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Supraharmonics in Power Grid: Identification, Standards, and Measurement Techniques

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ABSTRACT In the electric power distribution system, power electronics technologies associated with renewable energy systems (RES) and smart grids have gained growing interest. The power electronics devices are used to convert, control, or transfer electric power from RES to the power grids. However, the continuous increase in switching frequencies resulting from these power electronics technologies has led to the emergence of new emissions in the range of 2–150 kHz, outside the classical frequency range for power quality. These emissions are known worldwide as supraharmonics (SH). These emissions negatively affect the power quality of electrical distribution systems and reduce their efficiency and lifetime. Thus, the supraharmonics emissions have been investigated in the literature, and several methods were developed focusing on identifying, measuring, and setting new standards to mitigate the impact of these emissions on the power quality. Although these individual studies have been well documented, a comparative overview of its identifications, current standards, and measurement techniques had not been described so far. Therefore, this study extensively reviews the related techniques and standards for identifying, measuring, and mitigating SH emissions. Moreover, the current research gap in this important field is highlighted, and an illustration on how this problem was tackled in the past few years is presented. Additionally, the SH characteristics alongside insights into the mitigations and measurements are highlighted and analyzed accordingly. Finally, some important recommendations to mitigate SH emissions are suggested. This review will hopefully strengthen the efforts toward the development of SH domain by providing the necessary groundwork for further mitigations, standards, and measuring techniques improvement.

INDEX TERMS Grid integration, harmonics emissions, high frequency, power quality, renewable energy sources, supraharmonics.

I. INTRODUCTION

As the societies at large across the globe continue to adopting solutions to address CO_2 environmental concerns, the electricity grids are being transformed through (1) the ever-increasing integration of renewable energy generation such as solar photovoltaic and wind energy generation, (2) the electrification of the transportation sector requiring battery charging technologies, (3) the forthcoming distributed energy storage revolution, (4) the use of electrical motor drives toward gaining efficiency, (5) the conversion of lighting loads from being typically resistive ones to now being LED-based, (6) the explosion of other nonlinear type loads such as data power centers, and (7) the availability of battery-powered equipment for household applications such as robots for cleaning and grass cutting, drones, and others.

The above-listed technological solutions to CO_2 concerns are made possible by the enabling technologies of power

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electronics. However, all these new technologies create problems to the grids through emissions at frequency bands within the classical power quality frequency range of 0–2 kHz. Moreover, in recent years, and as switching frequencies of power electronics converters continue to increase to deliver more compact and more efficient equipment, emissions within a new range of the frequency spectrum of 2–150 kHz known as supraharmonics are emerging. Power converters, including inverters, rectifiers, DC/DC converters, and DC/AC inverters, are the key elements of these technologies. Their integration into electrical grid networks poses significant power quality issues, particularly supraharmonic (SH) emissions. SH emissions are a new phenomenon in the electrical grid integrated into RES and can be characterized as the harmonics distortion with a frequency range from 2 kHz to 150 kHz. Furthermore, as previously described in the literature [1], the SH emissions range is extremely reliant on the number of power electronics devices connected to an electrical grid. Due to the continuing increase in the level of integration of renewable energy sources, consisting of many power electronics devices, SH emissions are injected into the power grid. Therefore, different researches have been conducted in recent years to identify, measure, and mitigate this new high-frequency phenomenon to ensure the grid feeding with a pure wave of current and voltage [2]. For instance, the authors in [3] have proposed a new tool to identify the SH in the smart grid as a new power quality issue. In this regard and due to the occurrence of high SH emission, multiple effects, such as impairments or malfunctions of household devices, capacitor overheating, interloping with power line communication (PLC), and electromagnetic incompatibility, have been highly observed recently. In addition to the power quality deterioration in the power network, the lifetime of electrical appliances becomes shorter because additional thermal stress is injected into these devices caused by the SH emissions [4], [5].

The SH emissions still lack a generally recognized measurement technique [6]. Several studies have been conducted in the last years, but the establishment of international standards is still ongoing [7], [8]. Presently, three different approaches would be employed in the standards of power quality measurement techniques. With up to 150 kHz, the first approach utilizes the mathematical techniques of discrete Fourier transform (DFT), which is described in the IEC 61000-4-7 standard. In the frequency domain with a scanning receiver, the second approach is developed based on the measurement technique of CISPR 16-1 [9]. In the third approach, which is considered as a new approach, the measurements deployed based on IEC 61000-4-30 are associated with DFT analysis but with some differences to the IEC 61000-4-7 technique. Recently, various studies have been conducted to study the possible mitigation techniques for SH emissions. For example, the authors in [10] proposed random-pulse position modulation (RPPM) method to mitigate SH emissions in neutral point clamped (NPC) inverters. Multiple filtering devices (e.g., variable capacitance filter) would be used to mitigate SH emissions [11].

A few studies have been reviewed and discussed the measurement methods derived from existing standards for SH emissions based on the literature. For example, the authors in [12] compared some of the SH properties based on existing standards, including EN 50065, IEC 61000-3-8, and IEEE Std. 519. In [13], some of the measurement methods described in the current standards have been deeply compared, including the method in CISPR 16-1-1. Other studies have deeply described the signal processing techniques to identify lower- and higher-frequency phenomena based on SH emission band identification. Some SH identification that commonly used low-voltage devices has been categorized accordingly in [14]. However, no comprehensive study has been conducted to review the SH emissions in power grids associated with identification, standards, and measuring techniques. Therefore, this study discusses a recent detail of SH emissions in the electrical grid based on standards and measuring techniques. Moreover, the recent mitigation techniques of SH have been highlighted to show the gap in this regard. Finally, this work considerably adds to the existing literature concerning research trends in the field. This study provides a detailed survey on the power quality issues according to SH emissions, which is considered a new phenomenon in the power industry. The main contributions of this paper are as follows:

I In this paper, SH definition is highlighted alongside its identifications, standards, and measuring techniques.
II State-of-the-art mitigation techniques of SH have been analyzed and evaluated.
III Multiple specific and important recommendations relevant to SH identifications, standards, and measuring techniques are outlined.
IV This manuscript can support the efforts toward the development of standards and mitigation methods of SH emissions.

The manuscript is structured as follows. Section 2 presents an overview on SH, which includes the effects of SH emissions on the grid. Section 3 then discusses accordingly the SH standards, which involve standards for low-order harmonic distortions, standards for SH range, and the dilemma of diverse standards. Section 4 reviews the SH measurement methods that are currently available in the literature. Section 5 further analyzes insights into SH mitigation. Finally, Section 6 summarizes the most important conclusions, and possible recommendations for further research are given.

II. OVERVIEW OF SUPRAHARMONICS

The well-known harmonics were within the classical range of frequency (i.e., 0–2 kHz). However, with more power electronics-based devices, especially with renewable energy (RE) sources, there is a huge concern about the high-frequency noise beyond 2 kHz, namely, SH. In this context, the expression of SH is being used to indicate any kind of voltage and current waveform distortion within the range of frequency from 2 to 150 kHz [12]. As the semiconductor switching devices suddenly chop the voltage sine wave through their transition between cutoff and conducting states, they create large harmonic such as SH. For instance, the inverter circuits, which are now widely used, are known for the creation of harmonics. These large harmonics may cause electronic devices failure, particularly touch technologies, noise induced by mechanical resonance excitation, or additional thermal stress, which may shorten the life span of the apparatus. Two main sources of SH in the grid are the power-electronic converter units and PLC systems [15]. To understand the generation of SH, it is important to explain the harmonics phenomena. In this regard, for linear loads, the voltage quality normally affects the load current, and the current quality, in turn, affects the grid voltage. The voltage waveform distortion thereby induces a distortion in the current waveform and later further distorts the voltage waveform, as depicted in Figure 1 [16]. It can be noticed that the distortion phenomenon tends to be heavier and more complicated since the load draws a distorted current even though the supply voltage is almost purely sinusoidal. Thus, the circuit yields a non-sinusoidal load voltage from a sinusoidal supply voltage.

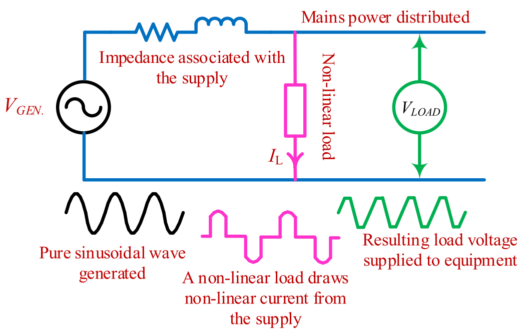

FIGURE 1. Distortion in the voltage waveform due to the nonlinear load's current.

Distortion in current and voltage waveforms at the lower-frequency range is defined to have an upper limit of 2 kHz. This limit represents the 40th harmonic order for the fundamental 50-Hz frequency. These waveform distortions are often generated from regulated power supplies and found as discrete spectral lines at multiples of the fundamental frequency, as shown in Figure 2. Other loads can create subharmonics at frequencies below the fundamental frequency, or inter-harmonics, which are harmonics whose frequencies are non-integer multiples of the fundamental frequency. Both types are also found in the lower-frequency range. Harmonic distortion in the lower-frequency range has been studied for nearly a century since the problem was defined and minimized when the designers succeeded in building generators that produce roughly sinusoidal voltage [17].

Today, the problem came back mainly due to the advent of power-electronic interfaced equipment such as regulated

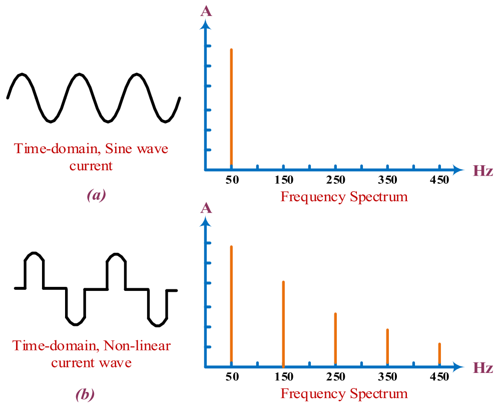

FIGURE 2. Comparison between current waveforms and spectra. a) Pure sinusoidal. b) Distorted wave.

power supplies and energy conversion units. The development of switch-mode power supplies has moved from the use of 50 or 60 Hz transformers to the use of high-frequency transformers. The transformers used previously were mostly linear, excluding the magnetizing current, which is very small compared to the nearly sinusoidal load current. Modern power supplies often use SCRs in which the current drawn is not sinusoidal. Hence, its waveform is recognized by Fourier analysis to be a spectrum of fundamental waves plus a combination of harmonic frequencies. Low-order harmonic distortion received a great deal of research activity due to the observation that whenever current distortion is recorded, the voltage distortion at these frequencies is found to have the highest level [12], [18]. The content of harmonics in the non-sinusoidal current waveform has many significant consequences on power systems, as illustrated in Figure 3.

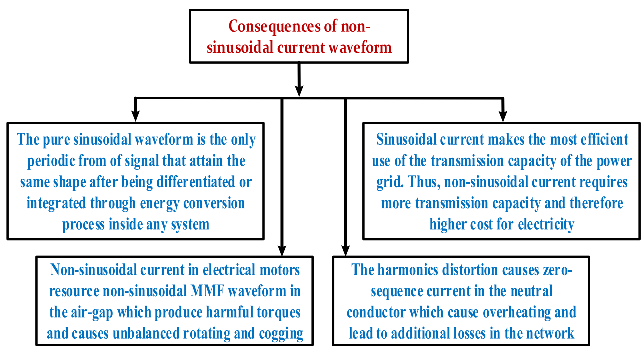

FIGURE 3. Consequences of a non-sinusoidal current waveform.

Power-electronic interfaced converters in modern smart grids and MGs generate harmonic distortions of higher-order due to their high-frequency operation [19]–[21]. The reason behind increasing the switching frequency is the benefit of reducing the cross-sectional area of the iron core of the transformer, which will reduce its weight, size, and cost. In general, little attention is paid to the distortion of frequencies above the low-frequency harmonic range. This is probably due to the relatively small disturbance levels found previously within this range. But with the change of equipment that

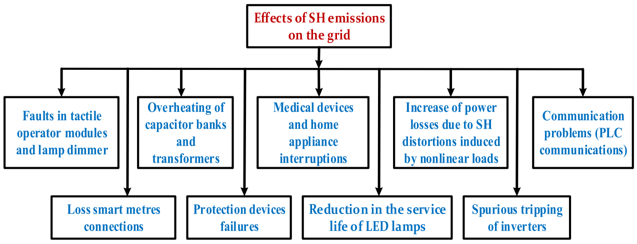

FIGURE 4. Effects of SH emissions on the grid.

is connected within the power grid, this may also have to be overlooked and taken seriously as its effects could be hazardous [19]. Figure 4 depicts these effects.

A. CONSEQUENCES OF SUPRAHARMONICS

Due to the potential effect on other networked devices, SH received more attention recently [22]. The SH will increase the capacitive currents, which can harm the power supply, thereby increasing the safety risks. In addition, it may lead to (a) faults in tactile operator modules and lamp dimmer,; (b) reduction of the operational life of LED lamps; (c) problems of contact (i.e., PLC communications); (d) overheating of transformers and capacitor banks; (f) protection devices failures; (g) loss of smart meters' communication; and (h) disturbance to domestic devices, semiconductor manufacturing equipment, medical devices, and security systems, even transportation controls. Besides, SH distortions induced by nonlinear loads will increase the power losses, thus having a detrimental effect on distribution systems and components of electric utilities. Finally, SH is proven to affect instability in poor networks with RE system inverters, resulting in spurious inverter tripping [4], [23]. Thus, it is also fair to conclude that the consequences of SH are close to dangerous if not taken seriously.

B. SUPRAHARMONICS CHARACTERISTICS

The initiative to raise the power factor and reduce the harmonic distortion in the low-frequency region of the inverters' output current used in grid-connected devices has contributed to increasing the emissions in the SH region [24]. In this case, the SH comes from the switching circuits of the inverter, which can be pumped into the grid as long as the inverter is in operation. However, If the inverter does not work or generate output (not operating), the unit will become a basin of SH [25]. The RE sources integrated into the main grid, which uses inverters as an output interface, can produce significant harmonics in the SH range. It is important to mention that the interface between the inverter and the grid provides two driving forces for the currents, i.e., "primary and secondary emission," as illustrated in Figure 5 [1]. Primary emission is a part of the normal- or supraharmonics of the current driven by power electronics devices or other power devices inside the system (driven by I1). On the other hand, the secondary emission is a part of the normal- or supraharmonics of the current driven by sources outside of the device (driven by V2).

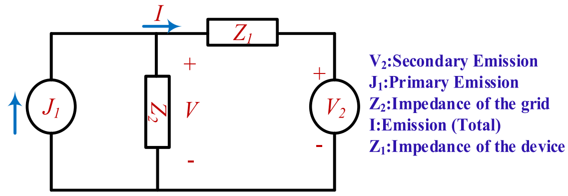

FIGURE 5. Primary and secondary emissions.

The calculated current at the device-grid interface (I) is the aggregate of secondary and primary emissions. It is also worth mentioning that V2 plays a more significant role in SH than normal harmonics (low frequency) [19].

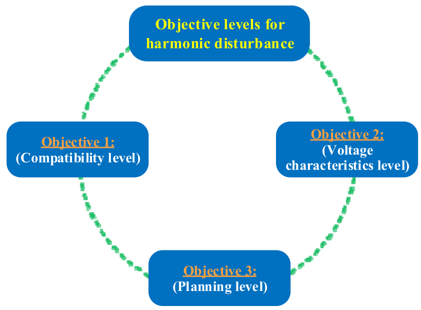

FIGURE 6. Three objective levels for harmonic disturbance standardization.

III. STANDARDS OF HARMONIC DISTORTION

During the advancement of the power converter and integration requirements of RESs into the grid, which contains many power electronics devices, different harmonic distortion standards are imposed to ensure the current and voltage waveform synchronized with the grid are ideal so far as possible [20], [21]. It is important to mention that there exist three objective levels of harmonic disturbances in international standards, as illustrated in Figure 6.

A. STANDARDS FOR LOW-ORDER HARMONIC DISTORTIONS

As presented in Table 1, IEC standards define the measurable PQ parameters, including harmonic distortion, and specify its permissible limits and measurement techniques. Such parameters include the fundamental frequency, voltage sags, and swells, voltage transients and flickers, voltage interruptions and sudden changes, voltage and current harmonics, subharmonics, and inter-harmonics [21]. However, there are no planning limits for LV consumers; hence, the responsibility lies within the equipment and is regulated by each standard individually. It should be noted that the standard IEC 61000-3-2 [26] is quite restrictive concerning the limits of harmonic emissions from loads produced by light equipment as compared with other loads.

B. STANDARDS FOR SH RANGE

The range between 2 and 150 kHz is referred to as an SH range without any standardization [12], [27]. However, this characterization is not precisely true since a few standards

TABLE 1. Current harmonic distortion limits [21].

Maximum harmonic current distortion (in % of I_L)						
Individual harmonic distortion (odd harmonics)						
System ratio I_{sc}/I_L	$3 \leq h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$35 \leq h \leq 50$	THD
$I_{sc}/I_L < 20$	4	2	1.5	0.6	0.3	5%
$20 \leq I_{sc}/I_L < 50$	7	3.5	2.5	1	0.5	8%
$50 \leq I_{sc}/I_L < 100$	10	4.5	4	1.5	0.7	12%
$100 \leq I_{sc}/I_L < 1000$	12	5.5	5	2	1.0	15%
$I_{sc}/I_L \geq 1000$	15	7	6	2.5	1.4	20%

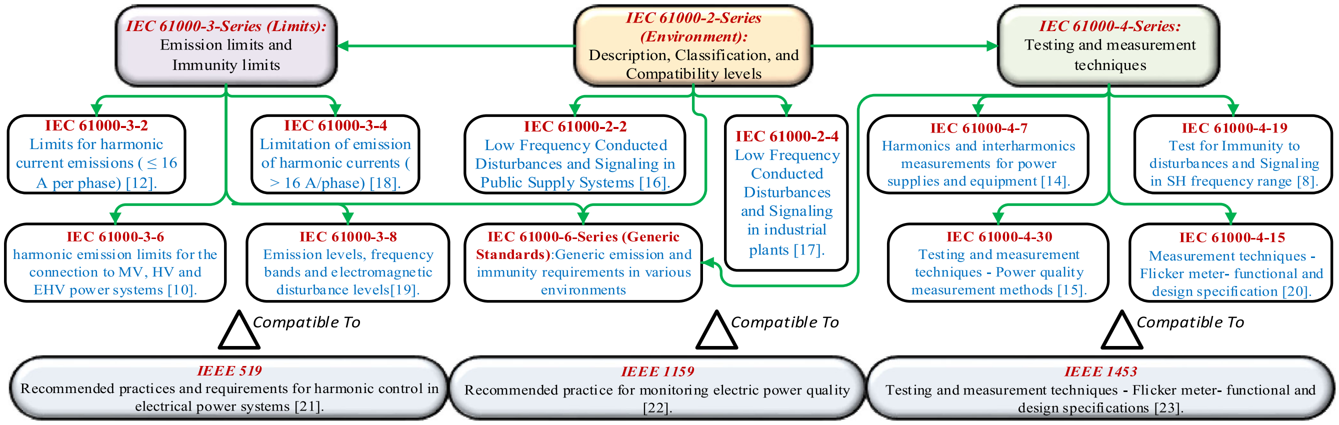

FIGURE 7. Overview of IEC 61000-series standards and its compatible IEEE standards.

are addressing this frequency range. A review of limits in these few standards is given in Annex A of the standard IEC 61000-4-19 [28]. There are not as many standards covering this frequency range as there are for harmonics, but of course, there may also be national standards or military standards that cover this frequency range. Table 1 presents these standards' details with all definitions, and PQ indices are specified. It should be noted that the standards covering the high-frequency range almost only describe measuring emissions under controlled circumstances in a lab, whereas for low-order harmonics, there are standards describing harmonic limits in the vicinity of the network. IEC standards-61000 series [29] cover subjects, including terminology, descriptions of electromagnetic phenomena, measurement techniques, and guidelines for installation and mitigation. Figure 7 shows an overview concept of parts 2, 3, 4, and 6 of this series and the characteristic relationships between these parts and their counterparts in IEEE standards.

C. THE DILEMMA OF DIVERSE STANDARDS

Various international and regional standards address the same topic of harmonic emission and have different approaches at the same time. Some of these standards are fundamentally different in certain ways [30]. From the viewpoint of a unified global standardization, this is considered a dilemma that has to be thoroughly viewed. Integrated, universal, and symmetrical standards are a crucial aim for mankind's technological community. Table 2 presents comparative criteria for these counterpart standards.

IV. SUPRAHARMONIC MEASUREMENTS

Recently, the SH measurement is taken high consideration due to the advancement of smart grid systems. The smart grid supports the use of new technologies, such as management of the demand side, electric vehicles, distribution generators (DGs), and RESs. These technologies can inject high frequency in the range of 2–150 kHz and then cause SH due to the existence of power electronics interfaces. Therefore, the finding of an efficient measurement for this type of high-frequency emission is crucial for the development of smart grids and RESs integration [33].

A. OVERVIEW OF SH MEASUREMENT METHODS

A comparative review to evaluate the effectiveness and validity of SH measurement methods available in the literature is intended to be given in this subsection. In [34], the pioneer researchers in this topic from Sweden presented a significant trial to distinguish between primary and secondary emissions. Their procedure uses sequential switching of SH sources in order to track the mentioned two types of emissions. Although remarkable, this contribution was still the beginning of an organized effort that should be made for better understanding and modeling SH emission behavior. Some authors, [14] and [35], have tackled the direct application of

TABLE 2. Comparative parameters for international/regional standards.

Comparison Parameters	Standard		
	IEEE	*IEC*	*CENELEC*
Degree of compulsory	Recommendatory	Mandatory	Mandatory
The comprehensiveness of the application	IEEE 519 standard sets limits on the total installation for compatibility and voltage limits level	It sets no limits for entire installations. IEC 61000-3-2 sets limits on individual devices Technical report IEC 61000-3-6 presents one based merely on the planning level	It does not set limits for entire installations. EN50160 sets limits on individual devices
Under methodology	Customers may invest even when voltage distortion is negligible	Customers may invest in mitigation when the grid shows significant harmonic emissions	Similar to IEC standards
Low-order harmonic limit	$35 \leq h$ (undefined)	$h \leq 40$	$h \leq 25$
Managing authorities	Sharing responsibility between utility and customer *	Assigning current limits derived from voltage quality objectives **	Assigning current limits derived from voltage quality objectives **
Constancy of V-limits	Voltage harmonic limits are constant versus frequency	Voltage harmonic limits decrease with frequency	Voltage harmonic limits decrease with frequency
Harmonic I-limit	Limits are slightly related to system voltage levels	Limits are correlated with system voltage and V-limits	EN 50160 limits are of compatible levels as IEC 61000-2-2
Time-dependent harmonics	Recommends that I-limits exceed 50% for short time intervals	Provides a multiplying factor to increase harmonic limits for very short time emissions	Similar to IEC standards
Odd/even harmonic order	- The even order of the V-harmonics does not address -Recommends that even current harmonics be limited to 25% of odd harmonics	- Addresses even V-harmonics -Allows greater even I-harmonic emission than IEEE	- Addresses even V-harmonics -Allows greater even I-harmonic emission
Inter-harmonics/subharmonics	New information of limits on inter-harmonic in Annex A of Std. 519 (2014).	Address inter-harmonic V-limits	Standard EN 50160 gives no values pending more experience ˣ
Addressing PLC emission	IEEE 1775-2010: Standard for Power Line Communication Equipment – electromagnetic compatibility (EMC) requirements – testing and measurement methods	Maximum emission due to PLC is given as voltage limits in IEC 61000-3-8	Maximum emission due to PLC is given as voltage limits in EN 50065-1
Addressing SH emission	IEEE 519 (2014) sets maximum limits for harmonic current distortion. Limits for orders $35 \leq h \leq 50$ are set without specifying SH band. Voltage limits are specified as THD only.	IEC 61000-3-8 and Annex A of IEC 61000-4-19 give limits for SH band and more restrictive limits for above 150 kHz	EN 50065 covers frequencies from 9 kHz to 148.5 kHz ˣˣ

(*) Customers are given some share of the system's ability to absorb harmonics. If V-distortion problems exist with all customers within their I-limits, the utility takes authorized action to restore voltage quality.

(**) Current limits are designed to ensure that if all consumers are kept within their individual limits, then voltage quality problems will not exist.

(ˣ) For inter-harmonics, see [31] and note that a next revision of the IEEE Standard 519 is discussed within the subgroup formed in the framework of the Harmonics WG (519) of the IEEE PES Transmission and Distribution Committee [32].

(ˣˣ) The main concern of emissions above 150 kHz is the interference with the radio-longwave band ≥148.5 kHz.

the standard IEC 61000-4-7 method to measure SH distortion using various sources of emission. However, the emission profile is either limited to the individual type of lamps, where combinational sources were not verified, or, in other cases, the grid impedance is required to be more investigated. Other authors tried to extend the IEC 61000-4-7 method for better outcomes, as in [36], where the bandwidth was increased from 200 Hz to 300 Hz. The method was tested on a site of 50 identical PV inverters. Unfortunately, the measurement was limited to the operation of all inverters simultaneously, whereas a combinational operation is essential for a better profile for SH emission. In [37] and [38], the IEC 61000-4-7 method was also extended to enable the setup of measuring the full range of SH frequencies. Experimental results show important mapping to the high-frequency interactions between inverters. However, the results were limited to a narrow band of frequencies which is around the inverter switching frequency. Multiples of inverter switching frequency was not reported to have been conducted. Another measuring method is an extension on the IEC 61000-4-7 method presented in [39]. A decomposition algorithm is used to enable measurement to be conducted for both harmonic and SH distortions at the same interval. Analytical results, comparing the proposed method with IEC 61000-4-7 method, show that SH measurements' significant merits were introduced.

In [33], the IEC 61000-4-30 method is modified by a compressive sensing approach to reduce the frequency resolution of SH measurement. More accurate results for SH current versus frequency were shown, although only one element, an EV charger, was used as a source of emissions. Some authors, [4] and [13], presented comparative applications for the standard-based methods. Through these tests, applying the two mentioned methodologies was performed individually for each of the four cases. In general, the results showed a clear convergence between the two methodologies except in certain situations where IEC 61000-4-30 methodology gave more obvious simulation to SH. The IEC 61000-4-30 method is reported to be less robust to noise, less complex, and less accurate for large emissions than the IEC 61000-4-7 method [4]. Additionally, the IEC 61000-4-7 method shows comparatively closer results to CISPR 16-1-1 method [13]. A group of similar methods, based on utilizing a multichannel wave recorder with measuring auxiliaries, exists as well. These auxiliaries include Rogowski coils, voltage, and current transducers with appropriate probes. Such approach is followed by [1], [5], [40], [41]. In this context, the results in [41] were withheld to be published in an upcoming paper, which was fulfilled in [5]. In [1], a valuable conclusion was accomplished, but the method was applied to LED sources only. Other SH sources, such as PV inverters, may have a more complex emission profile due to variable switching frequency. So forth, the challenge urges for such verification. An application of measurements was accomplished by [40], with the mentioned approach, on-site at the LV side of a real grid with solar PV. The resulting frequency response of SH current is limited up to 10 kHz, for which more analysis is required to be conducted to cover the entire SH range. In [42], a comparison of measurement methods for SH range of emissions was introduced. However, the comparison was limited to seven methods of measurements; the three candidate methods were listed in Annex C of IEC 61000-4-30, and the four other methods were proposed in [4], [13], [43], [44].

In this manuscript, 14 measurement techniques were examined with respect to 5 evaluating parameters. Table 3 summarizes the comparative review of SH emission's measurement methods.

B. THE GAP IN LITERATURE

The findings presented in the comparative Table 3 could be summarized and listed to show the gap in the literature for SH measuring techniques. Accordingly, the measurement methods are grouped, and the gap is illustrated, as presented in Table 4.

C. BASIC SH MEASUREMENT

The harmonic content of the spectra equivalent to the distortion can be divided into three ranges besides the fundamental 50-Hz component [34]. Firstly, the low-order harmonics contain frequencies below 2 kHz, and secondly, the SH range contains frequencies from 2 kHz to 150 kHz. Frequencies above 150 kHz are classified as the third range. In general, harmonic emission is basically measured using the signal analyzer and current transducer between the supply and the EUT, as shown in Figure 8 [26]. Two things have to be considered when performing tests on equipment to verify emission limits. The first is that the test should be reproducible, and the second is that the results should show a realistic match for the functional characteristics of the equipment while it is operating in the installation [15].

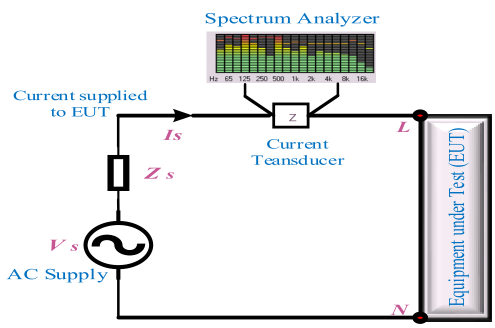

FIGURE 8. Basic measurement technique of harmonic emission.

D. EMISSION MEASUREMENT

Some studies of the measurements methods on SH [7], [14], [33], [34], [36], [37], [41] show that the current at the equipment terminals is heavily dependent on the presence of another equipment in circuitry. Therefore, a distinction is to be made so that the primary emission is separated from the secondary emission. The primary emission emerges mainly from power-electronic-based components in the device, whereas sources from other devices cause the secondary emission. Many authors suggested a measuring system which consists of four steps to measure SH [4], as shown in Figure 9. SH measurement illustrated in this figure consists of (a) input signal detector (harmonic sensor), (b) high-pass filter (HPF) to pass emissions above 2 kHz and low-pass filter to pass emissions below 150 kHz, (c) FFT analyzer with an interval of ten cycles which is equivalent to 200 ms for 50-Hz power frequency, and (d) recorder.

The conventional measurement for SH follows the criteria offered by the standard IEC 61000-4-30 for the time sampling of the FFT measuring instrument. In that criteria, FFT measures during the interval are ten cycles, corresponding to 200 ms for 50-Hz power frequency. This corresponds to 32 measuring subintervals, which consist of 512 samples transformed by the FFT equipment [45]. Another approach

TABLE 3. Comparative summary of methods used for SH measurements.

Measurement methods	Core objective	SH sources	Benchmarked output	Most prominent outcome	Limitations	Ref.
Sequential switching on/off between SH sources to discriminate secondary from primary emissions	Discrimination between primary and secondary SH emissions	PV inverters and household appliances	Frequency spectrum with spectrogram images and time-domain waveforms	Explanatory mapping of primary and secondary emission's propagation inside the installation	Measurement is limited to distinguish between primary and secondary emissions	[34]
Standard IEC 61000-4-7 method	Characterization of emission profile for different SH sources	Incandescent, LED, CFL, LCD	THD and frequency spectrum	A comprehensible plot for emission profile versus five source types	Emission profile is limited to individual type of lamps, whereas combinational sources were not verified	[14]
Setup of four-channel oscilloscope with two Rogowski coils and filters to separate the fundamental component from harmonics	Validation of SH measurement method in a smart grid	Industrial and residential PV inverters plus a residential load	Percentages of harmonic voltage and current	N/A	Detailed results have been withheld to be published in an upcoming paper. Later, it was shown in [5]	[41]
IEC 61000-4-7 method, with bandwidth modified from 200 to 300 Hz	To examine SH emission inside a 0.5 MW solar park	50 identical solar PV inverters	Peak and average values for V and I versus frequency over SH range	SH emissions flow mainly between the inverters rather than to the grid due to grid filters	Measurement was limited to the operation of all inverters simultaneously; combinational operation is essential for a better profile of SH emission	[36]
IEC 61000-4-7 method extended to measure the full range of SH frequencies	To determine the effect of measurement setup on SH emissions	Different LED lamps	V and I frequency responses over SH range versus line impedance LISN* or AMN**	Grid impedance significantly alters the results, putting a focus on the global, diverse systems of 220V/50Hz and 110V/60Hz	Power source output impedance affects measurement's accuracy and should be verified	[37]
IEC 61000-4-30 method modified by compressive sensing approach	To reduce the frequency resolution of SH measurement	EV charger	Current in frequency domain over SH range	Precise measurement by reducing the resolution from 2 kHz to 200 Hz	More than a single SH source is essential for the method's validation	[33]
IEC 61000-4-7 and IEC 61000-4-30, individually	To verify the effectiveness of standard SH's measurement methodologies	EV charger, PV inverter, and laboratory signal generator	V and I (time-domain and frequency-domain) over SH range	IEC 61000-4-30 method is less robust to noise and less accurate for large-amplitude emissions than IEC 61000-4-7	Evidence is still required to ensure that lab simulations are valid for on-site conditions	[4]
IEC 61000-4-7 method	To investigate the interaction of SH emission between multiple devices	PV inverters and household devices	V and I (time-domain and frequency-domain) over SH range	Grid impedance and the input impedance of the devices affect V and I distortions	Further investigation of system impedances is required	[35]
IEC 61000-4-7, IEC 61000-4-30, and CISPR 16-1-1 methods, individually	Review of standard measurement methods related to the standard "IEC 61000-4-30"	EV charger and signal generator	Emission voltages versus frequency with comparative tables	IEC 61000-4-7 method shows comparatively closer results to CISPR 16-1-1 method	IEC standards 610004-7 and 61000-4-30 are informative rather than normative	[13]
IEC 61000-4-7 method extended to measure up to the upper limit of SH frequency	To develop a high-frequency model for the PV inverters	3 PV inverters rated 2.5, 2.6, and 3.6 kW.	V/I inverter characteristics for different grid impedances	Experimental procedure for high-frequency interactions between inverters	Results shown were limited to a merely narrow frequency band around the inverters switching frequency	[38]
Setup of four-channel wave recorder with two Rogowski coils and filters to band-pass the harmonics	Identification of the effects and interactions of SH emission in the distribution network	Industrial and residential PV inverters plus EV charger and residential loads	A table that maps the effects and interactions of four SH sources, individually and in groups	Industrial PV inverter contributes effectively to SH V and I emissions at different bands of frequency	EV charger's effect on SH emissions was not shown in the results	[5]
Setup of power amplifier, data acquisition unit fed from I and V transducers, and LISN emulator	Developing summation models to predict SH emissions from LV installations	Three boars of 50, 90, and 100 LEDs	Plots for total SH current (of various combinations of LEDs included) versus frequency	As SH sources in LV installations increase, the distortion fed to the grid increases to a limit and then decreases due to the capacitive effect of power-electronic devices included	The method was applied to LED sources only, whereas other SH sources, such as PV inverters, may have more complex emission profiles due to variable switching frequency that needs to be verified	[1]
Setup of multichannel wave recorder and two Rogowski coils plus LCL filters	Developing an equivalent circuit model of grids with multiple VSCs ˣ and evaluate the SH current individually and totally	Two PV inverters rated at 630 kW	Harmonic current in the frequency domain for two load conditions and two measuring locations	Measurements are carried out on-site at the LV side of a real grid with solar PV	The resulting frequency response of SH current is limited to a harmonic order of 200, corresponding to 10 kHz. More analysis is required to cover the entire SH range	[40]
IEC 61000-4-7 method, modified by decomposition algorithm to measure harmonic and SH distortions at the same interval	Introducing a measurement method for harmonic and SH distortion with immunity against deviations in frequency and amplitude	PV inverter and EV charger	Comparative responses both in time and frequency domain for SH voltage emissions and %errors due to deviation in frequency and amplitude	Analytical results, comparing the proposed method with IEC 61000-4-7 method, show that significant merits in SH measurement were introduced	Results are shown for voltage distortion per a single SH source where no combination of sources was examined for validation	[39]

(*) LISN: line impedance stabilizing network; (**) AMN: artificial mains network; (ˣ) VSCs: voltage source converters.

TABLE 4. The gap in literature for SH measurement techniques.

Group	Measurement Technique	References included	The Gap
A	Utilizing multichannel wave recorder with measuring auxiliaries, such as Rogowski coils, voltage, and current transducers with appropriate probes	[1,5,40,41]	A generalized measurement method requires the inclusion of major SH sources and the benchmarked results of the complete range of SH frequencies. For instance, the method in Ref [1] was applied to LED sources only, whereas other SH sources, such as PV inverters, may have a more complex emission profile due to variable switching frequency that needs to be verified. In Ref [5], EV charger's effect on SH emissions was not shown in the results. In Ref [40], the resulting frequency response of SH current is limited to a harmonic order of 200, corresponding to 10 kHz. More analysis is required to cover the entire SH range
B	Sequential switching on/off between SH sources to discriminate secondary from primary emissions	[34]	Though the contribution of this pioneer research carried out in Lulea University, Sweden, was the sparking pulse in the topic, the objective of the measurement method was limited to achieve the distinguish between primary and secondary emissions
C	Application of standard IEC 61000-4-7 method.	[14,35–39]	Inclusion of multiple SH sources necessitates verifying measurements with combinational of sources in order to find a comprehensive profile of SH emissions. For the references in this group, measurement was limited either to the operation of all inverters simultaneously or to individual type of lamps, whereas combinational sources were not verified
D	Application of standards; IEC 61000-4-7, IEC 61000-4-30, and CISR 16-1-1 methods individually	[4,13,33]	The dilemma of standardization still existed, since IEC standards 610004-7 and 61000-4-30 are informative rather than normative. Additionally, evidence remains to be essential to ensure that lab simulations for SH sources of emission are valid for on-site conditions

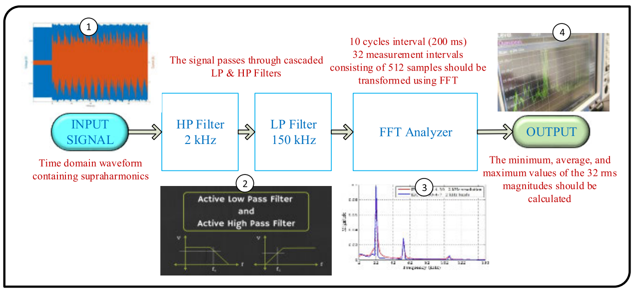

FIGURE 9. SH emission measurement according to IEC 6100-4-7 and 61000-4-30.

is proposed in [7] in which a filter bank is used after the HPF shown in Fig. 9 to decompose the signal into different band-pass signals. Then by means of the filter bank, the frequency ranges of 2–150 kHz is divided into ten segments of 15 kHz bandwidth each. A multiplexer is used to select the desired band where the SH is estimated. PQ analyzers and ADC can operate at 32-kHz sampling rate; hence, a down-sampling stage precedes the ADC to ensure 32 kHz sampling rate.

This proposed approach is claimed to give good agreement when tested on a source of LED lamp. However, this claim has to be verified experimentally. In MGs, SH emissions have increased concerns due to MG's heavily involvement of power-electronic interfaces that consist of devices such as converters and charge controllers. Additionally, an important step to consider in the assessment procedure is the mounting of the SH measuring instrument [46]. It is to be mounted between the grid and the switching converter, according to IEEE 519 (2014) for LV installations, as shown in Figure 10 [47]. For LV distribution's networks, the same IEEE 519 standard recommends that SH measuring equipment is mounted on the downstream side of the step-down distribution transformer, as shown in Figure 11 [48].

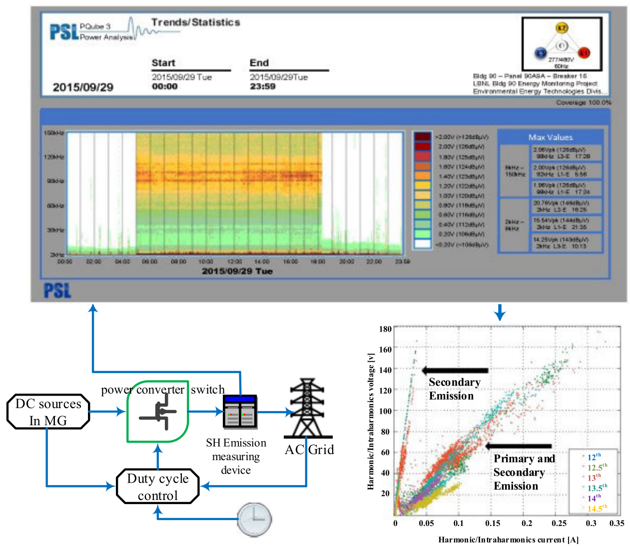

FIGURE 10. Mounting SH measuring device inside the MG.

E. MEASUREMENT THROUGH PRIMARY AND SECONDARY EMISSION SEPARATION

According to the pioneer researches in the literature on SH emission [7] and [49], high-order current harmonics have low amplitudes compared to the amplitude of the grid current at power frequency. Moreover, the characteristic behavior of such currents is time dependent. Therefore, spectrum analyzers' conventional measurement techniques based on band-pass filters are merely suitable for low-order harmonics, not for SH. That is why they are too slow in giving an accurate representation of time-varying emissions. Required results can be obtained by measurements in the time domain rather than the frequency domain. In time measurements, a series of key factors with their major impact on the accuracy of the spectral estimation should be taken into account [50].

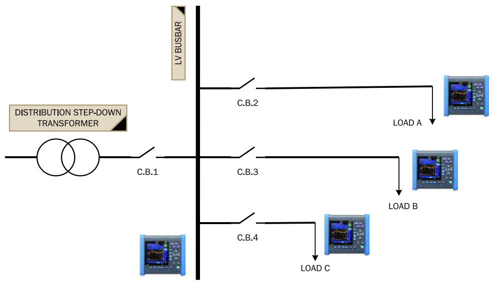

FIGURE 11. Allocation of measuring equipment in the LV distribution network according to IEEE 519 standard.

Low-frequency (<2 kHz) currents, from individual devices, flow toward the grid, whereas studies show that SH behaves differently. They flow mainly between consumer equipment and partly toward the grid. Figure 12 interprets the reason that within SH range, a distinction must be made between primary and secondary emission [49]. The primary emission is defined as the part of the current that is driven by the internal emission of an EUT and is represented by longer arrows. This type of emission is affected by the topology of the EUT and the impedance at POC.

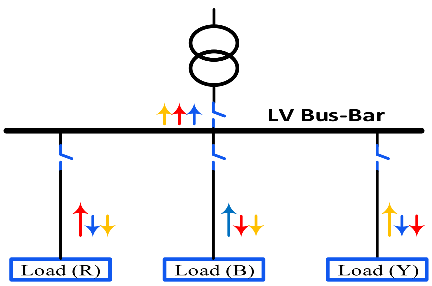

FIGURE 12. Propagation of SH band currents.

V. INSIGHTS INTO SH MITIGATION

Initially, harmonic distortion studies appeared to reduce low-frequency harmonics. Therefore, conventional PWM techniques were used to reduce those emissions which are below (2 kHz). However, it was sooner found that this leads to emissions of frequencies of multiple PWM switching frequency, which is inside SH spectra [23]. To ensure the required level of PQ in power grids, it is of great importance to make all available means to mitigate distortions caused by SH emission. As stated earlier, such distortions encounter serious problems in grid-connected equipment. This section reviews the techniques utilized in various grid configurations to mitigate SH emissions.

A. MITIGATION THROUGH IMMUNITY LEVEL

The first option in mitigation techniques to fortify the power grid against SH problems is to prevent or address them from the initial design stages. Reducing or preventing SH emissions at the level of immunity requires a prior decision to assess the level of emission compared to immunity [8]. As expected, such a decision should be taken by international and regional standardization committees. As has been stated in Section 3 (Figure 7 and Table 2), standards EN 55011 and EN 55015 set limits for non-intentional SH emission for harmonic frequencies from 9 kHz to 150 kHz and for intentional SH emission (in standard EN 50160) up to 95 kHz. Immunity levels are set in standards IEC 61000-3-8 and Annex A of IEC 61000-4-19 where limits for SH band and more restrictive limits for above 150 kHz are given. Maximum emission due to PLC is also given as voltage limits in IEC 61000-3-8. Standard IEEE 519 (2014) sets maximum limits for harmonic current distortion. Limits for the harmonic orders of $[35 \leq h \leq 50]$ are set but without specifying SH band. These voltage limits were merely specified as THD. The power grid community is in dire need of new regulations to put mitigations into the design stage, thus recommending or mandating technologies and schemes that modify the spectral characteristics of SH emissions.

B. MITIGATION BY ACTIVE FILTERS

It is important to assess the nature of the phenomenon when developing subsequent updates to the standards with which to comply. Once the new regulations are published, the solution can only be applied to equipment still in the design phase, such as the implementation of electromagnetic interference (EMI) filters and power electronics systems that, by controlling their mode of operation, can modify the spectral characteristics of high-frequency emissions [51]. The simplest method of SH mitigation is to use active filters which are necessary to compensate for wave distortion connected to the POC at the consumer side, as shown in Figure 13 [52]. These active filters comprise inductors and capacitors and could be either T shaped (LCL type) or π shaped (CLC type), depending on the filter equivalent circuit per phase [53]. The spread of SH emission among devices is examined for three cases, i.e., a single filter, combinations of CLC and LCL EMC filters, and the case under which the harmonic resonance occurs [54]. Table 5 summarizes the results.

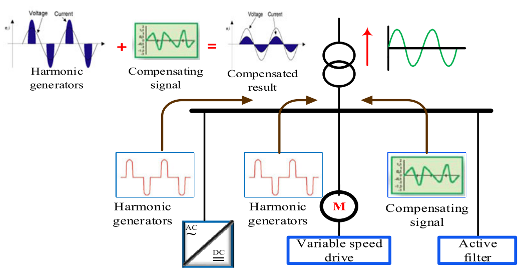

FIGURE 13. Mitigation of SH emissions by active filters.

C. MITIGATION BY MULTILEVEL CONVERTERS

Multilevel converter technology emerged as a sophisticated application of the voltage divider rule in electrical circuits. Thus, it makes the series connection of standard low-voltage switchgear to obtain a medium aggregate voltage output. This technology enabled power semiconductors to withstand only a portion of the rated voltage. This reduces the size and cost of the whole equipment, reduces voltage distortion,

TABLE 5. **Comparative results for mitigation techniques with proposed filters.**

No.	Case study	Findings	Consequence	Mitigation action	Ref.
1	Determine the SH-related characteristics of four selected interference phenomena, namely, audible noise, cable faults, undue tripping of RCDs, and light flickering	The relevant characteristics differ for different phenomena	Performance indicators and limits have been developed where applicable	Immunology tests with a large sample of equipment, recording, and quantification of SH effects using the indicators identified through the four interference phenomena	[51]
2	A. Single filter type for a single device B. Multiple CLC and LCL filters	A. SH current emission produced by the larger device, e.g., EV charger, can cause a relatively larger current flowing through a nearby smaller device such as an LED lamp B. The spread of high-frequency current emission among the devices	A. Possible damage to the LED lamp B. Current amplification may occur by harmonic resonances	A. Dimensioning the filter considering capacitor size and current emission B. Dimensioning of filters, considering capacitor and inductor sizes	[52]
3	The occurrence of harmonic resonances through filter devices with grid inductance	Current amplification rises proportionally to the square root of the number of devices connected	Resonance frequency drops with the same rate	Dimensioning of filters, considering capacitor and inductor sizes	[53]
4	Analyzing the effects of EV fast charging stations on the low-order harmonics and SH	Power interference results from the interaction between SH and the low-order current harmonic distortion and voltage harmonic distortions	Harmonic emission limits set in the standard IEEE 519 ought to cover SH range	Improved filters used within these chargers to prevent high- and low-order harmonics. Utilities should strategically position harmonic attenuation filters, to reduce harmonic distortion to be within the allowable range of low order	[57]
5	A three-phase bridge rectifier with a harmonic relief function is proposed using an electronic inductor	A combination of three-phase rectifiers can be in compliance with standard IEC 61000-3-12 initiated for low-order harmonic emission	The grid-connected converters have relatively acceptable harmonic performance, and the total harmonic current at PCC is controlled as a square wave under different load conditions	An electromagnetic interference unit can be used to reduce current harmonics of other conventional units connected to the same PCC	[58]

and improves equipment efficiency and raises power quality. The most common topologies of these converters which are now available include the NPC converter, the flying capacitor converter, and the cascaded H-bridge converter. SH emission as a parameter of comparison between multilevel converter and a conventional two level one shows an emission reduction multilevel converter by 30%–42% over the SH frequency range, for the same switching frequency and loading conditions [23]. Several techniques are developed for the operation and control of multilevel converters, such as the following:

- (SPWM): Sinusoidal pulse width modulation.
- (SHE-PWM): Selective harmonic elimination pulse width modulation.
- (SVM): Space vector modulation.
- (RPPM): Random-pulse position modulation.

When tested on a LED driver operating at switching frequency of 25 kHz, the later technique showed a reduction by 94% compared to the spectra that resulted from conventional PWM technique [55]. However, it is a challenging opportunity for future trend in SH research to conduct a comparative study to verify the most effective among the above control techniques in mitigating SH emission.

D. INTEGRATED MITIGATION

Based on [56], mitigation is best obtained by integrating the entire parts of the installation. This includes the supply and the consumer apparatus together with procedural steps to ensure compliance to standards, as shown in Figure 14.

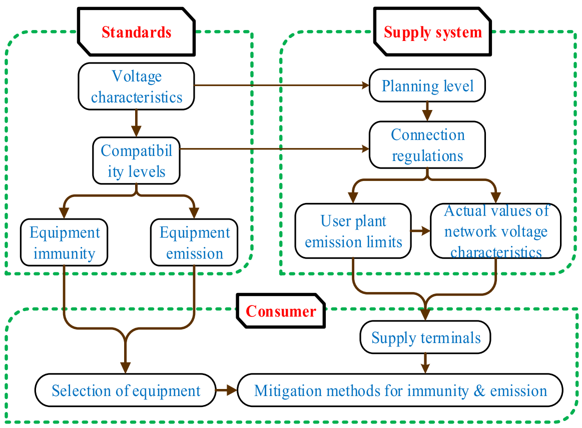

FIGURE 14. **Mitigation of SH emissions through integrated phases.**

When examining the three levels of standardization objectives, it should be stressed that the voltage characteristics serve as a reference concerning the electricity supply. It represents an indication for its expected performance and as a guide for selecting the immunity of consumer apparatus. Therefore, test levels that provide immunity to these equipment should be chosen with suitable margin depending on application type and reliability requirements. In that sense, Figure 14 shows the relationships between the standardization process, the supply system, and the consumer installation [53]. However, up to date, there is no clear and efficient mitigation technique for SH; hence, this issue implies further investigations.

VI. CONCLUSION AND RECOMMENDATIONS

The power-electronic converters, which are considered as the key technologies of RES, EVs, and smart meters, are generated harmonic distortions that cerate critical issues when integrating them in the electrical grid. Undesirable harmonic emission in the range of <2 kHz would be generated in traditional grid-commutated power-electronic converters. Using PWM signals with high switching frequencies in power-electronic converters, the desired output currents and voltages are obtained by mitigating these discrete low-order harmonics. However, these signals are potentially increased harmonic emission in a range of 2–150 kHz that behave differently from lower-frequency harmonics. Due to these supraharmonics emissions, several issues associated with the power quality of the power system are recently observed in multiple studies. Furthermore, the spread of SH emissions is impacting other neighboring devices. Therefore, this study provided a detailed survey of SH identification, standards, and measuring techniques. After providing a theoretical background on SH consequences and characteristics, this study reviewed the SH standards based on IEC standards-61000 series and its compatible IEEE standards. The main devices and techniques used to measure SH emissions are discussed consequently.

Based on the review provided, a number of significant suggestions and recommendations relevant to SH identification, standards, and measuring techniques for further studies are highlighted as follows:

I SH frequency range of 2–150 kHz is not sufficiently covered in power international standards. Moreover, IEC standards 610004-7 and 61000-4-30 are informative rather than normative. Therefore, serious attention from the international standard-setting community in knowledge about voltage and current distortion in SH frequency range is required.

II Thus, due to the insufficiency of relevant accurate standards, studies on SH mitigation methods are lacking. Besides, there is a lack of a potential method to mitigate SH emissions in previous studies.

III Serval existing studies describe the measurements but do not explain the measurement system. There is also a lack of information on the performance characteristics of the measurement system in the existing literature.

IV There is a lack of appropriate measurement equipment for higher frequencies, especially for SH. Therefore, development tools for accurate measurement of SH emissions in the power grid are essentially required.

V Attention should be paid in integrating large-scale RES, EVs, and smart metering, where a wide range of undesirable harmonic emission in the range of 2–150 kHz is expected to create multiple issues on the power grid.

VI We refer to Table 3 in this paper for the limitations which were diagnosed and in column 6 of the table for the 14 SH emission measurement techniques studied and compared in the literature.

The suggestions and recommendations above would be beneficial for future studies in mitigating SH emissions and power quality improvement in the electrical systems, particularly with the integration of RES, which is expected to grow sharply soon. Further research based on this study outcome may also help address the weaknesses of existing SH for potential standards development and prevention of SH emission.

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