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REVIEW PAPER

A Comprehensive Review on Supraharmonics—The Next Big Power Quality Concern

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Abstract
In recent years, electric power distribution systems have been focusing on power electronic converters. This is due to the integration of smart grids, electric vehicles, and renewable energy sources. As a result of incorporating renewable energy sources, nonlinear loads, and power electronics-based devices, modern electrical power grids are vulnerable to several power quality issues. The use of power electronics converters results in novel supraharmonic emissions, that do not fall within the traditional power quality frequency range. A detailed analysis of supraharmonic emissions is essential as they have a significant impact on the modern electrical grid. This paper starts by discussing the current scenario of electrical power systems and then introduces supraharmonics. The intentional and non-intentional sources of supraharmonics, such as power line communication (PLC), electric vehicle (EV) charging devices, lighting devices, solar and wind energy converters, along with their corresponding emission frequency bands, are also discussed. This paper presents a summary of the measurement methods and standards related to supraharmonic emissions. Finally, various research approaches addressing the reduction of supraharmonic emissions are proposed.

Keywords Modern electrical power grid · Power electronic converters · Renewable energy sources · Power quality · Supraharmonics

Introduction

In recent days, power systems are growing in size and complexity. Due to technological advancement and the modern lifestyle of society highly increase the consumption of electrical energy. The rapid rise in global energy consumption increases the continuous use of fossil fuels as well as greenhouse gas emissions, which have a significant impact on the power grid. This is a concerning situation in terms of supplying sustainable energy and environmental preservation worldwide. According to this, the Agenda 2030 for Sustainable Development, signed by 193 countries, incorporates worldwide efforts toward 17 goals, with a primary focus on the advancement of renewable energy and the reduction of global warming [1]. As a result, the deployment and integration of renewable energy sources (RESs) into the existing power system have increased [2, 3]. Wind and solar power are familiar sources of clean, renewable energy but are inherently unstable, intermittent, and unpredictable [4, 5]. Power electronics play a crucial role in renewable energy systems like wind, solar PV, hydro, and fuel cell systems. Power electronics are used for power conditioning and control, and converter topologies like modular multilevel-cascaded converters have been adopted for interfacing renewable energy systems to the grid. Thus, the integration of renewable energy into the power grid has been made much easier by the advancement of power electronics [6–8].

However, traditional power grids are restricted to some of those essential functions, such as electricity generation, distribution, and control. It is also unreliable, has significant transmission losses, poor power quality like brownouts and blackouts, provides inadequate power supply, and prevents using distributed energy sources. Also, the existing power infrastructure lacks real-time monitoring and control, presenting an opportunity to rebuild it as a smart grid [9–11]. The following changes have occurred in recent years as a smart grid: generation resources have been added to the distribution end, one-way power flow has been converted

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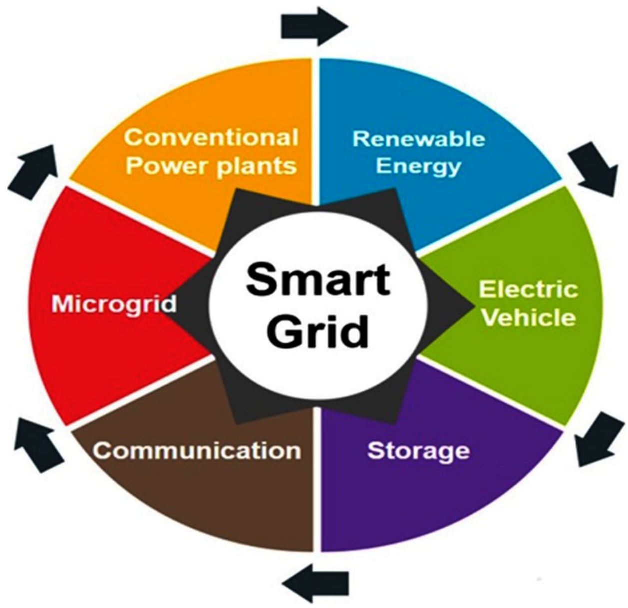

Fig. 1 Components of Smart Grid

Fig. 2 Various types of Power Quality issues

to bidirectional flow, the nature of the load has changed, renewable energy has already met grid power demand in most parts of the world, and electric vehicles can be used as a virtual power plant. Figure 1 shows the various components of a smart grid [12]. Smart grids are built using power-electronic converters, allowing the smooth integration of several energy sources into a power system, including solar PV, wind turbines, batteries, electric vehicles, and diesel engines. A smart grid satisfies the need for electricity and protects the environment by digitising the power infrastructure [13–18].

In contrast, recent advances in power electronics have resulted in several power quality challenges in power systems. Furthermore, the proportion of nonlinear loads in modern power systems is increasing, which also causes power quality issues. As a result, the worst quality of power affects the entire power system network. Furthermore, implementing new technologies of power electronics converters with increased switching frequencies causes a challenge like voltage sag, swell, transients, and waveform distortion, as shown in Fig. 2 [19–21].

Novel power system technology and the variety of power electronic devices used by residential, commercial, and industrial users have added to grid concerns by causing waveform distortion. Many waveform distortions occur in the frequency ranging from 0 to 2 kHz [22] Most switching devices and equipment raise harmonic levels in today's electrical distribution system.

The widespread expansion of wind and solar energy sources and the addition of EV charging to the grid boosts the harmonic level, affecting the smart grid's operation. Therefore, it is essential to analyse power pollution in today's electrical power network [23]. In addition to the conventional power quality issues, a new term known as supraharmonics also exists in the modern power system. The frequency range between 2 and 150 kHz is referred to as supraharmonics and is shown in Fig. 3A. McAechern proposed the concept of supraharmonics at IEEE P&E S GM 2013 in Vancouver, which was considered a new significant issue in the reliability of smart grid systems [24, 25]. Supraharmonics are likely to occur at any random frequency [26].

Supraharmonic interference is a serious concern to electrical equipment since it can shorten the lifespan of the equipment. Supraharmonics occupy the same bandwidth as power line communication protocols, which can lead to overheating of the compensation capacitors and transformers, as well as the malfunctioning of the protective devices. In addition, it creates a critical impact on the infrastructure for smart metering, communication, and control. Recent research has shown that supraharmonic emission causes significant inaccuracies in smart energy meters. This causes sensitive loads to be affected, which also has an effect on neighbouring circuits and interacts with the grid [27, 28]. Supraharmonics propagate into the medium-voltage network and generate more resonant frequencies within the supraharmonic range [29]. The effects of supraharmonic emission [30] are illustrated in Fig. 4. As a result, investigating and analysing the solution to this problem is necessary.

Based on the data obtained from Scopus using the keywords "supraharmonic" and "supraharmonics" Fig. 5(a) clearly indicates the type of publications over the years 2014 to 2023 and also it shows the increasing importance of studying supraharmonics in recent times. Similarly, Fig. 5(b) depicts details

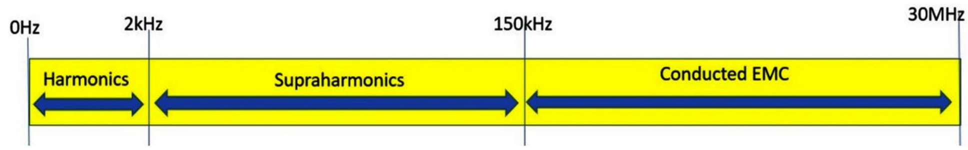

Fig. 3 Supraharmonic frequency range

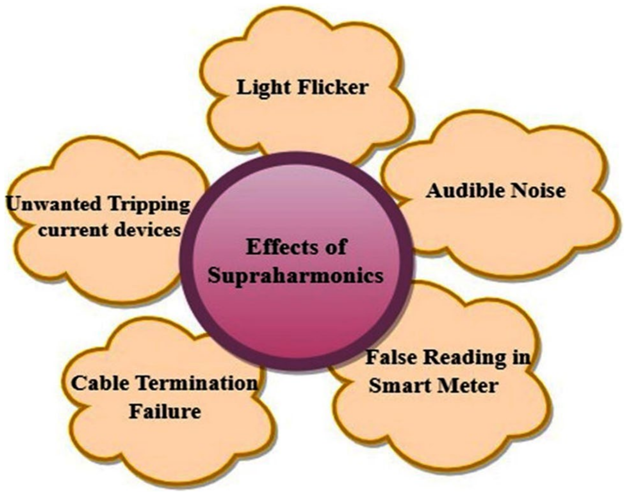

Fig. 4 Effects of Supraharmonics

regarding countries actively participating in this field and the number of research papers they have contributed. Therefore, this study provides a comprehensive overview of the current issues concerning supraharmonics in power networks.

This paper gives an overview of the supraharmonic issues in power networks. It is structured into the following sections: Section "Sources of Supraharmonics in Smart Grid" focuses on analysing the sources of supraharmonic emissions in modern smart grids. The details of the measurement techniques and power quality standards are discussed in Section "Measurement and Power Quality Standards", which covers requirements for higher frequency ranges, standards for low-order harmonic distortions, and the problem of specifications for the supraharmonic range of frequency. Finally, "Conclusion" Section gives the conclusions of this study and further research.

Nomenclature

I	Total emission
J_1	Primary emission
Z_D	Device impedance
Z_1	Grid impedance
V_2	Secondary emission

Sources of Supraharmonics in Smart Grid

The unfamiliar supraharmonics was introduced recently at the IEEE P&E Society General Meeting 2013. The term "supra" refers to beyond, i.e., high-frequency harmonics, high-frequency distortion, or low-frequency EMC [26].

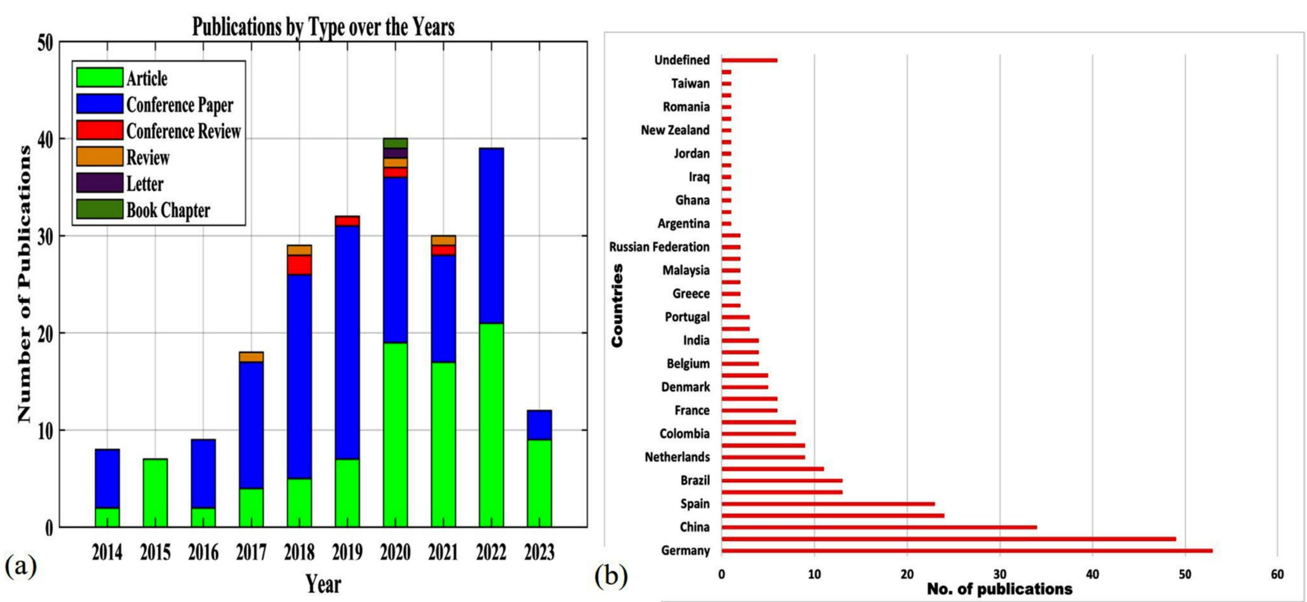

Fig. 5 **a** No. of publications and types from 2014 to 2023; **b** No.of publication vs. countries

Compared to harmonics and interharmonics, supraharmonics shows different behaviour. Bollen and Ronnberg [23] stated that changes in the generation of electrical energy from other sources and consumption of electrical power by modern loads cause supraharmonics in the network. EPRI started research on supraharmonics emission and the resistance of end-of-use equipment in 2017. Hence, researchers have a large pole of attraction to study the behaviour of supraharmonics in the most recent period [31, 32]. According to the latest research, combining renewable energy with the existing grid and increased use of power electronic converters produces supraharmonics in the power system. Supraharmonics may create electronic device failure, especially in touch technologies, noise generated by mechanical resonance excitation, or increased thermal burden [33]. The biggest issue of high-frequency components in power systems is expanding thermal stress, which shortens electrical equipment's lifespan [32].

Subhani et al. [34] classify the supraharmonics range into three categories depending on the interruptions in the frequency range.

1. Power line communication is primarily responsible for narrowband signals;
2. Disturbance in the frequency range of broadband signals is due to consumer equipment.
3. Recurrent oscillations in power electronic converters around current zero crossing.

Math H. J. Bollen et al. [35] classify supraharmonic emissions into two types: primary and secondary. Figure 6 illustrates the primary and secondary emissions of supraharmonics, where I is the total emission, J_1 is the primary emission, Z_D is the device impedance, Z_1 is the grid impedance, and V_2 is the secondary emission.

Harmonic distortion caused by the source, i.e., within the device or authority, is referred to as primary emission. However, secondary emission is also a harmonics distortion caused by external devices or sources. The generation of supraharmonics is mainly due to secondary emissions.

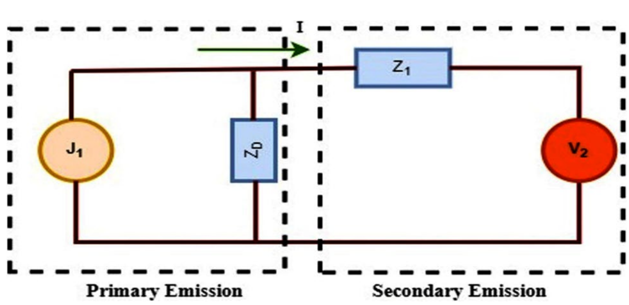

Fig. 6 Primary and Secondary emissions of supraharmonics

Some examples of sources of supraharmonic emissions are shown in Fig. 7.

Based on the literature survey [15–23], the frequency ranges of SH emission from various sources have been presented in Table 1. According to the early investigations; the frequency ranges from 2 to 9 kHz are considered supraharmonics. Later it can be upgraded to 150 kHz. PC and PLC are the two primary supraharmonic emission sources, irrespective of all other sources [36].

Power line communication is an intentional source of supraharmonics. The operation of power line communication with various types of end-user equipment may reduce device performance [37]. Power line communication (PLC) is a preferred communication method for smart grids and also provides reliable communication for Internet-of-things (IoT) [38]. PLC has been classified into ultra-narrowband, narrowband, and broadband PLC. The smart grid requires a frequency range of less than 500 kHz at rates of up to 100 kbps [39]. The narrowband operates at frequencies lower than the required range, making it suitable for applications

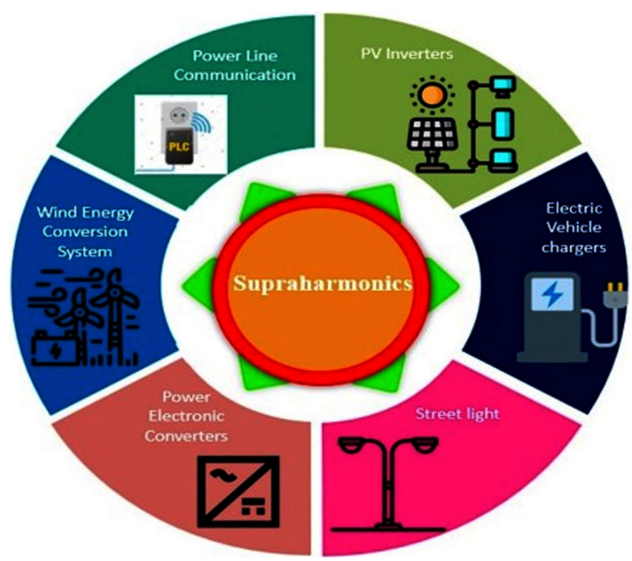

Fig. 7 Sources of Supraharmonics

Table 1 Frequency ranges of supraharmonics emitted by different sources

Source of supraharmonics	Range of frequency (kHz)
Power Converters (PC)	9 – 150
Lighting system	Up to 20
Chargers of Electric vehicle	15 – 100
Solar module inverters	4 – 20
Domestic appliances	2 – 150
Power Line Communication (PLC) for smart meter	9 – 95

such as automated metering infrastructure (AMI), power devices sensing/controlling and monitoring, recognition of system malfunction, and control systems for electric vehicles recharging in smart grids. Medium and low-voltage power grid systems, cost-effectiveness, and vast network coverage are achieved [40]. Different frequencies are used for narrow-band power line communication in Europe, Japan, and the United States. Table 2 summarises the frequency operating range of PLC [41–44].

J. Meyer et al. [45] stated that supraharmonics is produced by grid-connected harmonic sources and smart-meter signals, thus affecting both the consumer and generation sides of equipment. Math Bollen et al. discussed that the functioning of the customer equipment might be negatively impacted in many ways by the voltage distortion created by PLC. For example, modulation of the high-frequency signal on the fundamental frequency causes multiple zero voltage crossings, which leads to equipment failure [37].

Non-intentional disruptions in a frequency ranging from 2–150 kHz are introduced by some of the loads linked to the network in which PLC has been employed [46]. Some of the system components of electric vehicles, onboard battery chargers, laptop chargers, and electronic converters in photovoltaic (PV) and wind energy conversion systems operating in the supraharmonic frequency range are unintentional emitters [30].

Table 2 PLC operating range of frequency

Name of the country	Operating range of frequency
Europe	3–148.5 kHz
Japan	10–45 kHz
United States	10–490 kHz
India	0—500 kHz

The increased penetration of solar energy conversion systems in the modern grid has its issues. Solar PV systems comprise several power stage topologies with transformer or transformer-less choices. DC-DC converters are vital in solar PV energy conversion systems [47, 48]. In solar PV systems, the DC-DC converters act as switching mode regulators and convert uncontrolled DC voltage to a required DC voltage rating. The converters used in solar applications are a buck, boost, buck-boost, Cuk, sepic converter, and isolated DC-DC converter [49–59]. The choice of the DC-DC converter is determined by whether the PV arrays are connected in series or parallel [60]. The operation of DC-DC converters at high switching frequencies of 20 to 500 kHz will result in supraharmonics in the system [61]. Figure 8 shows the emission of supraharmonics from a grid-connected Solar energy conversion system.

A grid-connected solar PV system needs an inverter to convert the output of the DC-DC converter into AC, which will also inject supraharmonics into the system [62]. Voltage source inverters, current source inverters, and Z- source inverters are the different types of inverters used in solar energy conversion systems [63, 64]. The supraharmonic emission from the PV inverter is proportional to its output voltage and depends on its operating conditions [65]. PWM technology is commonly employed in single-phase and three-phase inverters, and it exhibits a supraharmonic frequency in the range of 1–20 kHz in PV systems [30].

Gianfranco Chicco et al. [66] employed an inverter with PWM controllers for a solar energy conversion system and analysed it for supraharmonic emission at PCC. From the analysis, the authors concluded that the inverter is the source of supraharmonic, and also supraharmonic emissions vary depending on the inverter configuration. The single-phase linked photovoltaic (PV) inverters with an installed power

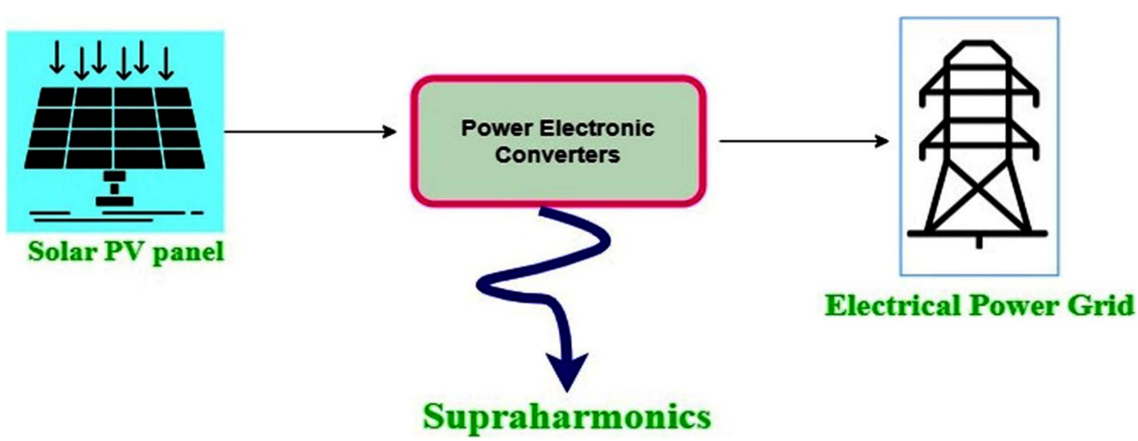

Fig. 8 Supraharmonics from Solar Energy Conversion System

rating of less than 4.6 kW act as the source of primary supraharmonic emissions at frequencies between 15 and 20 kHz as per the book titled "Power quality aspects of solar power" published by the working group of CIGRE/CIRED JWG C4.29, 2016 [67]. Jalil Yaghoobi et al. [68] examined supraharmonic emission in two sites with varying loads and 3 MW solar energy conversion systems by keeping inverter switching frequencies below 3 kHz. Finally, they discovered that levels of voltage harmonics were seen at frequencies close to or multiples of the switching frequency of the PV inverters in the range of 0-9 kHz.

Dilini Darmawardana et al. [69] examined three distinct PV energy conversion system topologies and found that the low-frequency single-phase inverter generates supraharmonics up to 8 kHz, the high-frequency inverter emits high frequency at a moderate level or 16 kHz, and the transformer-less inverter emits supraharmonics in the range of 20 kHz. Further, the authors observed that voltage harmonics had been developed near the switching frequency of the PV inverter. Anantaram Varatharajan et al. [70] carried out an extensive investigation of the supraharmonic emission from several three-phase converters with a power rating of 100kVA and single-phase inverters with a rated power of 1- 10kVA after a widespread investigation; the authors concluded that the supraharmonics emission by the inverters is close to its switching frequency.

Gaurav Singh et al. examined the supraharmonic emission from a solar PV plant with a 17 MVA capacity [71]. According to their analyses, the SH emission interacts with traditional telephone service and generates noise in the range of the switching frequency of the solar inverter. Finally, they found that the neutral line of the inverter carried the supraharmonic range of frequency and transmitted it into the telephone line and power distribution system.

Electric vehicle use in transportation infrastructure has a reduced environmental effect, and as EV technology progresses, a considerable quantity of highway charging stations are installed [72]. At a charging station, an electric vehicle receives electricity from both AC and DC sources, thus the charging station is an essential component of the EV charging infrastructure. EV chargers are categorised into several varieties based on source type, station integration, and power level. Wireless and wired chargers are the two main classifications of electric vehicle chargers. In addition, the EV chargers are classified into on-board and off-board chargers based on the charger configuration. While off-board chargers are placed outside the vehicle, on-board chargers are placed inside the vehicle. According to the amount of power the EV chargers deliver, they are divided into four categories: Level 1, Level 2, Level 3, and Level 4. Level 1 is often referred to as normal charging, Level 2 as semi-fast charging, Level 3 as fast charging, and Level 4 as ultra-fast charging. Off-board chargers are usually classified as level 3 of the commercial charging station [73–76]. Shimi Sudha Letha et al. [77] described three types of charging infrastructure: residential, public, and fast charging, as shown in Fig. 9. Charging modes are subdivided into 2 cases such as unidirectional and Bidirectional. In unidirectional charging mode, the vehicle gets power from the grid alone. In bidirectional charging mode, the power flows in both directions, from vehicle to grid and grid to vehicle [78–83].

Using DC level 2 chargers, Gaurav Singh et al. [78] examined the impact of supraharmonic emissions at a charging station on three electric vehicles. In level 2 chargers, a diode rectifier and an active rectifier with a switching frequency of 10 kHz are used to link the charging station at the point of common coupling. The authors found that EV chargers produce supraharmonic emissions in the narrowband and broadband frequency ranges. They concluded that the diode-end converters emit supraharmonics in the 1 to 3 kHz range, and PWM front-end DC chargers emit supraharmonics in the range of 20 kHz. Friedemann Moller et al. [84] tested 8 onboard charging batteries of two electric vehicle models with and without solar energy conversion systems on three-phase and single-phase supplies. The authors found from the test that the distinguishable supraharmonic voltage and current occurred at 10 kHz, 17 kHz, and 20 kHz.

S.Schottke et al. [85] proposed that EV chargers become a source of supraharmonics in the range of 3 kHz to 29 kHz. The author tested type-1 and type-2 chargers of six electric vehicles in the laboratory and found that the supraharmonic emissions occurred due to the switching frequency of the charger. In addition, the emission depends on the charging topology and the charging state. Dilini Darmawardana et al. [86] have proposed an analysis of supraharmonic emission due to DC fast charging and Level 1 onboard charging. Finally, the authors concluded that both types of chargers emit supraharmonic frequency, and it depends upon the characteristics of the charger as well as the charging characteristics of the vehicle.

Fuqiang Chen et al. [87] examined ten chargers with different maximum charging powers in five locations across two countries. The authors found the supraharmonic emissions from the EV chargers and identified that the range of supraharmonic frequency depends upon the switching frequency and type of the EV chargers. S. Cassano et al. [88] proposed an EV charging station model to measure supraharmonic emission in a low-voltage network. From the investigation, the authors reported that the number of devices connected to the grid and the length of the line impact primary emission less. Further to their investigation, grid resistance reduces primary emission while increasing secondary emission. Finally, the authors stated that the maximum supraharmonic emission occurred at 15100 Hz, and concluded there is still a lack of knowledge about the emergence and spread of supraharmonics.

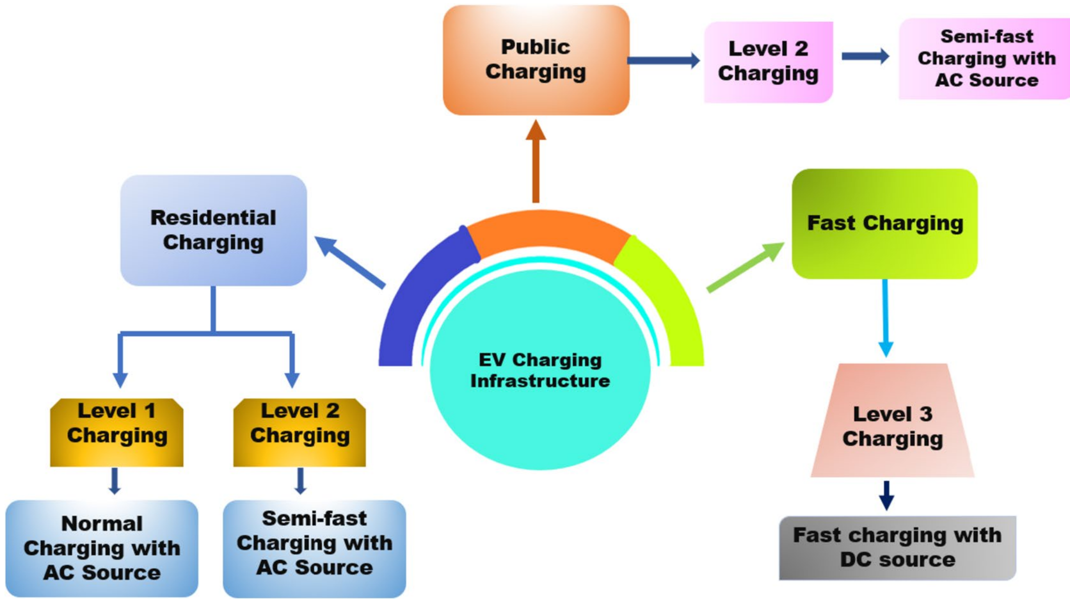

Fig. 9 Types of EV Charging Infrastructure

Tim Slangen et al. [79] have tested the propagation of supraharmonic currents in a low-voltage system. The researchers independently evaluated four kinds of electric vehicles linked to the public grid and microgrid. They discovered that EVs generate and absorb the supraharmonics in the range of their switching frequency. The authors concluded that DC fast chargers would be sources of supraharmonic emissions at a high-power level. The supraharmonic currents may be transferred from an LV grid to a medium-voltage (MV) grid via a distribution transformer. Tim Slangen et al. [89] tested fast-charging electric buses at a bus depot and identified that supraharmonics emitted by the EV chargers. The authors stated that converters in EV chargers are the primary source of harmonic and supraharmonics emissions. Further, they specified that there is no specific standard to limit the values of supraharmonic emissions in the EV chargers. Tim Slangen et al. [90] have analysed the supraharmonic from field measurement data of electric vehicle chargers with a rating of 350 kW connected in a different ratio. According to the author's result, the system's total supraharmonic current output increases when more chargers are turned on. At the same time, the researchers identified that the emission is not constant over time.

Manav Giri et al. [91] have demonstrated supraharmonics emission from EV rapid chargers with different charging modes at varying charging fields. The researchers concluded that EV chargers cause disruptions in both low-voltage and medium-voltage networks. Finally, they observed various emissions patterns in the power network and concluded that more detailed research is needed to understand the spread of EV emissions. Tim Streubel et al. [92] tested electric vehicles in three different sites and found supraharmonics in a different range of frequencies and interruption of EV charging due to supraharmonics.

Priyanka Mane et al. [93] reviewed the problems with the power quality caused by the solar-powered EV fast charging station. The authors stated in their review that solar and EV fast charging stations are the primary sources of supraharmonics. According to the author, EV emits supraharmonics at frequencies between kHz and 60 kHz in both narrowband and broadband. Also, the SoC of the EV battery influences the emission of supraharmonics from EVs. Bernhard Grasel et al. [94] investigated the impacts of vehicle-to-grid (V2G) chargers connected to the distribution grid. The authors analyzed Austrian electrical low-voltage distribution grids in different scenarios with different topologies. Based on the investigation, they observed that the frequency-dependent grid impedance is influenced by V2G chargers, LCL filters, and DC link capacitors. V2G chargers cause both series and parallel resonance in all conditions, and the number of chargers connected to the grid also affects the frequency range of resonance.

High energy-efficient lighting has recently replaced conventional lighting methods to reduce electrical energy consumption. Nearly 70% of worldwide lighting has been achieved by LED lighting. The use of CFL and LED lights to replace conventional lighting schemes negatively influences the electrical system due to the requirement of drivers [96, 97] is a result of the changeover from an electrical to an electronic load causes harmonic distortion and grid losses in the system [97, 98]. Supraharmonic emissions are observed

Table 3 Summary of Supraharmonic Sources

Source	Year	Observation
Power Line Communication	2011	Customer equipment might be negatively impacted in many ways by the voltage distortion created by PLC
	2018	Supraharmonics induced by smart meter signals affect the consumer and generation side equipment
Solar Energy Conversion System	2015	High switching frequencies in the range of 20 to 500 kHz will result in supraharmonics
	2022	The Inverter of a grid-connected solar PV system injects supraharmonics into the system
	2016	Supraharmonics is proportional to its output voltage and also depends on the operating conditions of the inverter of the PV system
	2015	Inverter is the source of SH emission and depends upon the inverter configuration
	2017	Source of primary supraharmonic emissions from PV at frequencies between 15 and 20 kHz
	2020	Frequencies close to or multiple of the switching frequency of the PV inverters
	2018	Voltage harmonics have been developed near the switching frequency of the PV inverter
	2014	3 phase and single-phase inverters are the sources of supraharmonics
Electric Vehicle	2022	• EV chargers produce supraharmonic emissions in the narrowband and broadband frequency ranges • Diode-end converters and PWM front-end DC chargers emit supraharmonics
	2019	EVs generate and absorb the supraharmonics in the range of their switching frequency
	2021	Tested EV with solar and without solar and identified distinguishable supraharmonic voltage and current
	2014	• Type-1 and type-2 EV chargers emit supraharmonic due to the switching frequency of the charger • Emission depends on the charging topology as well as the charging state
	2020	Supraharmonic depends upon the characteristics of the charger as well as the charging characteristics of the vehicle
	2021	The range of supraharmonic frequency depends upon the switching frequency of EV chargers
	2019	Dependent upon the switching frequency of EV chargers
	2021	Converters in EV chargers are the primary source of harmonic and supraharmonics emissions
	2022	Various patterns of emissions that occurred in the power network
	2022	Interruption of EV charging due to supraharmonics
	2023	EV fast charging station powered by solar PV system generates supraharmonics
Lighting systems	2011	LED bulbs and high-efficiency fluorescent lighting emits SH
	2013	• Produces electrical noise in the DC-DC converter part of the LED driver circuit with a frequency range of below 150 kHz • Affects PLC communication
	2021	• Supraharmonics have been related to the visible flickering of LED lights • Produce an audible noise, which is in the range of human audible frequency, i.e., 20 Hz to 20 kHz
	2015	Identify the supraharmonic current from low voltage devices – LED, CFL
	2016	Measurement of frequency emission from Low voltage devices
	2017	Analyze the CFL with a half-bridge resonant inverter
	2018	The buck converter in the driver circuit of LED emits supraharmonics
	2019	• Measurement setup used to identify the SH level • Network impedance affects the measurement of SH
	2016	Active Power Factor Correction (APFC) in the power circuit minimises the lower harmonics but simultaneously emits the supraharmonics in the system
	2019	Supraharmonics from LED causes flickering and affects the sensation of the human eye
	2022	Significant contributors to PLC transmission disruptions are CFL light sources (26.54%) and LED light sources (13.46%)
Wind Energy Conversion System	2019	• A variable-speed wind turbine's grid interface inverter emits 3.15 kHz • Analyse the secondary emission • Impact of grid impedance increases with the distance between the sending and receiving WTs
	2017	Supraharmonics from PMSG wind energy sources and measured the level of harmonics
	2017	DFIG with the back-to-back converter is analyzed, the switching frequency of the back-to-back converter is cause for supraharmonics
	2016	• The converter circuit's switching frequency generates supraharmonics in the 2–3 kHz range • Power line communications systems used in smart grids can malfunction
	2020	• The primary source of supraharmonics is the back-to-back converter • Supraharmonic emissions from wind turbines are detected in the inverters' switching frequency range

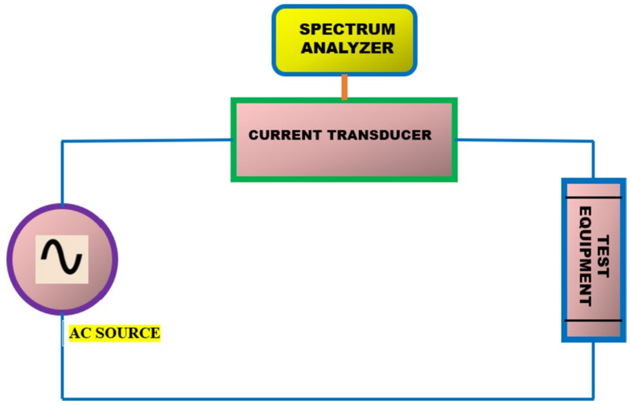

Fig. 10 General measurement of low-order Harmonics

from the lighting of several types of LED bulbs and high-efficiency fluorescent lighting [23, 99]. Allan Emleh et al. [100] stated that LED lighting produces electrical noise in the DC-DC converter part of the LED driver circuit with a frequency range below 150 kHz and also affects PLC communication. Gaurav Singh et al. [101] highlighted that supraharmonics have been related to the visible flickering of LED lights and produce an audible noise in the range of human audible frequency, i.e., 20 Hz to 20 kHz. Daniel Agudelo-Martinez et al. [102] identified that the buck converter in the LED driver circuit emits a high range of frequencies.

Tatiano Busatto et al. [103] stated that the power circuit's Active Power Factor Correction (APFC) minimises the lower harmonics. Still, simultaneously, it emits the supraharmonics in the system. Selcuk Sakar et al. [104] mentioned that the supraharmonics from LED causes flickering and affects the sensation of the human eye. According to Marek Wasowski et al. [46] work, the major contributors to PLC transmission disruptions are the CFL light sources (26.54%) and LED light sources (13.46%). Naser Nakhodchi et al. [105] measured supraharmonic emission during lighting installation and found that the emission level increases when the number of lamps increases.

One of the significant sources of renewable energy is the energy acquired from the wind. In recent years, several countries have seen a substantial increase in generation farms tied to sub-transmission and transmission systems. To connect to the grid, wind turbines need power electronic converters [106–110]. Wind power systems and their connections with the grid directly affect the harmonic levels. Therefore, harmonic studies are often a compulsory part of the connection of wind power [111–114]. Daphne Schwanz et al. [115] stated that wind power plant is the source of primary emission of supraharmonics. A variable-speed wind turbine's grid interface inverter emits 3.15 kHz.

Ana Maria Blanco et al. [116] investigated the harmonics, inter harmonics, and supraharmonics from wind energy sources and measured the level of harmonics. The suprahamonics in the wind energy conversion system were studied by Javad Behkesh Noshahr [117]. The author proposed that the frequency converter circuit's switching frequency generates supraharmonics in the 2–3 kHz range. A study on the generation of supraharmonics in power transmission systems caused by wind farms with PMSG technology was presented by Benhur Zolett et al. [118]. The power inverter was shown to be primarily responsible for the emissions

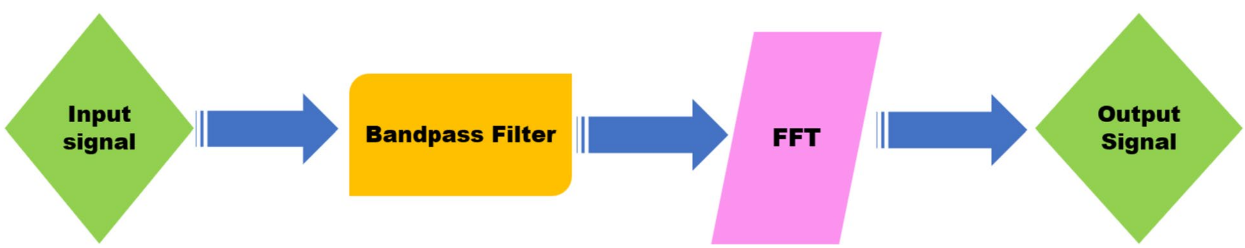

Fig. 11 Measurement method as per IEC 6100–4-7

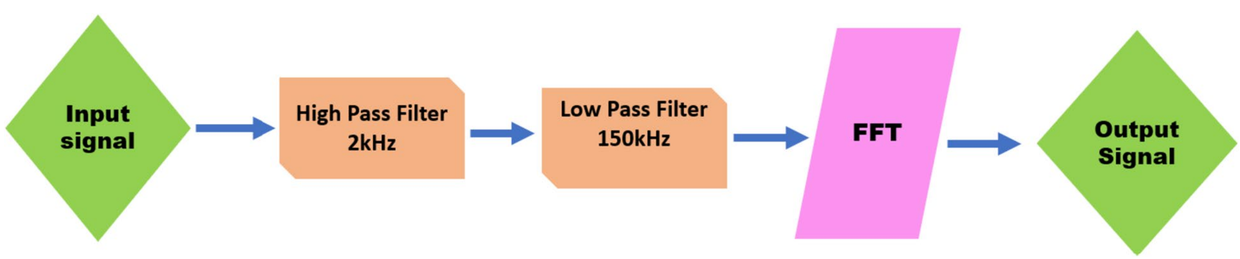

Fig. 12 Measurement technique is given by IEC 6100–4-30

Table 4 Measurement and Testing Standards for the supraharmonic frequency

Standard	Frequency Range	Measuring Method
IEC 61000–4–7	2 kHz—9 kHz	DFT with 5 Hz resolution, 200 Hz bandwidth, at 200 ms of signal interval, full sampling method
IEC 61000–4–30	9 kHz—150 kHz	FFT with 0.5 ms interval, 2 kHz frequency resolution, equidistant sampling method
IEC 61000–4–19	2 kHz—150 kHz	Immunity-related characteristics and testing procedures for electrical and electronic equipment
CISPR 16–1-1 CISPR 16–1–2 CISPR 16–1–3	9 kHz – 30 MHz	DFT of overlapping 20-ms, spectrum analyser, and quasi-peak detector suggested the equipment for testing emissions from the grid

from wind farms. The author concluded that the magnitude of supraharmonic voltage is less than that of low-frequency harmonic. Finally, the author stated that there is still no standard limit for this frequency range, so further research is needed to analyse the impact of supraharmonics on PLC.

Jil Sutaria et al. [119] analysed the supraharmonic emission from Data centres. To provide consistent power to the server loads, a data center functions as an essential hub for several converters. An uninterruptible power supply (UPS) regulates the incoming AC power from the utility, providing a backup in the event of a power outage. The UPS output is fed into the server's input power supply unit (PSU). According to the author, one of the primary sources of supraharmonics in the data center is the UPS. The authors investigated the supraharmonic emission from the UPS and the grid-connected solar energy conversion system in different operating modes. Analysis by the authors indicates that the SH voltage and current depend upon the grid impedance and the solar inverter. Also, in both online and offline operating modes of UPS, it was found that supraharmonics emitted by loads connected to the UPS do not travel to the grid side.

Supraharmonics are also emitted by cell towers and household appliances, including washing machines, compact fluorescent lamps, CRT television, and vacuum cleaner with brush motors [120–122]. Thus, the major sources of supraharmonics emissions in a smart grid include power electronic circuits and energy-saving equipment used in domestic applications [23, 24, 26, 27, 30, 31, 33–43, 45–48, 50–52, 54, 56, 57, 60–70, 72–77, 80–92, 95–118, 120–122]. Table 3 summarises the review of supraharmonic sources identified in the literature.

Measurement and Power Quality Standards

Monitoring signals in the 2–150 kHz band has become significant due to emissions on the power grid generated by power converters. Generally, the low-order harmonic content of equipment is measured by connecting the signal analyser and current monitoring device between the source and test equipment [27]. The measuring of harmonics in a system is shown in Fig. 10.

The IEEE EMC Society defines low-frequency emission as frequencies less than 150 kHz, but the IEC defines frequencies less than 9 kHz. As a result, there is no normative standard for quantifying supraharmonics. The informative testing and measurement methods for supraharmonic emissions are IEC 61000–4-7, IEC 61000–4-30, IEC 61000–4-19, Digital CISPR 16–1-1, IEEE 519, and CENELEC EN 50065. Time domain measurements are used in IEC standards, whereas frequency domain measurements are used in CISPR 16 standards. Appendix B of IEC 61000–4-7 recommends a measuring technique for equipment with a 2–9 kHz frequency range. This specification relates to CISPR 16–1. This measuring standard suggests a bandpass filter attenuating the fundamental frequency and components over

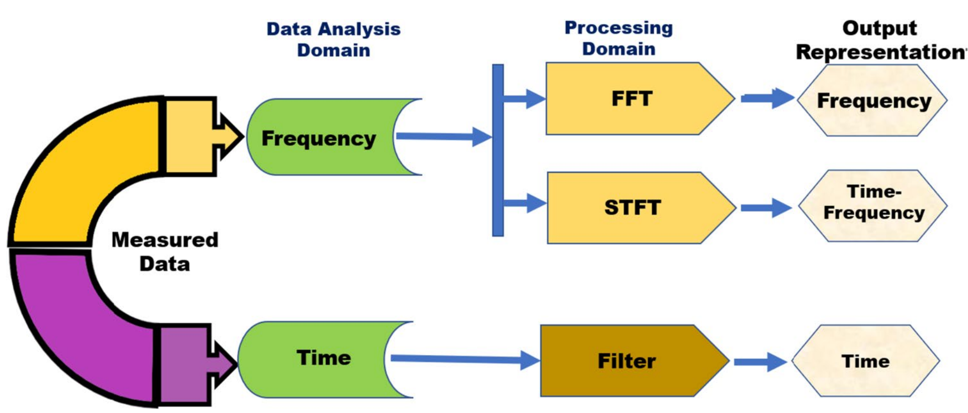

Fig. 13 Steps to measure supraharmonics

Table 5 Different measurement methods of Supraharmonics

Authors	Origin / Year	Type of Source	Standard	Measurement Method	Measurement Analysis Domain	Findings
J. Sutaria et al. Ref. [62]	Sweden 2022	LED lamps, Computers	IEC 61000–4–30	Laboratory experiment	Time domain	• Unbalanced voltage increases supraharmonics emission • Primary and secondary emission changes due to primary and secondary induced emission • The magnitude of SH current in neutral depends on the unbalanced load condition
Matthias Klatt et al. Ref. [65]	Germany 2016	PV inverters	IEC 61000–4-7	Laboratory experiment	Time domain	SH varies on • DC input voltage of the inverter • Inverter design • Inverter control scheme
Fuqiang Chen et al. Ref. [87]	China, Germany 2021	EV charging station	IEC 61000–4-30	Field Measurement	Time domain	SH frequency emission and its magnitude depends upon the type of EV charger
Tim Slangen et al. Ref. [79]	Netherlands 2020	EV chargers, microgrid	-	Both MATLAB simulation and Field measurement (DewetronDEWE-800 data-acquisition (DAQ) device)	Time–Frequency	EV chargers generate and absorb SH Distribution transformer act as a medium to transmit SH from the LV side MV side
S. Cassano et al. Ref [88]	European Countries (Belgium, Italy) 2019	EV chargers	-	MATLAB Simulation	Time–Frequency	The number of devices connected to the grid and the length of the line creates less impact on primary emission. Grid resistance increases the secondary emission and decreases the primary emission
Tim Slangen et al. Ref. [89]	Netherlands 2021	The fast charger of Electric bus	-	Field measurement	Time domain	EV chargers act as a source of SH
Tim Slangen et al. Ref. [90]	Netherlands 2023	EV chargers	-	Field measurement (Yokogawa DL350 mobile oscilloscope)	PQ instruments	SH current increases with no. of chargers turned on
Manav Giri et al. Ref. [91]	Sweden 2022	EV charger	IEC 61000–4-7	Field measurement	Time and frequency domain	Various patterns of SH occurred in the power grid

Table 5 (continued)

Authors	Origin / Year	Type of Source	Standard	Measurement Method	Measurement Analysis Domain	Findings
Tim Streubel et al. Ref. [92]	Germany 2022	Electric vehicles	IEC 61000–4-7 & 30	Field measurement	Time domain	SH occurred at a different range of frequencies and also it interrupts the EV from charging
O. Lennerhag et al. Ref. [133]	Sweden 2020	Railway system	IEC 61000–4–7	Field measurement (Hioki 8861-50Memory HiCORDER)	Time–Frequency domain	SH increases with an increase in the number of converters
G. Frigo Ref. [134]	Switzerland 2022	Power system	CISPR-16	New measurement method implemented in the field	Time domain	Compressive sensing (CS) theory and Taylor–Fourier multifrequency (TFM) models are implemented to find digital quasi-peak receiver
A.J. Collin et al. Ref. [135]	Italy 2020	LED lamps	-	New Measurement method in the laboratory	-	Combining a programmable power source and line impedance stabilisation network gives a better measurement of SH emission
G. Singh et al. Ref. [136]	Sweden 2017	LED lamps	IEC 61000 – 4 – 19	Pspice Simulation and laboratory measurement	Time–Frequency domain	SH affects the efficiency of the LED lamps SH does not depend upon the converter topology
T. Slangen et al. Ref. [137]	Netherlands 2020	Electric vehicles	-	MATLAB and DEW-ESOFT	-	Audible interference from EV charger
D. Amaripadath et al. Ref. [138]	France, 2018	PV inverter, residential load	-	Laboratory experiment	Rogowski coil sensors	PV inverter and residential load are sources of SH
Deepak Amaripadath et al. Ref. [139]	Belgium 2019	PV inverters, EV chargers, heat pump, washing machine	IEC 61000–4–7	Field Measurement	Time domain	Industrial PV inverter is the major source of SH
P.S. Wright et al. Ref. [140]	UK 2021	-	CISPR 16	New measurement (Digital heterodyne)	Time–Frequency domain	Easy to implement
Waniek Christian et al. Ref. [141]	Germany 2018	PV, LED lamp, Laptop, and mobile charger	EN 61000–4-7	Laboratory experiment	Time–Frequency domain	SH varies on the impedance of the grid and connected devices
S. Zhuang et al. Ref. [142]	China 2018	Wireless charging EV	-	Simulation and Field Measurement	Compressive sensing theory	Increases the frequency resolution and calculates the output effectively
D. Agudelo-Martinez et al. Ref. [143]	Colombia 2019	LED lamps	-	Laboratory experiment	Power Quality and Energy Analyser DEWETRON-2600	power sources, network impedances, and current sensors affect the SH emission measurement

Table 5 (continued)

Authors	Origin / Year	Type of Source	Standard	Measurement Method	Measurement Analysis Domain	Findings
A. Mohos et al. Ref. [144]	Netherlands 2018	PV inverters	-	Field Measurement	Dell XFR E6400 computer inbuilt spectrum analyser	SH current flow between the connected devices and into the grid
D. Darmawardana et al. Ref. [145]	Australia 2019	PV inverters	IEC 61000–4-7 & 30	Laboratory experiment	-	Solar panel acts as an SH source
Kaite Li et al. Ref. [146]	China 2023	PV inverters	IEC 61000–4-7	Laboratory experiment	Yokogawa DL850E used to measure the frequency; the Matrix pencil method	More accurately describe the dynamic characteristics of the supraharmonic emission
Rafael S. Salles [147]	Sweden 2022	Railway Pantograph	-	Field measurement	Deep learning	More accurate than traditional methods
Zhang Siyuan et al. Ref. [148]	China 2019	Electric Vehicles	-	Field measurement	Time–Frequency domain, Flexible atomic filter method	The algorithm can accurately measure the frequency and amplitude of supraharmonics
Zhe An et al. Ref. [149]	China 2022	Electric Vehicles	IEC 61000–4-7 & 30	Simulation and field measurement	Time and frequency domain analysis	SH from the EV charger is due to the switching frequency of the converter
Johannes Lambrechts et al. Ref. [150]	South Africa 2022	Inverters and Power line communication	-	Laboratory environment and a field environment	Spectrogram analysis using novel designed Active high-pass filter	Accurate measurements using the active high-pass filter
Shuangyong Zhuang et al. Ref. [151]	China 2019	PV inverter	IEC 61000–4–7	Simulation and field measurement	Multiple measurement vector of compressive sensing and orthogonal matching pursuit method	The highly accurate finding of frequency, amplitude, and phase of SH
Stefano Lodetti et al. Ref. [152]	Spain 2020	PV inverter, EV chargers	-	Simulation and field measurement	Wavelet-based hybrid measurement method	Suitable for continuous monitoring of the harmonics regardless of the amplitude value
Zijiang WANG et al. Ref. [153]	China 2019	Inverters	-	Simulation and field measurement	Partial Sampling and Hybrid Segmentation	High-speed measurement
Alexander Novitskiy et al. Ref. [154]	Germany 2017	Low voltage distribution network with different loads	IEC 61000–4-7 & 30	Field measurement	Time–Frequency domain	Identify the different sources and their range of SH emission
Mohammed El-Shahat et al. Ref. [155]	Egypt 2022	LED lamps	IEC 61000–4–7	MATLAB simulation	Frequency domain analysis Designing Rogowski coil in MATLAB software	Capable of measuring power frequency AC currents
Zesen Gui et al. Ref. [156]	China 2023	LED lamps	IEC 61000–4–7	MATLAB simulation and laboratory experiment	Time domain analysis Modified Compressed Sensing method	Accurate and reduced computational time compared to previous methods

Table 5 (continued)

Authors	Origin / Year	Type of Source	Standard	Measurement Method	Measurement Analysis Domain	Findings
Thais M. Mendes et al. Ref. [157]	Germany 2022	PV inverter and EV charger	CISPR 16	Simulation	Time domain analysis Phase- Locked Loop algorithm is used	Reduced computational cost and time
Mulualem T. Yeshalem et al. Ref [158]	India 2022	Compact Fluorescent Lamp	CISPR 16–2-1	Simulation and laboratory experiment	time domain and the frequency domain	SH emission occurs at a frequency multiple of the system's switching frequency

9 kHz. Figure 11 shows the measurement method of IEC 61000–4-7.

IEC 61000–4-30 suggested the measuring methods for the range of 9-150 kHz of frequency. Annex C of IEC 61,000–4-30 considers the measurement method specified in Annex B of IEC 61,000–4-7 for the frequency range of 9 kHz to 150 kHz. This standard limits the frequency range between 2 and 150 kHz by cascading high-pass and low-pass filters. The measurement method according to the standard is illustrated in Fig. 12. This measurement method is based on a normative standard which is given for below 2 kHz harmonics. It provides the root-mean-square (RMS) values. IEC 61000–4-19 provides the method of testing the equipment under the frequency range of 2-150 kHz and also specifies testing, and verification processes, test setup, and limits, test apparatus, and test waveforms. The CISPR 16–1-1 method specifies the measuring receiver by using different detectors. Quasi-peak detectors and analogue super-heterodyne receivers are suggested in this standard for testing the interference mainly in radio transmission. CISPR 16 is difficult to apply to the Low Voltage grid because it requires a line impedance stabilization network, which is not suited for distortion measurements.

CENELEC EN 50065 suggested the standard for electrical equipment using signals in the frequency range of 3 kHz to 1485 kHz to transmit data through PLC. IEEE 519 limits current and voltage harmonics from the customer and utility sides [123–132]. The summary of measurement range and testing procedure of supraharmonic frequency are given in Table 4 as per IEC and CISPR standards.

Time–frequency domain, Wavelet approach, Subsampling approach, and Compressive sensing domains are also used to analyse supraharmonics [128] Fig. 13 illustrates the method for measuring supraharmonics from the informative standards.

Research is ongoing to develop a standard measuring method and techniques for analysing supraharmonic emissions. The researchers have observed that measuring high-frequency harmonics can be challenging. However, several studies investigated the occurrence of supraharmonic emission from numerous sources using different measurement standards, as shown in Table 5 [62, 65, 79, 87–92, 126, 133–146, 148–158].

Alexander Gallarreta et al. [159] proposed a new measurement technique to measure the supraharmonic emission in the low voltage distribution grid. The novel method uses the Light Quasi-peak (QP) detection technique, a digital implementation of the CISPR 16 standard. This method reduces the memory requirement and computational process. The light quasi-peak method of measurement is shown in Fig. 14. The same author et al. [160] proposed another new method to measure the supraharmonic emission named as Statistical-QP method shown

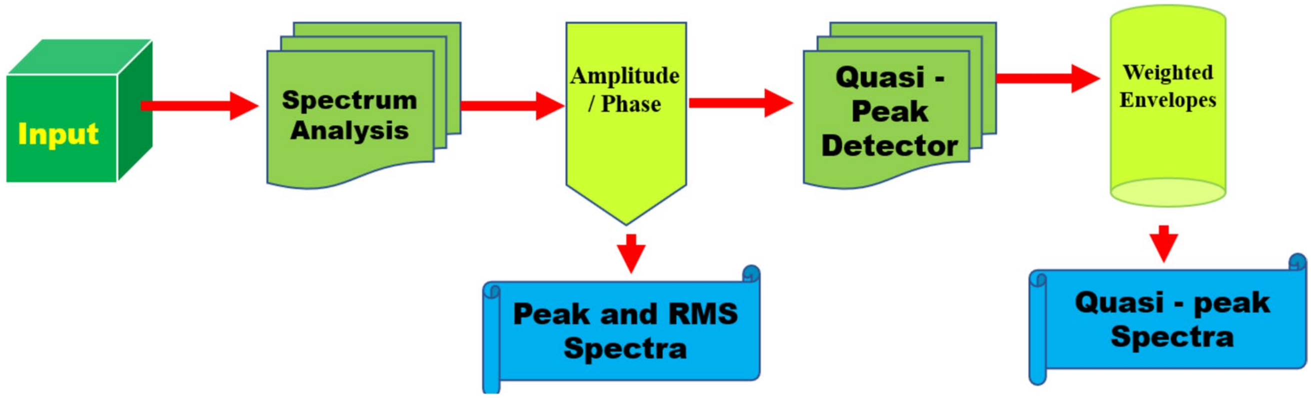

Fig. 14 The measurement method according to Light Quasi-peak

in Fig. 15. This method obtains an approximate QP value by statistically analyzing the instantaneous RMS values. As compared to CISPR 16, the Statistical-QP requires significantly less computation and memory.

These two methods require lower computational complexity and memory than digital CISPR 16 and have been submitted to IEC SC77A WG9 for inclusion in standard IEC 61000–4-30 [161].

IEC 61000–3-8 limits the supraharmonic maximum emission from power line communication is proposed for the frequency range of 3 to 9 kHz. Hence there is essential to suggest a new standard for supraharmonic emission. Additionally, the standards use different measurement intervals to analyse the supraharmonic emission therefore sudden fluctuations of emission are not able to measure properly. As a result, it is difficult to describe and measure the emissions from various types of equipment [27, 122, 127].

Different techniques are handled by the authors for reducing supraharmonic emissions. Antonio Moreno-Munoz et al. [162], mentioned that power electronics converters are a significant cause of waveform distortion, but at the same time, they may reduce the distortion. Appropriate design and implementation techniques can limit the production of supraharmonics. According to the authors, using multi-level converters can decrease supraharmonic emissions. S.K. Ronnberg et al. [163] proposed that innovative switching patterns in active converters can reduce supraharmonic emissions. The same author presented a pulse width modulation scheme based on random pulse position modulation in solar power plants and concluded this method would reduce supraharmonic emission in the system. The random pulse position modulation approach is complex, time-consuming and produces unreliable results [164]. According to the authors, the fuzzy logic controller is the most precise solution and may quickly eliminate the supraharmonic emissions. No specific method exists from the analysis to mitigate supraharmonic emissions; hence, the evolution of more studies in this area is essential. Table 6 summarises the review.

Discussion

In general, there is a lot of research being done on the topic of supraharmonics. The CIGRE C4 working group, the Electric Power Research Institute (EPRI) in the United States, and numerous universities are the few already working on this research issue.

- Most of the research findings are related to sources of supraharmonics and its emission level.
- Research work in measurement and analyses of Supraharmonic emission is very few compared to source identification of supraharmonics.
- Some research on measurement methods is limited to identifying primary and secondary emissions.
- No generalized measurement methods for supraharmonic emission.
- There is no normative standard for supraharmonic emission.
- According to the mitigation methods of supraharmonics, only a limited number of publications exist in the literature review.

Based on the literature review the research gap identified in the field of supraharmonics has been shown in Fig. 16.

- Supraharmonic sources will increase in the future. As a result, to handle this issue, a suitable measurement method and complete analysis are required to minimize the problem and mitigate the supraharmonics to regulate energy utilization.
- Supraharmonics can potentially be mitigated by employing high-frequency materials, which could be an area of future research.
- The integration of modern signal processing techniques with machine learning approaches to identify and classify supraharmonic emissions is a promising future scope.

Table 6 Review Summary

Summary and Findings from the Review			
Introduction	• Modern Power System with Power Electronic converters • Power quality issues occurred in the power system • New term Supraharmonics		
Sources of Supraharmonics	• Intentional source	Power Line Communication	The narrowband frequency used for smart grids negatively impacts the power grid
	• Unintentional • Source	• Solar Energy conversion system • Wind energy conversion system • Lighting system • Electric vehicle chargers	Power Electronic Converters used in these applications with high switching frequencies cause supraharmonics
Measurement techniques of supraharmonics	Power quality standards	• IEC 61000–4–7, 19,30 • CISPR 16–1–1,2,3	Lack of appropriate standard for supraharmonics There is no standard method to measure the supraharmonics, and an essential need to develop an accurate measurement method
	Measurement techniques	• FFT • STFT • DFT • Quasi-peak detection • Light Quasi-peak detection technique	
Mitigation techniques of supraharmonics	Reduction of Supraharmonics	• Appropriate design of converters • Multi-level inverters • Innovative switching patterns • Random pulse position modulation • Fuzzy logic controller	There are no clear and efficient mitigation techniques and mitigation techniques in the area of research
Conclusion	Based on this study, further work can proceed to identify the supraharmonic source by different techniques and mitigation of supraharmonics and its effects		

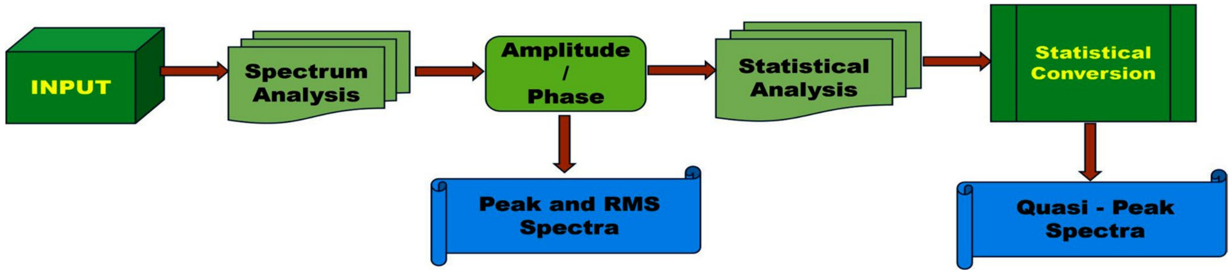

Fig. 15 Statistical – QP method

Fig. 16 Research gap in supraharmonic emission

Conclusion

Power quality issues in electrical distribution networks have become severe problems with the rise of many nonlinear loads and the integration of renewable energy. Supraharmonic emission is the source of many disruption issues in the modern electrical network. The most significant proposal for the future electricity system is the smart grid. Supraharmonic emission affects the functioning of the smart grid by creating problems in power line communication. This study provides an overview of the sources of supraharmonic emission in power systems from the power quality view and reviews the supraharmonic measurement methods and related standards. Based on the review reveals that the analysis of supraharmonic emission sources, the amount of emissions produced by these sources, and the effects on power system components are the research areas that researchers most frequently discuss.

Other significant topics addressed include forming new detection algorithms for supraharmonics, comparing various measurement techniques, and the effects of supraharmonics. The well-defined standards for measurement and mitigation are applicable for harmonics ranging in frequency below 2 kHz. However, according to this survey, the previous standards do not apply to supraharmonic emissions ranging between 2 and 150 kHz. Also, several issues have been identified in the measuring techniques. Developing suitable frequency analysis tools is one of the objectives of the expanding supraharmonics research. As a result, new frequency estimation techniques are being researched and recommended. Hence, serious consideration for the standard setting of the supraharmonic frequency range is required. The standards for measurements and mitigation techniques for supraharmonic emissions are in the area of research. Based on this study, further work can proceed to identify the supraharmonic source by different processes and mitigation of supraharmonics and its effects.

Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics Approval This article does not contain any studies with human participants performed by authors.

Conflict of Interest The authors declare no conflict of interest.

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