International Conference on Electricity Distribution

Working Group

Final Report

Monitoring and Control of LV networks

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Working Group

Final Report

Monitoring and Control of LV networks

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LIST OF ACRONYMS

ADMS	Advanced Distribution Management System
AI	Artificial Intelligence
AMI	Advanced measurement infrastructure
APP	Application
APS	Automatic Phase Shifting
BESS	Battery Energy Storage System
COSEM	Companion Specification for Energy Metering
DER	Distributed Energy Resources
DG	Distributed Generation
DLMS	Device Language Message Specification
DMS	Distribution Management System
DP	Dynamic Pricing
DR	Demand Response
DRMS	Demand Response Management System
DSO	Distribution System Operator
DTC	Distribution Transformer Controller
ENS	Energy not Supplied
ESS	Energy Storage System
EU	EUropean
EV	Electric Vehicle
FLISR	Fault Location, Isolation, and Service Restoration
FPI	Fault Passage Indicators
GIS	Geographical Information System
GSM	Global System for Mobile Communications
HAN	Home area network
HEMS	Energy Management System
HV	High Voltage
ICT	Information and Communication Technology
IDR	Independent Demand Response
IED	Intelligent Electronic Device
IT	Information Technology
KPI	Key Performance Indicator
LV	Low Voltage
LVC	Low Voltage Control
LVM	Low Voltage Monitoring
LVSE	Low Voltage State Estimator
ML	Machine Learning
MV	Medium Voltage
NILM	Non-Intrusive Load Monitoring
NIS	Network information System

OLTC	On-Load Tap Changer
PHIL	Power Hardware In the Loop
Plt	Long-Term Flicker Perceptibility
PMU	Phase Measurement Unit
PQ	Power Quality
PQM	Power Quality Monitoring
PQP	Power Quality Predictions
PV	Photovoltaic Systems
RES	Renewable Energy Source
RF	Radio Frequency
RTU	Remote Terminal Unit
SAIDI	System Average Duration Frequency Index
SAIFI	System Average Interruption Frequency Index
SCADA	Supervisory Control And Data Acquisition
SM	Smart Meter
SQL	Structured Query Language
SS	Secondary Substation
THD	Total Harmonic Distortion
TOU	Time of Use
TSO	Transmission System Operator
UPS	Unit Power Supply
V2G	Vehicle To Grid
V2H	Vehicle To Home
VVC	Volt-Var Control

Executive Summary

Electric distribution systems have been developing rapidly in the XXI century. New actors such as distributed energy resources (DERs) based on renewable energy sources (RESs), energy storage systems (ESSs), and electric vehicles (EVs) have been emerging, which pose new challenge to Distribution Systems Operators (DSOs). For this reason, additional flexibility is required together with new services that can support network operation. Moreover, new developments on information and communication technologies, together with recent trends on digitization and smartness of network components and systems are arising that result in new sources of information, thus a significant amount of data becomes available. Comparing to HV and MV networks, LV networks are usually characterized by a poor observability, given the limited metering data available (mostly for economic reasons), and lack of automation.

In order to overcome these deficiencies, there is a need for near real-time[1] data for monitoring and control purposes. Information coming from smart metering infrastructures, collecting technical data relevant to operation, can partially cover this issue; however, it needs to be complemented with other advanced techniques, namely Artificial Intelligence (AI) and Machine Learning (ML) techniques, to promote algorithms that enable proactive actions and predictive management of the LV system, which seems to be reliable and economically beneficial.

Consequently, DSOs need to develop a Low Voltage Monitoring (LVM) infrastructure, with several functionalities ranging from long term actions to near real-time. LVM can be used for near real-time monitoring of reliability, power quality, flexibility, proactive and predictive analyses and even control to some extent. The main condition is that the customer meters meet the technical conditions for so-called smart technology, as a suggestion, smart meters of the second generation. Measurement, collection and data accessibility must be available without delay associated to advanced tools for data management in near real-time, as well as for back office analyses. Since delay is inevitable in communication systems, time-tagging schemes like the idea used in synchrophasors might be very beneficial in LVM, which is already in service in MV as MicroPMUs (Micro Phasor Measurement Units). LVM is expected to be a central system in processes between the operations center, field crew and the customer where data and information exchange between all stakeholders must be secure, thus minimizing the risks of data intrusion. LVM can also be used to anticipate maintenance actions and help the DSOs expanding their network and improving their knowledge, especially on load and generation patterns. The interest of LV control functions depends on the electrical parameters of the networks (resistance over reactance ratio, topologies, types of technical problems encountered), the level of deployment of Distributed Energy Resources (DERs), the control mode (centralized, decentralized or hybrid) and the remuneration mechanisms. Many demonstration projects have proven their effectiveness in several conditions and countries, yet still regulation rules need to be defined for their large-scale deployment.

[1] Near real-time monitoring means monitoring with a delay of some minutes (typically 5 to 15 min.).

INTRODUCTION : BACKGROUND AND SCOPE

Historically, power systems have been split into three main grids: the transmission, sub-transmission and distribution grids following a logic of unidirectional power flows from big generation units usually located far from the consumption areas. Distribution grids and especially Low Voltage (LV) grids were the final link in the chain with a simple structure, usually arborescent with short lines lower than one kilometer, simple protection schemes, mainly fuses (sometimes breakers), off-load tap changer, almost no measurement and no automation functions. Some Distribution Systems Operators (DSOs) actually do not have the entire detailed topology and electrical characteristics of their networks. Since several years, the role of distribution grids is evolving due to the development of smart meters, Information and Communication Technologies (ICTs) functions and new kind of customers: Renewable Energy Sources (RESs), Electric Vehicles (EVs), controllable loads providing Demand Response (DR) services and Energy Storage Systems (EESs). Smart Meters (SMs), already deployed in several countries such as Italy, Portugal and Sweden, enable to get a huge amount of data opening the possibility of monitoring and controlling the LV customers. The new type of customers previously mentioned modify the power flows in the networks and can create technical constraints such as over-voltages, under-voltages, over-currents and malfunction of protections. It is more and more necessary to monitor the LV networks in order to control the power flows to avoid these constraints but also to optimize the assets management.

The objective of this working group is to investigate the possible solutions for the monitoring and control of the LV networks considering the background previously described. In particular, their advantages and drawbacks will be highlighted and analyzed in order to provide a set of recommendations for the future based on feedbacks from demonstration projects.
The report is structured as it follows: after enumerating the perquisites for low voltage monitoring, the report will focus on the interest of monitoring the LV network for both near real time and long term actions. Then several LV control functions are described and illustrated with demonstration projects when available trying to compare their technical efficiency and costs. The last section will provide some recommendations for future monitoring and control of LV networks.

1. PREREQUISITES FOR LOW VOLTAGE MONITORING (LVM)

Automation of the LV network has historically been ignored. DSOs have focused on technical modernization in Medium Voltage (MV) and High Voltage (HV) networks. Accordingly, is the electrical topology of LV networks, based almost only on fuses and neither active operation, nor control can be made from dispatcher centers. Electric supply disruptions in the network or at customers’ facilities are handled reactively, usually after customers' complaints. Communication between customers, field crew and dispatcher centers is carried out by typical call-taking and trouble-call services. These services are sometimes integrated with MV/HV SCADA (Supervisory Control and Data Acquisition) systems so that a limited form of LV network visibility can be achieved. Fast changes appear in the energy market with introduction of DERs (Distributed Energy Resources) - RESs such as PVs (PhotoVoltaics), EVs, microgrids and new services like flexibility. These changes require a high level of digitalization which can be provided only with considerable level of automation in the network, frequent exchange of data, AI (Artificial Intelligence) and other cutting-edge technologies. In the following section, an overview of necessary prerequisites that the DSOs need to implement to address the new challenging conditions in the networks, as well as, the expectation from different market players are detailed

1.1. Requirements on metering equipment in the field

Digitalization

Metering equipment in the field needs to follow trends of digitalization and communication to provide smart services to consumers. It is expected that communication and metering equipment will be soon improved with 5G technology. DSOs are already affected by some trends like AI, edge computing and blockchain. The development of digitalization at the distribution level will increase in future.

Metering equipment upgrade

Metering equipment still have to measure billing data accurately and properly, but additional parameters need to be computed. That requires further memory for metering equipment, increased resolution for collection of data (1 min, 10 min, 15 min, hourly, etc.), new functions of alarms, events, outputs of different sensors, different tariffs among others. To provide smart services metering, equipment needs to be upgraded also with additional inputs, outputs, relays, communication paths, advanced limitation functions (disconnectors can be more used to prevent overflows).

Edge computing solutions

Based on the premise that second-generation smart meters are able to collect more data and possess algorithms to refine it, so that certain control functions can be moved closer to the customer and the network, human involvement can be reduced and the operation related workflow accelerated.

Modernization

As mentioned, the entire measurement infrastructure needs to be modernized.

Smart circuit breaker

Intelligent Electronic Devices (IEDs) of circuit breakers in the LV networks can acquire measurement and fault data and communicate with edge computing controllers and LV Distribution Management systems (DMSs).

Smart secondary substation

To upgrade LVM from monitoring to control actions, the ability of smart meters needs to be supplemented with functions in secondary substations where metering equipment as well as other equipment are able to provide services to the network (voltage/current regulation functions). Some DSOs choose to equip secondary substations with smart meters (the same type as smart meters for customers installations) in order to monitor transformers condition, measure and predict network losses, capacity and other power quality issues.

1.2. REQUIREMENTS ON DATA EXCHANGE

Data exchange between meters/sensors and the DMS for further handling

The meters/sensors are configured to register various parameters, can refine data and also perform certain calculations. Collected/calculated data needs to be sent with different frequencies and in different resolutions, which implies a huge amount of data. The new generation of smart meters are expected to collect and transfer data in the order of Gb/day. Through intervals, smart meters transfer data to the measurement center. DSOs use mostly 1 min, 10 min, 15 min, and hourly interval. To increase the benefits from the Advanced Metering Infrastructure (AMI)[2], DSOs need to collect data in near real time. Some DSOs start usage of push communication i.e. the meters must be configured for sending all, as well as, determined events systematically or in predefined methodology. Transmission of near real time data can create overloading of the mobile network, especially if the number of smart meters is large. 5G seems to be able to facilitate near real time data collection from smart meters since it improves 4G network and enables to solve performance problems in the mobile network. 5G is also supposed to be a solution that will enable near real time communication from big amount of different IoT (Internet of Things) devices such as smart meters. There were some tests but DSOs still use most 4G communication for data collection from smart meters [1].

Data exchange between the internal systems of DSOs

Data accessibility between different systems in the (Information and Telecommunication) IT infrastructure is a complex procedure. Consequently, the IT infrastructure should be equipped with advanced enterprise software, like ArcGIS Geo Event for data management needs in near real time. Raw data must be sorted continuously and unnecessary data excluded from further handling in order to avoid performance problem.

Data exchange between the DSO and the customer

Customers are a key to establish new energy market and flexible LV grid. To encourage them in participating actively, DSOs and suppliers have to provide attractive and useful APPs (APPlications), web interfaces or other access to data from meters. Consumption data in 15 min time slots needs to be available for all consumers. To enable better energy management and active participation of consumers, even other kind of data such as voltage, current, power and data related to power quality need to be available to the customers. Depending on regulations in diverse countries, approaches of DSOs are different to provide data to consumers. In some countries HAN (Home Area Network) interface is used. With HAN interface, the consumer is connected directly with smart meter in his own facility. Benefits are that data are not transferred through the whole communication network. Negative consequences are possible vulnerabilities that can negatively affect customer privacy and AMI security. Because of IT security risks with HAN platform, some DSOs provide data that are

[2] An AMI refers to a complex measurement system that includes smart meters, communication networks, and data management systems.

collected in databases through Web interface or APPs. Through such APPs, two-way communication with consumers can be also established. That will improve communication with consumers and enable DSOs to get more benefits from digitalization and increase consumer satisfaction, which will be an increasing challenge in the coming years.

Data exchange between the DSO, TSO (Transmission System Operator) and other actors of the energy market

New energy market, who requires flexibility of the LV grid, will increasingly consist of completely different stakeholders who, not infrequently, are influencing in a contradictory ways. For successful data exchange, all stakeholders have to use the same formats and technical standards in order to provide interoperability. New roles, such as aggregators, arise with the aim of coordinating the use of data by stakeholders of diverse nature. National and international hubs are created for handling services or data submission and retrieval. With that variant of the solution, point-to-point communication is avoided and new services and features can be provided.

1.3. Requirements on data management and analysis

To understand what is happening in the network and what the data indicate, the refined data or results from different algorithms and analyses need to be visualized in a GIS (Geographical Information System). In this way, user-friendly presentation of the delivery status is made possible. Operator sees where in the LV the error has occurred, what type of error it is about, its propagation in the network and all that together with geographical topology of the network. Figure 1 depicts basic LVM infrastructure.

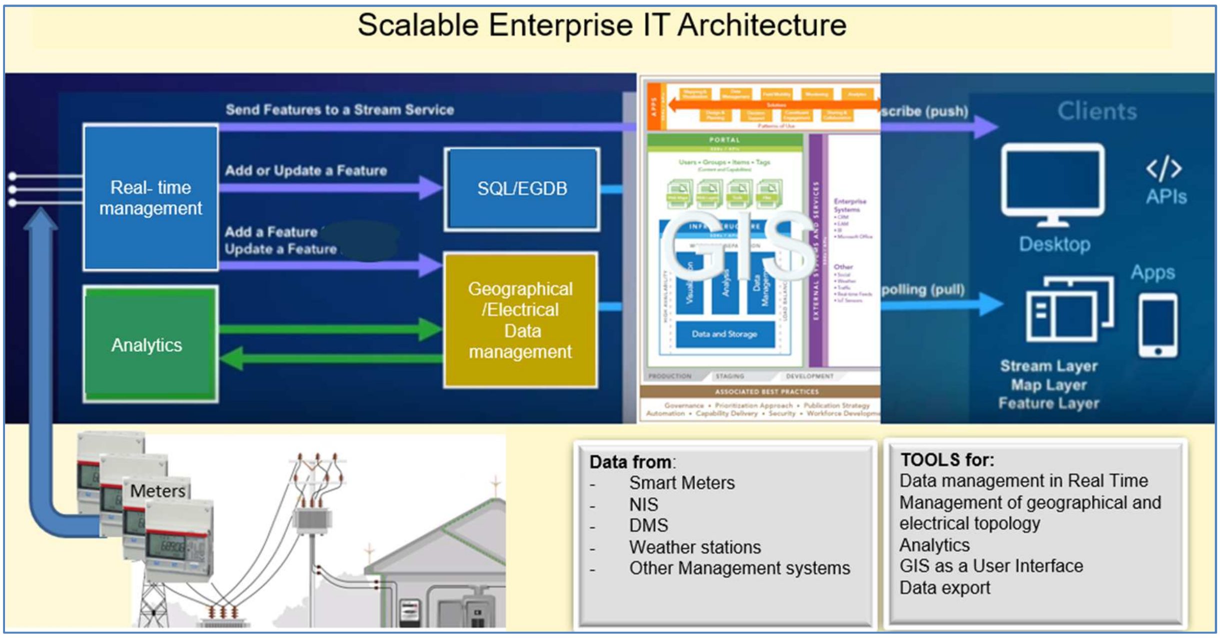

Figure 1: Basic Enterprise infrastructure[3]

In summary, near real-time monitoring requires:

[3] IT infrastructure created within PQP project (Sweden). Cooperation between Vattenfall and ESRI

- Meters / sensors that can be configured to register deviations in current, voltage per phase, etc,
- Data transfer as soon as a the deviation in meter is registered,
- Near real time management tools,
- Analytics tools for the use of AI, Machine Learning and self-developed algorithms,
- User-friendly GIS with options for visualization and advanced selection tool,
- Interface for information exchange in standard formats.

1.4. REQUIREMENTS ON IT SECURITY CONDITIONS

One of the outstanding topics related to AMI security is data protection and privacy. DSOs have to establish data management that will protect personal data and inform consumers how their data will be used and analyzed. The best option will be if DSOs give opportunity to customers to choose which data can be collected and analyzed from metering equipment on their measurement place for additional smart services. Currently, security on metering equipment is provided using DLMS (Device Language Message Specification) and COSEM (Companion Specification for Energy Metering) (IEC 62056, EN13757-1) standards and authentication i.e. passwords at different level (smart meters and applications). The development of AMI functionalities increases the consequences of potential vulnerabilities such as cyber-attacks which can damage the AMI. For this reason, it is important to improve and prepare strong IT security to prevent cyber-attacks. Some DSOs already use key management system that provide additional security to AMI.

1.5. REQUIREMENTS ON LAWS AND REGULATIONS

Law-makers and regulators are striving to establish unified energy market with best solutions for consumers, reassuring competition between diverse stakeholders. From this point of view, regulators prepare requirements that DSOs are obliged to reach. Regulators provide guidelines on technical abilities for meters, proclaim network and measurement regulations for DSOs - all this in order to improve services and encourage customers to actively engage in energy market - however, in an orderly manner and with strong IT security precautions. Currently regulations can differ between countries, but the trend is to harmonize rules across Europe. It is important that regulators expectations are linked with laws. Hopefully regulators shall not require improved data collection, granularity and data management if there is no law that supports the usage of such data. Additional prescriptions are necessary to clarify rules which data from AMI on LV grid DSOs should be collected to support requirements for reports about reliability and power quality in LV grid [2].

1.6. CONCLUSION

This section has set out the main conditions for LVM based on data from smart meters:

- An LVM infrastructure can be different, depending on what is being focused on.
- LVM can be used for near real time monitoring of delivery, power quality, flexibility, for proactive and predictive analyses and even control to some extent.

The main condition is that the customer meters meet the technical conditions for so-called smart technology. The proposal is that LV is equipped with smart meters of the second generation. Measurement, collection and data accessibility must be in near real time. In addition, scalable enterprise IT infrastructure is proposed. Advanced tools for data management in near real time, as well as, for back office analysis is needed. User interfaces that support GIS are suggested to be intuitive, ought to be supported by dynamic and interactive graphs, as well as, to be able to perform quick complementary ad hoc analysis through various selections in the filters. LVM shall be central system in processes between the operation centers, field crew and the customer. Data and information exchange between all stakeholders have to be secure and risks of data intrusion must be minimized.

2. State of the art of monitoring and control in LV distribution systems

A state of the art investigation of LV networks is needed, as well as feedbacks from different countries having already deployed smart meters and other monitoring devices, components for LV distribution system operation automation and corresponding control functions, to be able to draw relevant conclusions and recommendations for future monitoring and control of LV networks. Consequently, the CIRED WG 2019-5 decided to disseminated a survey to DSOs around the world to collect information on:

- the data available by the DSOs from the level of the MV/LV substations to the LV customers,
- the ongoing deployment of smart meters (data measured and granularity),
- the control functions by means of use cases deployed or under experiment.

The list of the questions asked in the survey is provided in the appendix. Up to now, 20 answers have been received from DSOs in 14 different countries: 14 from Europe, 3 from South America and 3 from Asia (see Figure 2). DSOs of different sizes have answered the survey: all of them supply more than 100 000 customers and about 65 % of them are large DSOs supplying more than 1 million customers (see Figure 3).

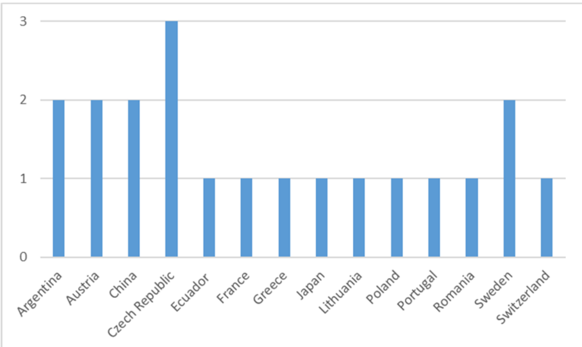

Figure 2: Number of DSOs per country answering the survey

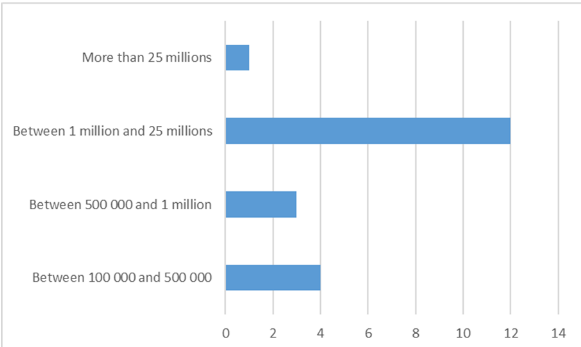

Figure 3: Number of LV customers supplied

The size of LV networks they operate range from lower than 10 000 km to more than 500 000 km (see Figure 4). Around 75% of the DSOs come from three different departments: conception planning and asset management, operation and maintenance and innovation departments showing their good knowledge of their networks and the challenges associated to future LV network design and operation.

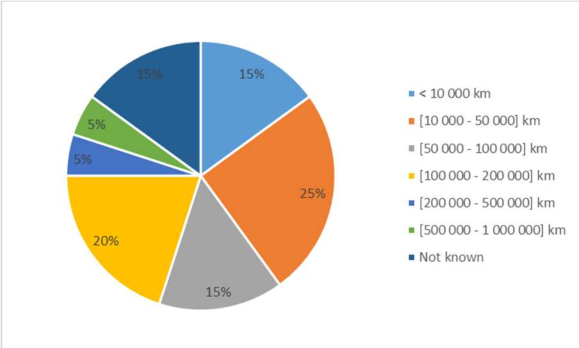

Figure 4: Percentage of DSOs per LV network length

2.1. GENERAL OVERVIEW

2.1.1. MV/LV substations

About 50% of respondents operate between 10 k and 50 k MV/LV secondary substations (see Figure 5). As shown in Figure 6, in average, DSOs used mainly typical installed capacity lower than 700 kVA per secondary substation. Two of them use only installed capacity lower that 100 kVA and one DSO mostly uses substation higher than 700 kVA. This choice is very dependent on the load density of the area covered by the DSO.

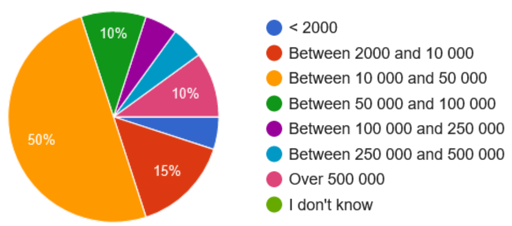

Figure 5: Number of MV/LV substations

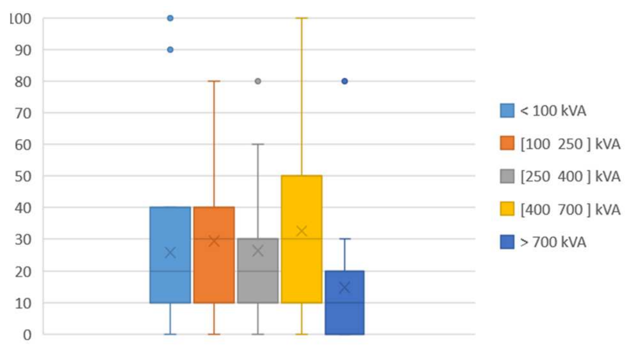

Figure 6: Installed capacity per capacity range (in percentage of occurrence)

The LV side of the MV/LV transformer is mostly solid grounded (one DSO uses a resistance neutral grounding and another a isolated neutral). About 55% of respondents do not use transformers with on load tap changer (OLTC) at the level of the MV/LV substations and 35% consider this solution only in particular case studies and it concerns either very few substations (<1%) or pilot projects. Only two countries reported to having installed OLTC at every MV/LV substations. The control of this OLTC is based on the secondary side voltage for most of the answers. For two DSOs, this control is based on feeder's voltage profile, provided by distributed measurement in the LV grid. Most of the OLTC used by respondents have 3 tap positions (-2.5%, 0%, +2.5%) but it can differ between countries. In the literature, other OLTC structures can be found such as 5 tap positions (nominal and +/- $2 \times 2.5\%$), 3 tap positions (-5%, 0%, 3.5%) and even 9 tap positions in [3] (nominal and +/- $4 \times 2.5\%$).

2.1.2. LV network topologies and protections devices

The main phase-to-phase voltage used in Europe is 400 V (80% of respondents), both 400 V and 210 / 105 V in Asia and 380 V or 220 V in South America. More than 50% of the LV networks have overhead lines for about 45% of respondents (see Figure 7). The main LV network topology consists of three-phase main feeders with single-phase connections for small customers and three-phase connections for larger ones (about 80% of respondents). This topology can be radial or looped / meshed with a radial operation mode since 65% of respondents answered that more than 50% of their LV network is radial (see Figure 8) and 20% of respondents answered that more than 50% of their LV network is looped / meshed with a radial operation. In some rare cases (less than 10% of the LV networks for 3 countries), the LV network can have a meshed operation. Only one DSO operates between 70 and 80% of its LV network as meshed. In case of LV looped / meshed topology (either operated radial or meshed), the LV network does not support reconnections (neither manual nor automatic) for 69% of DSOs. Some of them are investigating this service in pilot projects, especially for the case of underground LV networks. When known, the farthest distance between a customer and the MV/LV substation is usually lower than 250 m (about 60% of the customers concerns for 54% of DSOs having this information). For less than 10% of their customers, this distance can be higher than 1 km.

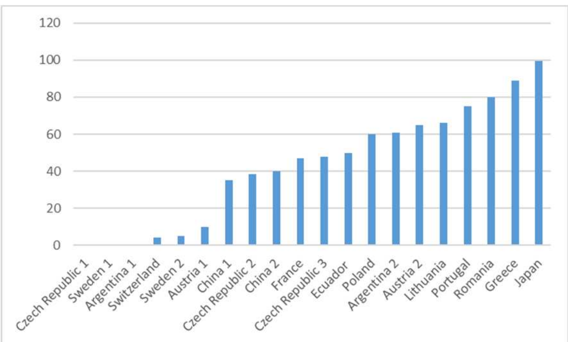

Figure 7: Percentage of overhead LV lines

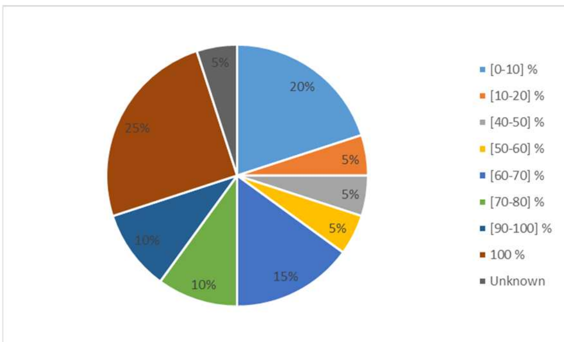

Figure 8: Percentage of DSOs having a radial topology

LV feeders are mostly protected by fuses since 74% of respondents have more than 90% of their LV feeders protected by fuses and 63% have less than 10% of their LV feeders protected by circuit breakers. Regarding the protection of the MV/LV substations, the answers are not so clear: a little bit more than one third of respondents have breakers and another third fuses to protect more than 90% of their LV busbars. Also, 90% of respondent are using fuses along the LV grid and 25% breakers (for example China use only circuit breakers in their LV networks).

2.1.3. LV network performance indicators

About 40% of respondents follow the EN 50160 standard for LV power and voltage quality assessment and 60% of them follow national standards. For about 60% of the respondents, the LV voltage magnitude must be between +/-10%. The remaining 40% have more restricted margins from down to +/-5% for three DSOs. As shown in Figure 9, voltage and power characteristics do not seem to be a significant issue at the LV level. Indeed, considering a scale from 0 (no importance) to 10 (very important), all the indicators except for the voltage magnitude variations / deviations has a median value lower than 4. The indicators having at least one time a grade of 10 are voltage frequency and magnitude variations / deviations, voltage fluctuations, rapid voltage changes, voltage flicker and long-term supply interruptions (typically longer than 3 minutes).

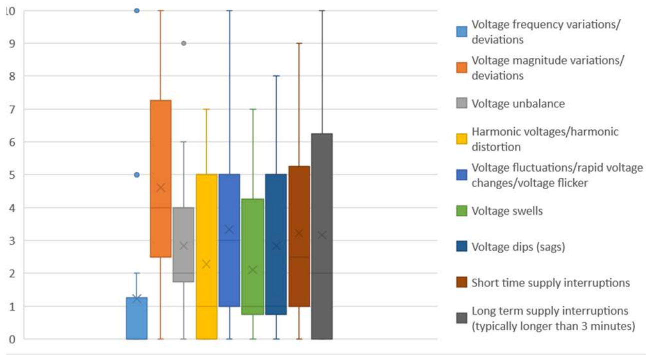

Figure 9: Degree of severity of quality indicators from 0 (no importance) to 10 (very important)

2.2. DATA AVAILABILITY AND CONTROL FUNCTIONS

2.2.1. Availability of topological data

As shown in Figure 10, only 63% of DSOs have a good knowledge of the LV network geographical representation on Geographical Information Systems (GIS). Most DSOs have information of the feeder where each customer is connected to and on the LV line diagram (knowledge of more than 80% for 68% of respondents) but not on the connection phase (only 32% of respondents). Some DSOs do not have any information of the feeder (10% of respondents), of the line diagram (15% of respondents) or of the phase (26% of respondents).

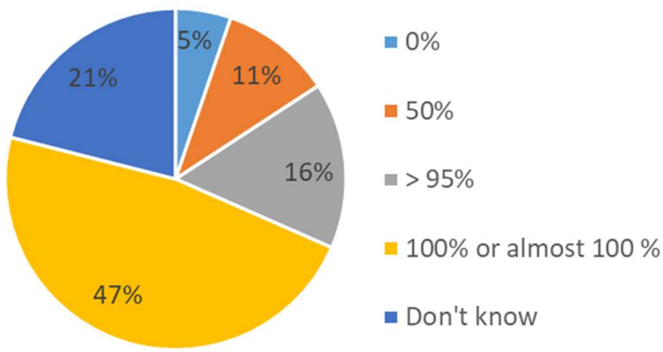

Figure 10: Percentage of GIS information of the LV network

2.2.2. Availability of measurements at the level of the MV/LV substations

About 73% of respondents have both on-line and off-line measurements but only 15% have a significant amount i.e. more than 90% of their data measured on-line. Most of them (57%) have less than 10% of their data measured on-line. Two DSOs have all their data measured (one on-line and the other off-line). Three DSOs do not have any measured data and use mathematical models they develop themselves. As shown in Figure 11, the main data measured are RMS values of voltages and currents, powers (per phase and summed three-phase values). Among the respondents who have measurements, 46% follow the European standard EN 61000-4-30, 18% a national standard and 36% stated they do not follow any standard. 35% of respondents use specialized meters or sensors along the LV lines in specific cases.

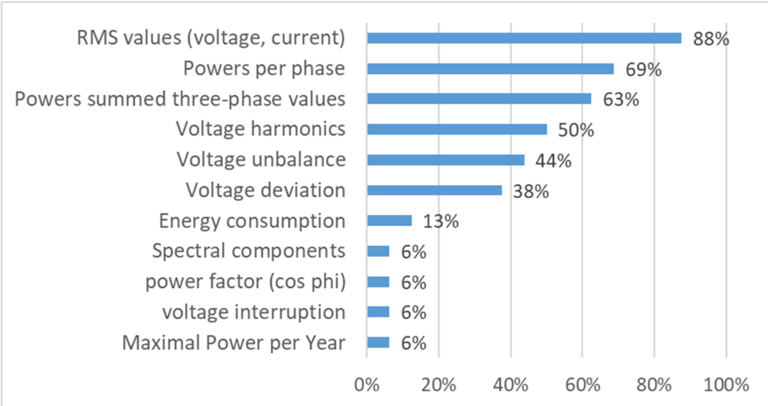

Figure 11: Quantities measured, recorded and collected

2.2.3. Smart meters

Figure 12 shows that only about 30% of respondents have more than 75% of smart meters in their network. The oldest starting date was in 2000 and the oldest ending date was in 2008. It can also be seen that 26% of respondents have no smart meters or only have some pilot projects. 80% of them plan to deploy smart meters in a near future (between 2021 and 2024). In the rest of this section, the percentage of respondents will be expressed regarding the number of DSOs having at least a percentage of smart meters higher than 0, i.e. 14 DSOs in total. Figure 13 provides the list of data measured by the smart meters.

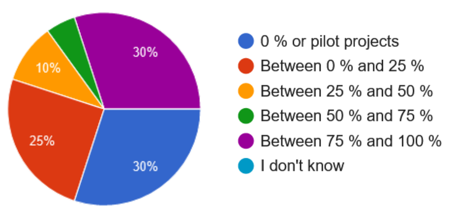

Figure 12: Percentage of deployment of smart meters

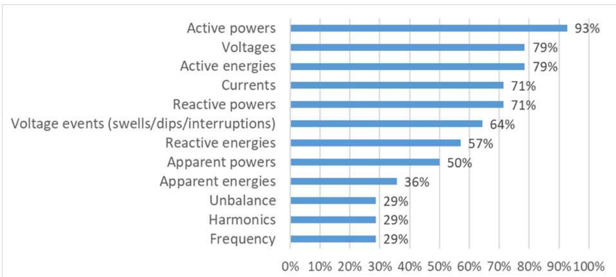

Figure 13: Data measured and provided by the meters

It can be noticed that the main ones are:

- Active powers (more than 90% of DSOs) every 15 minutes for 50% of DSOs. Few of them have smaller step times (from 1s-snapshot to 10 minutes).
- Energies and voltages with the same granularity as for active powers.

- Reactive powers and energies, currents and voltage events such as swells, dips and interruptions (more than 64% of DSOs).

According to the respondents, these data are mostly stored in a cloud, in a dedicated central data storage or in the meter, or sometimes in the data concentrator. These data are available in near real time for 64% of the respondents but are downloaded only once a day for most of the cases. Possible time delays can range from several seconds to minutes depending on the communication system. Some meters (for 20% of DSOs) can send or record messages based on a condition fulfilment such as the date and time of the power restoration after an outage, which will be available when the meter will be read by the DSO. Currently, the smart meters are mostly used for performing remote disconnection and reconnection of customers (around 80% of the respondents). About 30% of DSOs also use the meter for the remote control of loads as shown in Figure 14.

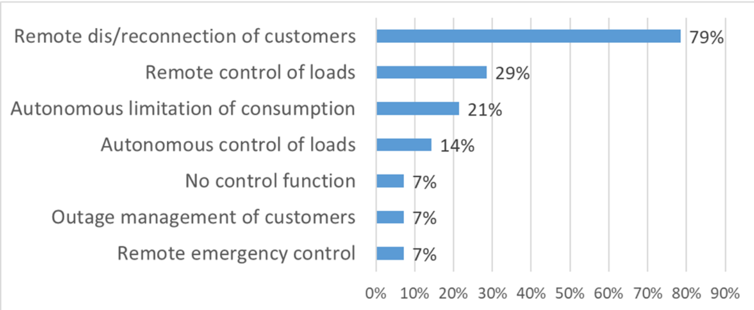

Figure 14: Smart meter's control functions already deployed

About one third of the DSOs are using or testing the smart meter data to control the voltage profile automatically (software embedded in the system) and 14% claim to use it to perform optimal power flows. In the future, the main use cases envisioned by DSOs to be developed are: outage identification, voltage quality violation identification, technical losses refinement and non-technical losses identification and delimitation (see Figure 15).

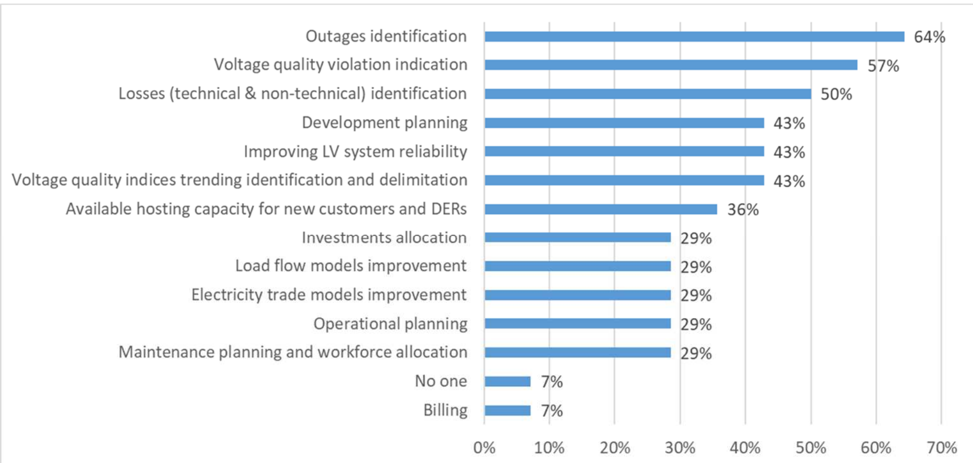

Figure 15: Use cases of the smart meters' data for LV distribution system management

2.3. FUTURE MONITORING AND CONTROL OF LV NETWORK

2.3.1. Synthesis of the DSOs' motivations

The survey that was conducted has highlighted five main drivers for developing monitoring and control functions at the level of LV networks.

- **LV network operation Improvement**: voltage profile control, remote management of loads, balancing of consumption and production, optimal power management, fault detection, location and management, reduction of operation and maintenance workload, regulation of prosumer connection and development of flexibility services.
- **Distributed Energy Resources (DERs) accommodation**, particularly microgeneration and electric vehicles.
- **Network efficiency improvement**: quality of service, power quality, reliability, minimization of power interruptions (SAIDI and SAIFI).
- **Management cost improvement**: OPEX reduction (including losses costs) and investment planning optimization.
- **Society expectation**: compliance with customer expectations and regulatory obligations.

2.3.2. Requirements for a successful deployment

The requirements identified from the survey for a successful deployment of monitoring and control functions have been classified into 4 categories:

- **Communication and technologies**
    - **Smart meters** must be implemented with remote control functions both at the level of the customers and at the level of the secondary substations. The equipment used must be autonomous.
    - **Simple and plug and play technologies** for both measurements and control.
    - **Standardization** of equipment and communication protocols: definition of telecommunication network (wired such as metal cable or optical cable, wireless including 5G) compliant with the IEC 61850 standard, monitoring granularity (1 s, 1 m, 1 h, etc.) and control points (control devices, smart meters, etc.)
    - **Autonomous equipment** such as smart secondary substation or other autonomous devices able to communicate between them.
- **Data**: the availability of good quality and reliable data and their integration into the system.
- **Market evolution**: Thorough tender preparation, IT implementation, suitable multiple vendors on the market and staff technical training.

2.3.3. Ongoing demonstration projects

About 60% of respondents have provided examples of ongoing projects either national or European where they are involved. These projects can be classified in 4 categories:

- **Metering infrastructures**: projects investigate the deployment of smart meters for customers but also at the level of the MV/LV substations in order to develop Advanced Distribution Management Systems (ADMS) for the low voltage level. Some projects are testing the interest of advanced LV controller for one or several of the following functions: remote self-healing, monitoring, DER management, Smart meter mapping, Fault and quality issues detection: broken neutral, phase loss, short-circuit.
- **New technologies in LV**: smart Secondary Substations (SSs), OLTC, series LV/LV transformers, storage mainly for voltage control purposes.
- **New topology**: LV network operated in closed loop (operation of two transformers in parallel), internal projects.
- **Interoperability platforms between DSOs and flexible market**

2.3.4. LV Use cases of interest for DSOs

Figure 16 represents the classification of uses cases made by the DOSs following their interest and the status of deployment. For the use cases “voltage quality improvement” and “continuity of supply improvement”, the same proportion of DSOs has either on-going development or appears to be very interested in it. As stated before, this may be explained by the ability of some smart meters to record some events and send the information to the DSO. More than 50% of DSOs are interested in enhancing the utilization of the LV distribution system, managing flexibility and enhancing the hosting capacity. Unlike the two previous use cases, there is almost no on-going deployment because the complexity is higher since more equipment and actors may be involved. DSOs are interested in better allocating their investments to optimize their TOTEX as well as non-economic indicators such as reliability and environment. Finally, respondents point out additional use cases that they would like to be developed in the future: application of machine learning and advanced analytics to smart metering data, smart EV charging functions, protection function for meshed low voltage network (this last use case is very specific to a country having meshed LV networks).

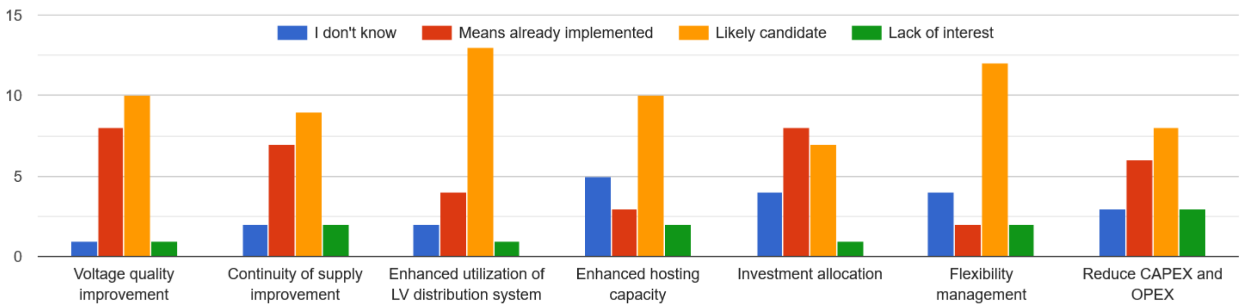

Figure 16: Use cases of the smart meters’ data for LV distribution system management

2.4. CONCLUSION

This survey provides an overview of the way LV networks are designed and operated, as well as the visions of a number of DSOs on their future evolution, especially in terms of monitoring and control. A total of 20 answers have been received from three continents and various sizes of DSOs. The main conclusions that can be drawn are that the deployment of smart meters (or any other device able to make measurements) are the first brick essential to develop control functions in the LV network. Many use cases are envisioned by DSOs, yet their development will depend on the associated cost, their compatibility with other equipment (communication issues), their adaptation to the existing system and the training of operators.

3. MONITORING OF LV NETWORKS

3.1. MONITORING FOR POWER QUALITY AND RELIABILITY

Most DSOs deploy regular monitoring only on the MV network, while monitoring on LV network is done occasionally, usually in response to consumers' complains. However, to meet the modern power quality and reliability standards, DSOs need to perform regular monitoring, which requires a large number of devices deployed over the LV network. Most of the DSOs have implemented AMI on their LV network, since smart meters are the most promising solution to enable control and observability over the LV network. Some smart meters implementations are already compatible with EN 50160 standard, expressing useful and indicative results for power quality measurements. Smart meters enable DSOs to detect important power quality measures like voltage variations, voltage dips and swells, interruptions, harmonics, and power frequency.

3.1.1. Standards review

Power quality can be described as the electrical characteristic of the electric power at a given point on an electrical system, represented by a set of reference technical parameters [4]. Developments in technology have made it possible to monitor power quality with smart meters installed at customers. The challenge is that the new matters in the subject are rapidly growing while the establishment of standards take a long time. Practically, we have every day a new deviating power quality patterns that are not described in standards, for instance, new types of super harmonics and subharmonics [2]. Nevertheless, it is important to perform Power Quality Monitoring (PQM) to verify compliance with standards, assess the performance of the system, and enable troubleshooting as well as advanced applications.

Voltage variations

Standards instruct that measurement should be taken under normal operating conditions, when supply voltage variations should not exceed ± 10 % of the nominal voltage, for 95 % of the rms values during one week and should not exceed + 10 – 15 % of the nominal voltage, for 100 % of the rms values during one week. In cases of electricity supplies in networks not connected to transmission systems or for special remote network users, voltage variations should not exceed ±10 - 15 % of the nominal voltage [5]. If smart meters are configured to follow up voltage deviation, digressions can be detected in similar way as with certified PQ (Power Quality) analyzers. One important thing that has a considerable influence on power quality measurements is "Flag Detection" which currently can´t be conducted by smart meters. Certified PQ analyzer includes flag detection function as required by the standard EN 61000-4-30. During a dip, swell, or interruption, the algorithm for measurements of other parameters (for example, frequency measurement) might produce an unreliable value. The flagging concept prevents counting a single event more than once in different parameters (for example, a single dip is counting either as a dip in voltage or a frequency variation), and indicates that an aggregated value might be unreliable. Flagging is only triggered by dips, swells, and interruptions. The detection of dips and swells depends on the threshold selected by the user; consequently, this selection will influence which data are "flagged" [4]. Instead of flagging data, smart meters detect dips and interruptions as events. Smart meters are supposed to work with the following specifications:

- Observability time slot of 10 min.
- Predefined threshold for detection of deviation.
- If a dip/swell or another interruption occurs within the time slot, an event has to be created. Most significant difference between certified PQ analyzer and smart meters measurement occurs if power outage happens.
- Smart meters have to detect power outages, which are substantial fault sources for event registration. If power outage is detected within observability time slot, voltage should not be validated.

Voltage dips and swells

Voltage dips are typically caused by faults occurring in the public network or in customers' installations. Voltage swells are typically caused by switching operations or load disconnections. Both phenomena are unpredictable and random. The frequency varies depending on the type of supply system and on the point of observation. Moreover, the distribution over the year can be very irregular. Conventionally, the dip start threshold is equal to 90 % of the nominal voltage; while the start threshold for swells is equal to the 110 % of the nominal voltage. Voltage dips are, by their nature, highly unpredictable and variable from place to place and from time to time [5]. Smart meters scarcely meet/follow standards regarding capture time for dips and swells. Instead, we are talking about thresholds for dips and swells that is +/- 10% of the nominal voltage.

Voltage interruptions

Reliability can be defined as the ability of power system to deliver electricity to all points of consumption - in an adequate quantity and with the quality demanded by the consumer. SAIFI (System Average Interruption Frequency Index), SAIDI (System Average Duration Frequency Index), and ENS (Energy not Supplied) are some of the indicators used to measure distribution system reliability [6]. Power outages are, by their nature, usually unpredictable and variable from place to place and from time to time [5], [7], [8]. Traditionally, DSOs were forced to wait for customers complaining for interruptions in LV networks to take actions, while smart meters are providing a chance to detect interruptions individually for each measurement place. DSOs are now able to know the extensions, start-time, duration, and even locations of the interruptions directly for measurement places [9]. Standards separate long (sustained) and short (instantaneous) duration interruptions. Sustained interruptions are the interruptions that carry on longer than three minutes (or larger- depending on the DSO or regulator), while the interruptions that remain less than three minutes (or larger, depending on the DSO or regulator) are regarded as momentary interruptions [5], [7], [8]. Using smart meters, we can detect all sustained interruptions, while any of instantaneous interruptions remain undetected. On the other hand, it is important to detect interruption as fast as possible, to enable DSOs to find rapidly outages in the network, in order to improve distribution systems reliability.

Smart meters

One of the most important and useful features of smart meters is enabling DSOs to detect all sustained interruptions, which in turn, empowers calculation of SAIFI, SAIDI, ENS, and other distribution systems reliability indicators. Furthermore, DSOs need another type of data (for instance work orders and weather conditions), to anticipate interruptions causes, like external events, exceptional weather conditions, third party interference, industrial action [10], [11]. Combining data from all these sources, DSOs can prepare monthly and yearly reports for consumers and regulator. Furthermore, this back-office data analytics empower DSOs to detect and explore the weakest parts of his network, as well as, a critical components. Results from back-office analysis can be advantageously used proactively to initiate extra inspection, maintenance or investment in rebuilding.

Voltage harmonic

Smart meters can detect harmonics following the standards, which indicate that the measurements should be performed under normal operating conditions, during every of “one–week period”. In the measurement period, 95% of the 10 minutes, mean RMS values of each individual harmonic voltage shall be under a threshold required by standard. The THD (Total Harmonic Distortion) of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8% [5].

Flicker

The new generation of smart meters have functionality to detect disturbances called “flicker”. The intensity of the flicker annoyance is evaluated by the following quantities: short term severity measured in a 10 minutes period and long-term severity calculated from a sequence of twelve short severity values over a 2 hours interval. Measurements should be taken under normal operating conditions, during every one-week period. The Long-Term Flicker Perceptibility (Plt) caused by voltage fluctuation should be less than, or equal to 1 for 95% of the time [5].

3.1.2. Regulator's requirements

Regulatory agencies put pressure on DSOs to provide information about power quality from LV level in the future. DSOs need to find solutions how to obtain constant PQ monitoring on LV level. Monitoring of quantities like voltages, currents, frequencies, harmonics, on LV level will also help DSOs to control the whole system, more efficiently, as, to care for individual measurement points and consumers [2]. Usually, all DSOs are applying the standards, but a small difference may occur due to their national own guidelines. In Europe, DSOs are not obliged to report shortcomings in power quality, but as mentioned in the paper, everything says that the issue is becoming more and more topical and it is expected that power quality on LV will be also followed. In most of European countries, there are currently no demands to make reports for LV power quality. PQ measurements are compulsory just in a case of consumers complaints. However, in the future, the regulation will integrate requirements on LV power quality [2].

3.1.3. 5G technology

To enable quality in near real time data flow from smart meters, or other sensors for constant PQ monitoring on LV level, it is necessary to establish high quality communication infrastructure. Some projects have already shown that 5G mobile networks is a solution to overcome previous standard limitations [11]. It is expected that 5G mobile networks can efficiently support the basic IoT requirements, which includes also smart meters, such as a good coverage, high data throughput, low latency, high scalability, etc. [11]. Development in communication technologies will enable near real time collection of extreme amounts of data that DSOs need for smart applications solutions and LV monitoring. However, even 5G mobile networks are not expected to bring all solutions for communication issues. Massive number of IoT devices brings challenges to 5G network from the perspective of access reservation protocols and transmission performance [1].

3.1.4. Lessons learnt from real projects

Case of Slovenia

Project description

A Slovenian DSO, Elektro Ljubljana, performed a project that has tested and compared voltage variations results between certified PQ analyzer and smart meters. Smart meters has 10 min time slot of voltage measurement like standard requires [5]. The average difference between smart meters and certified PQ analyzer measurements of voltage was 0.16 V per 10 min time slot. The difference has been based on calculations from weekly measurements of 20 houses. Figure 17 compares voltage measurements of the three phases (L1, L2, L3) from a PQ analyzer (Uref) and a smart meter (UG3) for one house.

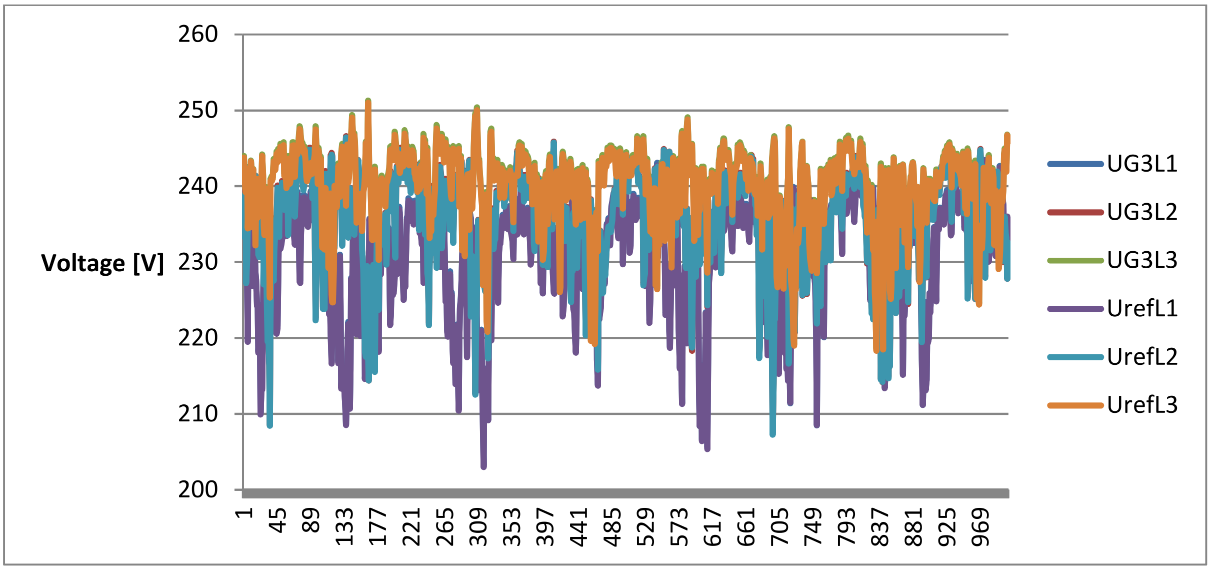

Figure 17: Voltage measurements from a PQ analyzer and a smart meter

Measurement was scheduled for one week like standard requires and there are 1008 measurements in 10 min time slots available for comparison [5].

Voltage measurements done with smart meter (UG3) do not deviate too much from voltage measurements done with certified PQ analyzer (Uref). With both measurement tools we confirmed that voltage variation is like standard require on that house [5]. Table 1 presents the average and maximum differences of voltage measurements between both measurement devices on each phase. We see that the average difference between measurements is small and that smart meters follow standards and certified PQ analyzer regarding voltage measurements. There were just three 10 min time slots during the week when voltage measurement was not like the standard requires ($V < -10\% \, V_{nom}$).

Table 1: Difference of voltage measurements between PQ analyzer and smart meter

	L1	L2	L3
Average difference [%]	0,09	0,07	0,14
Maximal difference [%]	0,81	0,61	0,52
Number of measurement time slots when voltage deviation is bigger than expected from standard (V > $10\% \, V_{nom}$ or V < $90\% \, V_{nom}$)	3 only detected by PQ analyzer and smart meter	0	0

Outcomes of the project

The project has confirmed that the smart meters can be as efficient as PQ analyzers to detect low voltage quality locations. The project also confirmed that the smart meters do not enable flagg detection as certified PQ analyzers automatically do and that this obstacle can be solved with post-treatment analyzes of smart meter data. When smart meters detect interruptions voltage, frequency and harmonics, measurements should not be taken into account (wrong measurements).

Case of Sweden

Project description

LVM and PQP (Power Quality Predictions) pilot projects were performed by the Sweden DSO Vattenfall Eldistribution from January 2016 to December 2020 in cooperation with ESRI (Environmental Systems Research Institute), a GIS provider, and VOLUE, a technologies supplier. The goal was to investigate whether data from customers' smart meters could be used for monitoring the LV network. More precisely, the purpose was to investigate whether the data of the meters sent in near real time could be used for the detection of various faults, such as broken neutral, phase loss, serious voltage variations at facilities in the network and customer´s installations. The next step was to test if the data from the smart meters could be used to detect incipient errors and accordingly be used in proactive and predictive analyses. Preconditions of these projects are:

- Data from 750 000 first generation smart meters configured to deliver events as soon as they appeared. These events were available for analysis 2 to 10 minutes after detection of a deviation in the network.
- Analytics platform: several data-based algorithms were created using AI techniques such as machine learning, data mining and cutting edge technology in order to deal with the huge amount of data registered in the smart meters. These algorithms enabled in particular to detect broken neutral fault, phase loss and extreme voltage swells/deeps [12].
- GIS mapping for visualization of network topology and results of home-built algorithms

Outcomes of the projects

LVM has enabled to change fundamentally the way of working of the DSO. Approach became proactive from previous fully reactive. With LVM algorithms, in combination with NIS (Network Information System) data and with help of GIS tools, LV network became suddenly completely "visible". Shortcomings in the delivery were possible to detect before customers had complained and the fault was located without field crew having to patrol along lines and search for fault location. Figure 18 shows that LVM will arise alarm as soon as problem was detected and operator in the dispatching center can react immediately. Time to pay attention to and correct the error has decreased four times.

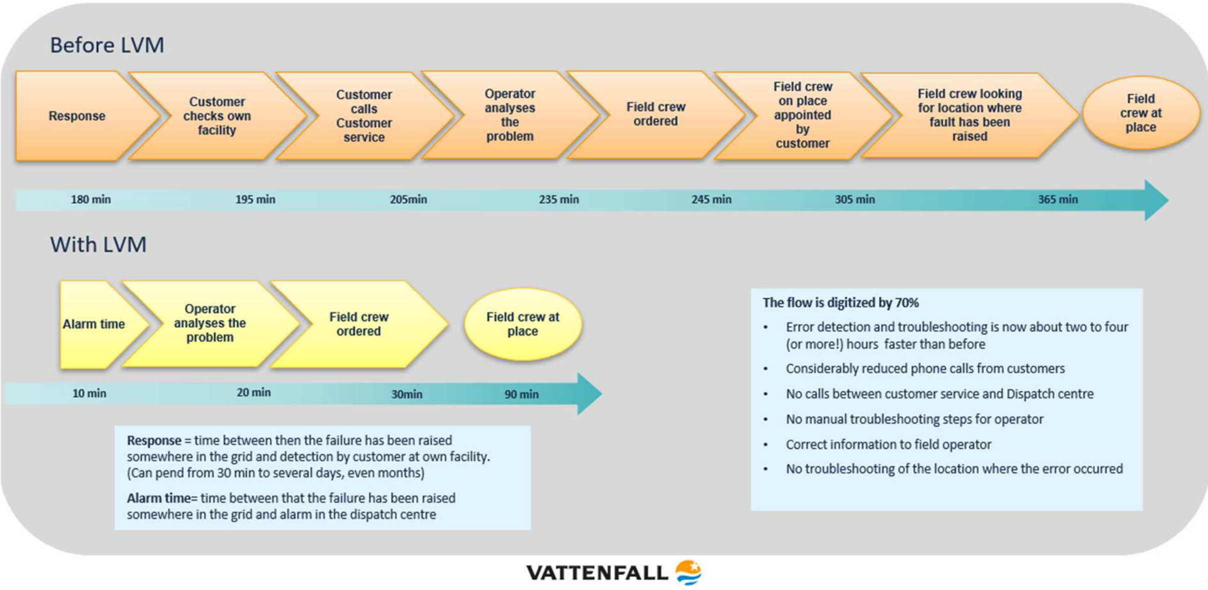

Figure 18: Savings in time achieved by implementation of LVM – Pilot project *Low Voltage Monitoring* performed at Vattenfall Eldistribution -Sweden through period 1 January 2016 - 30 September 2016

The results of various algorithms [12] and calculations, as well as tools for different filter functions are visualized in GIS dashboards. Ongoing acute disruptions or electrical quality problems at assets, or network area level can be followed in near real time or as animation in time[4]. Figure 19 shows an example of user interface where different symbols and colors were used to symbolize type, severity and extension of the power quality deterioration. In this particular case, the intensity of colored facilities (circles) in the map indicates the severity of

[4] *Animation in time* means being able to choose start and slut datum/time and with simple tool follow up the evolution of power quality through that period.

the voltage worsening (white meaning no deterioration to yellow meaning strong deterioration at the customer facility), while the size of circles describes the fuse size in the facility. Facilities (circles) colored in pink symbolizes problems with impedance and even here the color intensity symbolizes the seriousness of the problem. White colored facilities have no problem for the selected time span. In the same dashboard several maps and graphs can be presented, depending on chosen filters[5] (selection of a particular time or period, selection of a network area or facility, selection of a particular phenomenon you want to follow, predefined warnings and so on). Chose in the filters, graphs and map are interactive and are updated every 30 seconds.

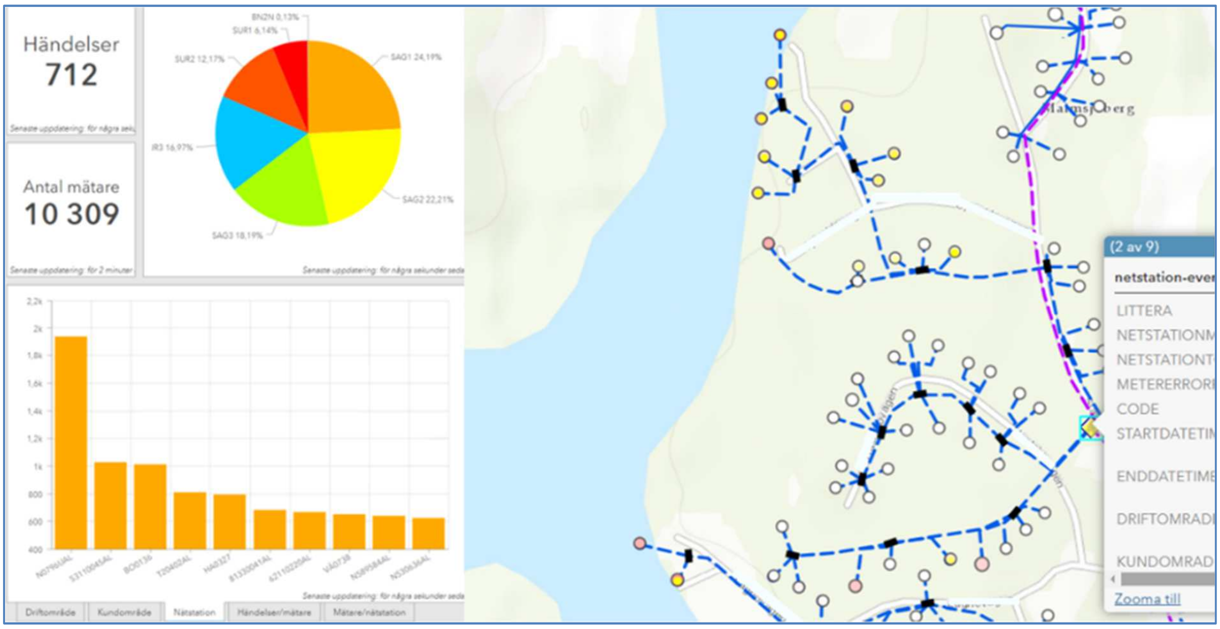

Figure 19 : LVM dashboard- developed within PQP project- Vattenfall Eldistribution- Sweden[6]

According to the experience during the project, user interfaces are suggested to be intuitive, should be supported by dynamic, interactive graphs, as well as the ability for quick complementary ad hoc analysis through various selections in the filters. Back office analysis are represented in interactive, sequentially windows (cards) as showed in Figure 20.

[5] Filters are not presented in the picture due to security restrictions

[6] Dashboard and belonging algorithms are developed in the PQP project performed during the period 1 January 2020- 30 December 2020 at Vattenfall Eldistribution Sweden

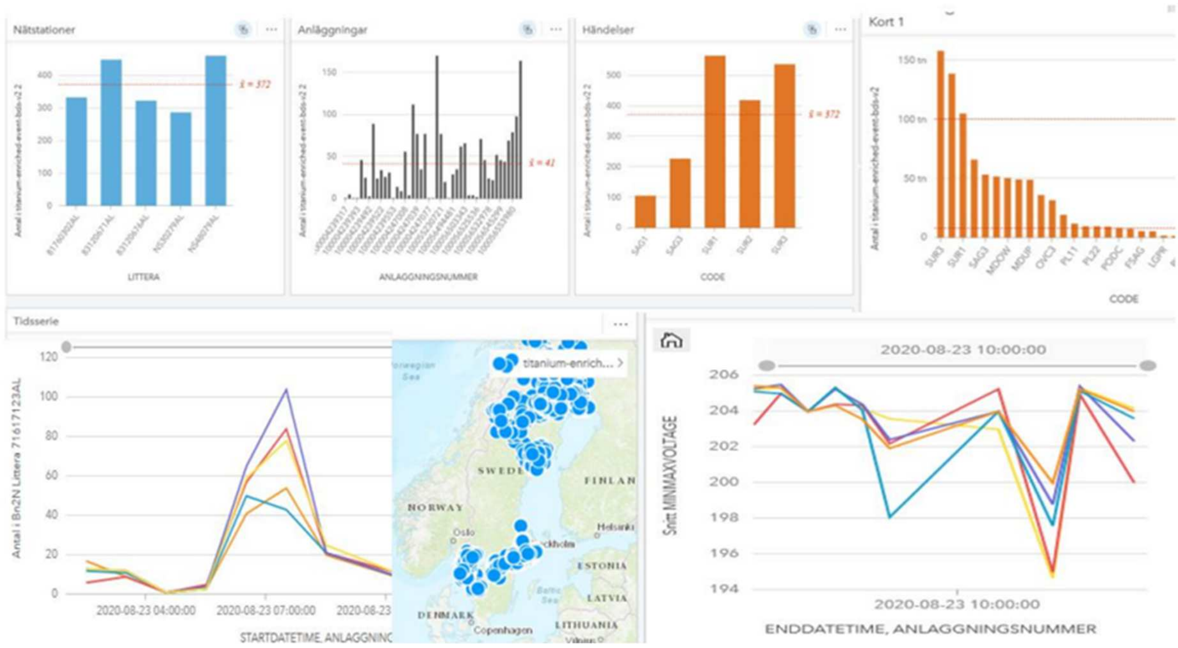

Figure 20: Interactive cards for back office analyses[7]

One, or several different patterns can be followed up simultaneously and presented in singularly graphs. All graphs are interactive with each other and can be animated in time, namely, the cards can show results in near real time, for a particular time or chosen period. All cards use the same data and are programmed to perform a particular analysis on a selected time or period. If the time or period changes then all cards will show appropriate results. The cards are interoperable to the extent that even if the network area in card 6 is zoomed in / out, requirement is accompanied by execution of corresponding results in all other cards.

Case of Japan

Project description

Kansai Transmission and Distribution Inc. (KT&D), one TSO and DSO in Japan, is currently operating a system that can visualize the outage area in low-voltage by utilizing the communication system of smart meters with a multihop wireless system[8]. Data measured at a given smart meter are transmitted to the adjacent one and so on by multihop routing method, and aggregated data is delivered to a concentrator, and then delivered to offices via optical cables. In this communication system, even if a fault occurs and uncommunicable smart meters cannot transmit their data, communicable meters are capable to transmit their data to the concentrator through the route avoiding uncommunicable smart meters. As a result, it can be expected that the uncommunicated location can be recognized as the fault location because the fault location and the uncommunicated location almost coincide. As of March 2021, the installation rate of smart meters is 93%, and the connection rate is over 99% in KT&D area. By taking advantage of this high installation and connection rate, it is possible to visualize outage area by displaying uncommunicated locations on a map.

[7] In the PQP project - Vattenfall Eldistribution Sweden used Microsoft Power BI to do back office analyses using outputs from own built algorithms.
[8] "One or more intermediate nodes along the path that receive and forward packets via wireless links" [86].

Outcomes of the project

The LVM system is able to discriminate the fault status by combining the presence or absence of faults in the MV network and monitoring information from customers. Detailed information such as the address of the utility pole and the number of outages can be collected, saving time and effort of consolidating information. The location information associated with the displayed utility poles can be linked to Google Maps, and make it possible to check the surrounding environment easily, which will help with fieldwork. This system will contribute to the improvement of reliability by enabling active and efficient initial response without monitoring from customers.

Case of United Kingdom

Project description

In the LV Network Solutions project (2012-2014), the DSO Electricity North West have equipped 200 MV/LV substations with the retrofit monitoring system developed by GridKey [13] in order to:

- better understand the LV network performances : transformer utilization, substation busbar voltages, voltage unbalance factor across phases, power factor, neutral currents, indicative values of total harmonic distortion, renewable hosting capacity;
- improve load estimation and prediction as well as the capacity headroom

The GridKey system used current sensors (typically flexible Rogowski coils) which enables live installation on individual cable cores. The date measured are sent by GPRS to the DSO's iHost server [14].

Project outcomes [14]

About 10 000 days of valid data per phase and per feeder were collected on 200 MV/LV substations covering 1000 LV feeders providing a good knowledge of the MV/LV substation and LV feeders behavior. In addition, a collaboration with the University of Manchester enables to:

- increase the knowledge of the monitored LV networks (connectivity, impedances, lengths)
- validate conventional load and low carbon technologies (such as PV and electric vehicle) profiles
- develop a Monte Carlo based method to assess the hosting capacity (maximal amount of low carbon technologies that customers can install without creating voltage or thermal constraints).

Case of Portugal

Odite-e is a French company, which develops data-driven algorithms to find the connectivity of LV networks, predict the LV network behavior as well as the future impacts of DERs [15] and propose back-office analysis and future planning actions (rebalance, reinforcement, reconfiguration) [16]. In particular, Odit-e has validated an algorithm able to find the complete topology of an LV network (feeder identification, phase identification and network tree) based on the voltages measured from smart meters over a period of one month with a step time of 15 minutes. In collaboration with EDP Distribution, it has validated their algorithm on two test cases [17]:

- Allocation of 483 LV meters to 5 MV/LV substations with 99% of accuracy
- Research of the complete topology of three LV networks (215, 125 and 112 meters)

3.1.5. Technical and economic interests for LVM based smart meters data

Improvement of reliability and safety

Even serious faults, like broken neutral fault and phase loss, can be detected, which increases safety in the network for both society and field crew. An early detection, localization and determination of fault enables proactive actions, which in turn, decrease SAIDI and prevent disturbances in power quality.

Optimization and savings

Smart meters can provide power quality management teams with power quality data of the whole LV network. In that way, complex back office analyses can be done such as predictive maintenance, both short and long-term network investment plans that can benefit from synergies from other internal and external investment projects. Other proactive (such as the reduction of the restoration of supply) and predictive actions (work prioritization) can also be taken thanks to the faster recognition of network having a declining power quality. Accordingly, there will be fewer complaints from consumers, which will reduce DSO expenses. Indeed, in case of complaints, the DSO is forced to do expensive field measurement with certified PQ analyzers. Once smart meters are deployed, the cost of LVM is low (between 200 k€ and 300k€) but LVM requires a knowledge on how to build algorithms: data understanding, being proficient to combine and analyze the data and finally to translate them to algorithms.

Digitalization of processes

LVM paves the way for further digitalization in processes between customers, dispatch center and field crew since most of the manual work done in the dispatching center can be digitized. A first benefit is related to the streamlined process for handling of customers´ complaints. LVM based on data from smart meters, supplemented with data from other sources, can be easily upgraded with functions for monitoring of new additional services such as flexibility.

3.1.6. Conclusions

The DSO Slovenian Elektro Ljubljana has concluded that voltage quality can be estimated indicatively using smart meters. It should be noted that smart meters give DSOs a chance to gain control over the LV networks, nevertheless, they may not substitute the certified PQ analyzers. Swedish project outcomes shows that smart meters can be used advantageously for proactive and predictive monitoring of phenomena in Low Voltage networks. Smart meters data are an economic solution that, in combination with the advanced cutting-edge AI and data analytics, provide a reliable and powerful tool, which gives possibility to avoid unnecessary costs for installation of extra sensors (as demonstrated also by Odit-e in several trials). LVM based on data from meters, combined with data from other sources, like weather stations, DMS and some data from SCADA systems as well as PQ meters can provide a progressive tool for capacity/hosting capacity and later also flexibility monitoring. Also, as demonstrated by the DSO Electricity North West, existing MV/LV substations can be upgraded to embed LV monitoring functions. Future monitoring functions could also include ambient and transformer tank temperature, which can assess, for example, their real reserve instead of the theoretical one. Future applications may also include some partial discharge monitoring, particularly where there may be switchgear known to be susceptible to partial discharge and nearing end-of-life.

3.2. MONITORING TO ANTICIPATE LV NETWORK PLANNING

Low voltage network is planned according to the type of area (urban, rural for example), power levels and quality of service. Also, electromobility and DERs will have a high impact on the network regarding power flows and voltage stability [18]. In some cases, it is possible to reconfigure the current network topology to another type, but in most cases, it is not feasible due to technical issues or economical costs. Therefore, especially new network extensions or extensive reconstruction should be considered in terms of network topology.

3.2.1. Description and comparison of network topology

Radial network

Feeders in the radial network are connected and supplied from one substation and can branch out in multiple directions. Network usually includes fuse cabinets[9], where the network can be reconfigured in case of fault or planned maintenance [19], [20]. Table 2 describes the basic equipment of an LV radial network and some possible advanced one.

Table 2: Basic and advanced equipment of LV radial network

Basic equipment	Possible advanced equipment
Manual transformer tap-changer	OLTC transformer
Main busbar circuit-breaker with overload protection	Remotely controlled main busbar circuit-breaker with overload protection, comprehensive protections including short circuit faults and earth faults
Busbar online/offline PQ monitoring	Frequency protection for load-shedding
Station feeders with fuses	Station feeders with remotely signalized fuses / remotely controlled circuit-breakers
Network cabinets with fuses	Busbar and feeder online PQ monitoring and measuring
	Network cabinets with remotely signalized fuses

Figure 21 shows an example of a radial LV network architecture.

[9] boxes where the network divides into more branches

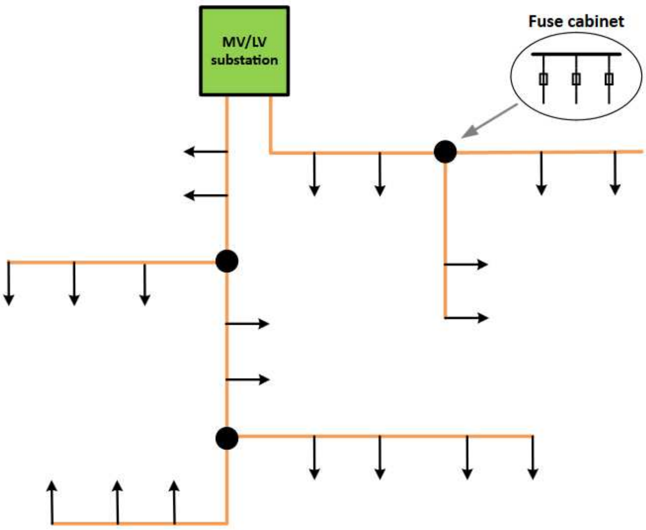

Figure 21: Example of radial network topology

Open/closed ring network

In high density cities, the LV network may have an open ring/loop topology. As for the radial network, ring network is supplied from one substation but with the difference that some ends of branches are linked together. The network can be operated in two configurations whether the link is normally open or normally closed as depicted in Figure 22 [19], [20].

- **Open ring** – network is normally operated equally to radial network and link is used for maintenance or fault switch-over
- **Closed ring** – network is normally operated in ring connection with weak coupling fuses in breakup points which in case of fault separate the healthy branch from the afflicted one

The basic and advanced equipment of the LV ring network are the same as in Table 2. One network cabinet with fuses is located one each ring.

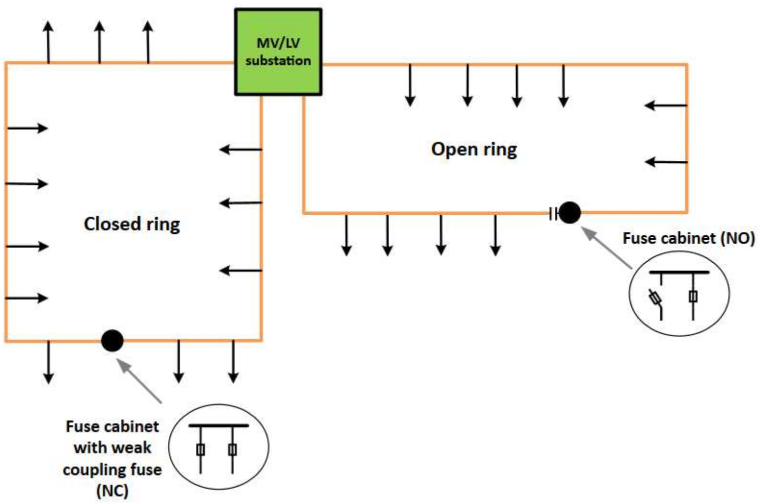

Figure 22: Example of open/closed ring network topology

Open/closed loop network

In contrast to the ring network, loop network is supplied from two substations with linked branches together. Then loop and substations can be supplied from one or two MV lines and therefore MV fault may not affect the LV network. In order to prevent powering MV fault from LV network, the substations must be equipped with reverse power flow protection. The network can be operated in two configurations when link is normally open or normally closed [19], [20] as depicted in Figure 23.

- **Open loop** – network is normally operated equally to radial network and link is used for maintenance or fault switch-over
- **Closed loop** – network is normally operated in loop connection with weak coupling fuses in breakup points which in case of fault separate the healthy branch from the afflicted one

In addition to the basic equipment Table 2, there are also reverse power flow protections in the case of closed loop. As for the ring network, weak coupling fuses enables reconfiguration of the network in case of faults.

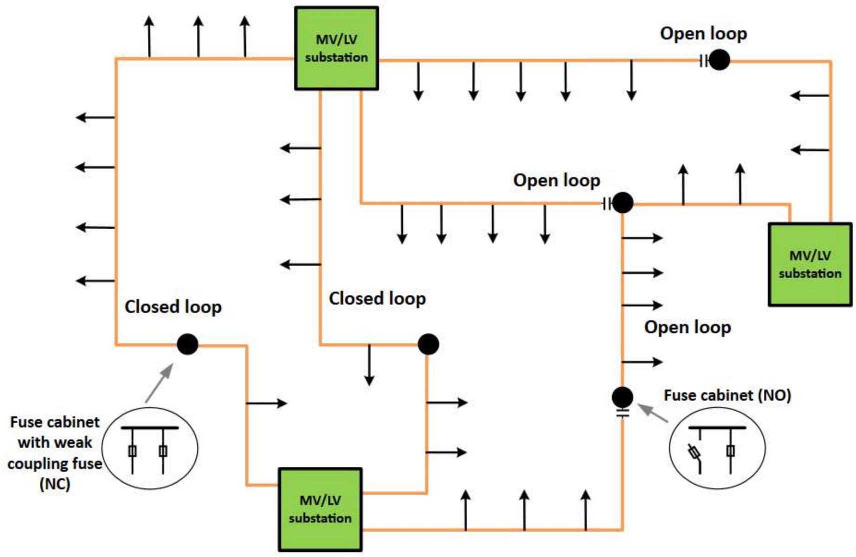

Figure 23: Example of open/closed loop network topology

Mesh network

Mesh networks are used especially in cities with high power consumption density. The entire network is interconnected together, supplied from a minimum of two MV/LV substations and from a minimum of two MV lines. Branches are linked together with fuse cabinets with weak coupling fuses and in case of fault only afflicted branches are disconnected [19], [20] as depicted in Figure 24. The basic and possible advanced equipment are the same as for the looped network.

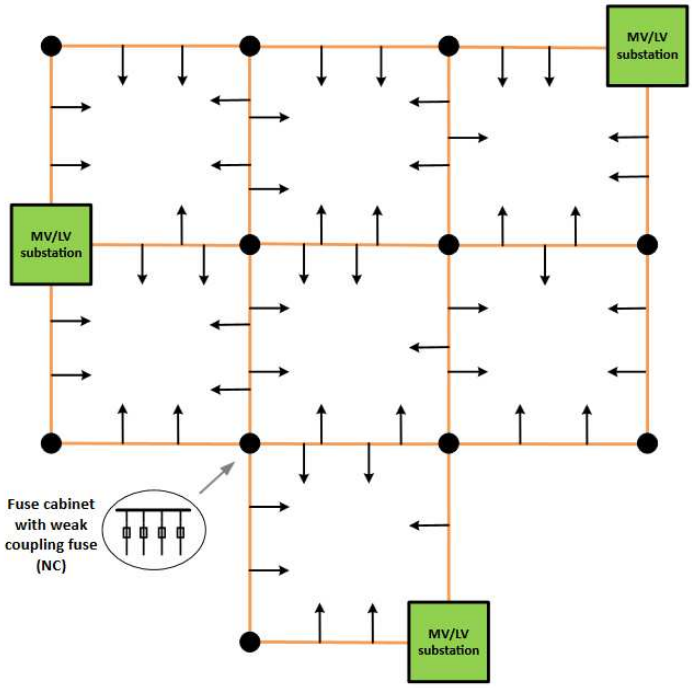

Figure 24: Example of mesh network topology

Comparison of network topologies

Radial networks are usually operated in low power consumption density regions, where distances between customers are long and thus, the power lines are too extensive to form rings or loops. Table 3 provides the advantages and drawbacks of the radial network.

Table 3: Advantages and drawbacks of the radial network

Advantages	Drawbacks
Low costs (investment and operational)	Elimination of one element during planned work cannot be easily switch over
Easy to maintain in terms of network topology and protection (long distances may make difficult maintain in field)	Fault impact is unpredictable (may cause disconnection of one customer or entire feeder)
	Voltage drop at the end of line may be significant (high voltage difference between start and end of line may cause unfeasible solution of voltage drop)

Open ring/loop networks are a modification of radial network to eliminate impact of planned work and speed up power restoration after fault. The enhancement requires higher investment costs when it is necessary to connect ends of the lines together, which reduces length of specific lines but increases density of the network and total length of lines. Table 4 provides the advantages and drawbacks of the open ring/loop network.

Table 4: Advantages and drawbacks of the open ring/loop network

Advantages	Drawbacks
Work in network mostly do not affect electricity supply, because of switching over	Fault affects entire line or section behind blown fuse
Restoration of electricity supply after fault can be carry out immediately only with disconnecting afflicted section	Interconnection of network put higher requirements on control and maintain
	The costs increase

Closed ring/loop networks are step further in interconnecting network. Instead of dividing line into halves, the line is connected with weak coupling fuse. This brings enhanced solving faulty phenomena but also more complex control of network. Table 5 provides the advantages and drawbacks of the closed ring/loop network. Mesh networks are complete interconnection of MV/LV substations though LV network, which grant the highest reliability and the most options for the price of complexity. Table 6 provides the advantages and drawbacks of the closed ring/loop network.

Table 5: Advantages and drawbacks of the closed ring/loop network

Advantages	Drawbacks
Lower impact of faults, fault is circumscribed by blown fuses and unaffected sections keep operating	Higher requirements for protection due to parallel operation of transformers
Supplying lines from two directions enhance voltage stability	Energy overflow between transformers
	The costs increase

Table 6: Advantages and drawbacks of the closed ring/loop network

Advantages	Drawbacks
Lower impact of faults, fault is circumscribed by blown fuses and unaffected sections keep operating	The highest requirements to protection and maintenance due to parallel operation of several transformers
Opportunity to connect consumption/source without voltage stability problems	In case of disintegration of network may cause loss power supply in entire area
	The costs increase

Table 7 compares the different LV network topologies following economic, operation and fault criteria.

Table 7: Network topology comparison [18], [21], [22], [20]

Economic criteria	Radial	Open-ring	Open-loop	Closed-ring	Closed-loop	Mesh
Investment costs	Low	Medium	Medium	Medium	Medium	High
Equipment requirements for control and monitoring	Low	Low	Low	Medium	Medium	High
Operation criteria						
Network transparency	High	High	Medium	High	Medium	Low
Maintenance	Low	Low	Low	Medium	Medium	High
Impact of service work	High	Medium	Medium	Medium	Medium	Low
Utilizing transformers and lines	Low	Low	Low	Medium	Medium	High
Voltage stability	Low	Low	Low	Medium	Medium	High
Distribution losses	High	High	High	Medium	Medium	Low
Opportunity to connect electromobility and DER	Low	Low	Low	Medium	Medium	High
Fault criteria						
Impact of fault	High	High	High	Medium	Medium	Low
Speed of restoration power supply	Low	Medium	Medium	Medium	Medium	Medium
Short-circuit currents	Low	Low	Low	Medium	High	High

3.2.2. Equipment for control and monitoring

LV networks are, in contrast to higher voltage level networks, very widespread and branched with a large number of control, measuring and protection elements. Therefore, high expectations are required especially on the following features:

- **Reliability** - due to large number of equipment and distance among them, it is necessary to ensure maximum reliability of equipment to prevent growth of operational and repairing costs and thereby negation of positive benefits from installing advance equipment
- **Cost effectiveness** – in general, most of the elements in LV networks serve only a very small number of customers. In order to reach cost effective ratio, the cost of the equipment must to be appropriate to provided functionalities. In most situation this means that cost of equipment should be very low with minimal installation and operational cost, which is related to large number of equipment.
- **Communication technology** - in most LV network lines, there is no connection to wired or optical communication network therefore importance of wireless communication networks also growing in energy sector. New technologies in wireless communication especially from 4G a 5G standards, including IoT, ML, Low-power wide-area network, etc., can satisfy the need to communicate in large number of places and/or in inaccessible places [18].

3.2.3. Project example in Czech republic

Project description

PREdistribuce is currently testing a pilot project of parallel-connected distribution transformers to determine the advantages and disadvantages of mesh networks and closed ring/loop networks. The aim of the project is to analyze the parts of the network suitable for reconfiguration and evaluate the benefits of these types of network topology in terms of voltage stability, energy losses and load flow.

Methodology

In the first phase, a mathematical model was created from the data of GIS, SCADA, enterprise information systems, measurements of distribution transformers in substations and measurements in selected fuse cabinets. The demonstration area consists of seven MV/LV substations in the city center with a total of 2500 customers. In the first step, the steady-state operation of the network for radial connection was calculated. In the next steps, the network was reconfigured by switching on fuses in fuse cabinets and again the calculation of the steady-state operation of the network was performed.

Outcomes of the project

Outcomes of the mathematical model show a slight reduction of energy losses, better power distribution among substations and in some parts of the network improving voltage stability after reconfiguring the network. Verification of mathematical model outcomes will take place in 2021/2022 on a practical test, which includes network reconfiguration and installation of measurement, signalization and communication units. Figure 25 shows three network configurations where substations used are marked with text “TS xxxx” and lines used are marked with different colors. Each color represent individual power supply branch. First image shows radial configuration with color-coded branches, second image shows closed ring configuration with color-coded rings and third image shows simple mesh configuration with color-coded lines between substations.

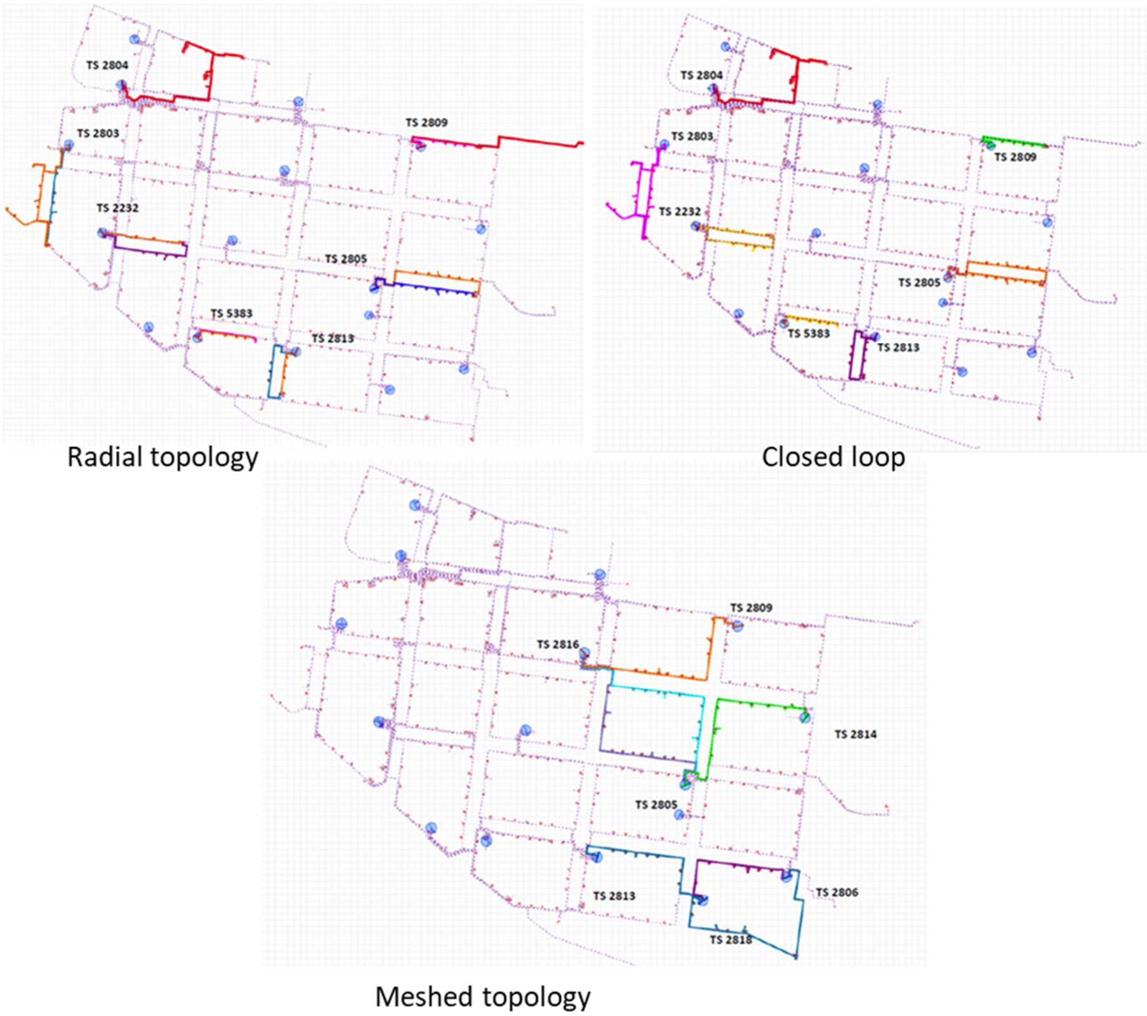

Figure 25: Radial, closed ring and simple mesh network topology

3.2.4. Conclusion

LVM is able to present network topology, delivery status, including power outages and power quality problems. LVM can easily visualize even facilities of small producers or charging points for electric car parks. With data from those facilities and plans for new connections, different algorithms can be developed. For example, to calculate locations with existing and future capacity problems, or even suggest locations for new connections. Therefore, especially new network extensions or extensive reconstruction can be supported by LVM. LVM actually enables the economization of existing resources and provides great help in decision-making processes regarding new constructions versus rebuilding of existing network.

4. LV CONTROL FUNCTIONS

4.1. STATE OF THE ART OF LV CONTROL FUNCTIONS

The integration of DERs in distribution networks is becoming a reality in most European countries. In particular, the connection of Distributed Generation (DG), especially PV panels directly to LV grids is expected to grow significantly in the next years as well as storage and

EVs. These DGs units may be used to feed local demand, thus contributing to reduce energy flows in LV grids but may also cause overvoltage problems when large amounts of power are injected into the grid and local demand is low, which may even originate reverse energy flows. In addition, with the advent of electric mobility it is expected that large amounts of power may be required in LV grid because of several EVs charging simultaneously. This will originate undervoltage problems especially in peak demand periods unless smart charging schemes are used. Consequently, several approaches and solutions have been studied and proposed in order to address these issues and support the DSO in operating its LV distribution grids. These works are available in the scientific literature, including publications from CIRED, and are summarily described next.

In the UPGRID project, ENERGA-OPERATOR SA has launched a pilot project that aims at supporting the management and control of LV network [23]. New possibilities to improve LV network management by IT systems were identified, namely:

- The implementation of smart meters system.
- New smart secondary substations with monitoring of both the MV and LV side.
- Development of ICT solutions.
- GIS system with information about LV network.

The Polish demonstration team involved in the project developed new LV functions to support the operating center. Using the existing data, in particular: AMI and the digital GIS network model offers a new way of enhancing the operating efficiency of the power grid and optimizing the operation system. Also, in the UPGRID project, a net-load forecasting algorithm for LV grids was developed, which main goal was to ensure high scalability [24]. The proposed solution is simple and combines a non-relational Structured Query Language (NoSQL) database with a job-server node responsible for distributing the tasks. The developed statistical model, based on analogues search and kernel density estimation, outperforms the naive approach (i.e. net-load profile equal to the previous day). With forecasted information, chronological power-flow analysis can be used to provide a new level of awareness to the LV dispatch operators (generate alarms), while allowing a proactive management of potential grid problems, such as reconfiguration, transformer tap changes, demand response or load/generation curtailment actions. In near real time, smart meter measurements can be used to run power flow and validate the planned control actions against the newly updated loading situation.

In [25] a study on an OLTC-based smart solution is verified using a real rural LV network in Slovenia. The field trial revealed that redundancy and cyber security are the main concerns for distribution system operator, which are addressed in this field trial. In the future, the field trial will be extended to test the coordination of active power output from PVs and OLTC operation.

Also, according to [26], Scottish Power Energy Networks is investigating, as part of this work, the installation of distribution voltage regulating transformers on sites where voltage unbalances are expected. As a result, five units will be installed in the Scottish Power network as a first trial to identify the feasibility of the system as a future business as usual solution.

In [27], a study is presented for an economical distributed control scheme for operations in the low-voltage network. The scheme aims to keep bus voltages within the desired statutory range of values while increasing the penetration of solar PV renewable energy within the network. Rather than curtailment, Battery Energy Storage System (BESS) is first brought to action by the controllers during periods of high output from PV. This is followed by reactive power action if overvoltage persists, and finally PV power curtailment as a last option. Simulations carried out on the test network show that in addition to successful overvoltage mitigation, the scheme is economical as it employs use of fewer BESS.

In this section, the working group as decided to focus on the following four control functions: voltage control, self-healing, active power management and automatic phase balancing.

4.2. VOLTAGE CONTROL FUNCTIONS

4.2.1. OLTC MV/LV transformers

Due to the increasing presence of new LV loads such as EVs and DGs, the observability and control of the LV network is necessary. This requires a new control and communication architecture of all the assets of the secondary substation. The OLTC transformers can provide a real time response to control the new challenges of the LV network. This solution can be implemented with standard communications (Ethernet) and protocols (DLMS) which is widely used in LV and provide to the system the opportunity to control different elements in the secondary substation (OLTC transformer, automated switchboards). Figure 26 shows a possible telecommunication architecture of a distribution substation OLTC. It consists of the following elements:

- Smart meters: they recover information from each client (load curves, events...).
- Data concentrator: it recovers information from all the smart meters of customers supplied through the MV/LV transformer.
- LV RTU (Remote Terminal Unit): It is the core of the system enabling recover information from line feeders and smart meters (through data concentrator), manage all the LV equipment (OTLC transformers, automated switchboards...) and send information to the central system.
- OLTC transformer: equipment with voltage regulation capabilities.

The OLTC based transformer uses, in this architecture, the smart meters information to select the OLTC set-point value in a dynamic way, promoting the local control and reducing action times instead of current centralized control strategy. This architecture is future proof for edge computing scenarios. The OLTC transformer could be, in special use cases, a cost-effective alternative comparing with traditional grid reinforcements to facilitate the integration of EV and PV, both in cost and delivery time. It is much suited for real time network optimization and customer satisfaction.

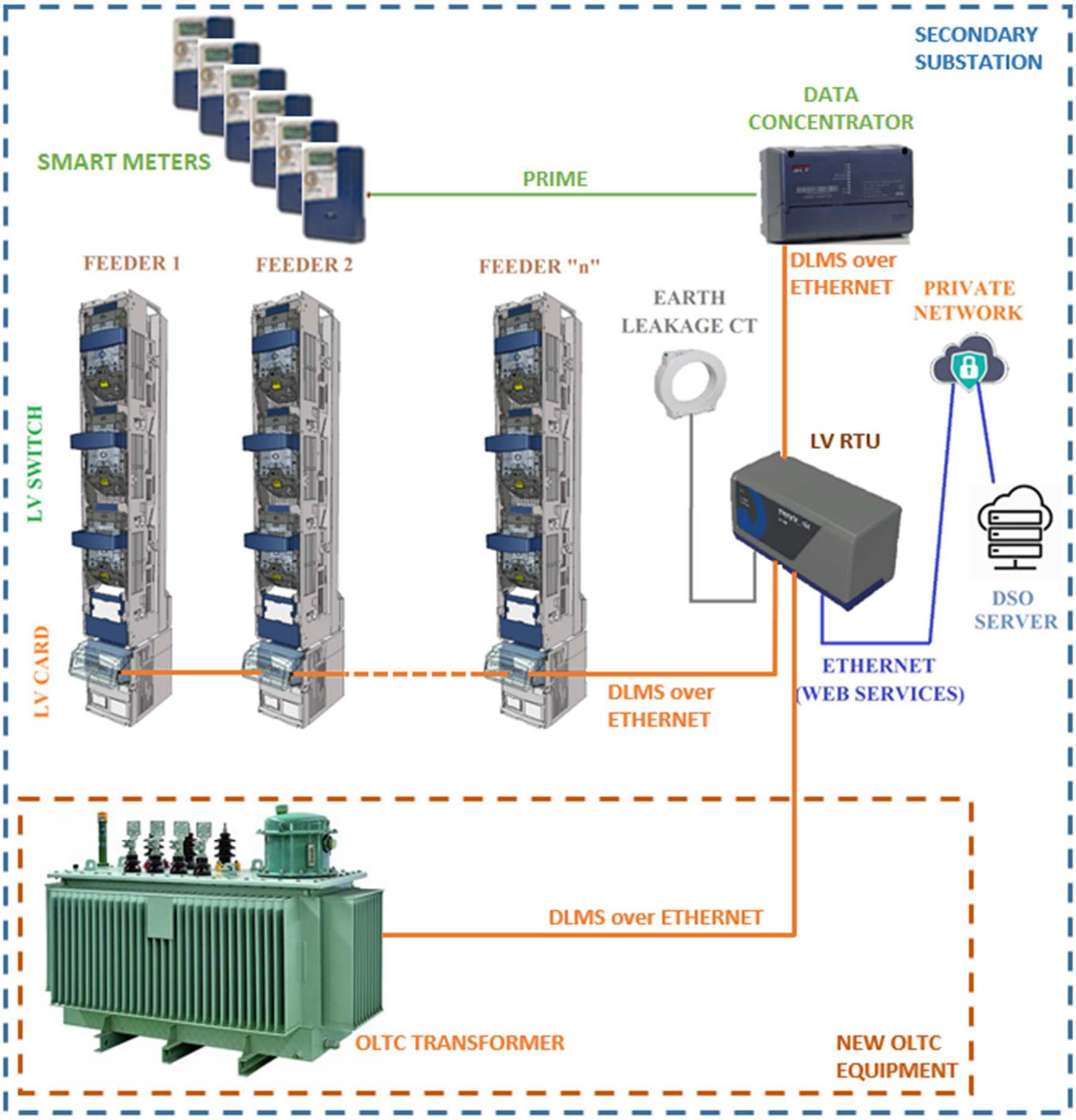

Figure 26: Use of OLTC transformers in MV/LV secondary substations[10]

4.2.2. Volt-Var Control (VVC): centralized and decentralized approaches

Voltage control at high voltage levels is traditionally based on reactive power management. This approach can also be used to some extent for LV grids; however, in some situations, other actions such as active power generation curtailment may be required (see section 4.4). The idea behind it is to reduce the active power output of the DG unit when the voltage magnitude exceeds predefined limits, given the resistive nature of most overhead distribution grids (where line resistance can often exceed its reactance). Alternatively, decentralized control can also be achieved by allowing the unit to manage its reactive power output instead of operating at a constant power factor. In this case, when predefined voltage limits are exceeded at the DG unit's terminals, reactive power is adjusted in order to avoid overvoltage situations.

[10] PRIME is a specification for narrow band powerline communication (narrow band PLC) [85].

This type of voltage control can also be performed locally through the power electronic converters that are used to connect DG units to the LV grid. Droop control, either in the form P-V or Q-V, is a form of local approach where a proportional control is applied to react to voltage deviations. These droop curves can be parametrized and adjusted to local operating conditions. The main advantage of this type of control is that it relies mainly on local data and therefore does not require the deployment of more advanced communication infrastructures.

On the other hand, centralized voltage control is based on information about a large portion of the distribution network, in order to determine the control actions to be implemented. One way of obtaining the voltage values in all or most network nodes is through AMIs or similar. For this reason, centralized voltage control usually relies on data and communication infrastructure, as well as sensors and advanced control systems. However, compared to decentralized and local control strategies, centralized voltage control is able to ensure coordinated and optimized management of the available resources.

Voltage control can also be performed centrally through dedicated systems for monitoring and control of LV distribution networks, such as SCADA systems or ADMS. These systems may take advantage of the AMIs that is being setup in LV grids in most EU (EUropean) countries for remote metering and billing purposes.

4.2.3. Lessons learnt from demonstration projects

Case of Portugal: SuSTAINABLE project

Project description

A voltage control strategy for LV networks was demonstrated in the InovGrid demo site in Portugal under the framework of EU project SuSTAINABLE [11] [28]. It consisted on a hierarchical methodology to control distributed power injection and solve voltage constraints. The proposed voltage control approach was tested using a facility with several controllable DER facilities built in a real LV network operated by EDP Distribuição. Both centralized and decentralized algorithms for voltage control were tested for a period of several months. Two main different schemes for the voltage control algorithm were developed [29]:

- Local control based on droops implemented at the inverter level of distributed resources such as PV panels or storage systems that react to local voltage conditions and change their power injected (or absorbed in the case of storage).
- Centralized control based on a simple set of rules embedded in the Distribution Transformer Controller (DTC) at the secondary MV/LV substation that generate set-points for distributed resources located in the LV grid following the detection of a voltage violation.

For the centralized control scheme (scheme implemented in the demo), there are two distinct situations for each the proposed methodology is capable of solving voltage problems:

[11] Smart Distribution System OperaTion for MAximizing the INtegration of RenewABLE Generation

- **Full knowledge of the LV grid**: Topology and access to smart metering devices and possibility of running a power flow routine.
- **Limited knowledge of the LV grid**: Unknown topology; access only to smart meter readings and geographic coordinates of customers.

If there is full knowledge of the LV grid (including topology, characteristics of lines/transformers), there is sufficient information to run a three-phase unbalanced power flow. This power flow routine may be embedded in the corresponding DTC's software as a local function to be used primarily for voltage control purposes.

With limited information and without the possibility of running a power flow, the algorithm used is based on a recursive approach. In this case, apart from the availability of smart meter readings, the minimum information required is the geographical position of each unit (load, microgeneration unit or storage device) as well as the phase to which it is connected. In this case, a voltage violation is identified, and its location is determined. Then, the proposed control actions management system is used, and successive control actions are applied to the controllable assets until the voltage deviation is corrected, according to the priority rules previously established. These control actions correlate the severity of the voltage violation with the distance to the controllable asset to be actuated, therefore working as a type of sensitivity analysis.

The main difference between this case and the previous one is that here there is no possibility of evaluating the actual effects of the control actions determined through simulation. This has obvious implications on the level of accuracy of the control procedure as well as on the total time of response required to solve the voltage problem.

The proof of concept (demo site) implements the second approach (without the possibility of running a power flow). In order to obtain the real time measurements, dedicated smart meters had to be installed at the customers' premises. In order to evaluate the proposed algorithms, a controllable PV micro-generator and batteries were also installed.

Figure 27 shows the communications and interfaces setup of the project and Figure 28 shows the synoptic of the Voltage Control Algorithm. In Figure 29 the evolution of the load and voltage profiles for a day test are shown for illustration purposes. More details on the tests carried out can be found in [30].

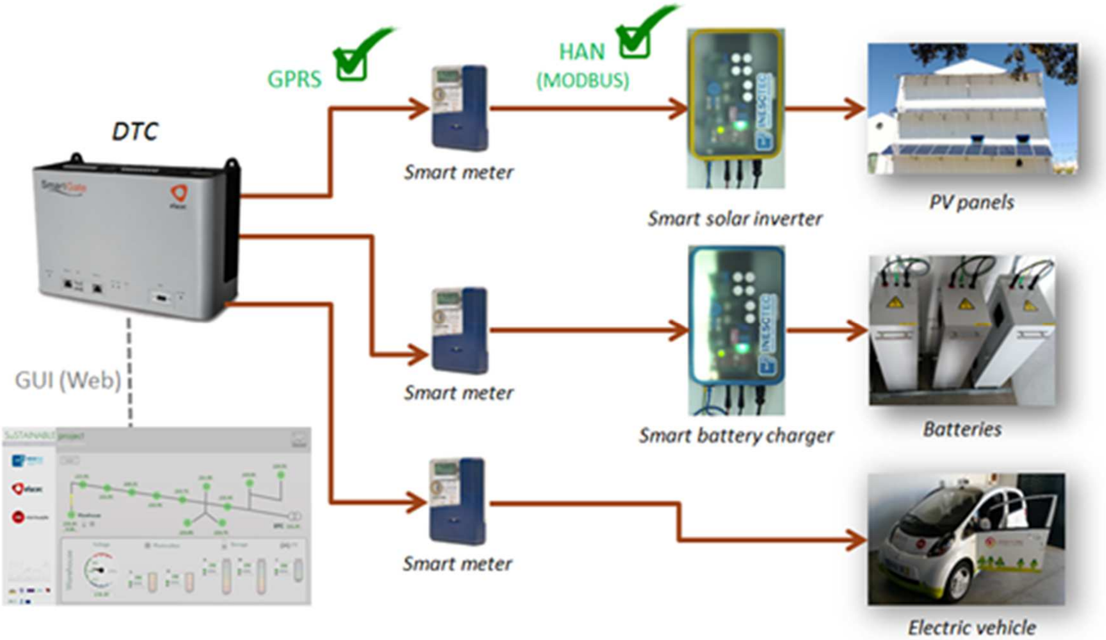

Figure 27: Voltage control demo in Portugal (communications and interfaces setup) [30]

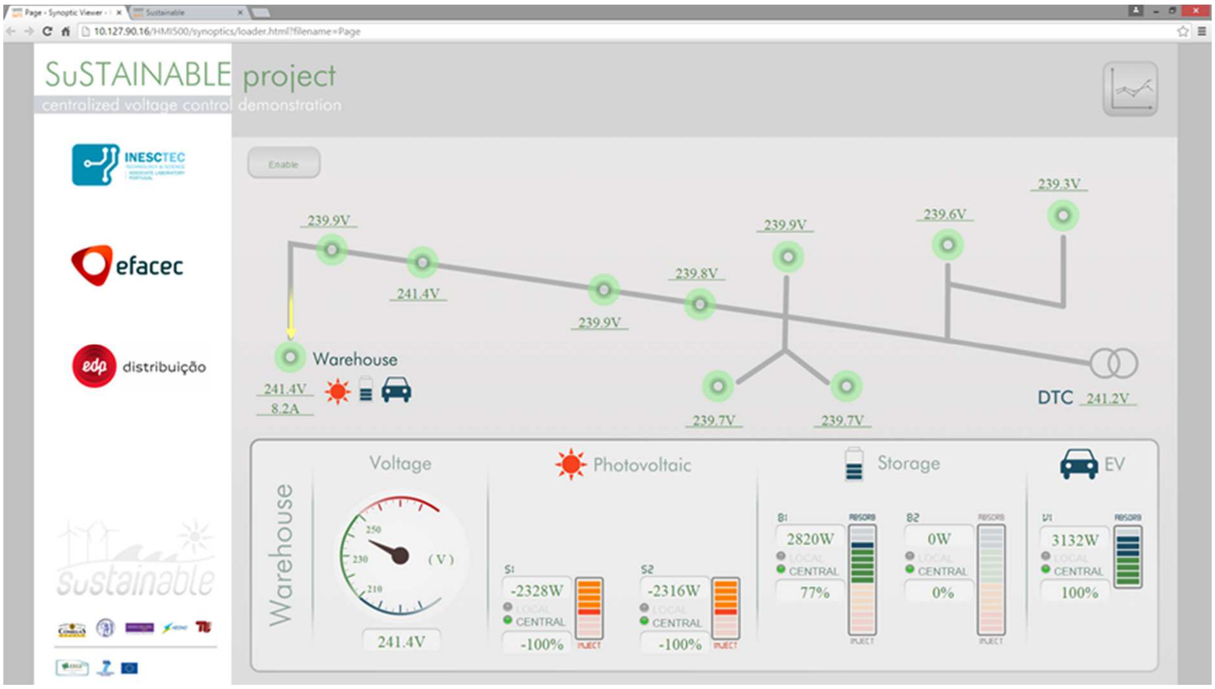

Figure 28: Synoptic of the Voltage Control Algorithm embedded in the DTC [30]

Figure 29: Detailed voltage and load profiles [30]

Outcomes of the project

The results obtained show that a hierarchical methodology is able to control power injection and optimize RES energy production while maintaining voltages within bounds, thus enabling a larger deployment of RES at the LV level [30]. Moreover, the following KPIs (Key Performance Indicators) were calculated [31]:

- Voltage and Power Quality performance: improvement of 1.05% (respectively 3.23%) in the voltage deviation index for the entire network (respectively for the controllable RES)
- Reduction in RES cut-off due to congestion: relative reduction of 76.4% in the RES energy curtailed due to voltage violations for both entire network and only controllable RES.

Case of Portugal: InteGrid project

Project description

In the framework of EU project InteGrid[12] [32], a voltage control tool was also developed. The proposed approach is based on a predictive voltage control algorithm to be used in LV distribution networks in order to make use of available flexibilities from domestic consumers via their Home Energy Management System (HEMS) and more traditional resources from the DSO, such as transformers with OLTC and storage devices.

The LVC (Low Voltage Control) tool operates in two main timescales:

- Preventive scale (typically one day ahead),
- Near real time scale (typically 15 min ahead).

[12] INTElligent grid technologies for renewables INTEgration and INTEractive consumer participation enabling INTEroperable market solutions and INTErconnected stakeholders

In the preventive stage, the algorithm requires forecasts of generation, load, and flexibility available provided by the private consumers in order to determine a preventive control action to apply to the LV network controllable resources. The control actions produced by the preventive control module are communicated to the DSO, for validation purposes who can accept or perform changes to the control action determined by the LVC algorithm. In real time the algorithm uses a state estimation algorithm, the Low Voltage State Estimator (LVSE), to obtain a snapshot of the network in real time recurring to a subset of the smart meters' measurements available in the network.

The main objective of the real time control module is to assess the actual network conditions registered in real time and compare them to the conditions that were forecasted in the preventive stage. If these significantly differ, the control action is updated accordingly, and the new set-points (control action) are generated and submitted to the validation platform. Therefore, the real time control module of the LVC tool has a corrective character, acting solely if the network conditions significantly differ from what was forecasted. A simplified schematic of the proposed framework is shown in Figure 30. The solution was tested through simulation using a real Portuguese LV network and real consumption and generation data, in order to evaluate its performance in preparation for a field-trial validation in a Portuguese smart grids pilot. In this case, it was assumed that the voltage control would be installed in the central systems – ADMS – operated by the DSO [33]. The algorithm was then demonstrated in a set of smart grid demo networks operated by EDP Distribuição, located in Portugal, including the exact same network that was used for the simulation studies. Some screenshots of the validation platform during some of the live tests that were conducted are shown in Figure 31.

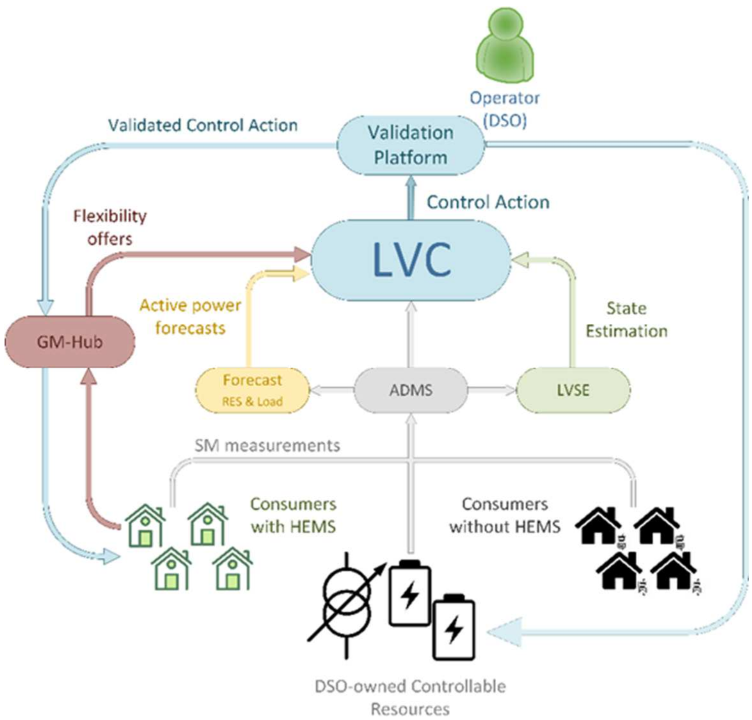

Figure 30: Proposed control for predictive voltage control in InteGrid [33]

Figure 31: Screenshots of the validation platform during tests in the EDP Distribuição's environment

Outcomes of the project

Case of France: SMAP[13] project

Project description

From December 2015 to November 2018, the SMAP project involved 11 partners:

- one DSO: Enedis, the major in France,
- two industrials: ATOS worldgrid, Nexans,
- One association: HESPUL,
- National agencies and communities : SYDER for syndicat d'énergie du Rhône, the AURA-EE for Agence Régionale de l'Énergie et de l'Environnement en Auvergne-Rhône-Alpes, the Natural Park of the Pilat, the village of Les Haies),
- one university: Grenoble INP
- a small company: the CVRC for "Centrales Villageoises de la Région de Condrieu" which manages rooftop PVs owned by citizens.

The objectives of the SMAP project were to investigate with both experimentations and simulations the interest of LV voltage control functions as an alternative to traditional investments. Indeed, when PV are connected to the LV network, some upgrades (increasing the line sections or changing the transformer) can be necessary to avoid overcurrents or overvoltages leading to expensive costs for both DSOs and producers. This could stop the deployment of PV interconnection projects, as it was the case for the CVRC area, which had to reduce the installed PV capacity to limit the costs. The area covered by the SMAP project is

[13] https://www.centralesvillageoises.fr/projet/le-projet-smap

a rural network, the village of Les Haies (see Figure 32), inside a Natural Park with strong incentives for the development of PVs but subjected to specific constraints such as the authorization for only rooftop PVs (and not grounded-mounted PVs). To avoid potential heavy investment costs to accommodate future PVs and encourage their development, the SMAP project investigates several solutions summarized in Table 8.

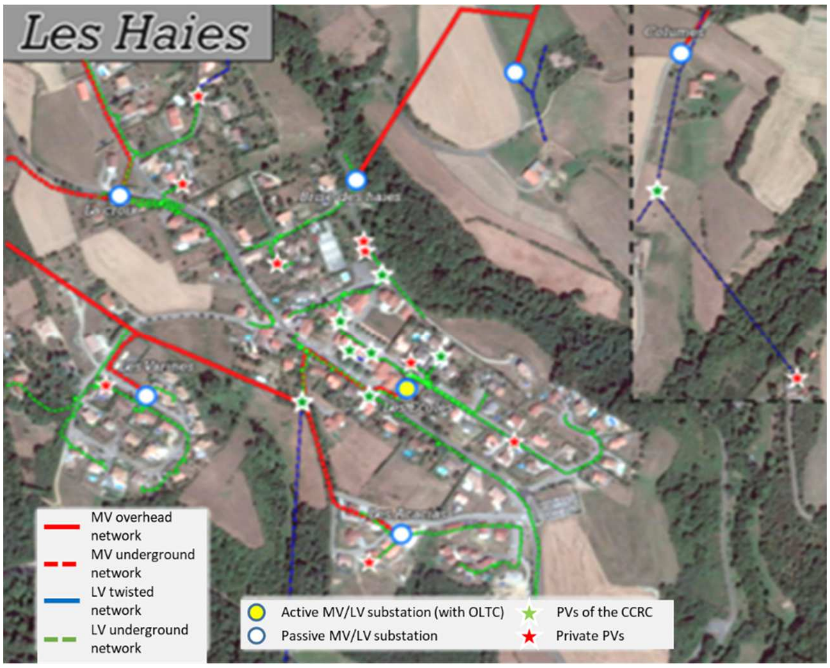

Figure 32: LV network of the village of Les Haies

Table 8: SMAP solutions investigated

	Experimented solutions	Simulated solutions
Wire-alternatives		
Reinforcement		✓
MV/LV OLTC	✓	✓
Non-wire alternatives		
Centralized dynamic PV Volt Var control (VVC)	✓	✓
Fixed $\tan\varphi$ PV VVC		✓
Static active PV limitation		✓

The LV network of the village of « Les Haies » consists of 6 MV/LV substations, one of which is equipped with an OLTC. The data are provided in Table 9.

Table 9: Data of the village of Les Haies

N°	MV/LV substation capacity (kVA)	Number of customers	Number of PV	Installed PV capacity (kVA)	Maximal length i. e. farthest load from the substation (m)	Maximal consumption[14] (kW)
1	50	6	2	12,1	500	14,2
2	250	61	11	45,1	770	191,1
3	50	12	1	4,5	200	33,6
4	250	36	1	3,0	270	80,1
5	160	20	1	3,0	300	57,1
6	160	35	2	6,0	360	78,5

Experimented solutions

Figure 33 represents the electrical and communication architecture deployed in the village of Les Haies. The technologies implemented are the followings: 166 smart meters Linky, one OLTC, 7 remotely controlled PV inverters and one MV sensor. About 60 smart meters measure the voltage of loads and PV and send them to a concentrator every two minutes via PLC with a quite good reliability (less than 0.4 % of measurement errors). An algorithm embedded in the concentrator sends orders to an OLTC and 7 inverters to regulate the voltage as a function of the state of the network.

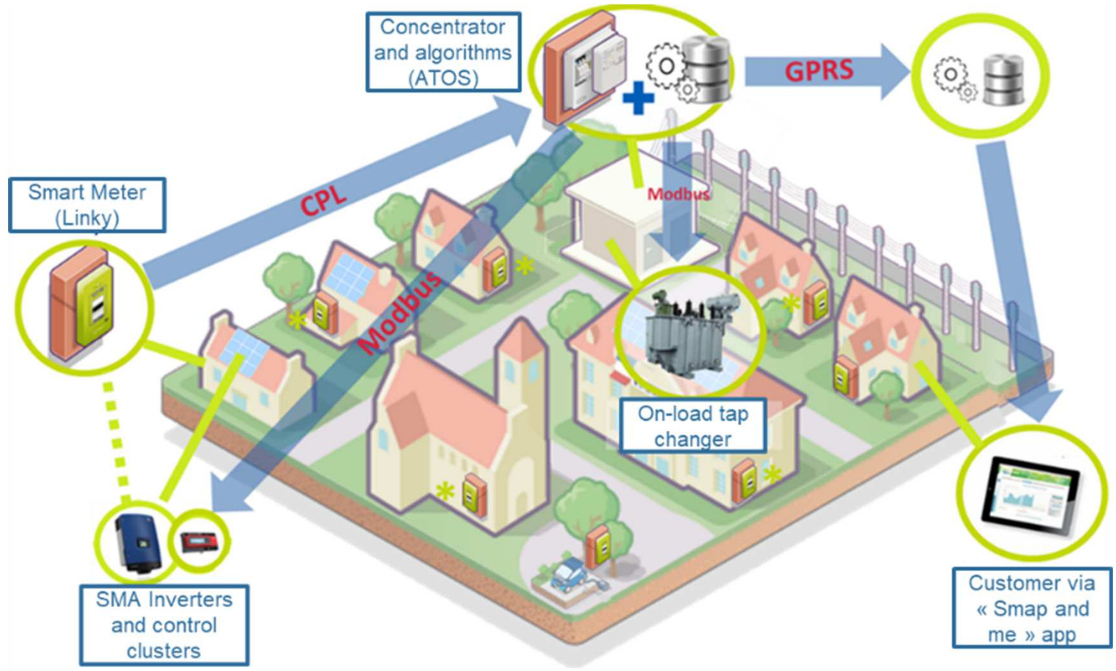

Figure 33: Architecture of the experimentation in the SMAP project

The voltage control function with the OLTC, technical details of which are provided in Table 10, is based on a few smart meters, called sentinel meters, chosen to be representative of the minimal and maximal variations of the voltage in the network. The rules used to change the tap position of the OLTC are the followings:

[14] Estimations of year 2016

- If at least one voltage measured by the sentinel meters is lower than 4% of the nominal voltage and if no voltage is 4% higher than the nominal voltage, then an order "increase the voltage" is sent to the OLTC.
- If at least one voltage measured by the sentinel meters is higher than 4% of the nominal voltage and if no voltage is 4% lower than the nominal voltage, then an order "decrease the voltage" is sent to the OLTC.
- If one of the two above mentioned actions is sent to the OLTC, the latter makes the requested action and stays in the new tap position while the voltage remains between +/-4 %.

The +/4 % interval (instead of +/-10% interval) has been chosen to validate the proper functioning of the OLTC. Indeed, on the village of Les Haies, during the SMAP project, the PV penetration was low and there were no voltage constraints. During the experimentation period (from April 30th to June 10th, 2018), 47 tap changes has been recorded. Figure 34 shows the minimal and maximal voltage variation during this period and it can be seen that the it remains between 221 V (3.9% of 230V) and 243 V (5.6 % of 230V). The moments where the voltage is higher than 4% of 230V are moments where no voltage control was tested. Figure 35 gives an example of successful tap changing. Table 10 provides the characteristics of the OLTC used in the SMAP project.

Table 10: OLTC parameters

Power of the transformer	250 kVA
Number of taps	9
Voltage variation per tap change	1,5%
Number of tap changes	> 500 000
Latency time between an order sending and its realization	5 to 7 seconds

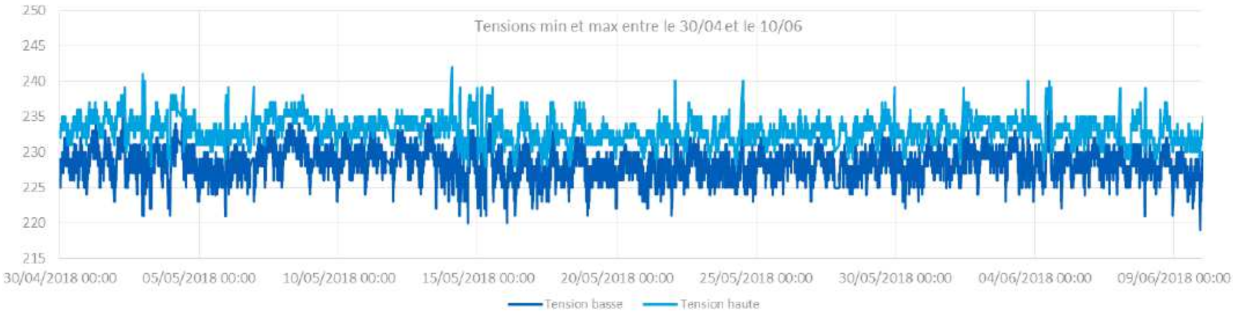

Figure 34: Minimal and maximal voltage of the village of Les Haies from April 30th to June 10th 2018

Figure 35: Example of tap changing

Two types of SMA inverters were tested: Sunny Boy (single-phase, 1.5 à 5 kVA) and Sunny Tripower (three-phase, 5 et 60 kVA) and some of them were centrally controlled via the concentrator. It the latter detects a voltage outside the +/-4% interval, it sends an order to the “cluster controllers” of the inverters. Two type of actions are possible: reducing the active power (active PV limitation) produced or absorbing/injective reactive power (VVC). Only the active PV limitation was experimented on the field: if the concentrator detects an overvoltage, it sends an order to all the inverters to reduce their power by 25% during a given duration. An agreement between Enedis and the producers has been signed in order to limit the produced energy losses. Two options were tested:

- 6 curtailment orders of 10 minutes can be sent per day by the concentrator
- 3 curtailment orders of 20 minutes can be sent per day by the concentrator

Figure 36 shows the example of the power produced by a PV on June 20th, 2018. The concentrator sent 4 curtailment orders. The energy produced this day was 100 kWh with about 40 minutes of curtailment. Considering the maximal theoretical production curve, the total energy produced would have been 102 kWh. The energy lost is about 1.8% of the energy produced without curtailment. The CBA presented in section 4.2.3 shows that this solution was more economic than reinforcement but, as for the OLTC, it is not robust to uncertainties. Again, these conclusions are dependent on the R/X ratio of the network. If it is high, this solution will have higher benefits and even more with a dynamic adaptation of the power curtailed rather than a fixed power curtailed.

Figure 36: Example of the active PV limitation

Simulated solutions

The interest of the simulation of the LV control functions is to validate their economic interest over the planning period (35 years in the SMAP project) compared to classical reinforcement strategies, subject to uncertainties on the future development of the loads and PVs. In that purpose, the algorithm of Figure 37 based on Monte Carlo simulations has been developed under PowerFactory in order to take into account these uncertainties. The principle of the Monte Carlo algorithm is to make random modifications of the uncertain parameters and to run the cost benefit analysis in order to have a mean value of the cost of NWA versus WA. For each random generation of uncertain parameters, a load flow is run on production and consumption time series in order to identify the number of constraints as well as their location. Non-wire solutions combined if necessary, with wire-solutions are applied to solve these constraints and are compared to traditional wire-solutions.

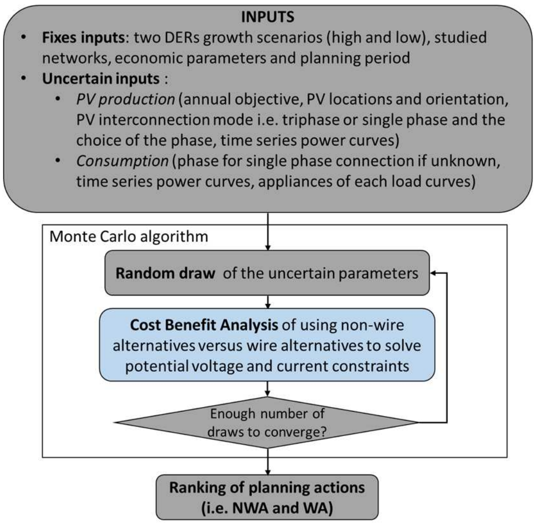

Figure 37: General algorithm

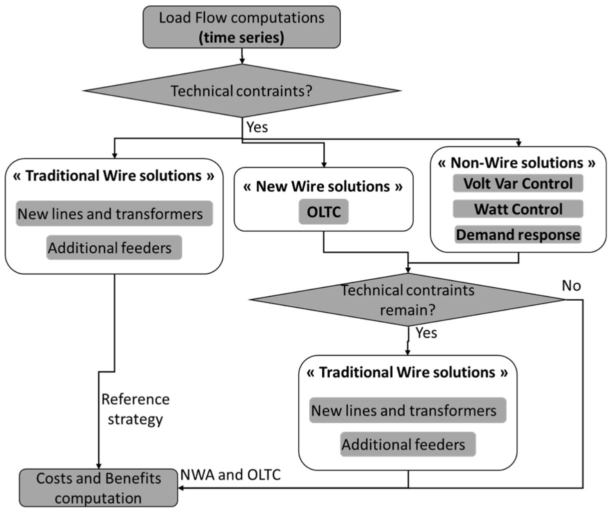

Figure 38: Detail of the Cost Benefit Analysis box

The inputs of the study came from four partners of the project, HESPUL, AURA-EE, Enedis and Grenoble INP, who provided real network data and two evolution scenarios in 2050 of consumptions (conventional and electric vehicles) and PV productions:

- High scenario: high production and low consumption
    - Energy consumed in 2050: -41 % (Les Haies) and -46 % (CCRC[15])
    - Energy produced by PV in 2050: 50 % of the PV potential
- Low scenario: low production and high consumption
    - Energy consumed in 2050: +18 % (Les Haies) and -3 % (CCRC)
    - Energy produced by PV in 2050: 15% of the PV potential

To estimate the impact of NWA, it was necessary to use time series. To reduce the number of simulations, for each year, the PV production was split in 4 typical days representing 4 seasons

[15] CCRC means Communauté de Communes de la Région de Condrieux and consists of about 200 LV networks including the village of Les Haies.

(spring, summer, autumn and winter) and the consumption was split in 2 typical days (working days and holydays). Then, instead of simulating a full year, only 8 days are used.

The Monte Carlo algorithm consists in generating load curves, PV locations, connections and power curves during 35 years and in estimating the current and voltage constraints using a load flow (see Figure 38). If constraints appear, the reference strategy is computed which consists of making classical upgrades such as reinforcement to erase the constraints: increase of the section if lines, dedicated feeders, and reinforcement of the MV/LV substation in case of overloading. Other strategies are also simulated:

- OLTC (described in the experimentation part)
- Volt Var Control
    - Centralized PV inverter control Q(V): no limitation is considered regarding tan(φ) and the reactive power. There is a priority on the reactive power so the active power can be reduced. The Q(V) control used is depicted in Figure 39.

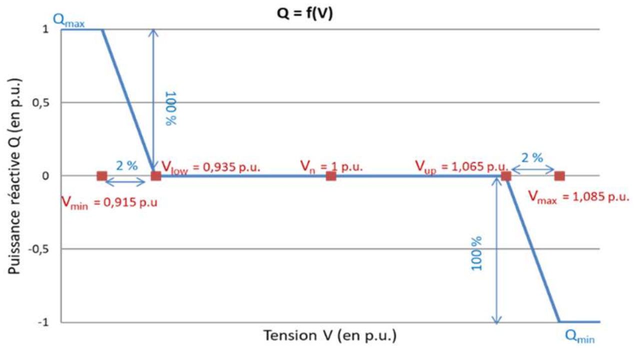

Fig.8

Figure 39: Centralized PV inverter control Q(V)

-
    - Fixed inverter control (fixed tan(φ)): tan(φ)=0,4
- PV active power limitation: PV active power produced is limited to 70% of the maximal power. which represents only 3% of the total energy yearly produced by the PV.

If these strategies do not enable to erase all the constraints, additional reinforcements are made. To compare these strategies the total cost (TOTEX) is computed using the equation below.

$$TOTEX(2050) = \sum_{N=2016}^{2050} \frac{1}{1+\tau^{N-2016}}$$
$$\times \left[\left(C_{reinf}(N) + CAPEX_{alternative}(N) \right) \times \frac{2050 - N + 1}{Depreciation} + C_{losses}(N) \right.$$
$$\left. + OPEX_{alternatives}(N) + C_{energy\ non\ injected}(N) \right]$$

With:

- τ: discount rate

- $C_{reinf}(N)$: CAPEX of reinforcement strategies

- $CAPEX_{alternative}(N)$: CAPEX of alternative (for example OLTC)

- $C_{losses}(N)$: cost of power losses for year N

- $OPEX_{alternatives}(N)$: OPEX cost at year N related to the use of alternatives (for example maintenance cost of the OLTC)

- $C_{energy\ non\ injected}(N)$: cost of the energy not injected at year N

Figure 40 and Figure 41 show the results of the cost benefit of each solution compared to the reference solution (in %) as a function of the years for the low scenario and high scenario. It can be seen that the VVC functions, both centralized Q(V) and fixed tan(φ), have good performances: between 38 and 82% of the benefits estimated compared to the reference solution (reinforcement). The performances of the PV active power limitation are not relevant: there are often better than the reference solution but there is a risk of negative benefit is we consider uncertainties on the loads and PV evolution scenarios. The OLTC is also not robust from an economic point of view.

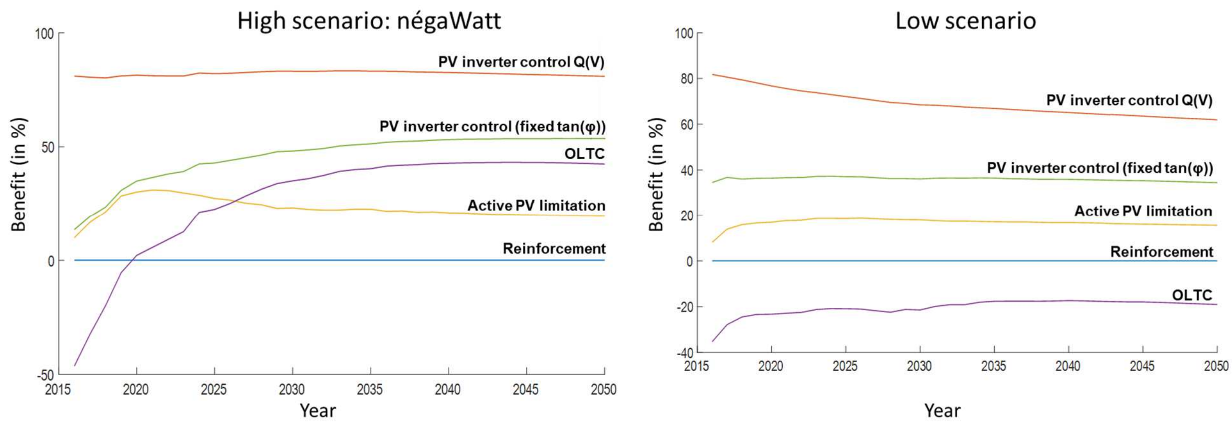

Figure 40: Cost benefit analysis of LV control functions (village of Les Haies)

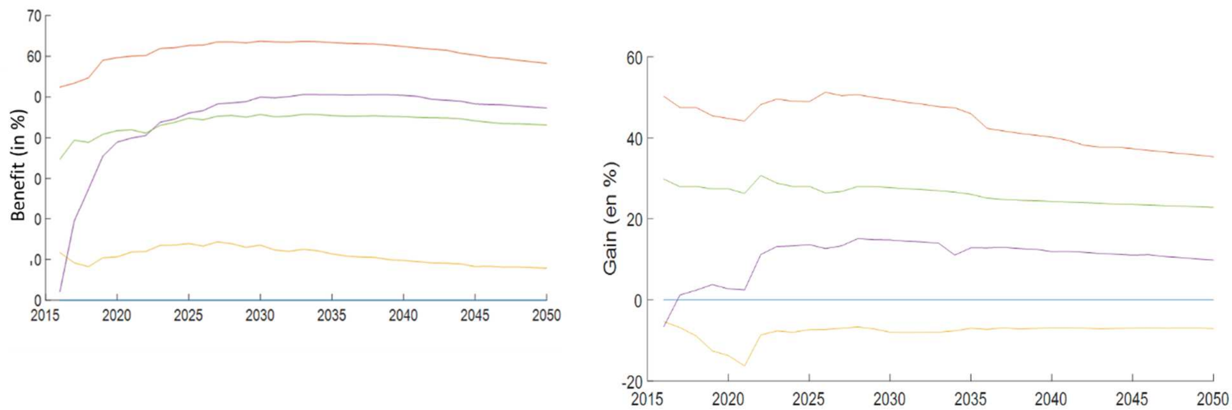

Figure 41: Cost benefit analysis of LV control functions (CCRC)

To assess the robustness of the VVC control functions, some limitations were tested independently:

- Limitation 1: The reactive power is limited to 0.4 times the maximal apparent power of the inverter
- Limitation 2: tan(φ) must be lower than 0.4
- Limitation 3: CAPEX cost of 4k€ to implement the centralized PV inverter control

Figure 42 shows the results obtained in the CCRC area: the benefits of the PV inverters control Q(V) decrease by 10 to 17% so remain good. Nevertheless, the benefit brought by the centralized control compared to a fixed control is very small. The cost models for the solutions and their limitation have a clear impact on the global benefits for the network on the long term. These results were published in [34].

	CCRC – high scenario	CCRC – low scenario
Q = f(V) without limitation	58 %	35 %
Q = f(V) ; |Q| < 0,4 x S_{max}	41 %	25 %
Q = f(V) ; |Q/P| < 0,4	42 %	23 %
Q = f(V) ; extra cost of 4 k€	48 %	22 %
Tan(φ) = Q/P = -0,4	43 %	23 %

Figure 42: Comparison between PV inverter control Q(V) without and with limitations and fixed tan(φ)

Outcomes of the project

Monitoring of LV network	The smart meters enable a reliable voltage monitoring of the LV network thanks to the dynamic data measurements. It was possible to use these measurements to develop LV control functions managed in a centralized way in the concentrator located in the MV/LV substation. The intelligence located in the concentrator enabled an automated control of the equipment involved in the voltage control (OLTC and inverters).
LV control function using a MV/LV OLTC	The connection between the concentrator and the OLTC is working in the real field and enables to control the voltage based on measurements from the smart meters. During the experimentation, the OLTC succeeded to maintain the voltage on the village of Les Haies between +/-4% of the nominal voltage.
LV control function using PV inverters	The communication between the concentrator and the PV inverters to control the PV active power limitation is working. The amount of curtailed power, its duration and frequency per day have been defined through a contract between Enedis and the producers. The PV active power limitation is automatically controlled by the concentrator meaning that it does not required any action of the producer. Nevertheless, the preferred option is the reactive power control in order to minimize the curtailed active power of producers.

To confirm these results, other case studies need to be simulated especially with a high level of PVs and voltage constraints. An alarm and some alternatives have to be implemented in case of instability in the regulation process of the LV control strategies. In particular, for the PV inverters control, manufacturers have to homogenize communication protocols to reduce the communication problems between inverters and between inverters and other equipment (concentrator, OLTC etc..), especially in the case of a centralized control, otherwise the regulation and maintenance of these algorithms might be expensive.

Finally, a cost benefit analysis has evaluated the economic interest of these solutions compared to classical reinforcements as well as their robustness under uncertainties. Under a set of hypotheses, especially regarding the costs of these strategies, which depend on the type of control i.e. centralized or decentralized, some conclusions could be driven regarding the more promising control strategy. The first results show that the volt var control of LV PV inverter seems to be an efficient solution even if further investigations are necessary especially regarding the impact of network topology such as the R/X ratio (resistance over reactance).

4.3. SELF-HEALING FUNCTION

The significance of the term “self-healing” was initially promoted by S. M. Amin in early 2000s [35] [36], as automating —i.e. “self”ing— the restoration or healing system. The self-healing concept is intended to boost the recovery speed of the system after failures, leading to a more reliable power system. The self-healing notion was practically implemented to achieve perfect power system at IIT campus [37].

4.3.1. Biological Inspiration

Self-healing is inspired by nature, namely, by the behavior of creatures’ immune system in response to injuries. The immune system in injuries, indeed, tries to clear the damage and to prevent its spreading without external interposition. In human, like most mammals, minor wounds (cuts and scrapes) are healed automatically in four phases, namely: *hemostasis, inflammatory, fibroblastic (or proliferative), and reconfiguration (maturation or remodeling)* [38] [39]. In the *hemostasis* phase, the progression of injury process is stopped. Subsequently or simultaneously in the *inflammatory* phase, the neutrophil cells remove foreign materials, bacteria, and damaged tissue by phagocytosis. Then, fibroblasts proliferate in the region and construct (repair) an extracellular matrix in the *fibroblastic* (or *proliferative*) phase. Finally, the hastily constructed tissue is well-organized and remodeled, to form a similar site to the pre-injury one which is known as *reconfiguration* phase [38] [39]. The process of self-healing in smart grid intends to be similar to the wound self-healing in mammals [40].

4.3.2. How does self-healing work in distribution systems?

The basic notion of self-healing in energy distribution systems is an autonomous development of the FLISR (Fault Location, Isolation, and Service Restoration) process used by dispatch operators. Once a fault occurs in a distribution system, all downstream customers are de-energized due to the circuit breaker trip. The location of the fault should be determined by a system of interconnected sensors and fault indicators (Fault Location phase). Subsequently, the functions of the FLISR process are sequentially conducted to accelerate re-energizing and feeding as most customers as possible. In the Isolation phase, the fault is isolated by opening the upstream and downstream switches of the faulted section. Then, energy is restored to the de-energized customers outside the isolated area. After the fault section is isolated, the repairing will be done by field crew [41].

Control and protection devices can be used to reduce the outage time, and thus increase the system reliability. Although it seems a simple procedure, decreasing the outage time requires fast determination of fault location which is extremely challenging in distribution system [42], due to a vast number of variables, e.g. undetectable faults, false positives, reduced number of circuit breakers along the line and remote operated switches, complexity of the network due to branches. The location of switches and number of interruptible sections is determinant to the efficiency of FLISR. Several studies have been presented regarding the optimal switch placement model [42], to deal with economical and technical issues.

Although the High Voltage (HV) network is the most important, usually its architecture is simpler than the lower voltage levels, because it is mostly based on point-to-point architectures with remote controlled circuit breakers on both ends and with redundant lines or paths. This leads to a fully watchable/observable network with low line complexity. When faults occur, the circuit-breakers isolate the faults and redundant feeders prevent outages from customers.

Medium Voltage (MV) networks are much more complex, with many more branches and less, or sometimes, no full redundancy. Overhead networks are also closer to trees and more exposed to external factors. Thus, self-healing has been promoted mostly on MV networks, taking advantage of remote operated switches and circuit-breakers. It is still an under-construction work with many companies developing and adjusting the systems to these new algorithms.

4.3.3. Implementation reports on LV networks

Although most of studies in self-healing research area concentrate on MV, a few works can be mentioned for LV evaluation. For instance, an automatic framework is presented in [43] for fault location, isolation, and restoration in Netherland. This framework is tested in real word system on MV. During the tests, as it is reported in [43], it is noticed that LV network owing to mesh structure can be used as a bridge for coupling MV nodes to each other. Thus, considering MV and LV in self-healing process could decrease the prospective outages. It is important to remember that by doing so, the operation of automatic and manual switches must be prepared to prevent energizing of the fault. Furthermore, a smart application of advanced metering infrastructure (AMI) is introduced in [44] as named “last gasp”. Based on this application, smart meters and LV sensors with RF (Radio Frequency) mesh communications report alarms on-event to the DTC, such as power failures on LV feeders. Since meters have no battery power backup, when the meter detects a low voltage event on the LV network, it report the event to the NIS, and then shutdown gracefully. The NIS then transmit the last gasp message to the nearest DTC (working as access point) that relays this message to the DTC that is supplying that meter. The corresponding DTC then reports the alarm to the central systems.

As an extensive self-healing implementation in LV, Dubai Electricity and Water Authority (DEWA) can be mentioned [45]. DEWA, in fact, consists of an underground cable system for electricity distribution. Therefore, all of the occurring faults are sustained failures and its clearing requires considerable time which results in financial losses. In this implementation, remote Fault Passage Indicators (FPI) are used with GSM (Global System for Mobile Communications) communication. Remote FPI helps dispatchers in operation control centers to reduce fault localization time and crew traveling time which contribute is shorter interruption duration.

4.3.4. Ongoing Portuguese DSO E-REDES pilot project NEXTSTEP

The self-healing function is defined on a Portuguese pilot project to be developed and tested on laboratory environment. The function is based on LV reconfiguration strategies that can be totally automated or human-assisted. The present LV grid topology is completely passive, based on fuses and without any information about electrical behavior. So, to implement self-healing functions a completely improvement on the LV is required, with the integration of several sensors spread along the grid, near real time communication functions, remote circuit breaker devices and a local intelligent system to manage all the components. The benefits of such a system are obvious although the cost/benefit analysis and the capillarity of the LV grid leads to a difficulty to justify its implementation, firstly because the outage incidents are not frequent, secondly because the economic effect is negligible and by last and most important, it needs huge investments and innovation on hardware and software. However, it can be justified for some special customers or situations and preparatory work has to be done. In addition to the self-healing function, other functions can benefit from the technology, namely to have near real time information about the LV network and to have load balance between secondary substations or grid branches.

The designed function in the Portuguese pilot project uses the intelligence of the secondary substation RTU to implement the self-healing algorithm. It can be autonomously by the RTU or by the interaction from an operator at the dispatch center. The underground LV Portuguese grid has typically an open ring configuration, with fuse-protection distribution closets, and the customers are directly feed from an output of the closet. So, the self-healing algorithm must have fault detection information from the surrounding spots to take decisions and can count on the information from smart-meters to complement the information about the overall grid situation. Additionally, deeply structural changes must be made on the grid, upgrading from fuses to remote operated LV circuit-breakers and near real time communication from the last-mile devices to the dispatch. Based on all the information collected from the LV grid, an advanced algorithm must take decisions on the reconfiguration to be made and then give the orders to the remote operated devices.

The Pilot project, NEXTSTEP, is being implemented on the field but the self-healing functionalities will only be evaluated on laboratory, for now, for security, maturity and grid management reasons. The field sensors will collect real data that will be collected to be used on laboratory for simulation purposes. That will allow developing algorithm teams to simulate the behaviour of the algorithm to real situations and to compare it with the real actions that were done on the field. This simulation work will allow to adjust the algorithms and to trust the reliability of it to a possible implementation on a real environment. More information are available in [46].

4.3.5. MV self-healing ideas exportable for LV

In the most research studies, although MV and LV networks are not dissociated from each other, the proposed models are theoretically applicable to both systems, although several aspects are quite distinct on each network :

- The R/X ratio in LV networks is much bigger than MV network [47],
- LV is much more instable and has unbalance trend,
- Structure and energy losses cannot have higher magnitude in LV network [47],
- The communication network is critical to self-healing implementation and is more controllable and stable in MV [46].

Hence, the self-healing models which are provided for MV can be utilized in LV, but there are a lot of aspects that must be adapted to the LV network structure. Beyond automatic operation of the FLISR process, other self-healing developments are proposed for MV that can be regarded as ideas for LV networks too; for instance, the use of DERs as temporary feeding sources to restore the de-energized customers is considered in a couple of works. Accordingly, DGs, ESSs, EVs and their parking lots are considered to act as both backup energy sources in the faulted/isolated zone, as well as the backup feeding path energy sources to facilitate restoring as much as possible restorable customers [48] [49] [50]. Furthermore, DR has also been utilized as a tool to reduce consumption in the backup feeding path to facilitate restoration process [51].

4.3.6. Economic discussion

There are several issues to be addressed before advancing with self-healing to LV networks.

Outage impact on LV networks
The LV network has a vast capillarity, and the outage impact is contained. The number of customers affected is incredibly low and the energy not distributed is low too. Additionally, the frequency of outages due to network fault is very low. Hence, not like in MV networks, the benefit/cost ratio is very low and the investment economic return on self-healing systems on LV networks is very difficult to justify by outage reaction benefits.
Other important aspect is the level of automation and monitoring of LV networks by now. Unlike the MV and HV networks, most of the DSOs do not have LV dispatches with SCADA systems. Therefore, the logistic is also made by human communications and no real time operation exists at all. Firstly, it is necessary to implement a telecommunication network to allow SCADA control of most important parts of the LV network, with real time outage detection and sensor communication (voltage, current and defect detection) on the main spots of the LV network. Although study reveals that smart meters and AMI system can improve the fault location performance on LV side [41], due to the prospective delay on the detection using AMI system, it might not be as effective as the SCADA system. Additionally, the economic losses due to

outage can be insufficient to justify the investments needed to implement self-healing on LV [46].

LV new entrants and trends

The EVs penetration can unbalance this equation and can, in some cases, justify a more careful look to the self-healing technologies, since the reliability of the service is mandatory because people's mobility depend on it. By the other hand, EV will be huge and massive loads on the network that will intensify consumption and concentration on the nocturne hours and first labour hours in the morning. The load demand on the several branches of urban networks can be distinct during the day and stress hours can swing between LV branches. The self-healing algorithms can be used preventively to adjust network capacity to the demand without a reinforcement of the cable or network infrastructure. This approach can justify the economic benefits of implementing self-healing architectures on some cases [46]. Other use-case can be to implement self-healing to ensure continuity of service to essential services, such as emergency and other public or critical service customers. With self-healing algorithms, it is possible to drastically reduce outage time to critical customers, avoiding emergency generators or ultra-capacity UPS (Unit Power Supply).

However, in any case the upgrades to implement self-healing in LV networks are neither easy or cheap to implement and the cost benefit analysis is essential to take decisions.

4.4. ACTIVE POWER MANAGEMENT

4.4.1. Introduction

Generally, DR is introduced as a tool for increasing network reliability, reducing peak demand, managing network development, electricity commercialization policies, and deploying integrated technologies in power systems. On the one hand, a DR plan should upgrade the smart grid information processing requirements [52]. On the other hand, it should increase customer awareness of its benefits to adapt or change the power consumption pattern [53]. The main reasons for encouraging consumers to participate in these projects can be summarized in cost savings, avoidance of blackouts, and liability [54]. Accordingly, the DR program will utilize various resources, including distributed generation, dispatchable loads, storage systems, and other resources, to contribute to the power supply modification [55]. Furthermore, increasing the power system's efficiency and productivity is another issue that is pursued in the restructured environment of the electricity industry. Power companies are looking for new and creative solutions to reach energy-efficient networks managing losses, costs, and increasing asset performance. To this end, business models should be designed and developed to meet the electricity industry's strategic objectives [56]. Moreover, climate change and the pressure on the electricity industry to reduce greenhouse gas emissions are severe challenges for the industry in the new environment [57]. Applying methods and measures to overcome this dilemma of the electricity industry in critical and sensitive situations while not imposing higher costs than before is perhaps one of the sector's most critical challenges. Therefore, a rigorous rethink of energy management activities is required. In addition, the deployment of a vast number of smart meters around the world can provide a platform for offering smart prices to customers such as different price rates and variable electricity costs [58]. Such infrastructures will enable possibilities to engage and interact with consumers to reduce costs, manage energy consumption, and reduce peak demand. As one of the most basic strategies for realizing the smart power system, DR can provide significant flexibility in demand so that the electricity industry can use its economic and technical benefits [59]. This flexibility will be realized to increase or decrease the load within a specific time frame. Therefore, applying DR is valuable for power companies, consumers, energy policy-makers, and regulators as a precondition for decision-making [60]. Furthermore, DR in the smart grid is a practical approach that can influence different demand behaviors with different pricing or incentive policies [61].

4.4.2. Sustainable control of the LV network

The information from the smart metering systems, stored on a data basis, is processed by different cutting-edge technologies, (like AI, ML, deep learning, etc.) to better understand consumption patterns as well as problems in the operation of LV network providing an opportunity to the DSO and TSO new actions proactively and predictively. Providing customers with real time information at an aggregate level can induce them to adopt energy conservation behaviors that could save between 10 and 15% in consumption [62]. Smart meters are called upon to play an essential role for the customer, helping them manage their demand response (DR) more efficiently [63]. An essential part of smart grids is the AMI, which enables remote reading of consumption and provides real time information on electrical quantities to monitor and control the distribution system through a power management system demand, as shown in Figure 43.

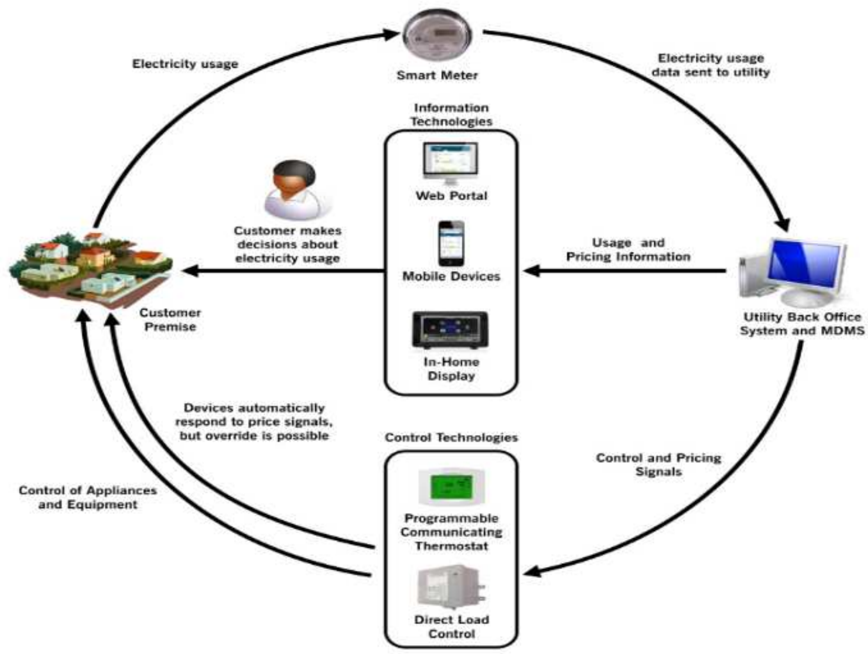

Figure 43: Advanced Measurement Structure [63]

The implementation of smart meters has promoted the so-called "Non-Intrusive Load Monitoring (NILM)" [63], which DSOs can use as a complement to advanced demand management software. If regulators support the mentioned procedure with the right regulations then implementation of sustainable energy consumption habits in the long term will be possible [64]. Direct control of the load is expected in the residential sector through smart meter communication via Power Line Communication (PLC) to transmit load curves with sampling every 15 to 30 minutes. In some countries, such as the UK, smart meters may include a wireless port (e.g. ZigBee, RF) to allow higher resolutions, i.e. load curves sampled every 1 to 10 seconds through the HAN, a fictitious device can capture this data and send it to the cloud for disaggregation [63].

4.4.3. DSO/TSO coordination

The reasons for interfacing between the TSO and the DSO can be structured into three groups:

- **Market framework.** All the resources connected to the transmission and distribution networks, such as generation, storage and active demand, can participate in the energy markets and offer services to the system (frequency response, voltage control, balance, etc.). In particular, active demand should be treated as a resource (producers, consumers, prosumers) and (response to demand).
- **Operational interaction.** Given that the network is increasingly active at the distribution level, it is necessary for the DSO to have sufficient observability at the distribution level, sufficient, adequate and pertinent to their respective functions and roles, to serve all the actors, DSOs, aggregators and TSOs. The TSO and the DSO must supervise the services; in this scenario, the DSO should collect the data from the sparse generation and provide it appropriately. The TSOs should be responsible for coordinating the control of the system, the defense plans and the special protection schemes that could progressively involve more resources at the distribution level, in such a way that they respect and foresee the possibility of dealing with any impact or congestion of the distribution network.
- **Interaction planning.** Given that the main changes will take place at the distribution level, an exchange of information between the DSOs and the TSOs on the behavior of the network is crucial and necessary. System security is increasingly dependent on the distribution system and load forecasting and DERs for short and long-term planning.

4.4.4. Indirect active power management through pricing

State of the art

An essential element of the demand response is the TOU (Time of Use) rates, which incentivize customers to adjust their electricity use voluntarily, either through automation or manually, to reduce their expenses. Price signals can be static or dynamic, or a combination of both [65], vary over time and reflect the marginal costs of the network and/or power generation costs in the wholesale market. Dynamic pricing (DP) is a form of demand-side response which is an evolving field of innovation in retail markets. It is made possible with the availability of smart meter data and flexible consumption. DP can be achieved through real time / spot pricing and advanced forms of time of use and critical peak pricing.

Consumers may be interested in dynamic pricing if they are well informed and if the systems are designed in a user-friendly way to allow them to save on their bill [66]. To maximize flexibility consumers potential, appropriate retail pricing structures are needed to incentivize consumer investment in electric heating, cooling and transportation, and their consumption decisions. Real time hourly pricing is predominantly used in six European countries: Estonia, Latvia, Spain, Slovakia, Slovenia and Bulgaria. Peak hour pricing is used to a lesser extent in different countries, such as France, where the "Time" rate has been chosen by 1.2% of households [65]. For example, in Denmark, consumers pay for electricity in advance every month and face subsequent corrections to reflect the actual price paid by suppliers on the spot market instead of the expected price. Like electricity tariffs, static pricing is the most common type of TOU pricing for power grids, applied in 15 of the 22 countries for which information is available [65]. Time-based tariff programs require advanced metering infrastructure (AMI) [67].

Table 11 Summary of TOU rate applications

Key parameters	Description
Countries where TOU fees apply	17 European countries (including Sweden, Germany, Finland, France), USA, India.
TOU rate types adopted	**Static ToU pricing**: Differentiation of the TOU day/night (this is very common in Europe; for example, in Italy, all low voltage consumers are compulsorily exposed to TOU rates if they do not choose a provider on the liberalized market). **Dynamic real time pricing**: Estonia, Romania, Spain, Sweden, and the United Kingdom apply this type of tariff (for example, between 25% and 50% of all households in Estonia and Spain pay their supply costs on the hourly prices). **Other dynamic pricing methods**: Applied in Denmark, Norway, and Sweden, where electricity consumers incur spot market-based pricing through the monthly average wholesale price. **Critical peak pricing**: Applies to a lesser extent in the UK, Lithuania, Portugal, Romania and France.
Services provided	• Implied response to demand (consumer participation in the energy transition). • Benefits for consumers such as savings on the electricity bill. • Rates that reflect the costs that benefit providers. • More competition between suppliers in the retail market as an engine of innovative business models.

Both static and dynamic pricing could be defined for both EVs and DGs in order to improve the control of LV networks (such as avoiding overloading, overvoltages or undervoltages situations).

Smart chargers and power management units

The massive penetration effects of EVs technology in distribution systems motivates research in smart charging strategies in order to reduce the costs of electrical energy for recharging, avoiding an overload to the operating system while reducing system losses [68].

Smart Charging V2G Technology

Smart charging adapts EV battery charging patterns in response to market signals, time-varying electricity prices or incentives, or in response to consumer acceptance of the offer, alone or through aggregation, to sell reduction/increase in demand (grid to vehicle) or injection of energy (vehicle to grid) in organized electricity markets [69]. One of the technologies adopted to reduce the impact on distribution networks is V2G (Vehicle to grid); here, the vehicle will be equipped with bi-directional chargers; the EV battery is used to store energy during low consumption hours and discharge the battery when required. This technology allows the flow of electrical energy to and from the EV, that is, being able to charge and export surplus energy to the grid. In networks where renewable energy sources such as solar and wind are available, bidirectional charging regulates the variable flow of electricity generation by these generators [70].

Intelligent control methods for loading

There are two architectures used for the implementation of control methods, centralized control and decentralized control. The first is based on decision making remotely controls the charging power of an EV. Decentralized control depends on the owner of the EV; he will be the one who makes the decision and responds to the signals of a third party, for example, price or control signal [71]. A large body of research focused on EV smart charging and the development of optimal charging strategies. In [72], an analysis of intelligent load for EV is performed from the algorithmic perspective; it focuses on the intelligent interactions between the intelligent network, the aggregators and the EVs from the algorithmic perspective to achieve the flattening of the load. Direct and indirect control approaches have been used to maximize the overall satisfaction of all EV customers. Stochastic optimization approaches have been used to design the optimal program to minimize the cost of charging individual EV customers. The smart charging function is achieved by communicating the charging system with DSO through a data connection to optimize EV charging. The information provided by the smart charger can include the charging time and speed, the capacity of the local network and energy consumption data of the place where the recharging takes place.

Project example in Japan

Description of the project

In Japan, a demonstration project for remote control of EV charging was implemented in 2020. The control of EV was based on the electricity tariff linked to the electricity market price, which is dynamic pricing. The system image of the project is shown in Figure 44. Thirty-two V2H (Vehicle To Home) units in each of the households were controlled remotely by an aggregator to shift the EV charging time. A control method was considered to ensure that the amount of charge required by the customer is charged through remote control from the server during inexpensive times based on dynamic pricing rates, the chargeable amount of EVs, and the customer's EV usage plan.

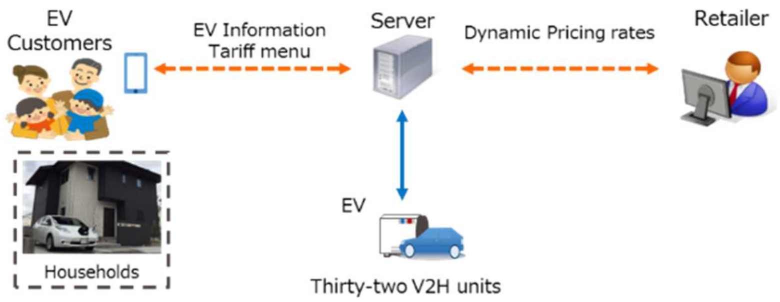

Figure 44: System image

The effects related to the shifting of charging times were found by conducting the following two demonstrations and comparing them with normal charging data.

- Price Proposal: A method in which dynamic pricing rates is presented to customers and they charge EV during inexpensive times by themselves (manual control).
- Remote Control: A method in which the aggregator controls the charging remotely during inexpensive time based on DP rates and chargeable amount of EVs.

Outcome of the project

The results of the two demonstrations are shown in Figure 45. Compared to normal charging data, the charging time shift could be confirmed for both “Price Proposal” and “Remote Control” strategies. The amount of charge per week during the lowest-price time period were respectively 908 kWh for “Price Proposal” and 1258 kWh for “Remote Control”, compared to 137 kWh for normal use. As a result, a larger shift was observed with “Remote Control”, indicating its superiority in terms of shifting the charging time. In addition, “Remote Control” is presumed to be superior from the viewpoint of customer burden because EVs are automatically charged during inexpensive times. Once the user has set the EV usage plan and target its State of Charge (SoC) in the smartphone app, the system is designed to remotely charge the required amount of electricity by avoiding the times when the user uses the EV.

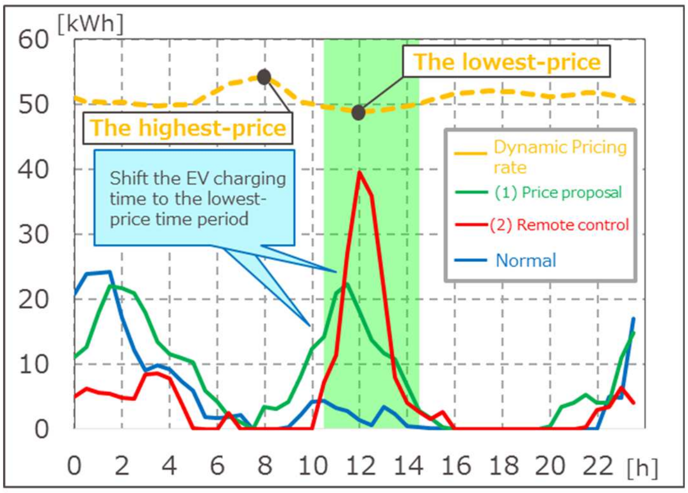

Figure 45: Hourly EV charging data

4.4.5. Barriers

Data accuracy, reliability, volume and security

For proper measurement, computational, control, and communication capabilities, energy markets need a good platform with high measurement resolution to conduct accurate transactions. In addition, it is crucial to know how to implement measurement technology. Therefore, the need for accurate and reliable measurement of values in such a way as to identify the flexibility of demand will be one of the essential obstacles. Excessive data computation considering uncertainty in DR potential and its prices can be an obstacle to choose the optimal DR program. Assuming that the measurements of the data and the calculations on it are done carefully, the correct transfer of information to the decision-making centers can be considered another obstacle. In addition to this issue, compliance with information security and data privacy can be a significant challenge in this area.

Standardization

As the integration of DR and other renewable resources in the smart grid, will grow continuously, the decentralized character of the energy grid will increase [73]. To match the different parts of this complex technology, the lack of a clear and codified standard can be a significant obstacle to other technologies' entry. The need for experts in technology, proper design of technology, proper implementation, and good local support requires skilled professionals, the absence of which is a significant obstacle in the performance of DR programs [74].

Estimation of the value of DR for the system

Grid capacity limitations, the power system loading to the maximum capacity, which then requires upgrading the existing network, is one of the main obstacles to implementing DR programs. As a result, the value of DR is very high in parts of the system that need to be upgraded, but in cases where there is spare capacity, its value is usually low [75].

Coordination requirement

In the liberalized structure, for specific times, some participants can provide power supply downstream of the network. In contrast, the imitations in transmission capacity can lead to an obstacle to transferring power. Accordingly, attempts to incorporate multiple goals on a time horizon with competitive effects are impractical and may lead to opaque economic incentives [76] .

4.4.6. Recommendations

In general, the direction of future actions of DR programs can be categorized as follows:

- **Development of communication systems and telecommunication platforms** within consumer premises so that it is possible to establish two-way communication with devices and manage them to run DR programs. In this way, data sharing between the company, third parties, and consumers should be possible so that all stakeholders can see the implementation results of DR programs, compare costs or rewards. Also, they can plan to participate in DR schemes with each other's help.

- **Development of small local markets (including local energy communities) to promote DR programs.** The small markets make DR programs better manage the network and use all of its potentials to meet the goals of the bulk electricity grid. In addition, local markets need to provide solutions and attract customer engagement by targeting small capabilities at electrical loads and identifying all available load response capacities.
- **Development of novel technologies such as smart meters and moving towards real time prices** can lead the DR programs to be run in real time conditions. In this case, consumers should constantly monitor electricity prices, especially at different times by themselves or their agents, if necessary, to change their consumption or possibly their contracts.
- **Identification of the potential of DR schemes in gaps that resulted from the uncertainty of local power generation**, such as PV, EV, and wind at certain hours. These energy sources can cause problems for the network when they are interrupted. Therefore, the definition of specific DR strategies in these situations should be clear so that the necessary planning can be done in case of an emergency.
- **Standardization of DR schemes** can also make DR actions practical in all countries. For example, a standard definition of DR activities, along with their range and performance, can be useful in consumer-type-based planning. This can be seen locally or overall, or even in any area so that the actions are entirely targeted considering the defined limits.

4.5. AUTOMATIC PHASE BALANCING

According to [77] the impacts of new services such as electrical motorbikes, inductions cookers, and DGs cause a considerable increase in the required power and adverse effects such as significant overloads and imbalances. The development of a system able to select the best phase of connection of DGs could be interesting in some areas where the imbalance is very high.

4.5.1. Case of France and Ecuador

State of the art

The research done in [78] presents a methodology allowing DSOs to determine the DGs (mainly photovoltaic panels) optimal phase connection, using smart meters and network topology data. The aim is to present a highly adaptable solution allowing DSOs to get a simulation tool, which can find the best phase connection with a short study time. On the presented method the DG phase connection is fixed, contrary to [79] where the DG phase connection change with the unbalance. Nowadays the end-users are able to install local generation, generally single-phase because of low power levels (some kW). It means that now, the DSO has to deal with the effects derivate of DGs such as bi-directional flows or increase in the losses. The most common approach is connecting the single-phase PV system in the same phase of the load; however, it could generate unbalance increase and voltage problems. A methodology for analyzing the best phase for the connection of single-phase DGs is presented. Using weighting functions, each phase is classified; the phase with lower coefficients is chosen. Nevertheless, in the medium or long-term, the selected phase could not be the best option. In order to avoid having permanently the same phase and to enable the PV for choosing the optimal phase based on network state, in [80], a system named Automatic Phase Shifting (APS) has been patented. The system is designed for working with configurations 3P4W; it means 3 phases - 4 wires (three phases + neutral) and then with single-phase PV as illustrated in Figure 46. It could also work with other types of DG, interruptible loads and EV charging stations.

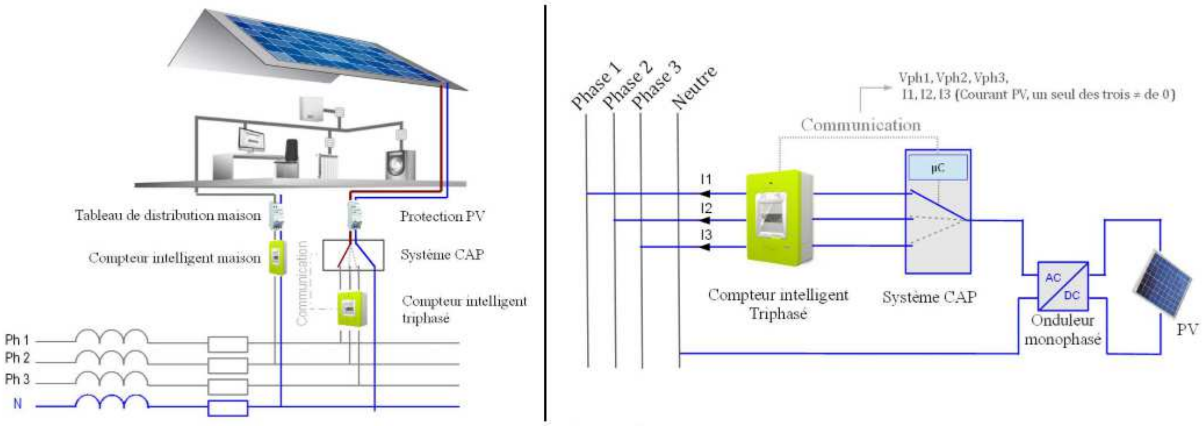

Figure 46: APS System [80]

The patent developed for APS system was tailored for working properly in the most typical configuration in South America, in other words, 1P3W (1 phase 3 wires) as is depicted in Figure 47. It means that the system would choose between Phase L1 or Phase L2.

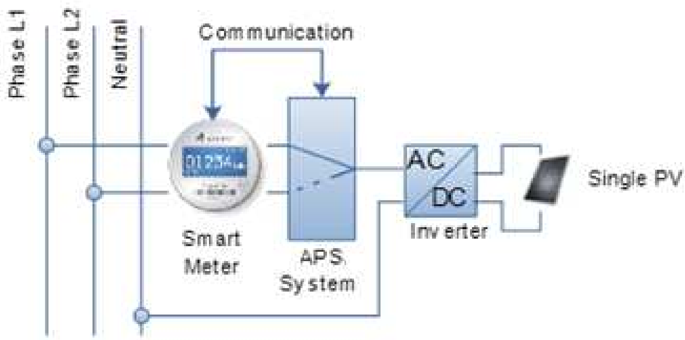

Figure 47: Tailored APS system for Galapagos

For testing purposes, in [81] three APS systems are installed at different distances from the transformer; One at the secondary bus bar of the transformer, one at the end of a feeder, and one approximately in the middle of a feeder, see Figure 48.

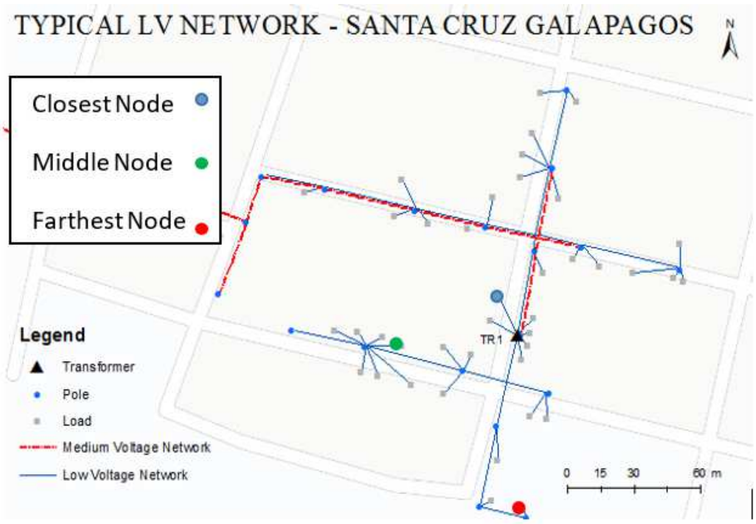

Figure 48: Topology for testing APS System

The algorithm uses the local voltage measurements of the two phases and the current produced by the DG as input data. These quantities make it possible to perform an estimation of the impact of switching on the phase voltages and give thus a switching validation if required. A phase change is allowed if the two inequalities remain valid for a minimum time.

$$\left(V_j + S_{pj(\frac{V}{W})} \times P_{DG}\right) \times 0{,}96 < V_i \,, (i,j) \in [1;3]^2, i \neq j \qquad \text{Eq. 1}$$

$$P_{DG} > 0.1 \times P_{maxDG} \qquad \text{Eq. 2}$$

Where:

- i and j: phase index,
- V_i : voltage magnitude of phase i,
- $S_{pj(\frac{V}{W})}$: phase j sensitivity gradient at the moment computed with the measurements of voltages and powers,
- P_{DG}: power produced by DG,
- P_{maxDG}: DG rated capacity.

For validating Eq. 2, the voltage in the phase *i* must be 4% higher than the estimated one of phase j after the switching. The phase *j* voltage is determined employing $S_{pj(\frac{V}{W})}$. Moreover, Eq. 2 guarantees that the DG supply is at least 10% of its rated capacity, which means that the impact of a switching will not be negligible.

On-going project in Ecuador - description

Throughout the Trans-National Access user projects option of the ERIGrid project, the University Catholic of Cuenca has been working in testing in a real environment a prototype for selecting the best phase for connecting a PV installation. In the simulation, the results were promising. Hence, the stage building of a prototype for analyzing real scenarios was completed. The new prototype will be installed in Santa Cruz Island – Galapagos, a typical LV network would be chosen to install the CAPS2 system; a decrease in the unbalance and improvement in the voltage profile are expected results. The CAPS2 has to be designed to report in real time the information to the ADMS already deployed in Galapagos. Once the results have been analyzed, the local utility, ELECGALAPAGOS, can decide if it will massively deploy the system, or focus the efforts on the points with the highest unbalance. Here, it is worth mentioning that due to the pandemic situation originated by COVID 19 the prototype is not yet installed.

On-going project in Ecuador – technical requirements

The last prototype, depicted in Figure 49 and validated using an architecture PHIL (Power Hardware In the Loop), was developed between Grenoble INP and the Institut National des Sciences Appliqués of Lyon – INSA- [82].

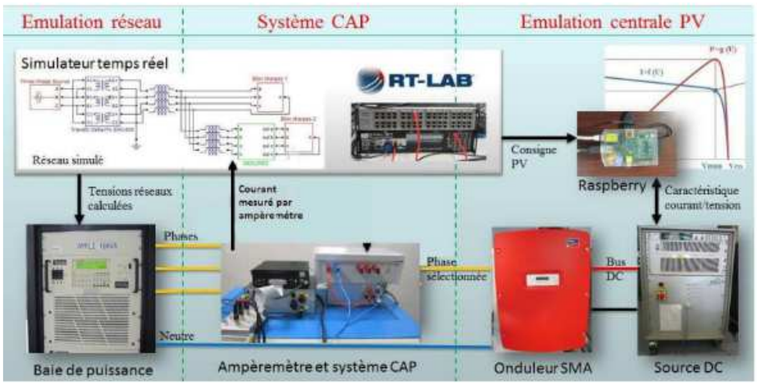

Figure 49: Real time simulation model [82]

According to [83], the prototype is easy to build, not expensive (about 200$) and could be implemented with common electronic elements. A brief list of the elements depicted in Figure 50 is: ultra-fast fuses, zener diodes, resistances, filtering capacitors, DC / DC converter, current transducer, light diodes, switches, Arduino. Figure 50 shows a APS system interior view.

Figure 50: APS system components [83]

4.5.2. Case of China

In the 3-phase 4-wire LV network in China, the customers' loads are a mixture of single-phase and three-phase loads. There are unpredictable and irregular unbalance in the customers loads. The system component parameters are also not always balanced. Therefore, three phase current unbalance commonly exists. According to statistics, over 85% of LV network in China have different levels of unbalance. Unbalanced loads increase the losses on the network. Current through the neutral conductor further increases the power loss and may even cause damage to the conductor. In the past, utilities used their experience to re-distribute the loads and to increase the size of the neutral conductor to minimize safety risk, but there was no other effective way to handle this situation. In order to alleviate these conditions, manufacturers in China have developed products such as capacitive regulators or reactive power regulators. However, because the inductive loads have complex and variable operating conditions, these regulators were not very effective to minimize the losses. More sophisticated automatic load balancing methods are now being developed. The methods typically measure the three-phase voltages and currents in real time, and using algorithms to automatically re-distribute the loads.

The technique is based on the well-established technology of 3-phase load transfer switches. The input to the switch is 3-phase 4-wire, the output is single-phase 2-wire. An automatic load-transfer switch, when receives a command, can perform phase change to a single-phase load without affecting the normal operation of the load, as shown in Figure 51.

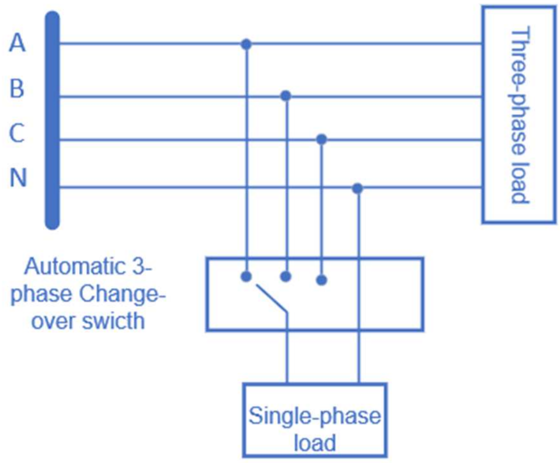

Figure 51: Automatic load-transfer switch

The three-phase load balance control system is made up of terminal units (see Figure 52) installed on the LV network. The unit consists of a data acquisition module to monitor voltages, currents and digital status, a communications module to communicate to a master station, a control unit to control the three-phase change-over switch, and a man-machine interface for change of settings.

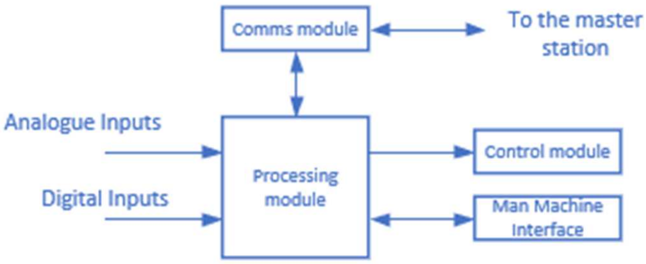

Figure 52: Smart terminal units

The master station collects both the real time data and the historical data. Together with the network parameters, it is able to establish the necessary information about the load imbalance situation of a region in the network. It can then perform an optimum load transfer strategy to control the three-phase change-over switches, thus providing an automatic LV load monitoring and phase balance system. The cost of this equipment widely used in China is about 1500 $.

4.6. *Other advanced use cases*

Another advanced use case concerns the ability of the LV networks to be operated temporarily as an off-grid microgrid in special conditions such as:

Service restoration in case of faults at the MV, MV/LV transformer or LV feeder level: DERs in the LV networks could be used to reenergize customers while DSOs are repairing the damages. Advanced control functions need to be developed to deal with the following issues: black-start of the LV network, stability and protections of the microgrid and switching management from the interconnected to the isolated mode.

Constraints in the upstream networks: in case of thermal or voltage constraints in the MV/LV substations or MV networks, LV clusters could be disconnected waiting for the DSO to find a sustainable solution.

The CIRED working group 2018-3 on “Microgrids in interconnected and islanded modes” whose report is available in [84] provides the technical requirements of such operations.

5. Conclusions and recommendations

A digitized energy market is a consequence of an extremely rapid technological, IT and business evolution, as well as, increased customer awareness and maturity for active participation. The LV network is expected to be an enabler of technical and business requirements from involved actors. This can be achieved solely if the whole complex system, consisting of quite different, but mutually very dependent, circumstances meet all necessary requirements. DSOs should, without any reservation or constraints, be qualified to:

- Connect producers/consumers with completely unknown generation/consumption patterns to the grid;
- Monitor the network in near real time;
- Act proactively and even predictively;

- Communicate with customers and field workers in digital way;
- Make use of flexibility services;
- Minimize outages and any kind of disturbances in energy supply or power quality.

To achieve these requirements, DSOs cannot simply apply a technical adaptation as for the HV and MV networks. It would require a considerable financial and most likely late-profitable investment. A combination of well-advised workarounds and precisely considered financial investment in installation of a new metering equipment (sensors, meters) in the network, combined with an increased knowledge in and usage of IoT, AI, data analytics and machine learning are expected to meet the set goals.

Near real time monitoring of LV Network

To provide this service, there is a need of metering equipment able to record a deviation in voltage, current, phase shift, etc. The collected data have to be distributed immediately for further analyses in the LVM and DMS. Due to the huge amount of data, some sophisticated algorithms must be developed to sort out noise and get the relevant information. Using standard ML methods supplemented with other custom adapted algorithms and AI technologies, different delivery deviations can be detected. Some are of an urgent nature and require urgent control actions (such as interruptions), while other provide information on ongoing power quality issues, problems that can be expected (such as dips, flicker etc.) or faults (such as earthing faults, serial arc faults).

Back-office monitoring

Similar to the monitoring of many parameters for MV transformers in a proactive and predictive way, data coming from the meters and sensors belonging to LV networks can be used to understand where in the network temporal or permanent power quality problems are to be expected. In back-office analysis of historical data, breakdowns can be discerned and accordingly be successfully used in order to initiate unplanned maintenance, inspection or rebuilding.

It is important to point out that LVM cannot be done only with the help of metering data from the smart meters. The most reliable and useful conclusions are usually based on analyses and algorithms that put the data from smart meters in relation to data from other sources and with physical models of the network. Other data types can be network structure data, theoretical parameters such as transformers and lines impedances, consumption profiles, consumption / production data, weather data and so on. Back-office algorithms simultaneously monitor several parameters, superintending changes in delivery status over time, where the time window can vary from one hour to several months or years. Tools for visualization of back-office analyses should be able to handle presentations of interactive, dynamic sub-results based on various available parameters.

Proactive and predictive monitoring

While SCADA systems monitor power delivery on HV networks in real time, without taking into account the history of the delivery or ability to give a hint of upcoming delivery problems, LVM can present ongoing delivery and power quality status, but also alert about any upcoming problems. This means that LVM needs to have algorithms to handle historical and near real time data from the meters, as well as possess advanced dashboards for visualization of the results.

LV network control

Since DGs, particularly the ones based on variable RESs, started to increase, and with the introduction of EVs, the impact on voltages and currents in LV networks has become greater. In addition to monitoring voltage variations and proactive, predictively evoke awareness for network areas that are in risk zones for voltage deterioration, LVM can be supplemented with functions for voltage control.

Voltage control can be done in different ways. For example, LVM can use active power generation curtailment or instead manage reactive power output (either dynamically or with a fixed value). The type of LV control functions deployed will depend on the nature of the network, typically the R/X ratio of the lines / cables. Smart meters themselves, as part of LVM infrastructure can be used for remote disconnections or to control certain services that can be activated / deactivated via the customer interface. If SCADA and LVM have a relatively integrated IT infrastructure with possibilities for data transfer from SCADA to LVM, a higher degree of control can be achieved. Different types of control can be considered: a centralized control requires the development of an IT infrastructures and a good knowledge of the network or observability algorithms while a decentralized control acting locally has a lower investments but the tuning of the controlled parameters is more complex and requires a good knowledge of the behavior of the network. A hybridization of these controls seems to be a good trade-off. It is also important to have a regulation framework for DER control (apart from the grid codes) as well as the identification of adequate business models and efficient remuneration for providing these types of services.

Self-Healing functions in LV network may be located in lower technology readiness levels, thus not technologically mature enough, comparing to that of the MV. Real time communication with the exiting devices to the dispatch center are already attained, however, structural alterations must be made on the grid, i.e., upgrading from fuses to remotely operated LV circuit-breakers.

DR programs and transactive energy can be widely used to solve network congestions. In general, the direction of future actions of R&D programs can be classified as follows: development of communication systems and telecommunications platforms within consumer facilities so that it is possible to establish bidirectional communication with devices and manage them to run DR programs. In this way, the exchange of data between the company, third parties and consumers should be possible so that all interested parties can see the results of the implementation of interruption recovery programs, compare costs or rewards. The development of novel technologies such as smart meters and the shift towards real time pricing can lead to interruption recovery programs running under real time conditions. In this case, consumers should constantly monitor electricity prices, especially at different times by themselves or their agents, and if necessary, be able to change their consumption or possibly their contracts. Standardization of the DR mechanism is necessary to increase their deployment.

New technologies to improve LV network operation

Depending on use cases, new technologies may improve the operation of the LV network reducing the global expenses. In this report, the example of automatic phase balancing is described. If this solution is interesting in the case of Galapagos island and China, it may not be the case in other countries if the level if imbalance is low. A cost benefice analysis has to be done to validate the economic interest of new technologies before their deployment.

Digitized data exchange between all stakeholders

Everything in the energy market depends on, or influence each other. Data supply is huge and the need for information exchange is increasing progressively. A lot of exchanges happen in real time, usually without the need for human intervention. As a result, communication will undeniably have to be largely digitized.

6. APPENDIX : SURVEY

This section details the questions asked to several DSOs worldwide whose answers are summarized in section 2

Q1. E-mail adress

6.1. PART I - GENERAL INFORMATION (9 QUESTIONS)

Q2. In which country are you operating the distribution network?

Q3. What is the name of your company?

Q4. In which department are you working (for example metering, network planning, network operation)?

Q5. What is the type of distribution in LV? - multiple replies are possible

- Three phases for the LV main feeders, single phase for small customers and three phases for big customers
- All in single phase
- All in three phases
- I don't know
- Other :

Q6. What kind of neutral grounding are you using on the LV side of MV/LV transformer? - multiple replies are possible

- Isolated neutral
- Solid grounding
- Resistance grounding
- Reactance grounding
- Impedance grounding

- Peterson Coil grounding
- I don't know
- Other:

Q7. What are the voltage levels used in the LV distribution network? - multiple replies are possible

- 400 V phase to phase
- 230 V phase to phase
- I don't know
- Other:

Q8. What standards do you use in LV for power/voltage quality assessment? (for example, EN 50160 or "I don't known" if not known)?

Q9. What voltage/power quality characteristics are an issue in your LV distribution system? Please indicate the severity of each chosen phenomena (from 0 to 10, where 10 means the most severe case). - only one possible answer per line

	I don't know	0	1	2	3	4	5	6	7	8	9	10
Voltage frequency variations/deviations												
Voltage magnitude variations/deviations												
Voltage unbalance												
Harmonic voltages/harmonic distortion												
Voltage fluctuations/rapid voltage changes/voltage flicker												
Voltage swells												
Voltage dips (sags)												
Short time supply interruptions												
Long term supply interruptions (typically longer than 3 minutes)												

Q10. What are the admissible voltage magnitude deviations from nominal value allowed in LV? - multiple replies are possible

- +/-10 %
- +/-5 %
- I don't know

- Other :

6.2. PART II – MV/LV SUBSTATIONS (6 TO 10 QUESTIONS)

Q11. How many MV/LV substations (distribution transformers) are you operating? - only one possible answer

- < 2000
- Between 2000 and 10 000
- Between 10 000 and 50 000
- Between 50 000 and 100 000
- Between 100 000 and 250 000
- Between 250 000 and 500 000
- Over 500 000
- I don't know

Q12. What are their main/most representative installed capacities (provide the percentage of occurrence per capacity)? - only one possible answer per line

	I don't know	0 %	[0;10] %	[10;20] %	[20;30] %	[30;40] %	[40;50] %	[50;60] %	[60;70] %	[70;80] %	[80;90] %	[90;100] %	100 %
< 100 kVA													
[100 ; 250] kVA													
[250 ; 400] kVA													
[400 ; 700] kVA													
> 700 kVA													

Q13. Do you employ on-load tap changer (OLTC) at the MV/LV transformers? - only one possible answer

- No (Go to question 14)
- Considered in some cases (Go to question 15)
- Yes (Go to question 15)
- I don't know (Go to question 14)

Q14. Is there any measurement (for example energies, powers, voltages, currents) in the MV/LV substations? - only one possible answer

- Online measurements (Go to question 18)
- Off-line measurements (Go to question 14)

- Both online and offline measurements (Go to question 14)
- No measurement (Go to question 21)
- I don't know (Go to question 21)

Q15. What is the percentage of MV/LV transformers equipped with OLTC (if not known, write "I don't know")?

Q16. What is the number and step of tap positions of the OLTC (example of answer: 3 tap positions -2.5%, 0 %, 2.5% or "I don't know" if not known).

Q17. What is the tap changer control based on? - multiple replies are possible

- Secondary side voltage
- Secondary side voltage with current based voltage drop compensation
- Feeders (voltage) profile provided by distributed measurement in the LV grid
- I don't know
- Other

Q18. Please indicate the percentage of data that are measured online and offline? - only one possible answer per line

	I don't know	< 10 %	[10;20] %	[20;30] %	[30;40] %	[40;50] %	[50;60] %	[60;70] %	[70;80] %	[80;90] %	> 90 %
Data measured online											
Data measured offline											
Data not measured											

Q19. If you do have monitoring in the MV/LV substations, are they measured according to International, European or another standard(s)? (i.e. EN 61000-4-30: class A, accompanied by percentage of cases estimation, write "I don't know" if not known)

Q20. If you do have measurements, what kind of quantities do you measure, record and collect? Please add in "other" additional quantities if relevant and available. - multiple replies are possible

- RMS values (voltage, current)
- Powers per phase
- Powers summed three-phase values
- Spectral components
- Voltage deviation
- Voltage harmonics

- Voltage unbalance
- I don't know
- Other

Q21. How do you estimate the loads curves and peaks of the transformers if not monitored? - multiple replies are possible

- Mathematical models developed by the company
- Statistics
- Energy aggregation on short periods
- I don't know
- Other

Q22. Do you plan to equip MV/LV substations with measurements? - only one possible answer

- No
- Yes, in some specific cases/if required
- Yes, wide retrofit is expected
- I don't know
- Other

6.3. Part III – LV customers (consumers/prosumers/producers) (between 6 and 16 questions)

Q23. How many LV customers are you supplying? - only one possible answer per line

- < 100 000
- Between 100 000 and 500 000
- Between 500 000 and 1 million
- Between 1 million and 25 million
- More than 25 million
- I don't know

Q24. What is the percentage of deployment of smart meters? (Currently or in progress)? - only one possible answer

- 0 % or pilot projects (Go to question 28)
- Between 0 % and 25 % (Go to question 30)
- Between 25 % and 50 % (Go to question 30)
- Between 50 % and 75 % (Go to question 30)
- Between 75 % and 100 % (Go to question 30)
- I don't know (Go to question 28)

Q25. Is there any LV control function deployed behind the meter and using data/signal from the revenue meter provided to the customer for that purpose? - multiple replies are possible

- Consumer power management
- Production power management
- EV management
- I don't know
- Other:

Q26. Do you operate any other system, independent on smart meters, implementing remote or autonomous controls on LV customer's side for LV network automation/control? - multiple replies are possible

- Remote control of loads - consumption profiles optimization task
- Remote disconnection/reconnection of customers (for instance for emergent load shedding),
- Autonomous disconnection/reconnection of customers (for instance for emergent load shedding),
- Remote emergency control – curtailment of generating units
- I don't know
- Other:

Q27. Do you require/demand autonomous voltage support (local volt/frequency-var/watt control) from generating units or even battery energy storage systems (newly) connected to LV grid? If yes, please specify regulation or standards to meet, write "I don't know" otherwise.

Q28. Do you plan to deploy smart meters? - only one possible answer

- Yes (Go to question 29)
- No (Go to question 25)
- I don't know (Go to question 25)

Q29. Please specify, when is the deployment of smart meters planned (write "I don't know" otherwise)

Q30. When did you start the deployment of smart meters? If not known, write "I don't know"

Q31. When did you finish or are you expecting to finish? If not known, write "I don't know".

Q32. What are the quantities measured and provided by the smart meters? - multiple replies are possible

- Active powers
- Reactive powers
- Apparent powers
- Active energies
- Reactive energies
- Apparent energies
- Voltages
- Currents

- Frequency
- Harmonics
- Unbalance
- Voltage events – swells/dips/interruptions
- I don't know
- Other:

Q33. What is the granularity of the data measured? - multiple replies are possible

	Not applicable	1 s values – snap shots	1 min values	5 min values	10 min values	15 min values	Single phase	Three phase sum
Powers/energies	☐	☐	☐	☐	☐	☐	☐	☐
Voltages	☐	☐	☐	☐	☐	☐	☐	☐
Currents	☐	☐	☐	☐	☐	☐	☐	☐
Frequency	☐	☐	☐	☐	☐	☐	☐	☐

Q34. Where are these data available/stored? - multiple replies are possible

- In the meter
- In a concentrator in the MV/LV substations
- In a cloud or in a dedicated central data storage
- I don't know

Q35. Are the data stored available in real time? - only one possible answer

- Yes
- No
- I don't know

Q36. Are the data stored available 1 - with some delay (please precise average or typical delay if known), 2 - Downloaded once a day, 3 - Downloaded several times a day, (please specify how many times if known)? If not known, write "I don't know".

Q37. Do the meters and communication infrastructure support push mode (irregular messages invoked by meters based on a condition fulfillment)? If yes, please comment shortly for what purpose. If not known, write "I don't know".

Q38. Do you use smart meter's control functions for one of the following LV network automation/control functions? - multiple replies are possible

- Remote control of loads – for consumption profiles optimization tasks for example

- Autonomous control of loads
- Autonomous limitation of consumption/loading
- Remote disconnection/reconnection of customers
- Remote emergency control – curtailment of generating units
- None of the above
- I don't know
- Other

Q39. Do you use smart meter's data for one of the following LV network automation actions (action automatically made and embedded in a system)? - multiple replies are possible

- Power flows optimization
- Voltage profile control
- None of the above
- I don't know
- Other

Q40. What are the use cases of the smart meters' data for LV distribution system management? - multiple replies are possible

- Outages identification
- Recognition of an island existence
- Voltage quality violation indication
- Maintenance planning and workforce allocation
- Operation planning
- Voltage quality indices trending identification
- Technical losses refinement and non-technical losses identification and delimitation
- Load flow models improvement
- Electricity trade models improvement
- Determination of available hosting capacity for new customers/new devices (generation units, EV chargers, etc.),
- Improving LV system reliability
- Investments allocation
- Development planning
- I don't know
- Other

6.4. PART IV: LV NETWORK (13 OR 14 QUESTIONS)

Q41. What is the overall length (in km) of LV lines you operate (if not known, write "I don't know)?

Q42. If kown, what is the ratio of LV overhead lines (in percentage of the overall length of LV lines, write "I don't know otherwise)?

Q43. Topology of the LV system: indicate the share in percentage from all operated LV systems - only one possible answer per line

	I don't know	0 %	[0;10] %	[10;20] %	[20;30] %	[30;40] %	[40;50] %	[50;60] %	[60;70] %	[70;80] %	[80;90] %	[90;100] %	100 %
Radial													
Meshed (loop included) and operated radial													
Meshed (loop included) operated meshed													

Q44. Do you have other topologies? (if known, please list them with percentual share or write "I don't know" otherwise).

Q45. If known, what is the percentage of GIS information you have of the LV system (write "I don't know" otherwise)?

Q46. Do you know exactly the topology of the LV system? Please provide the percentage of knowledge you have for the feeder where each customer is connected to. - only one possible answer per line

	I don't know	0 %	[0;10] %	[10;20] %	[20;30] %	[30;40] %	[40;50] %	[50;60] %	[60;70] %	[70;80] %	[80;90] %	[90;100] %	100 %
The feeder where each customer is connected to													
The phase where each customer is connected to													
The LV line diagram													

Q47. If known, can you specify cumulative percentage of customers being closer to MV/LV substation than indicated distance (the length means length of line)? - only one possible answer per line

	I don't know	0 %	[0;10] %	[10;20] %	[20;30] %	[30;40] %	[40;50] %	[50;60] %	[60;70] %	[70;80] %	[80;90] %	[90;100] %
L < 250 m	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
250 m < L < 500 m	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
500 m < L < 750 m	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
750 m < L < 1000 m	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
L > 1000 m	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

Q48. What are the protection technologies used at the secondary side of the MV/LV substation and/or for LV feeders? (please indicate by means of percentual share) - only one possible answer per line

	I don't know	0 %	[0;10] %	[10;20] %	[20;30] %	[30;40] %	[40;50] %	[50;60] %	[60;70] %	[70;80] %	[80;90] %	[90;100] %
Busbar protected with fuses	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
Busbar protected with breakers	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
LV feeder protected with fuses	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭
LV feeder protected with breakers	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭	⬭

Q49. Are you using other protection technologies at the secondary side of the MV/LV substation and/or for LV feeders than fuses or beakers? (please indicate by means of percentual share or write "I don't know" otherwise).

Q50. What are the protection technologies used along the LV grid? - multiple replies are possible

- Fuses
- Breakers

- I don't know
- Other

Q51. Do you utilize (specialized) meters (except revenue meters) or even sensors installed permanently along LV lines, for instance in switch boxes? Select the most appropriate option. - only one possible answer

- No
- Yes, but only in specific cases and for indication
- Yes, frequently, but for indication only,
- Yes, in specific cases, monitors similar to smart meters or better
- Yes, frequently and monitors similar to smart meters or better
- I don't know

Q52. Do you operate or plan to employ any of the following mitigation equipment to improve LV system performance? Please fill in number of units. - multiple replies are possible

- Series transformers
- STATCOMs/SVCs
- Battery energy storage systems
- I don't know
- Other:

Q53. In case your LV networks is meshed, does the infrastructure support reconnections, that you use for manual remote or even automatic reconfiguration? Select the most appropriate option and if yes selected, please provide more information about. If your network is not meshed, select "not applicable". - only one possible answer

- No (Go to question 55)
- Yes, but only in a pilot project (Go to question 54)
- Yes, but deployed for critical infrastructure supply only (Go to question 54)
- Yes (Go to question 54)
- I don't know (Go to question 55)
- Not applicable (Go to question 55)

Q54. Please provide more information if known (otherwise write "I don't know")

6.5. PART V: OPEN QUESTIONS (5 QUESTIONS)

Q55. To your mind, what are the motivations for monitoring and control of LV systems? (If not known, write "I don't know")

Q56. To your mind, what are the requirements (for example technologies, regulation etc…) for successful deployment of monitoring and control of LV systems? (If not known, write "I don't know")

Q57. Do you have some demonstration projects on that topic? If possible, give the name and references, if not known, write "I don't know".

Q58. What use cases enabled by smart grids on LV level are of your interest? - only one possible answer per line

	I don't know	Means already implemented	Likely candidate	Lack of interest
Voltage quality improvement	⬭	⬭	⬭	⬭
Continuity of supply improvement	⬭	⬭	⬭	⬭
Enhanced utilization of LV distribution system	⬭	⬭	⬭	⬭
Enhanced hosting capacity	⬭	⬭	⬭	⬭
Investment allocation	⬭	⬭	⬭	⬭
Flexibility management	⬭	⬭	⬭	⬭
Reduce CAPEX and OPEX	⬭	⬭	⬭	⬭

Q59. What other use cases might be of interest for you? (If not known, write "I don't know")

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