ONGOING WORK IN CIGRE WORKING GROUPS ON SUPRAHARMONICS FROM POWER-ELECTRONIC CONVERTERS

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ABSTRACT

This paper summarizes the state of part of the discussions in CIGRE/CIRED joined working group C4.24, especially where it concerns supraharmonics. There is an increasing interest from the international standard-setting community in knowledge about distortion in the frequency range 2 to 150 kHz, referred to as supraharmonics. The reduction of emission in the lower-frequency ranges appears to result in an increase in supraharmonic emission by equipment. Power electronics has emerged as a ubiquitous technology, which plays a critical role in almost any areas. Power electronics converter is an important source of waveform distortion, but, as shown in this paper, power electronics can also be the key to mitigate distortion, when the proper technology is employed.

WORKING GROUPS

Working group C4.24, "Power Quality and EMC Issues associated with future electricity networks", is a joined working group of CIGRE and CIRED [1]. The mandate of the working group, as defined in its scope, contains, among other objectives, the study of new emission from equipment connected to the low-voltage network. The occurrence of frequency components in the band 2 to 150 kHz, referred to as "supraharmonics" is an important part of the current activities of the working group.

The subject of supraharmonics is also one of the subjects discussed in CIGRE C4/C6.29, "Power-quality aspects of solar power." [2]. Potential interference issues in the frequency band 9 to 150 kHz are discussed in CIGRE C4.31 in relation to power-line communication. Within IEEE, supraharmonics have been discussed in IEEE P1250 (Power and Energy Society) and are an important part of the scope of TC 7 of the IEEE EMC Society.

Several task forces and working groups within IEC TC 77A cover this frequency range. Although the border between TC 77A (low-frequency phenomena) and TC 77B (high-frequency phenomena) is set at 9 kHz, this limit should not be seen as having any other than historical importance.

Within the European standardizing body Cenelec, the band from 2 to 150 kHz is the subject of a task force within the working group that among others is responsible for the European voltage characteristics standard, EN 50160. The need for standardization of supraharmonics is also mentioned in the application guide for EN 50160. Supraharmonics are also part of IEC/TS 62749 "Assessment of power quality – Characteristics of electricity supplied by public networks".

Gathering of information on observed interference due to emission of supraharmonics is gathered by CENELEC TC 210, with potential interference with power-line communication being the main driving force.

Definition of power-quality indices to quantify the emission in this frequency range is part of the latest draft of the IEC power-quality measurement standard, IEC 61000-4-30.

The European standard on power-line communication (EN 50065) and its IEC counterpart (IEC 61000-3-8) address the frequency range from 9 to 148.5 kHz. Also standards CISPR 14 and CISPR 15 should be mentioned in this context. The recently issued EN 56061-1 on power-line communication apparatus for use in low voltage networks covers the frequency range 1.6065 through 30 MHz, but its scope covers frequencies down to 9 kHz. Here again, the lower limit of 9 kHz has no other that historical origins.

STATE OF THE ART AND OVERVIEW OF SUPRAHARMONICS

The new developments in power electronics are producing photovoltaic inverters that are smaller and more efficient [3]. Inverters generate a slightly distorted current waveform with a close to unity power factor when complying with standards like EN 61000-3-2 and IEC 61727 [4][5]. The strive for low harmonic emission has also contributed to inverters that inject components into the system at frequencies between 2 and 150 kHz, so called supraharmonics [6][7][8][9]. The supraharmonics in this case originate from the switching circuits in the inverter and will be injected into the grid as long as the inverter is operating. The emission in the supraharmonic frequency range differs from the more known harmonic emission in several ways. One of the main differences is the propagation of the emission; harmonic currents propagate towards the grid while supraharmonic currents tend to stay within the installation and propagate to a high extent towards neighboring equipment. The reason for this is the low impedance offered by many household devices. The interface between the device and the grid is in many cases an EMC-filter with a capacitor connected between phase and neutral and hence the impedance will decrease with increasing frequency. In the supraharmonic frequency range the interaction between devices can be substantial [6]. As many small photovoltaic installations are made close to the customer, the interaction between the inverter and other household devices becomes an important aspect to consider.

MEASUREMENTS OF SUPRAHARMONIC EMISSION FROM PV PARKS IN SCANDINAVIA

Long term measurements have been performed at several locations with small scale PV installations, capturing both voltage and current waveforms.

The measurements show that the switching frequency from a PV inverter often lies below 20 kHz [6][10]. Smaller single phase inverters often lies in the upper range and bigger three phase inverters commonly below 5 kHz as seen in Table 1. Residues from the switching can be seen in the current as long as the PV is producing power. At times when the PV inverter is idle this emission is zero [11]. Supraharmonics could still be measured when the inverter is idle due to secondary emission as discussed in the following section.

Table 1 Four PV installations in Scandinavia

Installation	Single phase, tracking 1.5 kW	Single phase, fixed 2.5 kW	Three phase, fixed 20 kW	Three phase, tracking 20 kW
Dominating supraharmonic frequency	16.7 kHz	16 kHz	4 kHz	3.8 kHz

Primary and secondary emission

Another important conclusion from the measurements and simulations is that there are two driving forces for the currents at the interface between the inverter and the grid. The resulting currents are referred to as “primary emission” and “secondary emission” in [12]. The primary emission is driven by power electronics or other sources inside of the device. The secondary emission is driven by sources elsewhere. The latter one plays a much bigger role for supraharmonics than for (low-frequency) harmonics.

The need to distinguish between primary and secondary emission becomes evident when looking at Figure 1 and Figure 2. In the figures two measurements are shown, the upper curves show the emission from the inverter connected alone and the lower curves show the inverter when connected close to other household devices. The two measurements shown are of the same inverter, both measurements are done at the terminal of the inverter when operating and the fundamental component is of similar amplitude in both cases. The neighboring devices were connected to the same phase as the inverter and consisted of an electric vehicle, a coffee machine, a laptop, a TV and a LED lamp. Two things become evident when looking at Figure 1 and Figure 2; the primary emission at 16 kHz increases in amplitude as other loads are connected and primary emission from the other devices will propagate towards the inverter contributing to the secondary emission at the terminal [13]. The devices connected and hence responsible for the secondary emission at the time of the measurement had, with the exception of the electrical vehicle, all significantly lower power rating than the inverter. The switching frequency from the inverter at 16 kHz (the primary emission) is the dominating frequency component in both cases. In [6] several examples are given when the secondary emission is significantly higher than the primary emission. This is often the case when a low power device like an LED lamp is connected close to a higher power device like an inverter.

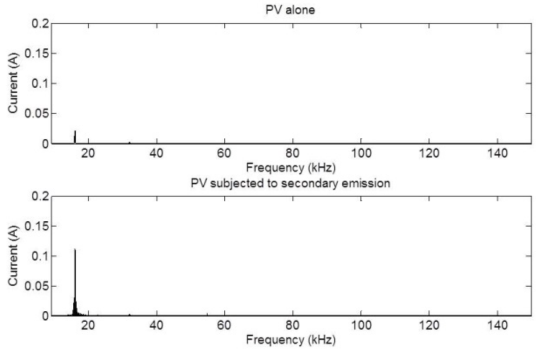

Figure 1 Emission measured at the terminal of an inverter shown in the frequency domain. In the upper curve the inverter is connected alone and in the lower curve it is connected close to other devices.

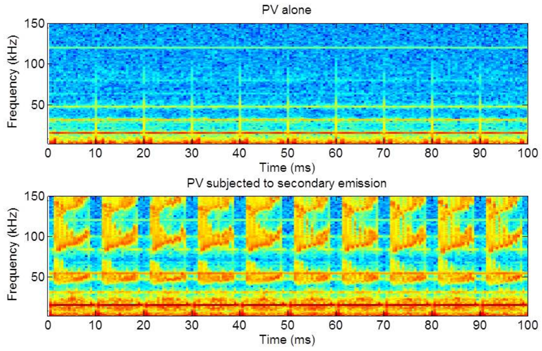

Figure 2 Emission measured at the terminal of an inverter shown as a spectrogram. In the upper curve the inverter is connected alone and in the lower curve it is connected close to other devices.

A grid connected PV inverter is often a part of an installation. This means that it will be subject to emission injected by other equipment connected nearby. For small scale installations this is an even bigger issue since they are connected close to the customer and as a consequence also close to a multitude of household equipment. As seen in Figure 3 the “stand-by” current of an inverter is shifted 90° in relation to the voltage, as a capacitor, part of the EMC-filter, is the interface between the inverter and the grid. As the inverter is connected in an environment with supraharmonic emission, the capacitor will create a low impedance path for supraharmonic currents and high frequency components will propagate towards the inverter as long as it is connected.

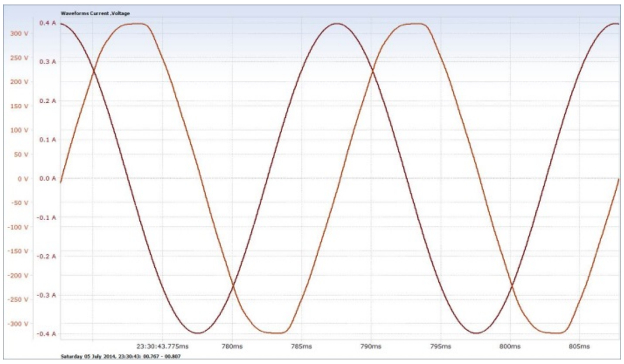

Figure 3 Voltage and current measured at the terminal of an inverter during no production

The current measured at the terminal of an inverter inside an installation will consist of both primary and secondary emission. A PV inverter will hence affect the supraharmonic levels in the grid and inside an installation both by injecting them and by shunting them.

THE SOLUTION PROVIDED BY MULTILEVEL CONVERTERS.

From the earliest times, power electronics (PE) has been mainly driven to improve the voltage and current-handling capability and the switching speed of power semiconductor devices. Nonetheless, even nowadays it is hard to connect a single power semiconductor switch directly to medium voltage grids. The series connection of standard low-voltage switching devices enables to synthesize a medium voltage output, while the individual power semiconductors need to withstand only part of the voltage. The addition of several low voltage cells per arm provides high scalability, leading to reduced cost and volume of the entire solution. Moreover, it allows a more creative use of these additional switches in novel modulation strategies, which enable to enhance the quality of output voltages and input currents, originating the multilevel converter (MC) technology.

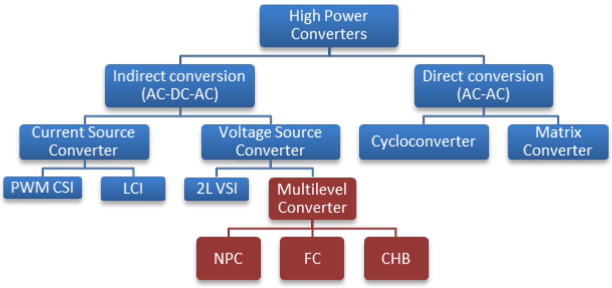

Figure 4 Overview of topology of high power converters

Since their first appearance in the mid-nineties, MCs have been gaining considerable popularity across all industries, mostly in the medium and high power applications. The recent applications of MCs have a variety including induction machine and motor drives, active rectifiers, power quality filters, interface of renewable energy sources, flexible AC transmission systems (FACTS), and HVDC. A comprehensive historical review can be found in [14]. Nowadays, the most common and established topologies are the neutral point clamped (NPC) or diode clamped, the flying capacitor (FC) or capacitor clamped, and the cascaded H-bridge (CHB). A brief comparison among their characteristics is presented in Table 2. Their schemes and detailed operation can be found in [15].

Table 2

Topology	NPC	FC	CHB
Power semiconductor switches	2(m-1)	2(m-1)	2(m-1)
Clamping diodes per phase	(m-1)(m-2)	0	0
DC bus capacitors	(m-1)	(m-1)	(m-1)/2
Balancing capacitors per phase	0	(m-1)(m-2)/2	0
Voltage unbalancing	Average	High	Very small
Applications	Motor drive, FACTS	Motor drive, FACTS	Motor drive, PV, fuel cells, battery system

In addition to these topologies, several modulation and control strategies have been developed or adopted for MC including the following: multilevel sinusoidal pulse width modulation (SPWM), multilevel selective harmonic elimination (SHE-PWM), and space-vector modulation (SVM). As in two level converters, it is very common practice in MC to use Third Harmonic injection PWM (THPWM). As seen in Figure 5, the modulation methods used in MC can be classified according to switching frequencies as follows [16]: 1) fundamental switching frequency, where each inverter has only one commutation per cycle, for example, multilevel SHE-PWM or SVM, and 2) high switching frequency, where each inverter has several commutations per cycle, for example, multilevel SPWM or SVM. For high-power applications, high switching frequencies are considered those above 1 kHz.

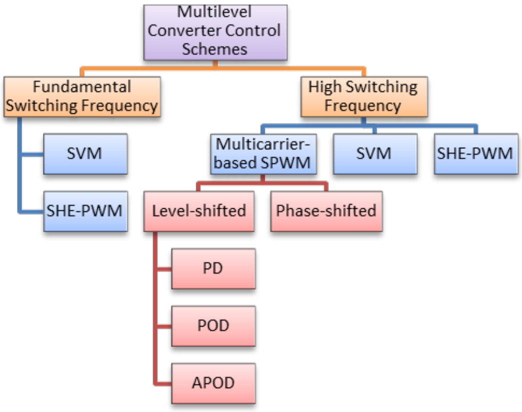

Figure 5 Overview of control schemes for multilevel converters

Methods that work with low switching frequencies generally perform one or two commutations of the power semiconductors during one cycle of the output voltages, generating a staircase waveform. Representatives of this family are the SHE-PWM and the SVM; techniques that can be easily extended to all MC.

Space-vector PWM methods generally have the following features: good utilization of dc-link voltage, low current ripple, and relatively easy hardware implementation. These features make it suitable for high-voltage high-power applications [17].

The SHE-PWM is one of the low-switching frequency strategies most used today, in which a few (generally from three to seven) switching angles per quarter fundamental cycle are predefined and pre-calculated via Fourier analysis to eliminate selected specific harmonics in the voltage and, thereby, in the current [18] [19].

Multicarrier-based PWM uses several triangular carrier signals, which can be modified in phase (Phase-shifted PS-PWM) or vertical position (Level-shifted LS-PWM) in order to reduce the output voltage harmonic content.

PS-PWM is the most commonly used technique, specifically for FC and CHB, because it offers an evenly power distribution among cells and it is very easy to implement. In a MC with ***m*** voltage levels, ***(m-1)*** triangular carriers are required. Thus, a phase shift of ***360°/(m-1)*** is introduced between carrier signal, producing a phase-shifted between the unipolar switching pattern of contiguous cells. An advantageous feature is that the effective switching frequency of the load voltage is ***(m-1)*** times the switching frequency of each cell, as determined by its carrier signal. This allows a reduction in the switching frequency of each cell, thus reducing the switching losses. Thereby, a better total harmonic distortion (THD) is obtained. (e.g. $m = 7$, $m-1 = 6$, $f_m = 60$ Hz, $m_f = 10$, $f_{sw,dev} = f_{cr} = f_m * m_f = 600$ Hz $\rightarrow$ $f_{sw,inv} = (m-1) * f_{sw,dev} = 6 * f_{sw,dev}$, $THDV_{AN} = 18,8\%$, $THDV_{AB} = 15,6\%$)

LS-PWM is widely used in NPC converters, since each carrier can be easily associated to two power switches of the converter. They can be arranged in vertical shifts, with all the signals in phase with each other, called in phase disposition (PD); with all the positive carriers in phase with each other and in opposite phase of the negative carriers, known as phase opposition disposition (POD); and alternate phase opposition disposition (APOD), which is obtained by alternating the phase between adjacent carriers. Among them, the PD is preferred because it provides the best harmonic profile. However the switching devices operate at different switching frequency with various conduction times, with an "average" device switching frequency equal to $f_{sw,dev} = f_{sw,inv} /(m-1)$. LS-PWM leads to less distorted line voltages since all the carriers are in phase compared to PS-PWM. However, this method produces an uneven distribution of power among cells, which produces a high harmonic content in the input current.

An example of the current spectrum, obtained from a simulation, for a conventional two-level inverter and multi-level converters is shown in Figure 6. The two converters have been exposed to exactly the same loading conditions (passive resistive/inductive load) and terminal impedance. The selected switching frequency is also equal for both converters. Looking into detail at different frequencies, the emission of the two-level converter reaches a maximum of 1.9% at 2.65 kHz;in the case of the five-level converter, the emission reaches a maximum of 0.8% at 2.45 kHz. Higher frequencies than 20 kHz reach values of 0.041% in the two-level and 0.0127% in the five-level case. Therefore, overall, the emission of the multi-level converter in the supraharmonic range is significantly less than for the two-level converter.

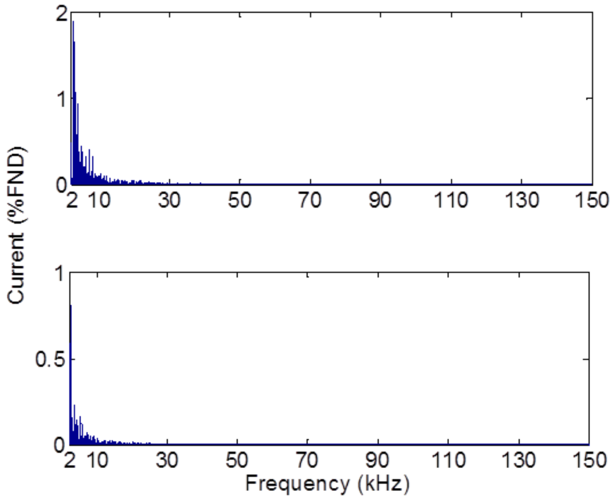

Figure 6 Spectrum of the current emitted by a two-level (top) and a five-level (bottom) converter. Note the difference in vertical scale.

CONCLUSIONS

Work towards describing the state-of-the-art on supraharmonics (2 to 150 kHz) is on-going in a number of CIGRE and other international working groups. Supraharmonics behave differently from (lower frequency) harmonics and interharmonics and the experience from lower frequencies cannot immediately be applied or extrapolated to higher frequencies.

The injection of supraharmonics is related to the shift from grid-commutated to self-commutated power-electronic converters. A proper design and the use of proper control algorithms, especially with multi-level converters, can reduce the emission of supraharmonics.

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