and thus the harmonic frequencies can move to lower frequencies [445]. These passive filters should be placed at strategic locations [446].

Various active power filters have been around since the 1960s [447], and are nowadays widely used all over the world [448]. While the technology itself has developed further into applications such as unified power quality conditioners [449] and smart impedance [450], the main research focus seems to have shifted towards implementing mitigation as a part of distributed generation (DG). Proposals that distributed generation converters could be used for harmonic mitigation when the DG is partially idle have been done in [451], [452]. As the number of electric cars increases, it might be also feasible to install active power filters at smart charging stations [453].

Converter based methods usually mitigate the emission of the harmonic content or actively mitigate the harmonic content of the network at the point of common coupling (PCC). If the harmonic issue is related to a high peak of a single harmonic introduced into the network, a random pulse width modulation (PWM) method can be used to smooth the harmonic content over a wider frequency domain [454]. If the orders of problematic harmonics are known, selective harmonic elimination (SHE) can be used. In addition to being itself a very versatile method [455], [456], it is a basis for the evolution of specialized methods including a fast, simplified method [457] and a more thorough one, which requires more calculation [458]. Converter based methods are also widely compatible with distributed generation [459].

10.2.2 Flicker

Nowadays, there is an increasing power quality concern that renewable energy sources will produce flicker, especially with the integration of wind generators to the power system. Most of the mitigation installations for reducing flicker emissions are placed at the generation end with appropriate control on converters. Overall, the mitigation methods are based on reactive power compensation and active power control.

The reactive power compensation is the most commonly accepted method, which compensates the reactive power in order to reduce the active power fluctuations and, consequently, reduces the flicker level. It can be realized by installing additional equipment such as Static VAR Compensators (SVC) based on Thyristor-Switched Capacitors (TSC) or Thyristor-controlled Reactors (TCR), Static Synchronous Compensator (STATCOM), and Dynamic Voltage Restorer (DVR) among others.

Earlier, the most widely-used method for flicker mitigation was the connection of shunt SVC based on TCR’s, but it has some disadvantages like low update control rate (two control rates per cycle); limited compensation level for voltage flicker and undesirable injection of harmonics into the system. The commonly adopted strategy is the STATCOM, which provides a faster response to such dynamic voltage changes, and FACTS, as they improve the power flow control.

It is also possible to control the reactive power, and the mitigation method can be embedded within the generator in the form of voltage control as dynamic Volt/VAR control [460], [461] or power factor control [462], [463].

Although reactive power mitigation is mostly adopted for flicker mitigation, the strategy has limitations in some distribution networks with a low grid impedance angle. In fact, [463] investigates and analyzes the impact of the possible wind generator reactive power control modes on the produced flicker levels, and proposes a frequency-selective reactive power control scheme for mitigation. Some authors have also proposed multi-objective reactive power control as a solution to that problem [464], [465]. Additionally, in [460] a two-level approach has been proposed as it combines voltage and dynamic Volt/VAR control methods.

The consequence of a reduced impedance angle is the increase in the amount of reactive power absorbed by the generator, which can exceed the rating of the machine and the power electronic converters. Therefore, active power smoothing appears as a potential flicker mitigation method by minimization of the output active power oscillations of the generators by proper machine control. Examples are shown in [466], [467], [468], [469].

Specific control systems for wind turbines have been recently proposed to reduce the high variations of generated active power, reducing consequently the flicker levels [468]. However, such techniques may have adverse economic consequences as they can reduce the generated energy.

10.2.3 Unbalance

Voltage unbalance is mainly caused by unbalanced grid components (i.e. three-phase transformers and untransposed transmission lines [470]), and unbalanced loads and generators. The impact of unbalanced loads and generators on voltage unbalance can be estimated by:

$$k_{\mathrm{U2}} = \frac{S_{\mathrm{Aun}}}{S_{\mathrm{sc}}}$$

Equation 10.1

with S_{Aun} as the unbalanced power of the device and S_{sc} as the short circuit power at connection point [470].

To reduce the voltage unbalance, the short circuit power S_{sc} has to be increased and / or the unbalanced power S_{Aun} has to be reduced. The increase of S_{sc} can be achieved by changing the network elements (replacement of overhead lines by cables, or use of transformers with higher short circuit power) or by changing the configuration of the network (feeder reconfiguration, use of parallel lines) [470], [471]. There are different mitigation strategies to reduce S_{Aun}, which can be classified in mitigation strategies deployed at network level or at the customer installation level.

***Mitigation strategies at network level**:* The unbalanced power can be reduced by balanced transformer couplings e. g. [472], [473]. This method has been used for a long time by DSOs and it is one of the most common methods to reduce the impact on unbalance for railway systems. Another method consists of coordinated (passive/dynamic) switching of unbalanced customers / generators, which is applied by the DSOs and in railway systems to avoid the unbalanced power caused by high power loads or distributed generators [474], [475], [263], [476]. Other alternatives include the use of STATCOM to eliminate the voltage unbalance of the upstream grid and reduce the unbalanced power [477]. With the technology of modular grids, which are formed by two converters instead of a transformer, it is also possible to eliminate the transfer of voltage unbalance and unbalanced power between different grids. Proper transposing of transmission lines can reduce the additional impact on unbalance caused by the network itself.

***Mitigation strategies at installation level**:* A common method consists of the reduction of maximum operating power of devices with high power consumption and a long operation period [263]. The unbalance power at the network level can be reduced with active power filters (APF) [478]. If devices with almost constant impedance are connected to the grid, it is possible to use reactive loads to balance the power. This effect is known as "Steinmetz law". An alternative way is the switching of additional DVR [479], which works like an online UPS (Uninterruptible Power Supply) system with self-commutating inverters [480]. The same idea is used to mitigate voltage unbalance with distributed generators [481], [482] or storage systems with three single-phase inverters [483]. It is also possible to use the STATCOM method at installation level with distribution STATCOM (DSTATCOM).

10.2.4 Voltage dips

The primary concern with voltage dips is the high costs due to industrial production stoppage. Voltage-dip mitigation aims at breaking the link between the fault (or another origin of the dip) and those high costs. Figure 10.1 shows both that link (left) and methods for breaking that link (right).

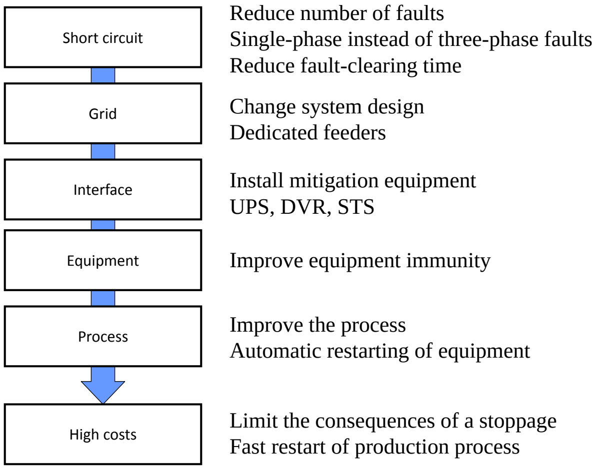

Figure 10.1. The link between a fault and high costs due to a dip (left); mitigation methods aimed at reducing or avoiding those costs (right)

The mitigation methods for voltage dips can, somewhat simplified, be divided into network oriented (reducing the frequency and/or severity of dips), and equipment oriented (reducing the effects of existing events). A comprehensive overview of the methods and literature [91], [484], [485] can be summarized as:

- Network oriented methods:
  - Replacing overhead lines with cables
  - Using covered wires for overhead lines
  - Increasing maintenance activities
  - Increasing insulation levels
  - Installing additional shielding wires
  - Reducing the fault clearing times (via protection settings or current limiting fuses)
  - Installing generators near the loads
  - Restructuring the supply pathways
  - Using current limiting coils [486], [487].
- Load oriented methods:
  - Uninterruptable power supplies (AC-DC-AC converters
  - Flywheels
  - Motor-generator sets
  - Dynamic voltage restorers (shunt or series)
  - Equipment with higher immunity levels [488],, [489], [490], [491], [492], [493], [494].

Some of these developments may have a significant impact on the network or the cost. For example, large-scale replacement of overhead lines with cables will reduce the number of faults. The impact of this will be bigger in systems with solidly-earthed medium-voltage systems than in impedance-earthed systems. Moreover, the increased share of distributed generation will result in operational states with a weaker transmission grid and a stronger distribution grid.

10.3 Summary of mitigation methods

Table 10.1 provides an overview of mitigation methods, which has been identified by the working group to be important or to become important in the future. The following abbreviations are used:

- Type:
  - E – Reduction of Emission
  - T – Reduction of Transfer
  - I – Increase of Immunity
- Application:
  - N – Network Side
  - I – Installation Side
- Method:

  - A – Additional Equipment
  - W – Without Additional Equipment
- Voltage level:
  - LV – Low Voltage
  - MV – Medium Voltage
  - HV – High Voltage
  - EHV – Extra High Voltage

The following power quality phenomena are considered:

- Harmonics (below 2 kHz)
- Interharmonics (below 2 kHz)
- Supraharmonics (above 2 kHz)
- Unbalance
- Flicker
- RMS-voltage (supply voltage magnitude)
- Dips
- Swells
- (Short) Interruptions
- Commutation Notches

If the considered mitigation method does not affect a power quality phenomenon at all, this phenomenon is not listed. Each phenomenon, for which an impact is expected, is listed separately and the expected effect is indicated by the following notation:

- + (intentional) positive impact
- - (non-intentional) negative impact
- ?+ positive impact possible, but depends on specific conditions
- ?- negative impact possible, but depends on specific conditions
- ? impact is expected, but cannot be qualified (e.g. due to lack of research)

Table 10.1 Overview of new mitigation methods

Mitigation method	Type Application Method	Voltage level	Effect
Active waveform conditioning by converter-based installations	E_I_W	LV/MV	Harmonics: + Unbalance: + Flicker: + Supraharmonics: -
Active waveform conditioning by dedicated, separate devices	E_I/N_A	LV to HV	Harmonics: + Unbalance: + Flicker: + Supraharmonics: -
Phase management for single phase equipment (EV charger, small PV inverter)	E_I_W	LV	Unbalance: +
Feeder reconfiguration	T_N_W	LV/MV	Harmonics: ?+/?- RMS voltage + Unbalance +
UPS system at installation level (inverter-based, flywheel-based, cap-based)	I_I_A	LV	Harmonics: ? Interharmonics: ? Supraharmonics: ? Unbalance: ? RMS-voltage: + Dips: + Swells: + Interruptions: +
Replacement of line-commutating by self-commutating topologies	E/I_I_W	LV to EHV	Harmonics: + Interharmonics: - Supraharmonics: -

			Dips: +
Voltage regulated distribution transformers	T_N_A	LV	RMS-voltage: + Flicker: - Dips: ?
SVG(static var generation)/DSTATCOM(Distribution Static Synchronous compensator)	E_N_A	LV to HV	RMS voltage + Harmonics: + Unbalance: + Flicker: + Supraharmonics: -
Passive harmonic filters	E_N/I_A	LV to EHV	Harmonics: +
Synchronous compensators (increasing short-circuit power, inertia, …)	T_N_A	LV/MV	Harmonics: + Unbalance: + Flicker: +

10.4 Description of mitigation methods

10.4.1 Active waveform conditioning

Active waveform conditioning devices are electronic devices that behave as a controlled current or voltage source that can compensate for harmonics, sags, swells, flicker, unbalance, and other power quality problems depending on their design. Examples of such devices are the shunt or series active power filters and the unified quality conditioner.

Modern inverter technologies can also be used for active waveform conditioning. As discussed in 2, modern inverter technologies are able to flexibly control their current waveforms. Beside their main functionality of supplying variable power to a load or injecting power of renewable sources into the grid, they are also a potential source for mitigation of different types of power quality disturbances, like harmonics or unbalance (in the case of three-phase inverters). As inverters are in place anyway, no extra equipment is required.

There are some possible issues that are still under discussion related to the use of these devices like: the possible impact on harmonic stability, the limited dynamic due to the speed of the control (only low order harmonics can be mitigated), and the required increase of the power rating of the inverters. Responsibility/legal issues can arise, especially in the case when the inverters are owned by customers. In this case, the DSO, who is in charge of the voltage quality in the network, relies on the customers in order to achieve this.

10.4.2 Phase management for single phase equipment

Phase management is the coordinated connection of new single phase equipment in order to balance the active power on the three phases. For example, new single-phase PV-systems should be connected to the phase that has the highest loading. The same applies for electric vehicles, but in this case the number of single phase charging boxes should be the same on all three phases. In case a charging station provides three-phase charging sockets, it has to be ensured that single-phase charging electric vehicles are equally distributed to the three phases (e.g. by circulating the allocation of the three phases of the socket to the three phases of the grid).It is important to check that the devices are equally connected on the three phases along the feeder.

Another method consists in select the connection phase of the new equipment according to the impact on the negative sequence voltage. If the characteristics of the network are known (symmetrical components of voltages, impedances and currents), then the impact of the connection of new equipment on the negative-sequence voltage can be evaluated, and the phase angle of the negative-sequence current can be influenced with the selection of the connection phase in such a way that negative-sequence voltage is minimized.

10.4.3 Feeder reconfiguration

Automatic feeder reconfiguration is achievable using several switches and additional measurement equipment which can connect feeders into meshed configurations, taking into account the network losses, balance of phases, and voltages at different nodes in the networks. The main idea is to have different configuration possibilities (not a single permanent mesh), which can be chosen based on the current loading/generation conditions.

The strong point of this approach is that it does not require any complex electronic devices (with lower reliability). However, complex protection systems are needed for those changing networks. Moreover, additional switching equipment requires more maintenance in the network than in radially operated networks.

10.4.4 UPS system at installation level

Uninterruptible power supplies (UPS) are widely used to supply devices that require a power quality superior to that offered by the traditional power supplies. The main components of the UPS are a PE converter, energy storage, and a fast switch. The duration of the operation of the UPS depends on the size of the energy storage and may be relatively short. However, it should be sufficient to start a standby power source or to transfer to a redundant power supply.

The UPS are available for a broad range of power, from a few hundred watts to several megawatts, to meet the availability and power quality requirements for a wide variety of loads. For example, the UPS are used to protect computers, data centers, telecommunication equipment, and other electrical equipment where an unexpected power interruption could cause damages, deaths, severe business disruptions, or loss of data. The UPS vary in size from units designed to protect a single computer without a monitor to large units powering data centers or entire buildings. A challenge of low power UPS units are the costs for maintenance due to the large number of UPS required for larger facilities.

High power loads such as paper industries, steel mills, and oil and gas processes require a high power UPS. While the cost for low-power UPS systems is appealing, opportunities are limited for medium voltage systems and high power UPS. Considering that the main elements, which form the high power UPS, have reached a high level of maturity and the reduction of costs of the Li-ion batteries, this may result in increased use of the high power UPS.

10.4.5 Replacement of line-commutating by self-commutating topologies

Self-commutating topologies shape the input current of a device to resemble the waveform of the sinusoidal line voltage by means of high frequency (HF) switching of a boost DC-DC converter. This will result in a high reduction of the harmonic emission and an improvement of the power factor. Nevertheless, there is a certain level of current distortion inherent for all active PFC circuits that involve zero-crossing distortion and non-sinusoidal shaping of the current waveform. It can be claimed that the control system of self-commutating circuits defines on its complete current harmonic spectrum.

10.4.6 Voltage Regulated Distribution transformers

Depending on network topology the hosting capacity of LV networks for PV installations can also be increased by introducing voltage regulated MV/LV distribution transformers, which are usually only used at higher voltage levels. The voltage control can be realized by on-load tap changers (OLTC) or electronic switches. Depending on the implementation, this type of distribution transformer can cause rapid voltage changes of different magnitude and can be, depending on the frequency of the switching, a potential source of flicker.

10.4.7 SVG(static var generation)/DSTATCOM(Distribution Static Synchronous compensator)

SVG/DSTATCOM devices are static devices which can produce and consume reactive power in the system and perform additional tasks such as active filtering, reduction of flicker, balancing of phases, and in some cases dynamic voltage restoration. They can cover a wide range of power quality problems without changing the network harmonic resonances. However, their complex electronic devices require additional maintenance in the system. Other possible issues are the increase in supraharmonic levels and the possible instable operation caused by the interference from several electronic devices.

10.4.8 Passive harmonic filters

Passive harmonic filters are well established for harmonic mitigation at this time. It is expected that they will still play an important role in future networks. Particularly, if higher frequency components (supraharmonics) need to be mitigated, passive filters will probably be the most efficient way.

10.4.9 Synchronous Compensator

Traditional synchronous generators are replaced by renewable energy sources connected to the grid by power electronic converters. In this process, the grid has lost its short-circuit capacity. The short-circuit capacity can be considered as the ability of the system to withstand the voltage variation due to the disturbances and harmonics that are generated. The synchronous generators by their nature naturally support the voltage and thus reduce voltage dips and swells, reduce the negative-sequence, and absorb low frequency harmonics generated by loads [495]. Synchronous compensators are considered as an attractive technology when combined problems concerning inertia and lack of short circuit power [496] need to be dealt with. One example is the installation of synchronous compensators in Denmark to support the grid after the installation of large windfarms [497]. The harmonic impedance of the synchronous compensator, which in a first approximation can be seen as a simple inductance for the harmonics, helps in reducing the grid impedance envelops in the R-X plane [498] to avoid severe resonances in combination of low tuned filters or capacitor banks.

The need of introducing devices such as synchronous compensators to support the grid will depend on the ability of the renewable source converters to fulfill the requirements at the PCC and will be related to different factors:

- The degree of requirements of the specific grid code
- The strength of the grid, and technology
- Improvements of the converter technology

Nowadays, many grid codes are requesting fast reactive current injection and reactive power support which can be realized by additional devices (STATCOM, Synchronous compensator) or to be integrated into the VRES converter. The requirements on low voltage ride through are evolving in the way as described in the Requirement for Generators of the EU regulation [499] to be applied in a neutral way for any power plants. The neutrality of the technologies from the technical performance aspect is not only the adopted definition in European Union requirement but the general trend worldwide because it is now considered that the VRES technologies have attained the maturity to meet the same technical requirements as traditional plants based on synchronous generators.

10.5 CONCLUSION

10.5.1 Findings

Mitigating one PQ phenomenon can often increase one or more others. Therefore, when trying to optimize a situation "the overall impact" should be taken into account. For example, to reduce low order harmonic emissions and to improve energy efficiency, more and more electronic devices use circuit topologies operating at higher switching frequencies. This development shifts emissions from low frequencies to higher frequencies (supraharmonics) and consequently the positive impact on "traditional" harmonics is accompanied by a negative impact on supraharmonics.

Any active frontend is able to be used for power quality improvement (e.g. active harmonic filtering by PV inverters). Besides positive aspects, such approaches may also raise some concerns, like legal issues, if the mitigation equipment is owned by customers and the DSO has to rely on its proper function. Furthermore, the robustness of the LV grid might be reduced by an increasing number of controls (e.g. by control interactions). Mitigation measures usually have positive and negative aspects. Both have to be considered carefully in a holistic way keeping the whole system in mind.

Often more than one solution exists for mitigating a specific power quality disturbance. For example, the proper allocation of single-phase equipment (e.g. EV and PV inverters) to each phase in a three-phase-system can reduce their impact on unbalance without the need for additional mitigation equipment, like an active filter. A decision for one particular option should include the following considerations: technical merit, robustness, simplicity, and costs.

10.5.2 Recommendations

Mitigation can be based on additional equipment (increase of immunity or reduction of emissions) or on grid modifications (reduction of transfer impedance for the interference phenomena). The additional equipment can be located either central, which affects multiple customers, or distributed (usually as part of a customer installation), which affects only a single customer installation or just a part of it. A certain overlap exists between grid modifications and additional equipment. For example, centrally placed harmonic filters will also affect the transfer impedance. The increase of equipment immunity can be done with mitigation devices or by improving the robustness of the equipment itself (e.g. EMI-filters or change of circuit topology).

Based on the EMC concept certain disturbance levels are acceptable in the network and mitigation should only be considered, if the probability of exceeding the limits is high or if any interferences occur. It should be mitigated only as much as required instead of as much as possible.

It is important to note that each mitigation method has positive and negative aspects. These should be carefully considered before implementing any mitigation.

New mitigation methods based on novel equipment topologies utilizing software controls, like PV inverters or EV chargers, as well as the combination of mitigations for different disturbing phenomena (e.g. harmonics and unbalance) into single devices are expected to become more common in the future.

10.5.3 Open issues

It is expected that traditional mitigation methods will still exist in the future. However, up to which extent is not fully clear. How they might adversely impact the stability of the network is also not clear.

The expected increase of mitigation based on novel equipment topologies utilizing internal software controls might adversely impact the overall stability in distribution networks, particular in the case of islanding. At present, the significance of this issue is unknown and further studies are still required.

Presently, there is also some discussion, if mitigation might be provided as a customer service. On one hand, this could enable a change of the actual concept of allocating customer contributions. On the other hand, it would require clear regulations in order to allow the DSO the needed control of the mitigation level. Before the introduction of a such service, further elaboration of the concept is required.

11. ECONOMIC ISSUES FOR POWER QUALITY

11.1 INCREASED COSTS DUE TO POWER QUALITY

As part of the transition to a sustainable society, large changes are expected in the type and amount of equipment connected to the electricity distribution network. Some examples are energy-efficient lighting and consumer electronics, photovoltaic panels (PV), electric vehicles (EV), and electric heat pumps. Some of the transitions have progressed further than others and the progress also varies strongly between countries.

Larger ranges of supply voltage variations will result from PV and EV. Energy-efficient lighting and consumer electronics will give fewer variations. When electric heat pumps replace resistive heating, the variations will in general become less. When electric heat pumps replace heating based on oil or gas they will give more variations in supply voltage. The latter could become the situation relatively soon in several European countries (Germany and UK might become the leading ones here) where the surplus of energy from wind and sun could be used for heating.

Most of the new equipment connected to the grid is associated with power-electronic converters. Such converters are known to emit harmonic currents. Although it is far from obvious that the harmonic voltage distortion will increase with increasing numbers of such converters, such an increase may occur and it should be considered in the future planning of distribution networks.

There are current trends and expected trends towards a bigger involvement of small network users in the electricity market and in the balancing of the system. The consumption and production in the distribution level will in that case be partly under the control of surpluses or shortages at transmission level. This may further increase the range of supply voltage variations in the distribution grid.

Related developments discussed under the names "microgrids", "virtual power plant" or "battery storage" may result in a wider range of supply voltage variations as well. They offer however also the possibility to reduce the range of supply voltage variations.

11.2 DIFFERENT SOLUTIONS

There are different solutions to avoid unacceptable supply voltage or unacceptable levels of voltage or current distortion. A general subdivision of solutions is as follows:

- Strengthening the distribution network through additional lines, cables and transformers.
- Setting requirements on equipment connected to the grid, for example: voltage-control requirements on solar panels and strict harmonic emission limits for PV installations.
- Curtailment of equipment by the network operator when voltage is outside of its acceptable range or when harmonic voltages exceed their limit.
- Market-based solutions in which a price is set on a network user's contribution to overvoltage, undervoltage or harmonic voltage distortion.

The introduction of a market for supply-voltage variations (or other smart-grid solutions) will allow more equipment to be connected to the grid without strengthening the grid (i.e. the fault level will remain about the same). As most equipment will contain a power-electronic converter, there is a serious risk that harmonic levels will increase.

One of the concerns, with both supply voltage variations and harmonics, is that there is large uncertainty in the type and amount of equipment that will be connected as well as in its variations with time and aggregation effects. The design of distribution networks is based on worst case situations, which may never be reached or occur very rarely. Market-based solutions are, several of which are part of what is referred to as smart grids, are more cost-effective that designing for the worst-case situation and/or treating all customers equals. As the customers themselves can make the trade-off between paying a high price for electricity or letting the temperature in the home drop by a few degrees, the societal costs are expected to be lower. Such market-based principles are not being discussed yet for power quality, but discussions on this for reliability have started 10 to 15 years ago under the term "custom power" and more recently under the term "microgrids".

It is expected that in the not too far future most of the larger equipment connectd to the grid, and even large amounts of small equipment, will contain control possibilities and a communication link with the outside world. The additional investments in hardware needed to make such equipment participate in the market mechanism is therefore expected to be limited.

11.3 COST SHARING BETWEEN STAKEHOLDERS

The costs due to increased risk of interference is carried by different stakeholders, depending on whether the risk materializes or whether the expected risk results in changes in EMC standards

- Investments are needed in the grid. This could because of changes in or additions to the compatibility levels or otherwise changes in requirements placed on voltage quality by standardization or regulations. The costs for this will initially be carried by the network operator. Based on the regulatory scheme those costs may be partly or completely recovered through the tariffs.
- Investment in the grid may also be needed because of increased emission or because of changes in the grid resulting in higher voltage-disturbance levels. Also in that case the costs will initially be covered by the network operator with the possibility to recover them through the tariffs.
- Emission standards are made stricter. This will increase the costs for the manufacturers of equipment that otherwise would exceed those limits. Costs may also increase when more or more costly testing is needed. These costs may partly of completely be recovered through price increases.
- More strict requirements are placed on customers through the connection agreements in the grid codes. This will make it more expensive to connect electrical installations to the grid. It will likely also result in some increase of costs for the network operator because studies are likely needed to assess the need for such limits. Also the costs for enforcement of the limits will be carried by the network operator.
- Immunity limits are made stricter. The economics of this will be similar to the economic impact of more strict emission standards.
- The expected risk of higher probability of interference materializes. This will have economic impacts on the customers whose equipment or installation is insufficiently immune. Those customers will be the one that carry those costs.

11.4 MARKET MECHANISMS

In the electricity market environment, it is also important to develop a market mechanism to limit voltage variations and harmonic emissions, and to setup proper market mechanisms. The market mechanism should be well-designed to fairly represent the cost of maintaining power quality, as well as the values of pollution absorptions at different locations.

Market mechanisms might not be the only solution for the future grid. But there are several advantages for market-based solutions. Using market mechanisms could significantly reduce the need for investment in the distribution network, without risking unacceptable levels of voltage quality. Instead there is typically small economic risk for one or more stakeholders. The distribution of this risk over the stakeholders depends on the market structure.

An investigation of the possibilities and limitations of power quality markets is of significance for the power industry.

A proper market mechanism [500], [501] for power quality could provide incentives or penalties for the market players to reduce the harmonic voltage distortion levels [502], the current unbalance [503], etc.. It could also encourage distribution companies to invest in devices to mitigate power quality pollutions. The proposed power quality market could be categorized as a service market in deregulated environment.

Market mechanisms can form the basis for control and communication involving photo-voltaics, electric vehicles and electric heating, storage installations and customers. Such market mechanism can also form the basis for future regulation on voltage quality and act as a base for future network markets.

11.5 CONCLUSION

11.5.1 Findings

To have a sustainable society, a large amount of equipment with DC technologies and power electronic converters are connected to the grid. They are known for emitting harmonic currents. To solve the problem, either the power grid is strengthened, or power quality requirements are set to the system. Another solution is to use market mechanisms to limit the power quality impacts caused by these devices.

11.5.2 Recommendations

It is recommended to use market mechanisms for limiting voltage variations and harmonic distortions in the grid. This might not be the only solution, however, it is possible to save the investment to strengthen the grid without risking unacceptable power quality issues. Well-designed market mechanisms can distribute the economic risks to more stakeholders. This economic method can be considered at the distribution planning level.

11.5.3 Open Issues

More and more devices using power electronic converters are connected to the grid. They emit more harmonic currents and result in voltage variations than business as usual. Besides traditional solutions like strengthen the grid and setup strict requirements, market mechanism is another option to limit voltage variations and harmonic emissions, which are included as economic means at the distribution planning stage. Whether the limiting of emissions are effective would depend on the design of the market mechanisms.

12. CONCLUSION

Each chapter of this TB comes with its own conclusions presented in a format:

- Findings
- Recommandations
- Open issues

And therefore no separate "Conclusion" chapter is written.

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APPENDIX A. EXAMPLES OF WAVEFORMS AND SPECTRUMS FOR PV

This section contains the examples of current waveforms and spectrums of four commercially available household PV inverters (inverters A - D). The examples are given at full power and 50 % of the full power of the inverter, and are showing that for different manufacturers (topologies and control algorithms) and operating conditions the spectrum of the emission cannot be generalised for PV inverters. In the figures with the spectrum, the components are displayed as relative to the fundamental, which is omitted from the graphs. It should be noted also that two of the presented PV inverters (B and D) no longer comply to the emission requirements of some countries, but such inverters can still be found in use (and might be sold in some countries as well).

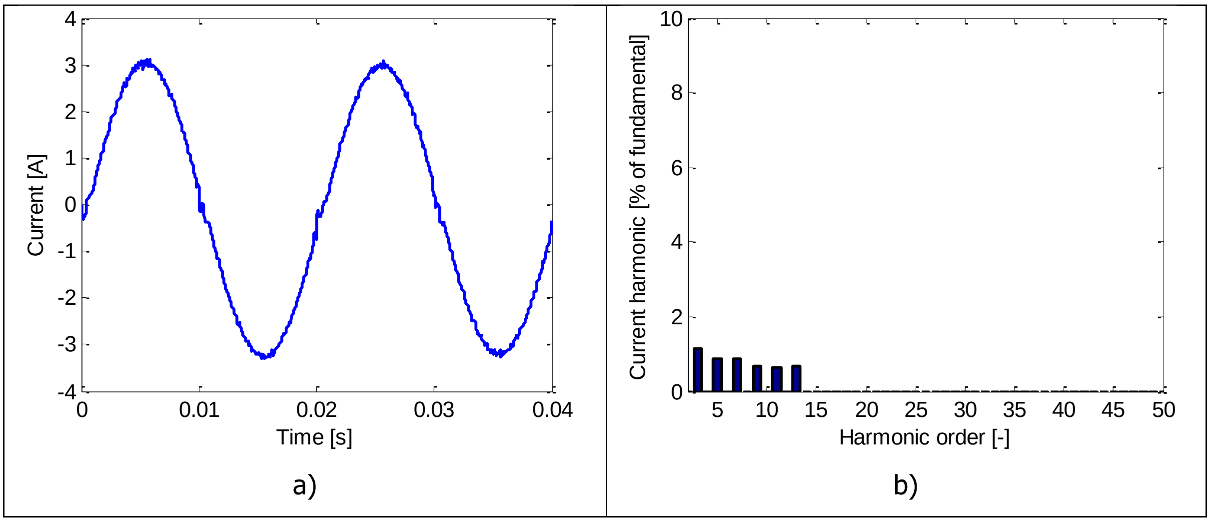

Figure 13.1 Inverter A at 50 % of nominal power: (a) current waveform, (b) current spectrum

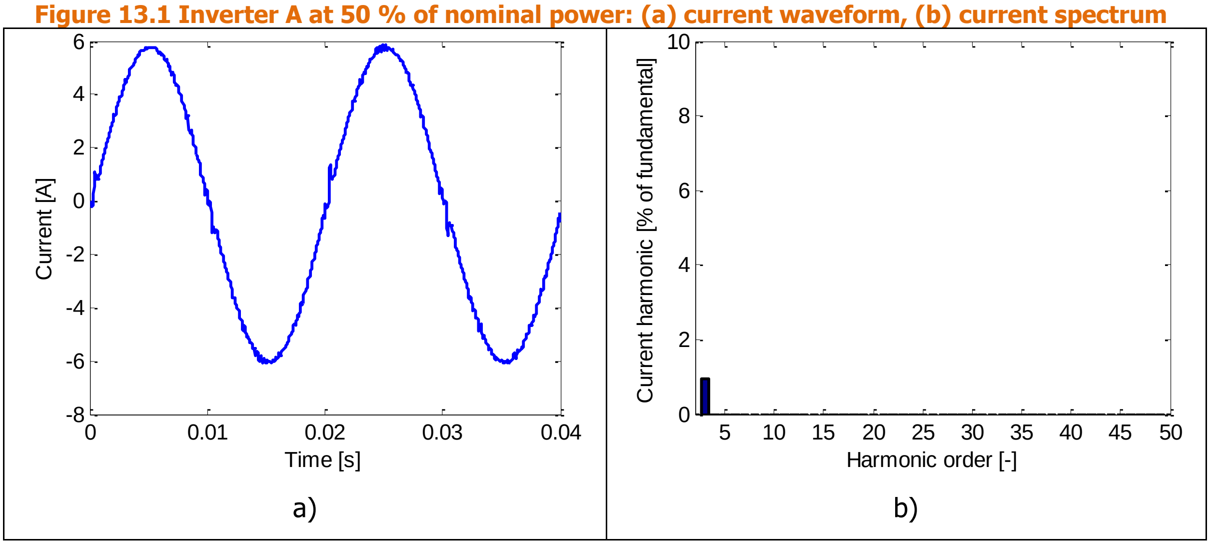

Figure 13.2 Inverter A at nominal power: (a) current waveform, (b) urrent spectrum

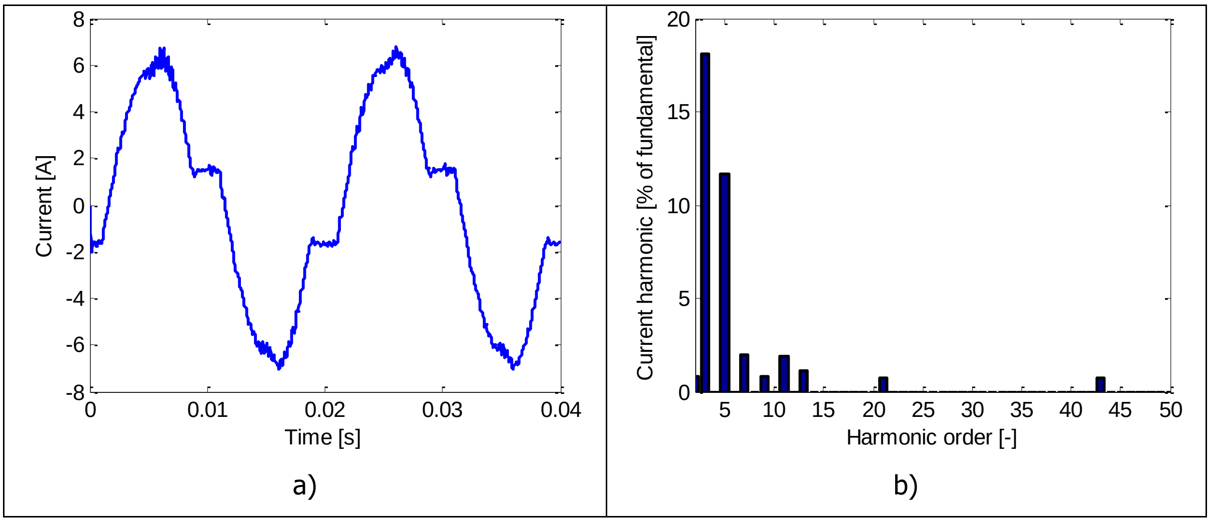

Figure 13.3 Inverter B at 50 % of nominal power: (a) current waveform, (b) current spectrum

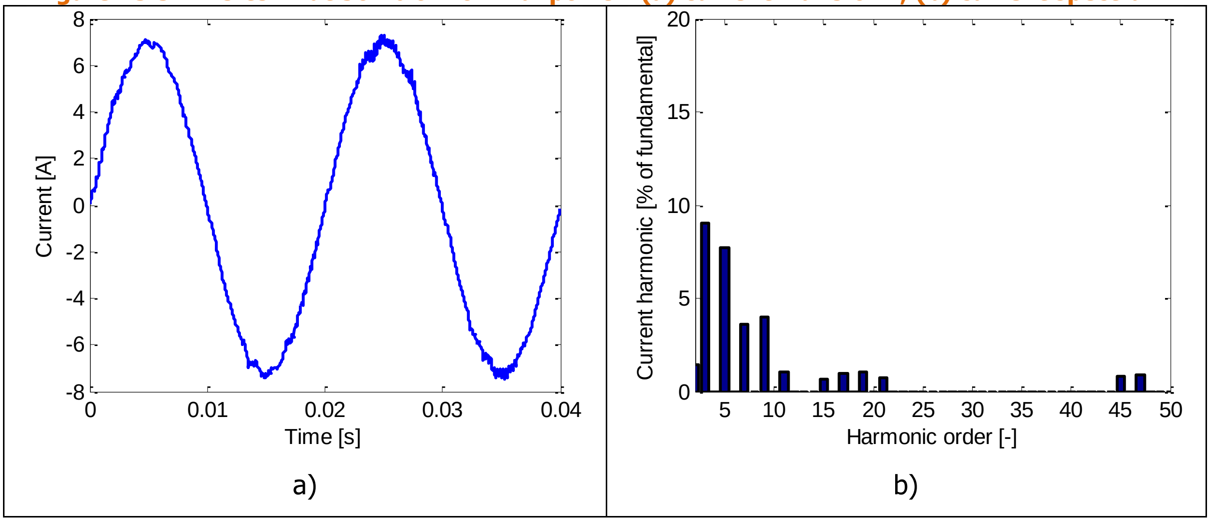

Figure 13.4 Inverter B at nominal power: (a) current waveform, (b) current spectrum

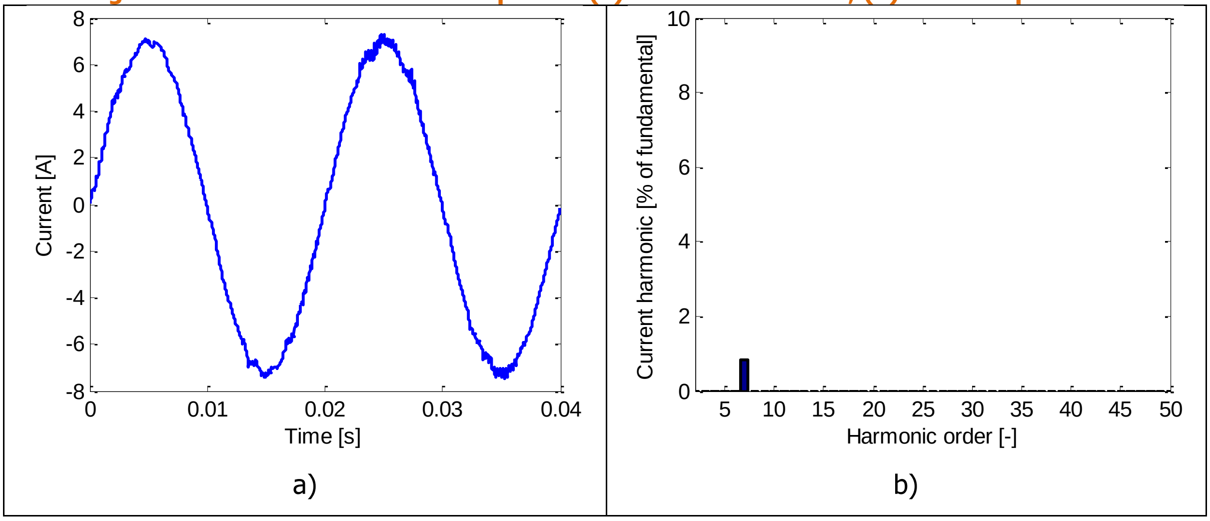

Figure 13.5 Inverter C at 50 % of nominal power: (a) current waveform, (b) spectrum of the current

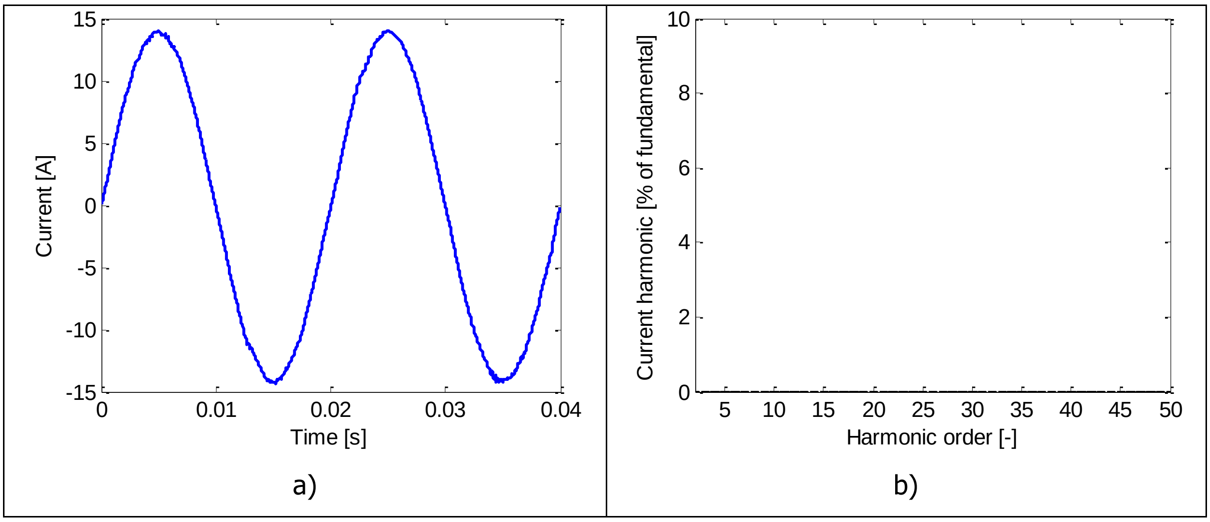

Figure 13.6 Inverter C at nominal power: (a) current waveform, (b) current spectrum

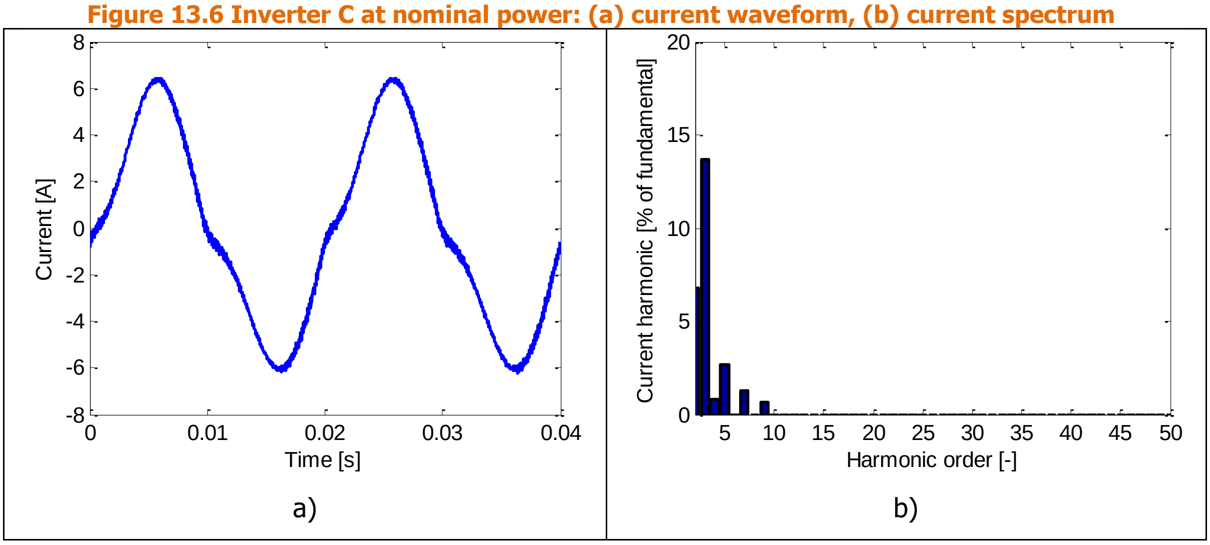

Figure 13.7: Inverter D at 50 % of nominal power: (a) current waveform, (b) current spectrum

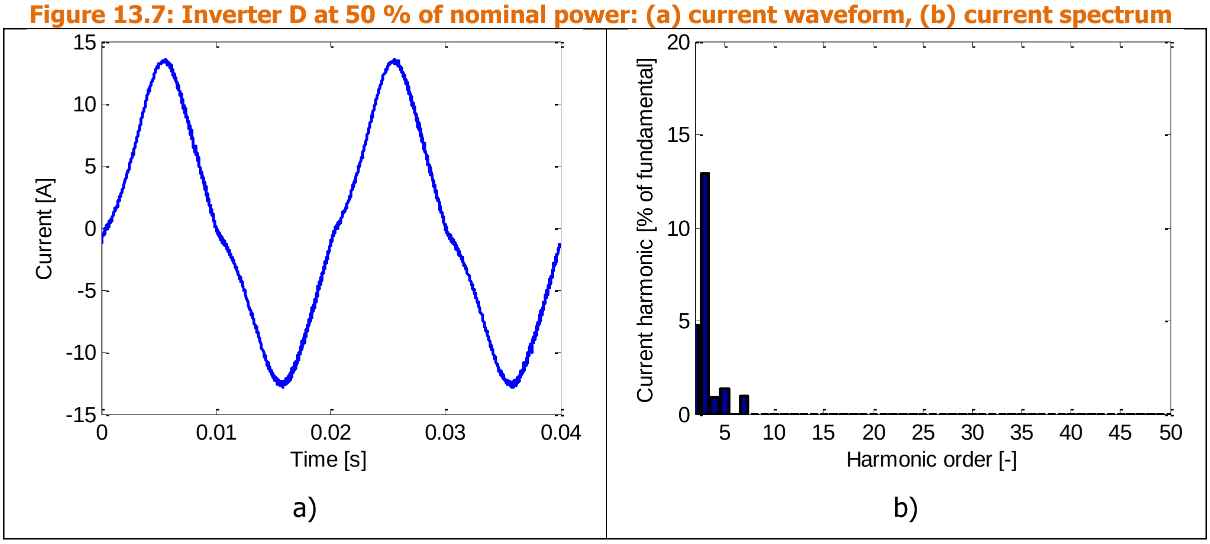

Figure 13.8 Inverter D at nominal power: (a) current waveform, (b) current spectrum

APPENDIX B. HARMONIC IMPEDANCE OF PV INVERTERS

In [504], [505] the equivalent harmonic impedance of PV inverters was measured, based on voltage excitations with the 50 Hz signal and additional frequencies, with a setup shown in Figure 13.9. The equivalent impedance of the inverter is then calculated based on the voltage excitation and the corresponding current response.

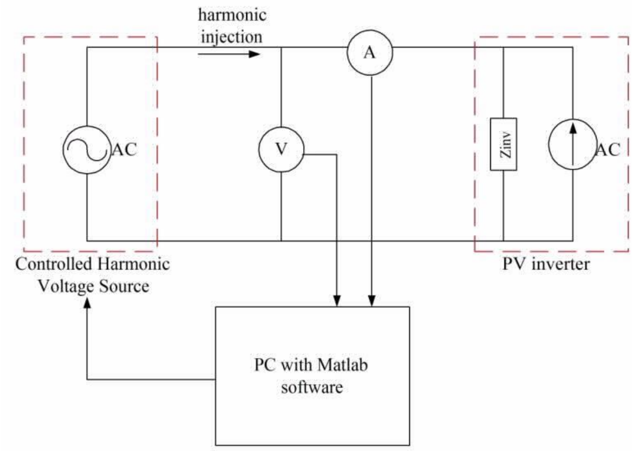

Figure 13.9 Schematic diagram of the experiment

The experiment is done on 5 commercial PV inverters: four single phase inverters, out of which one is a storage inverter, and one three phase inverter. More details on the harmonic modeling of PV inverters and the sensitivity of the model to different parameters can be found in [506].

Their equivalent shunt impedances of tested small-power single-phase inverters are shown in Figure 13.10. The calculated equivalent capacitance was ranging between 3.7 and 18.5 μF. Their frequency responses are given in Figure 13.11.

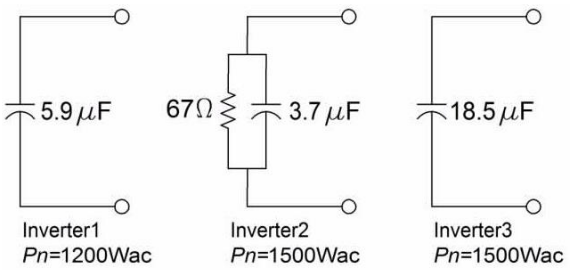

Figure 13.10: The impedance models of small-power single-phase PV inverters [13]

Looking at the similarity between the small-power single-phase inverters output impedances, a simple general model for 0-2 kW power class can be deduced. It is a single capacitor with values ranging between 4.8-18.5 μF. Typical values of output capacitor of commercial 1-3kW PV inverters are between 0.5-10 μF, as reported in [13]. A single capacitance value cannot represent every inverter but using several values from the range in a frequency scan gives a good idea of the influence of inverters on the network impedance. The applicability of these results is however limited due to the limited number of inverters which were tested. One general remark is that capacitance dominates in the response of the inverter. One reason for this is the fact that a filter with a larger capacitance and lower inductance requires less space. This makes it probably a preferred choice for the manufacturers, even though a filter with a higher inductance would be more beneficial for a reduced interaction with voltage harmonics present in the network.

The influence of capacitive filters in PV inverters on the resonant frequency in LV networks is analyzed in based on computer simulations. In a network with a high share of household PV generation the frequency dependent impedance is analyzed at the LV busbar of the MV/LV transformer, when the PV inverters are represented only as a capacitor. In these conditions, the assumed capacitance value has a very significant influence on the resulting network impedance. In Figure 13.12, the results of the frequency scan are shown with assumed capacitances of 2 and 8 μF per inverter, and also with a variation of ±20 % of the 8 μF. The sensitivity due to element tolerances (in this case 20 % was used as an exaggerated tolerance) did not influence the results greatly. However, the assumption of capacitance of the filter, if not know from the manufacturer, has a very significant influence.

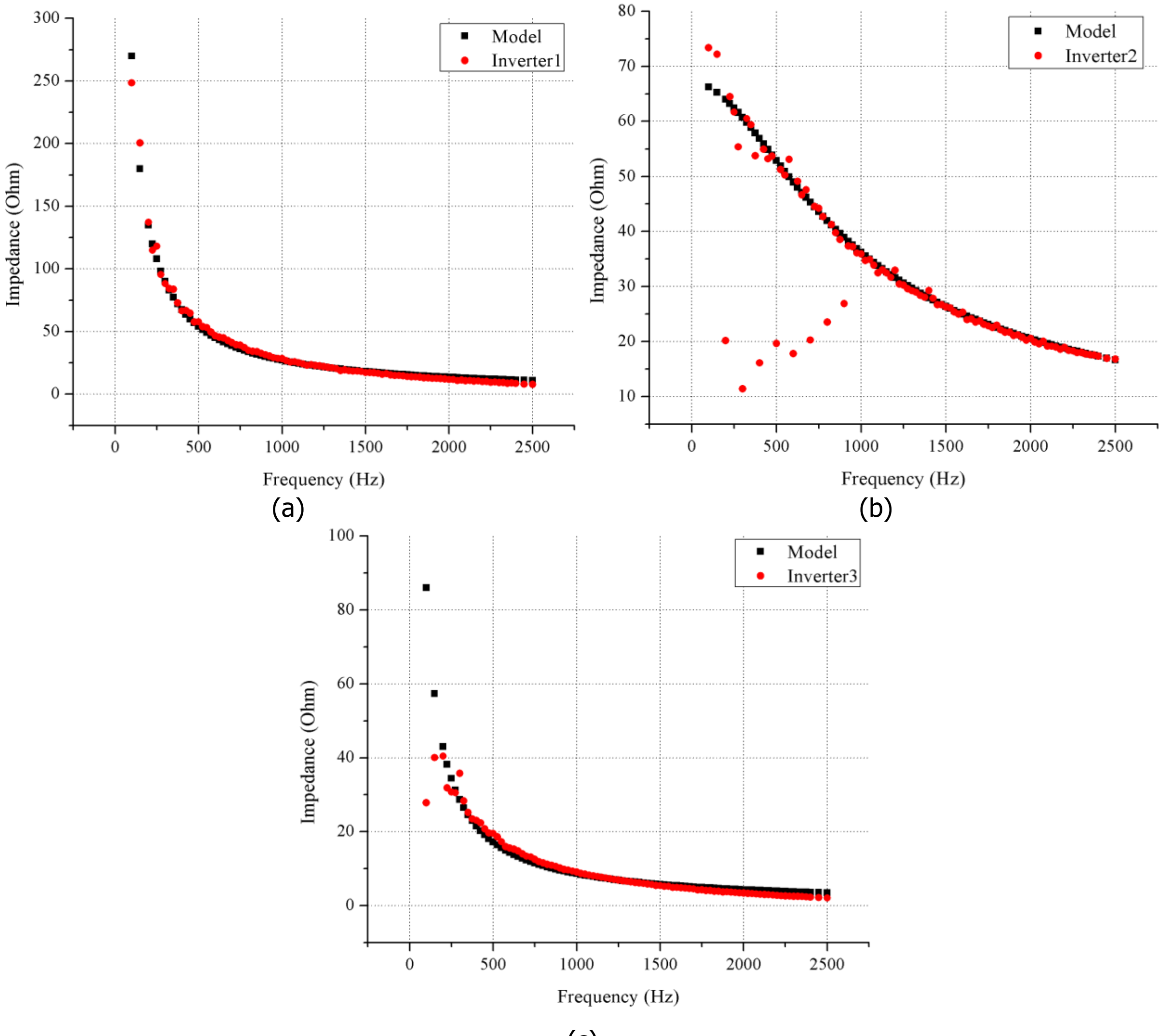

Figure 13.11: Frequency responses of tested single-phase inverters: (a) Inverter1, (b) Inverter2, (c) Inverter3

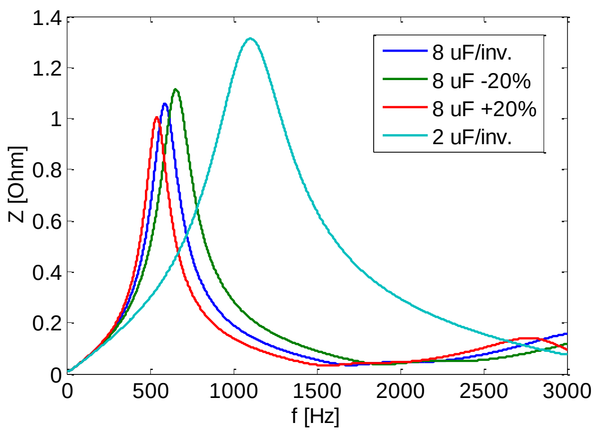

Figure 13.12: The effect of PV inverters capacitance on system impedance, based on computer simulations

APPENDIX C. ANALYSIS OF HYBRID DC/AC MICROGRIDS

Analysis of hybrid DC/AC microgrids in case of AC faults is conducted in [332]. The behaviour of the various energy sources in the DC grid supplying the local demand is analysed within the paper.

In a 4 wire three phase AC/DC low voltage microgrid, a three phase to ground fault occurs in the AC grid, and the AC voltages in this case study are illustrated in Figure 13.13 [332].

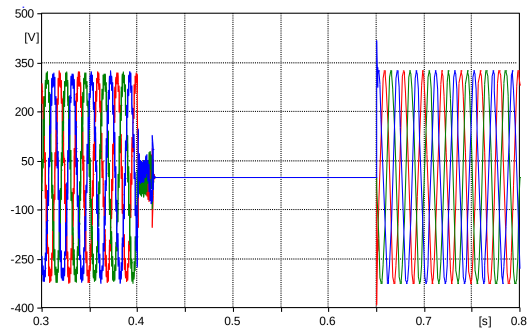

Figure 13.13 Voltages upstream the AC/DC interface converters during a three phase fault in the MV system

The DC voltage, maintained before the fault by the AC/DC interface converter at the nominal value, decreases, and the storage energy system will supply the load demand. In case of a sustained interruption, for avoiding the complete discharge of the battery, a Diesel power system can be used to supply the load. As shown in Figure 13.14(a), the red line represents the DC voltage sustained by the storage unit, while the green line represents the DC voltage sustained by the Diesel engine. When the Diesel group starts injecting power into the DC power system, the voltage regulator of the storage energy system will sense a load reduction and initiates decreasing the current flowing through the battery chopper inductor (see Figure 13.14(b)).

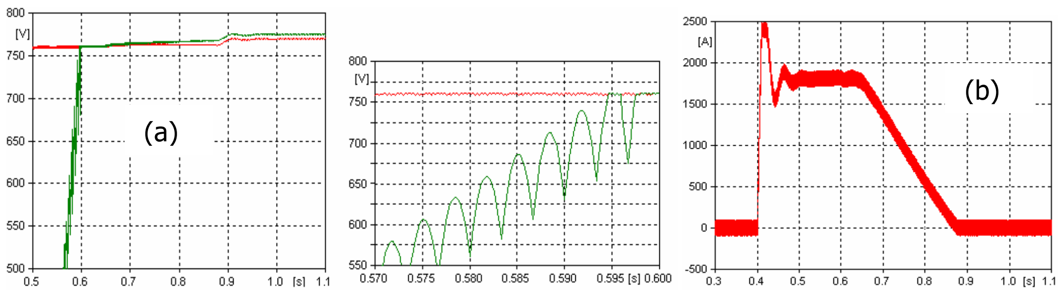

Figure 13.14: (a)Transition between battery and Diesel system, (b) current flowing through battery chopper inductor

The DC faults represents an importance challenge in DC grids due to the absence of periodic current zero-crossings. The interruption of direct current by mechanical separation can be achieved al low voltage level.

In the last years, the technological development of electronic methods of breaking DC current was achieved, available from few Amps to thousands of Amps at 500-600 Vdc. The protection of DC microgrids is analyzed in detail in [331]. When a DC line to ground fault occurs, the DC voltage is suddenly decreasing and the AC/DC interface converter cannot control the drawn current. In a 4 wire three phase AC/DC system, a DC line to ground fault can determine large short circuit currents that can be easily sensed by the maximum current relays (as shown in Figure 13.15 [331]. The high value of current cannot be tolerated by the power electronic valves, as the IGBTs can support a current maximum twice the nominal value for a 10 s duration.

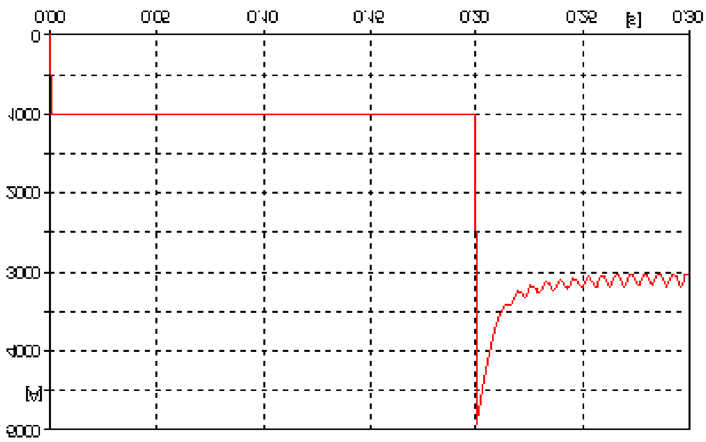

Figure 13.15: Current injected by the AC/AC converter after the DC line to ground fault occurrence

APPENDIX D. PRIMARY AND SECONDARY EMISSIONS

This is a theoretical treatment of the difference between primary and secondary emission. We are very much aware that a distinction between primary and secondary emission through measurements is not straightforward and might in certain cases not even be possible. The development of measurement and other methods to distinguish between the different contributions to the emission is not the aim of this appendix. Further work towards such is however encouraged.

Allocation of responsibilities between a customer and the network operator is also beyond the scope of this report and not the aim of the discussion in this appendix.

D.1. CURRENT AT THE INTERFACE BETWEEN A DEVICE AND THE GRID

The general case is shown in Figure 13.16, where the sources and impedance will be at least to some extent non-linear. The discussion covers individual devices as well as complete installations (like wind parks), but for simplicity we will use the term device in the remainder of this appendix.

However, for the description in this appendix, we will initially assume that the elements are linear. After that the case will be generalized to include all non-linear aspects.

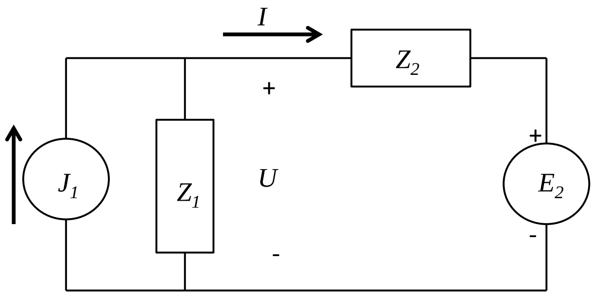

Figure 13.16 Model for the connection of a device or installation to the rest of the power system; the rest of the power system is to the right of the location at which the voltage U is obtained

Where:

- I: emission
- J_1: internal emission
- Z_1: device impedance
- Z_2: grid impedance
- E_2: background voltage

The emission of a device (i.e. the current I at the interface between the device and the grid) is impacted in a number of ways. Different phenomena that impact the emission are listed below. Alternatively, we can consider these as individuals contributions such that the current I is the sum of the different contributions.

The following contributions have been identified:

1. Device against ideal nominal voltage (background voltage has nominal voltage and frequency; zero distortion and grid impedance is zero)
2. Voltage is not nominal
   - Different voltage magnitude
   - Different frequency
3. Non-zero grid impedance
   - Device impedance conducts part of the internal emission
   - Internal emission changes because of the distorted voltage at the device terminals
4. Distorted supply (voltage at grid is already distorted before connection of the device)
   - Current through the device impedance changes
   - Internal emission changes because the distortion of the voltage at the device terminals is different
5. The rest of the grid is non-linear (due to non-linear devices being connected close to the device under study).
   - Grid impedance changes

- Background voltage changes

D.2. PROPOSED TERMINOLOGY

The following terminology is proposed.

- Contributions 1, 2 and 3 are referred to as "primary emission"
- Contribution 4 is referred to as "secondary emission"
- Contribution 5 is referred to as "interaction"

D.3. PRIMARY AND SECONDARY EMISSION

The terms "primary emission" and "secondary emission" were introduced in [102] to explain the spread of distortion from fluorescent lamps with high-frequency ballast in the frequency range of a few tens of kHz. The terms have also been used, and shown to be useful, to explain the current distortion at the terminals of a wind turbine and at the point of connection between a wind park the grid [65], [102]. The terms were defined by [65], [102] in the following way:

- Primary emission is the emission originating from the device.
- Secondary emission is the emission originating outside of the device.

A number of assumptions were needed to allow this distinction. In the remainder of this document, these assumptions will be discussed further including what will happen when these assumptions are not valid.

D.4. PRIMARY EMISSION

In this section we will discuss a number of cases, all in the form of thought experiments, in which the current only consists of primary emission.

D.5. IDEAL VOLTAGE SOURCE

For the first thought experiment the device is connected to an ideal voltage source, with a constant sinusoidal voltage of nominal voltage E_0 (e.g. 230 V) and nominal frequency f_0 (e.g. 50 Hz). In terms of Figure 13.16, $Z_2 = 0$ and $E_2(f) = 0$ for $f \neq f_0$ and $E_2(f_0) = E_0$.

The resulting (primary) emission is the internal emission as in Figure 13.16. Note that this emission cannot be measured in reality, as it is not possibly to create a voltage source with zero impedance. It is however possible to obtain the internal emission from simulations when a sufficiently accurate model is available. Experiments are possible to estimate the internal emission when it is possible to obtain a sufficiently low "grid impedance".

D.6. VOLTAGE DEPENDENCY

With varying magnitude of the background voltage E_2, the primary emission typically varies. This is called the voltage dependency of the primary emission against an ideal voltage source. In mathematical terms

$$\overline{J_1}(f) = \overline{J_1}(f, E_2(f_0))$$

Equation 13.1

Note that also this cannot be measured, for the same reasons as in the previous section

D.7. NON-IDEAL SINUSOIDAL VOLTAGE SOURCE

The next step in our thought experiment is a sinusoidal voltage source with non-zero source impedance: $Z_2(f) \neq 0$. The primary current depends now on the internal emission and on the ratio between device and grid impedance:

$$\overline{I_{prim}}(f) = \frac{\overline{Z_2}(f)}{\overline{Z_1}(f) + \overline{Z_2}(f)} \times \overline{J_1}(f)$$

Equation 13.2

This experiment is the basis of the standard tests to determine the emission level, where a reference impedance is defined.

Note that also this primary emission typically is a function of the amplitude of the background voltage. The non-zero source impedance will result in a distorted voltage at the terminals of the device. This in turn will impact the emission, as will be discussed later.

The difference between the (primary) emission as obtained in this way, and the emission in a real situation has been discussed a lot in the literature.

D.8. SECONDARY EMISSION

So far the background voltage has been assumed sinusoidal. The change in current at the device terminals due to the non-sinusoidal background voltage is called "secondary emission".

D.9. IDEAL NON-SINUSOIDAL VOLTAGE SOURCE

This is again the though experiment where the grid impedance is zero. The emission is impacted in three different ways:

1. A non-fundamental component in the background voltage will result in a current, at that frequency, through the device impedance.
2. A non-fundamental component in the background voltage will result in a change in the internal emission at that frequency.
3. A non-fundamental component in the background voltage will result in currents at one of more other non-fundamental frequencies.

The former impact can easily be described as a linear device in parallel with the (remainder of) the non-linear device. This second impact can be described as a non-linear relation between voltage and current at the non-fundamental frequency. The third impact is more difficult to describe. In frequency domain it would result in an impedance matrix where the off-diagonal elements link a voltage at one non-fundamental frequency with a current at another non-fundamental frequency. This relation will in general be non-linear as well.

D.10. HARMONIC FINGER PRINTS

Consider a linear device, i.e. a time-independent impedance. Such a device will not emit any primary emission, but it will emit secondary emission when the background voltage is non-zero.

For the ideal voltage source, with zero source impedance, the secondary emission of the linear device is:

$$\overline{I_{sec}} = \frac{\overline{E_2}(f)}{\overline{Z_1}(f)}$$

Equation 13.3

The harmonic fingerprint [507] for such a device will contain points along a number of straight lines through the origin, as shown in Figure 13.17: Harmonic fingerprint for a capacitor (used with permission from [507])Figure 13.17.

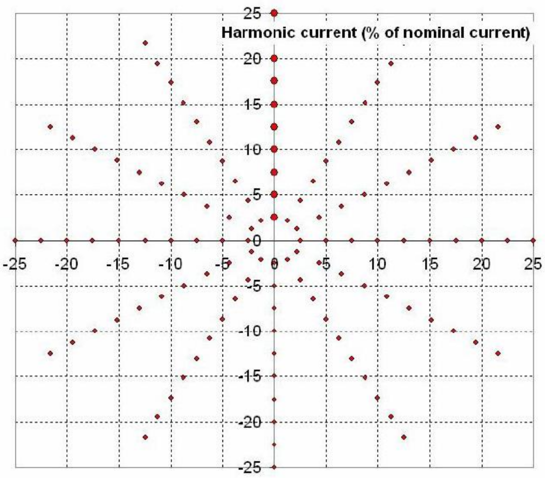

Figure 13.17: Harmonic fingerprint for a capacitor (used with permission from [507])

The measurement of the harmonic fingerprint will require, as mentioned before, a voltage source with very small impedance at the harmonic frequencies of interest.

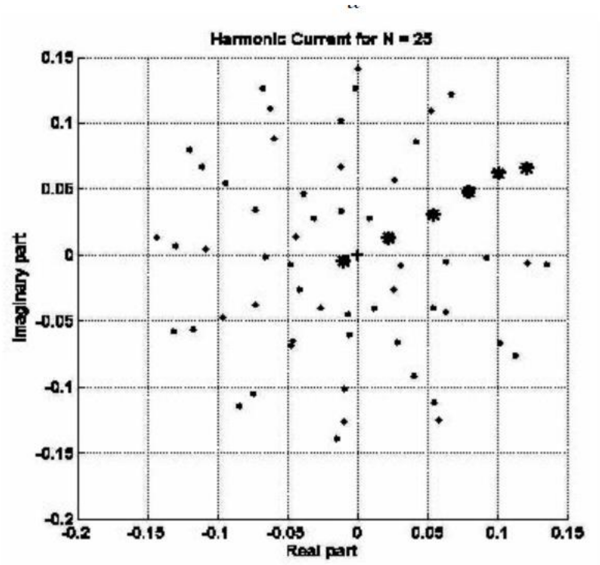

Figure 13.18: Harmonic fingerprint when the current through the grid impedance dominates; used with permission from [507]

The harmonic fingerprint only covers the first and second impacts as listed in the previous section. An example of the first impact is shown in Figure 13.18, and example of the second impact in Figure 13.19. It is possible to extend the concept to the third impact as well, but that could require a lot of diagrams.

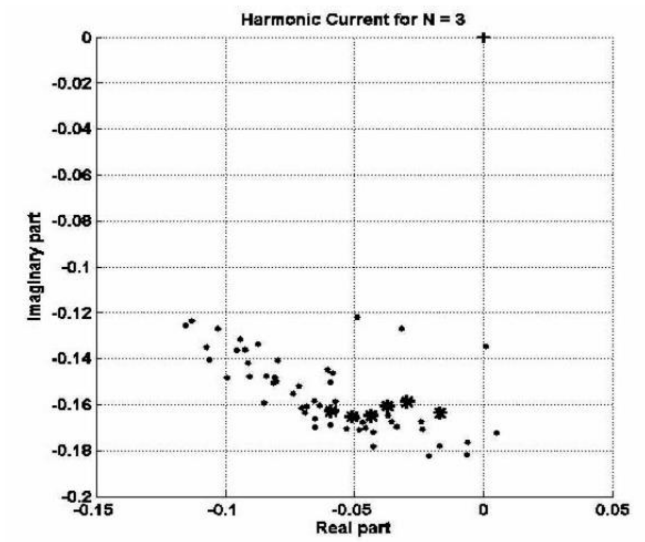

Figure 13.19: Harmonic fingerprint when the change in internal current dominates; used with permission from [507]

APPENDIX E. HARMONICS FROM HEAT PUMPS

E.1. INTRODUCTION

The drives of residential heat pumps are typically two-pole, single-phase induction motors. These directly drive the compressors. Various exotic strategies exist for adjusting the speed of the electric motor drive. These variable-frequency converter types include the pulse-width-modulated (PWM) voltage-source inverter, the square-wave voltage-source inverter and the current-source inverter.

While the inverter drives increase efficiency and reduce inrush current, the rectifier circuits are a known source of harmonics. In order to meet international standards, some form of power factor correction (PFC) circuitry must be added to the basic rectifier circuit [508].

The behaviour of the heat-pump as seen from the AC system depends largely on the particular PFC rectifier circuit used. Inverter-driven heat-pumps can exhibit a higher PF compared with directly connected induction motor heat-pumps. A schematic diagram of a heat pump is shown in Figure 13.20.

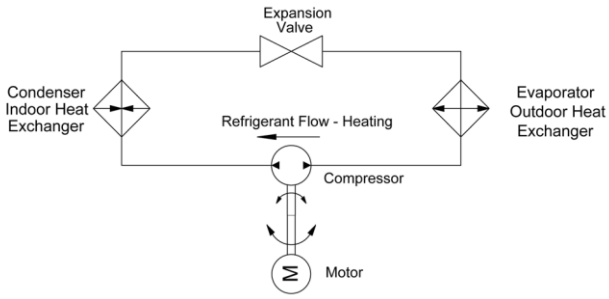

Figure 13.20 Simplified diagram of heat-pump in heating cycle

E.2. CURRENT WAVEFORMS

Figure 13.21 displays the current waveforms of the heat pump (A25) tested in New Zealand, on both heating and cooling cycles, at nominal voltage, for various power levels. In heating mode, it can be seen that the inverter-driven heat-pump A25 draws high harmonic currents, especially at low-power levels, with a distinct change in current waveshape above a certain power level.

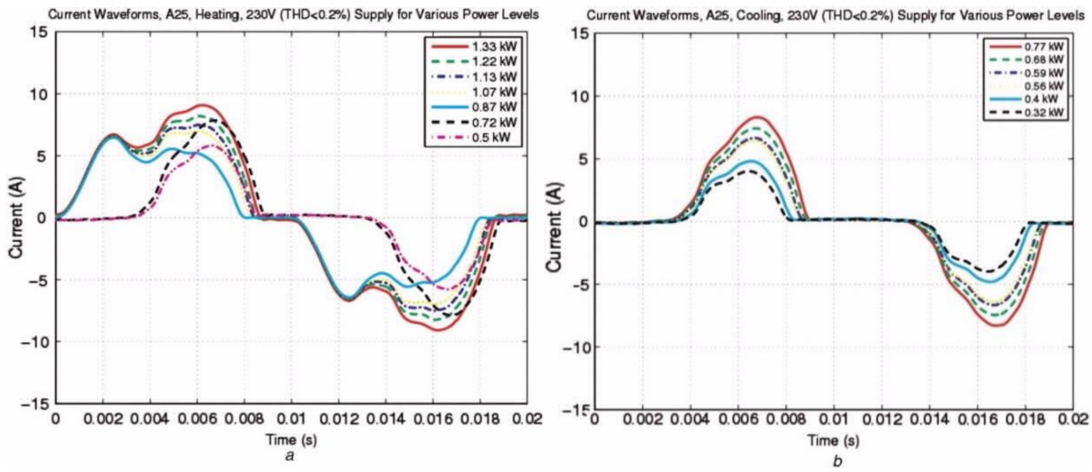

Figure 13.21 Heat-pump A25 current waveforms: a) Heating; b) Cooling

E.3. HARMONIC SPECTRA

The harmonic spectrum (showing the first 19 odd harmonics) of the current waveforms for unit A25, while heating, are shown in Figure 13.22.

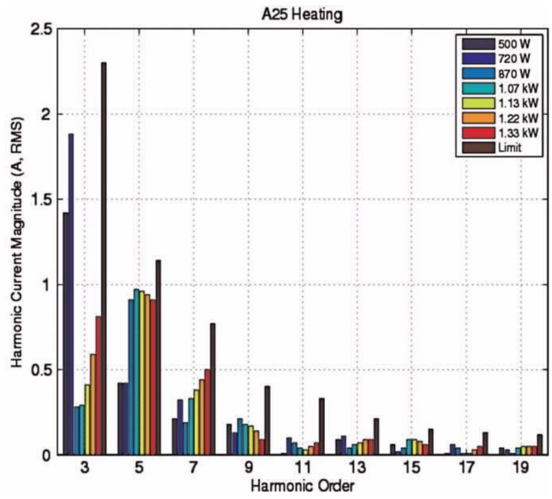

Figure 13.22 Comparison of harmonic current spectrum against AS/NZS 61000.3.2 - A25 when heating

E.4. COMPASS PLOTS

The test performed in New Zeeland included six different models of heat pumps. The Compass plots of third and fifth harmonic currents, combined waveform and spectrum of combined waveform, while heating, are illustrated in Figure 13.23.

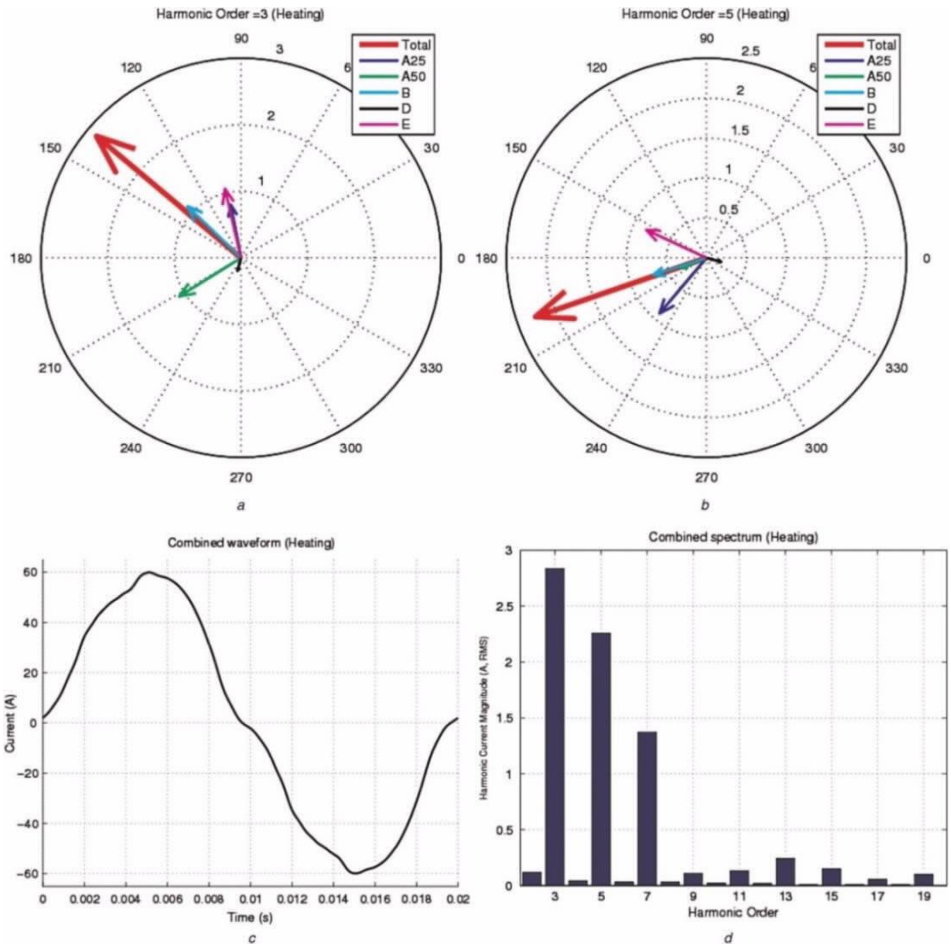

Figure 13.23: Multiple inverter-driven heat-pumps (heating): a) Compass plot of third harmonic current; b) Compass plot of fifth harmonic current; c) Combined waveform; d) Spectrum of combined waveform

The currents of all the inverter-driven heat-pumps running simultaneously in the heating mode, under conditions close to the manufacturers nominal power levels were summed vectorially. Although only valid for a stiff voltage source, where the current harmonics do not significantly distort the voltage waveform, this nonetheless demonstrates the effect of diversity in the harmonic phase angle. Figure 13.23 a and b show compass plots of the third and fifth harmonics (in heating mode), respectively, for the individual inverter-driven heat-pumps as well as the total. The combined total current waveform and its spectrum are displayed in Figure 13.23 c) and d).

Figure 13.24 shows the Compass plots of third and fifth harmonic currents, combined waveform and spectrum of combined waveform, while cooling.

Figure 13.24 also shows that the diversity is slightly worse when in cooling mode.

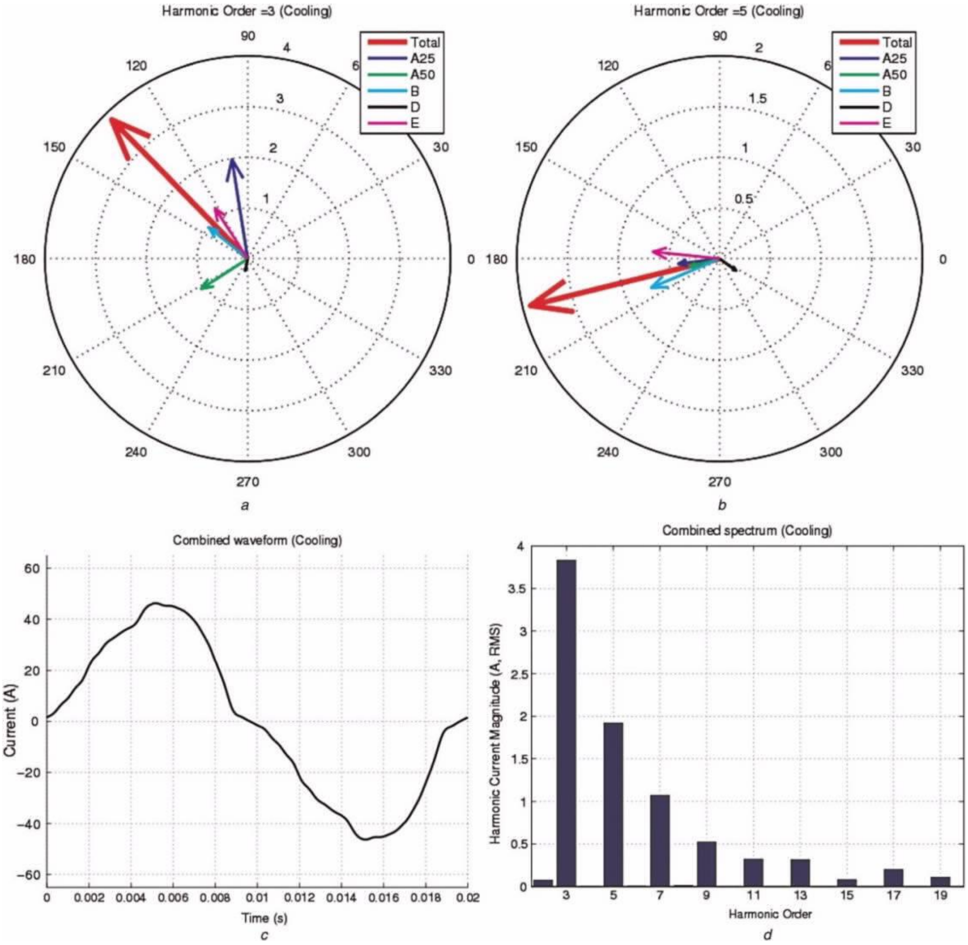

Figure 13.24: Multiple inverter-driven heat-pumps (cooling): a) Compass plot of third harmonic current; b) Compass plot of fifth harmonic current; c) Combined waveform; d) Spectrum of combined waveform

E.5. OVERVIEW OF THE TESTS

During the tests, It was noticed a significant diversity of the harmonic emissions of the six devices under test, regardless of heating or cooling period. The current ITHD of each heat-pump and the summation current THD of all six devices running together are presented in Table 13.1.

Table 13.1 ITHD of each heat-pump and their summation

Heat-pump	Heating		Cooling	
	THD [%]	I1[A]	THD [%]	I1[A]
A25	22.99	5.74	55.40	3.7
A50	15.09	8.04	17.24	7.00
B	17.00	8.32	16.73	7.89
D	3.32	9.52	5.32	7.36
E	16.35	8.95	30.74	4.60
All	9.64	40.44	14.97	29.96

E.6. VARIABLE-SPEED DRIVES FOR VENTILATION AND WATER PUMPS

Variable-speed drives in commercial buildings are used to power ventilation fans and water pumps. In the case of a variable-speed furnace, its fan motor can work with an outdoor air conditioner and thermostat with a humidity sensor to provide the same effects to the indoor air.

E.7. IMMUNITY OF ACTIVE CONVERTERS

For dynamic regenerative loads such as motors, reverse current flow is unavoidable and a clamp circuit is needed to protect the converter from experiencing overvoltages on the dc link. Clamp circuits have been proposed for bidirectional matrix converters to prevent the switching devices from incurring overvoltages and to permit ride-through under overvoltage conditions [509].

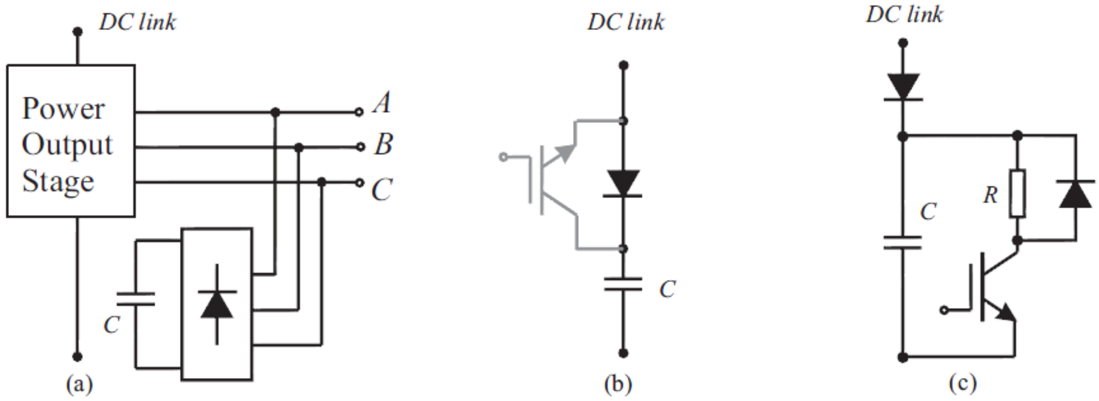

Figure 13.25 Clamp topology options. (a) Conventional clamp circuit (b) Capacitor-diode clamp with optional switch (c) Active clamp circuit

APPENDIX F. STREET LIGHTS AND SURGES

F.1. STREET LIGHTS

In some countries the street lights (see Figure 13.26) are currently retrofitted. The conventional lamps (mercury vapour, metal halide and sodium vapour), are replaced by LED lamps as a result of technological revolutions in LED efficiency (higher lumens per watt), secondary optics (better lenses/reflectors) and greater thermal dissipation [510], [511]. Other reasons include: lower wattage demand and maintenance cost and longer lifetime.

F.2. SUSCEPTIBILITY TO SURGES

However, compared to the other lights the LED lamps are more susceptible to the transient surge events in AC power lines, which can damage them.

Surges may be caused by:

- Direct lightning strike to the lamp or supply line,
- Indirect lightning strike causing conducted interference in the supply line as a result of capacitive or inductive coupling,
- Switching operations, earth faults/short-circuits or tripping fuses.

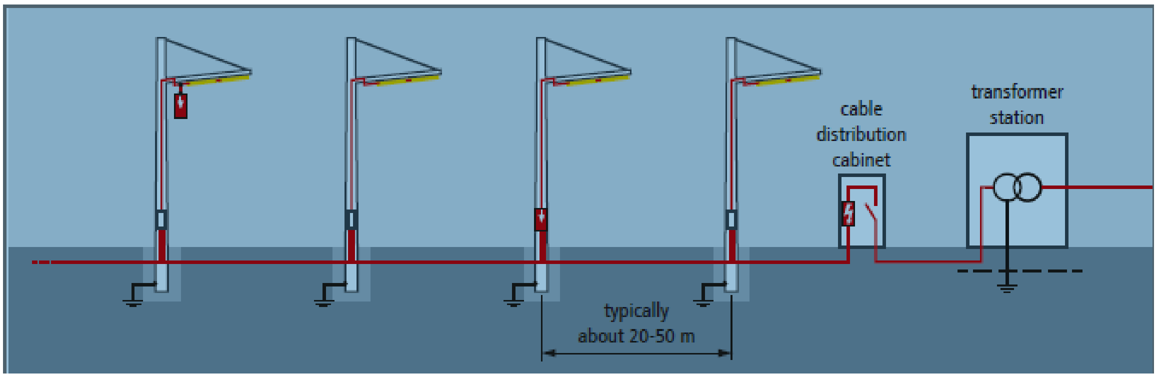

Figure 13.26 Basic design of street lights [102]

Surge overvoltages have two modes of circulation [512]. A well-protected luminaire should integrate protection for both modes.

- Common mode: High voltage/current transients between the Line-Neutral (L-N) or Line-Line (L-L) terminals of the luminaire could damage safety insulation in the power supply unit or LED module board, including the LED to heat sink insulation (See Figure 13.27).
- Differential mode: High voltage/current transients appear between the Line-Neutral (L-N) or Line-Line (L-L) terminals of the luminaire could damage components in the power supply unit or the LED module board (see Figure 13.28).

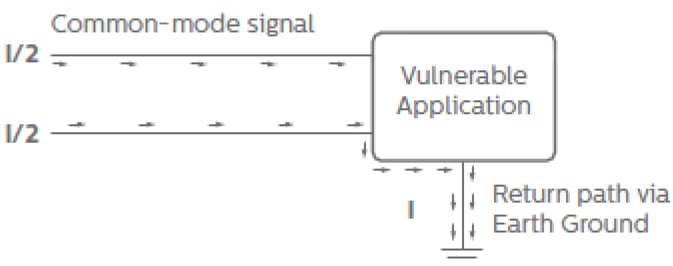

Figure 13.27: Common-mode circuit

Damage to LED street lamps due to lightning has been reported in Sweden and Denmark [513]. The lack of overvoltage protection is mentioned as the cause; however no mechanism is given to link the overvoltage at the lamp terminals with lightning strokes.

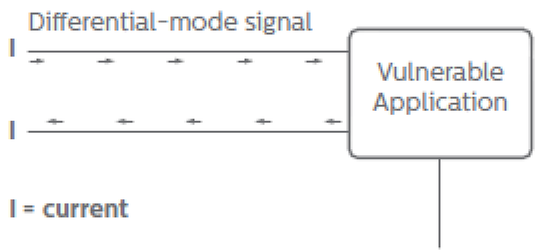

Figure 13.28: Differential-mode circuit

APPENDIX G. TRENDS IN HARMONIC VOLTAGE DISTORTION

Changes in the voltage distortion have been observed in a number of countries. There is no explanation for this, but it is likely at least in part due to the trends shown in sections 4.3 and 4.5.

G.1. AUSTRIA

An Austrian measurement campaign has shown a noticeable reduction in voltage distortion, at harmonic 5 [514] during the period 2000 through 2008. Harmonics 3 and 7 did not show any noticeable change, whereas harmonics 11 and 13 show a clear increasing trend at low voltage and a constant trend at medium voltage). The trends are illustrated in Figure 13.29 through Figure 13.31.

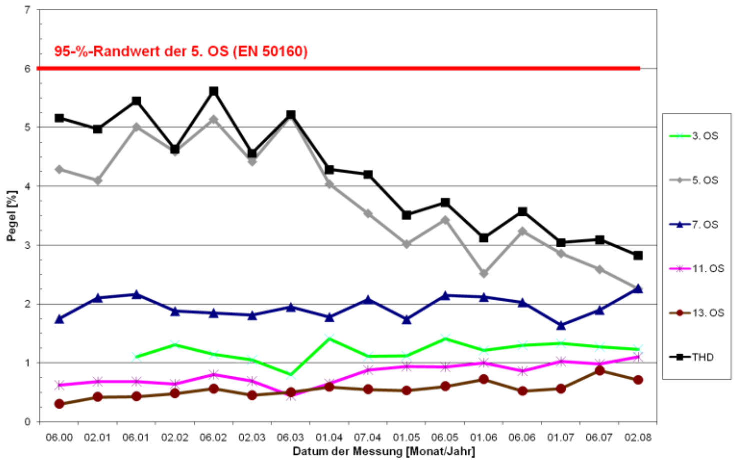

Figure 13.29 Trends in harmonic levels in Austria for low-voltage. Reproduced with permission

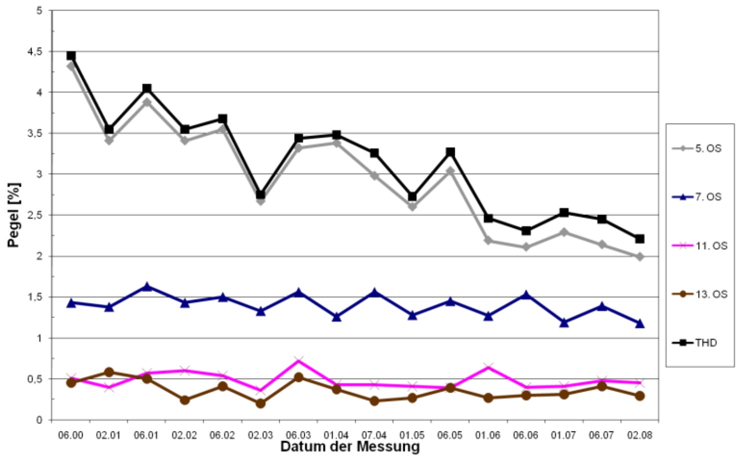

Figure 13.30: Trends in harmonic levels in Austria for medium-voltage. Reproduced with permission

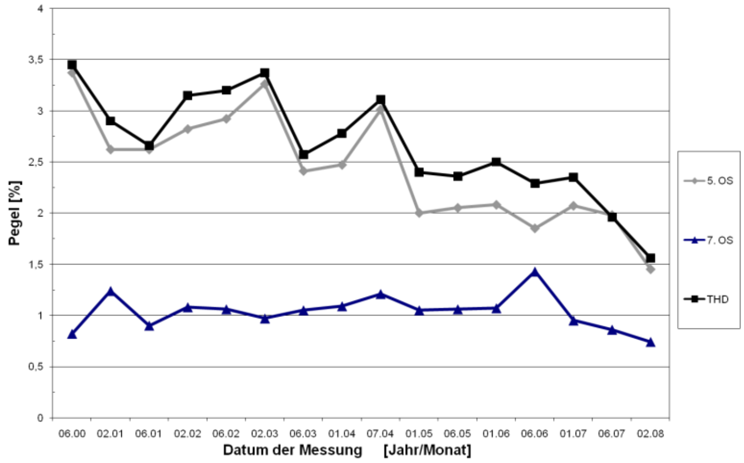

Figure 13.31: Trends in harmonic levels in Austria for high-voltage. Reproduced with permission

G.2. SWITZERLAND

A measurement campaign in Switzerland [121] showed that voltage distortion for triplen harmonics (9, 15 and 21) is much higher compared to the limits than other harmonic orders. Especially harmonic 15 exceeds the limit at several locations. This harmonic order also shows an increasing trend and the number of sites where the levels exceed the limits is increasing as well. Some results are reproduced in Figure 13.32 through Figure 13.35.

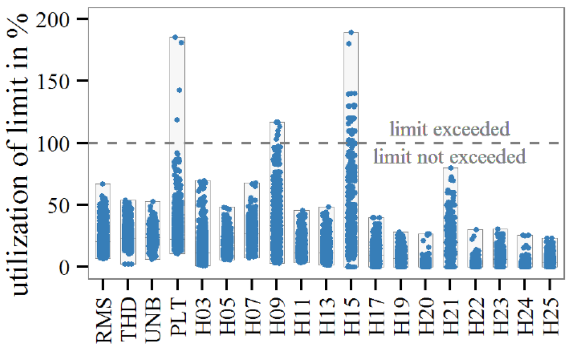

Figure 13.32: Overall performance (limit = 100%) in Swiss urban areas [121]. Reproduced with permission

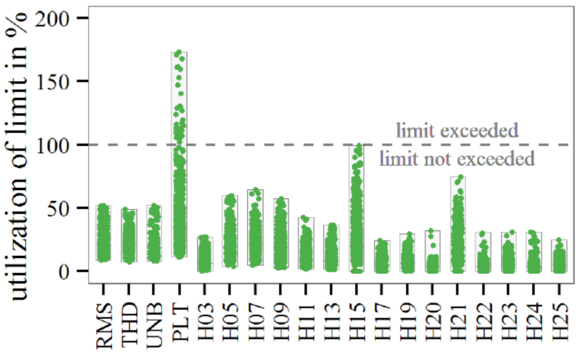

Figure 13.33: Overall performance (limit = 100%) in Swiss urban areas [121]; Reproduced with permission

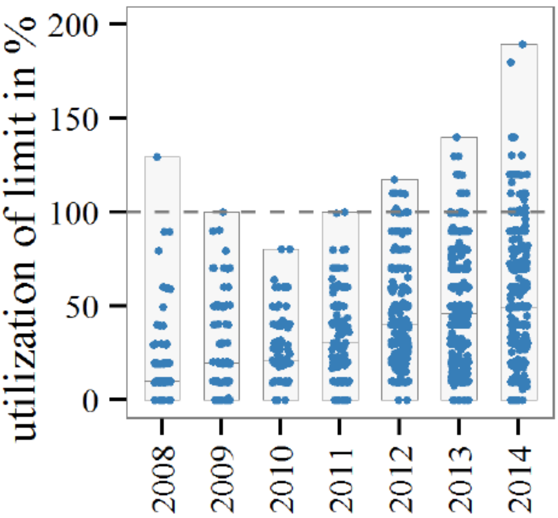

Figure 13.34: Trend in performance for harmonic 15 (limit is 100%) in Swiss urban areas [121]; reproduced with permission.

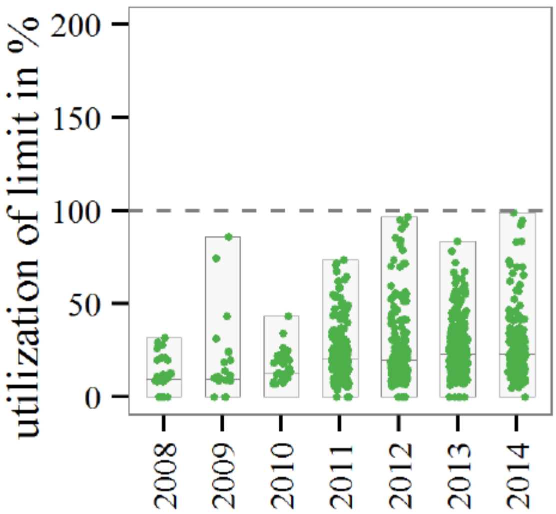

Figure 13.35: Trend in performance for harmonic 15 (limit is 100%) in Swiss rural areas [121]; reproduced with permission

G.3. UNITED STATES

An analysis of the data from a large survey in US [EPRI TPQ-DPQ IV] showed large increases in THD, over the period 2006 to 2011. An example of a location with a large increase is shown in Figure 13.36.

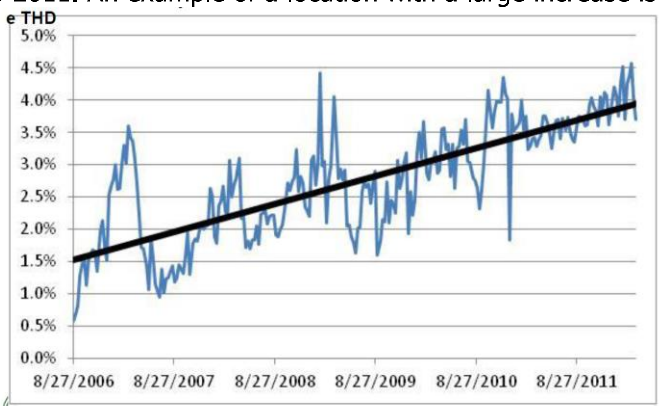

Figure 13.36: Trend of strongly increasing harmonic distortion at one of the locations of the EPRI DPQ4 survey, used with permission [125].

G.4. THE NETHERLANDS

Measurements in the Netherlands, between 1998 and 2013, show a decrease in THD that has however stopped somewhere around 2009. A sudden, stepwise increase in 15th harmonic voltage was observed between 2007 and 2008 [516], [517]. Some of the trends are shown in the figures below.

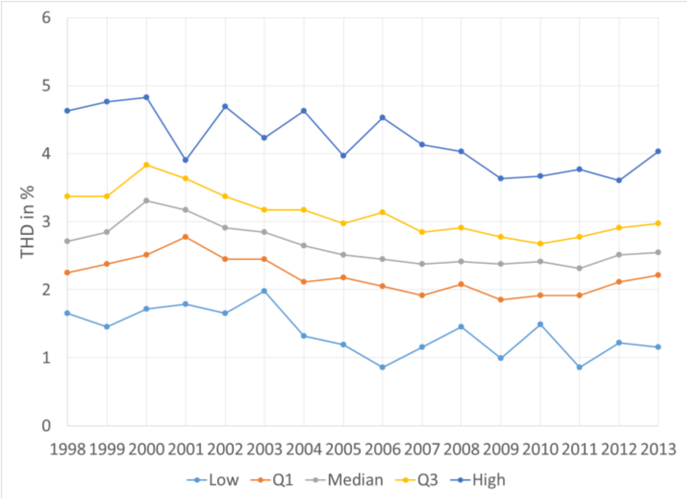

Figure 13.37: Trend in THD at low voltage 1996 – 2013 [516], [517]

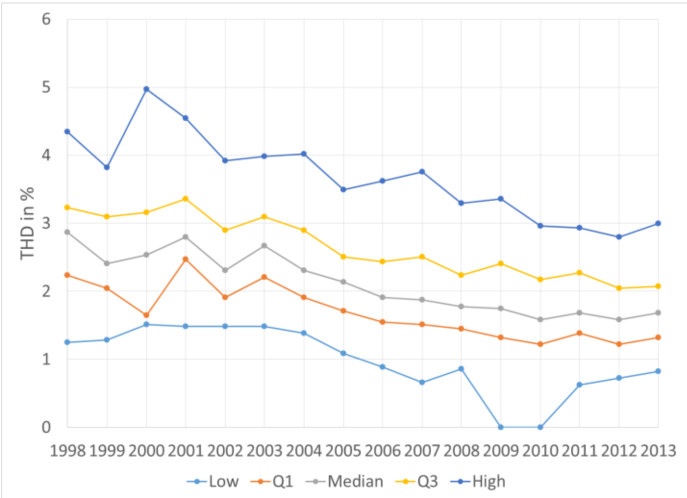

Figure 13.38: Trend in THD at medium voltage 1996 – 2013 [516], [517]

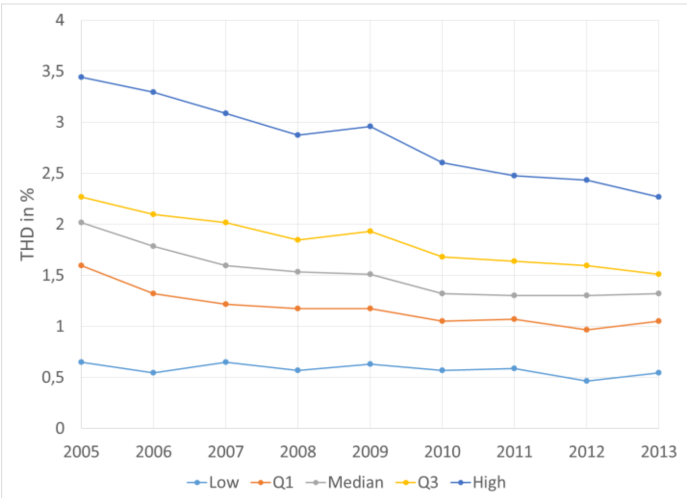

Figure 13.39: Trend in THD at high voltage 2005 – 2013 [516], [517]

The increase in the number of outliers for the last three years, in Figure 13.39 and Figure 13.40, could be due to an increase in the number of monitoring points.

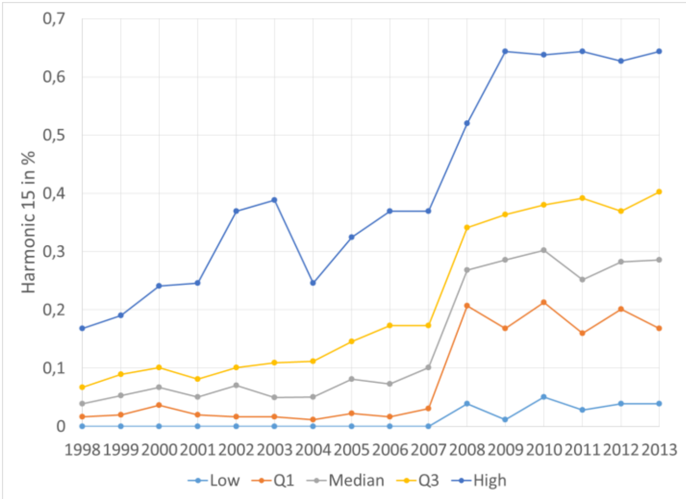

Figure 13.40: Trend in harmonic voltage 15 at low voltage 1995 – 2013 [516], [517]

There is a remarkable step up in harmonic emission from 2007 to 2008. This does correspond with the start of the phasing out of the incandescent lamps; but the transition is too quick to be due to this. Another explanation offered is a change in the measurement system. This really needs further investigation.

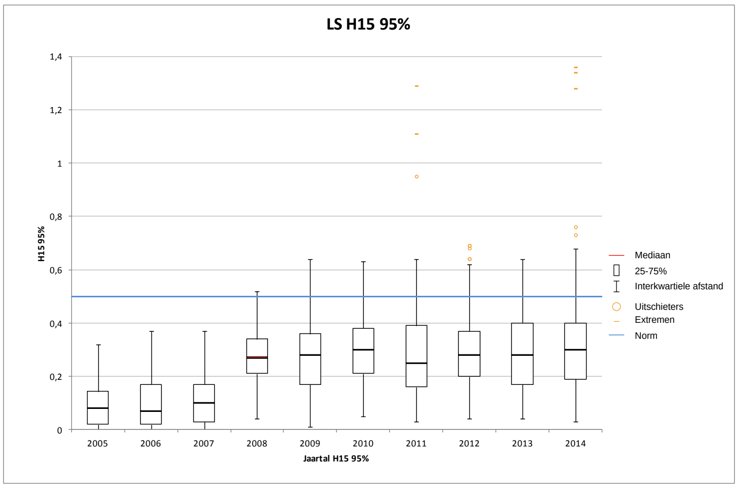

Figure 13.41: Trend in harmonic voltage 15, low-voltage 2005 – 2014 [516], [517]

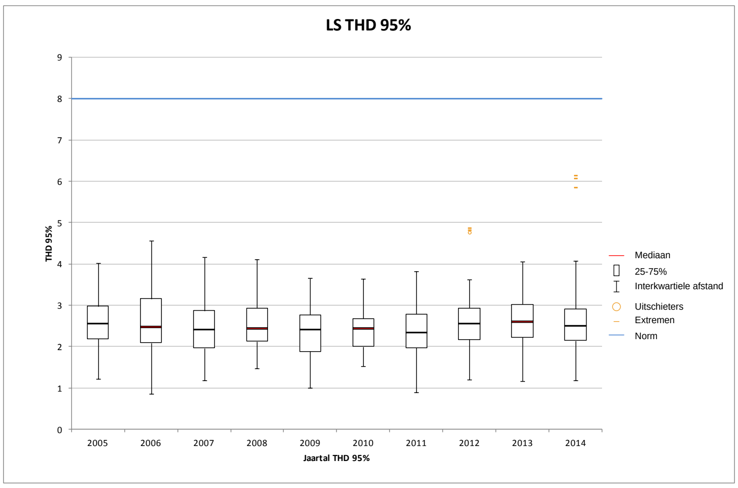

Figure 13.42: Trend in THD, low-voltage 2005 – 2014 [516], [517]

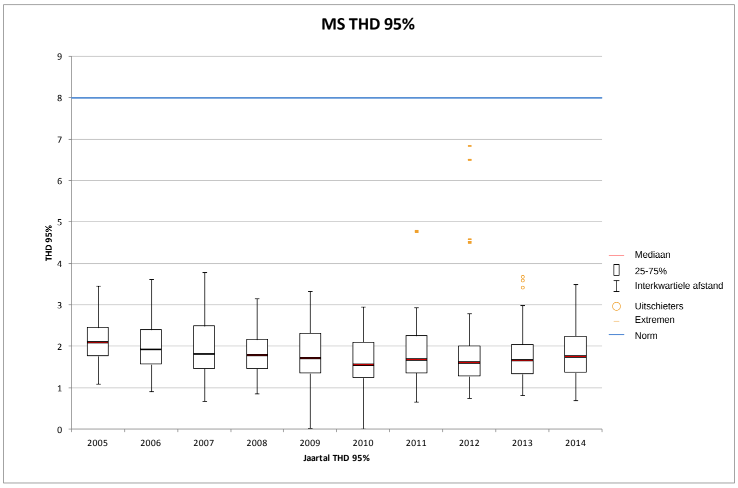

Figure 13.43: Trend in THD, medium-voltage 2005 – 2014 [516], [517]

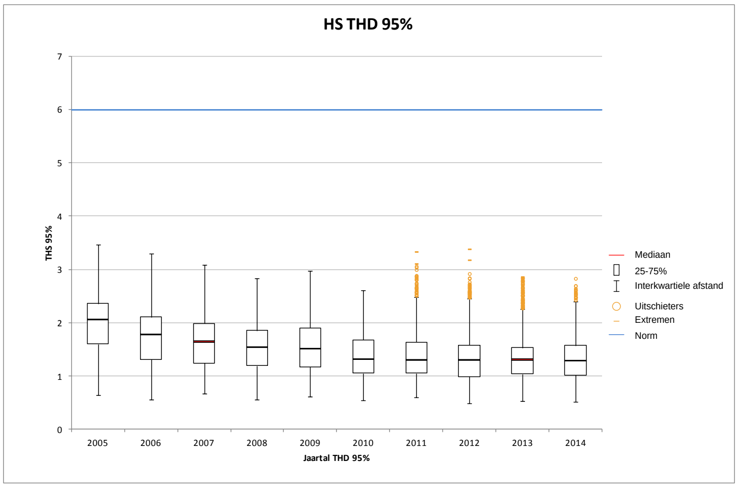

Figure 13.44: Trend in THD, high-voltage 2005 – 2014 [516], [517]

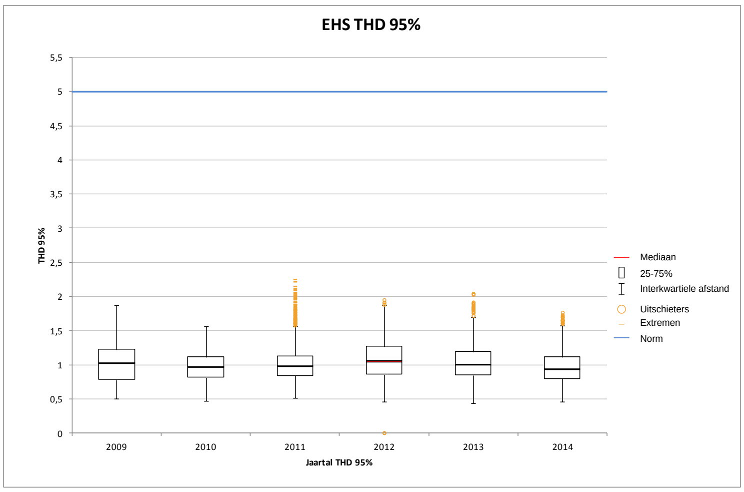

Figure 13.45: Trend in THD, extra high-voltage 2009 – 2014 [516], [517]

G.5. CANADA

An increase in the 15th harmonic voltage was allegedly also observed in Canada [518]

G.6. BRASIL

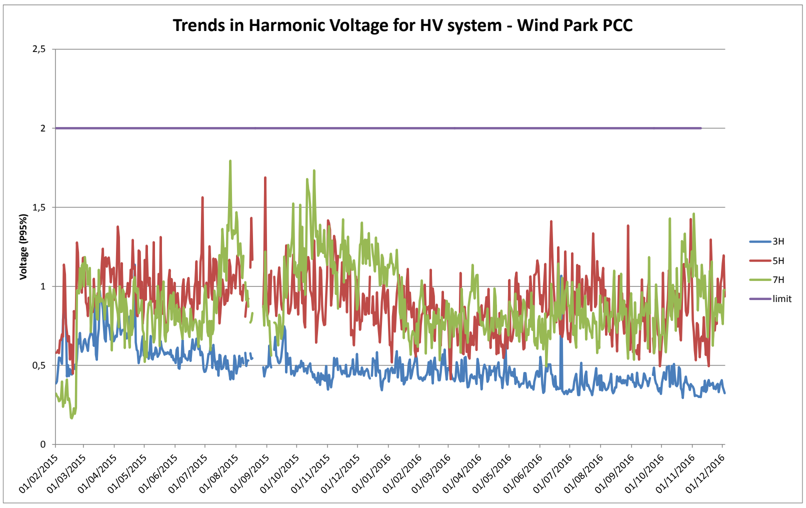

Figure 13.46: Dayly trend in Voltage Harmonic emissions at the PCC of a Wind Park

Due to an increasing number of connections in the Brazilian Electric System of new onshore Wind Parks, long term HV harmonic measurements are performed at the PCC. These measurements indicate that voltage distortions from 5th and 7th harmonic orders stay almost steady with some slight variations while the third harmonic order emissions have experienced some reduction.

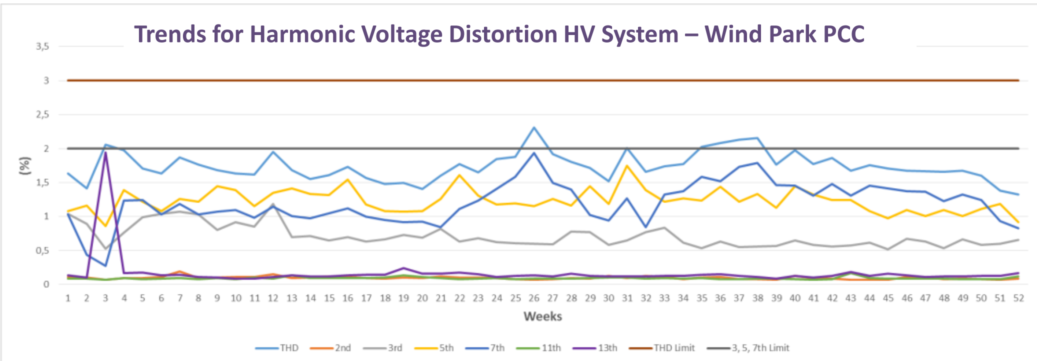

Figure 13.47. Weekly trend in Voltage Harmonic emissions at the PCC of a Wind Park

APPENDIX H. SUPRAHARMONICS

Emissions in the supraharmonic range (2-150 kHz) has different characteristics than emissions below 2 kHz. When analyzing measured data in this higher frequency range a different approach is therefore needed. The supraharmonic spectra are often of broadband character. Spectra at lower-frequencies contain mainly discrete or narrowband components at integer multiples of the power-system frequency.

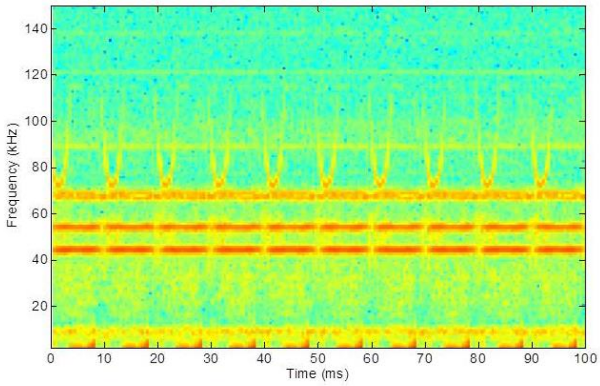

Figure 13.48 Spectrogram of the current drawn by a LCD TV

Narrowband components in the supraharmonics range are often not stationary and change amplitude over time in the millisecond range. The emission can also have other features like time-frequency variation which are not common in the harmonic range [70], [430]. One method used for analyzing supraharmonics is the Short Time Fourier Transform (STFT). A sampled signal is divided into smaller windows and a Discrete Fourier Transform (DFT) is applied to each window. The outcome is typically represented as a spectrogram. The spectrogram will show changes in the spectrum over time thus giving information on the characteristics of supraharmonics not given by traditional harmonic emission analyzing techniques. An example of the outcome of a STFT is shown in Figure 13.48.

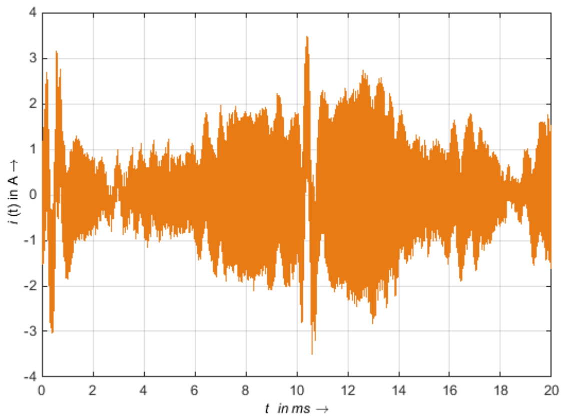

Figure 13.49: High pass filtered current waveform of a DC charging station (Chademo) for electrical vehicles (maximum value: 3.5 A; POW of maximum: 10.5ms/190°)

In order to quantify supraharmonic emissions, a comprehensive set of indices has to be developed, which should include time domain and frequency domain parameters. Time-domain parameters like maximum value or point on wave of maximum can be easily obtained from the filtered waveform (see Figure 13.49).

Frequency domain parameters could be the magnitude of a certain emission band or the total supraharmonic distortion (TSD). In order to ensure the comparability of results, some calculation parameters, like a specific bandwidth has to be defined in advance. The signal in Figure 13.49 has a RMS-value of 120dBμA RMS which corresponds to 1 A at 45 kHz. Compared to the maximum value in time domain of 3.5A, the averaging effect of classical FFT approach is clearly to see.