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Power Quality in Microgrids Including Supraharmonics: Issues, Standards, and Mitigations

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ABSTRACT A microgrid (MG) is a small-scale power system with a cluster of loads and distributed generators operating together through energy management software and devices that act as a single controllable entity with respect to the grid. MG has become a key research element in smart grid and distribution power systems. MG mainly contains different renewable energy sources (RESs) that use various technological advancements, such as power electronics-based technologies. However, it has an unstable output, thereby causing different types of power quality (PQ) events. As a result, standards and mitigation methods have been developed in recent years. To mitigate PQ issues due to MG integration, various methods and standards have been proposed over the last years. Although these individual methods are well documented, a comparative overview had not been introduced so far. Thus, this study aims to fill the gap by reviewing and comparing the prior-art PQ issues, solutions, and standards in MGs. We compare the main issues related to voltage sag, voltage swell, voltage and current harmonics, system unbalances, and fluctuations to ensure high-quality MG output power. The new technologies associated with MGs generate harmonics emission in the range of 2–150 kHz, thereby causing a new phenomenon, namely, supraharmonics (SH) emission, which is not sufficiently covered in the literature. Therefore, the characteristics, causes, consequences, and measurements of SH are highlighted and analyzed. The mitigation strategies, control, and devices of PQ issues are also discussed. Moreover, a comparison is conducted between the most popular devices used to mitigate the PQ issues in MG in terms of cost, rating, and different aspects of performance. This review study can strengthen the efforts toward the mitigation and standards development of PQ issues in MG applications, especially SH. Finally, some recommendations and suggestions to improve PQ of MG, including SH, are highlighted.

INDEX TERMS Microgrid, power quality, PQ disturbance, renewable energy sources, MG configuration, distributed generation, smart grid, supraharmonics.

LIST OF ACRONYMS

ANN	Artificial neural network
BFA	Bacteria foraging algorithm
CB	Circuit breaker
DES	Distributed energy source
DG	Distribution generator
DVR	Dynamic voltage restorers
EV	Electric vehicle
ESS	Energy storage system
FC	Fuel cell
GC	Grid code
GA	Genetic algorithms

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HVRT	High-voltage ride-through
LVRT	Low-voltage ride-through
MG	Microgrid
MPC	Model predictive control
PV	Photovoltaic
PCC	Point of common coupling
PQ	Power quality
RES	Renewable energy source
STATCOM	Static synchronous compensator
SVC	Static VAR compensator
SH	Supraharmonics
THD	Total harmonics distortion
UPQC	Unified PQ conditioner
VUF	Voltage unbalance factor
WT	Wind turbine

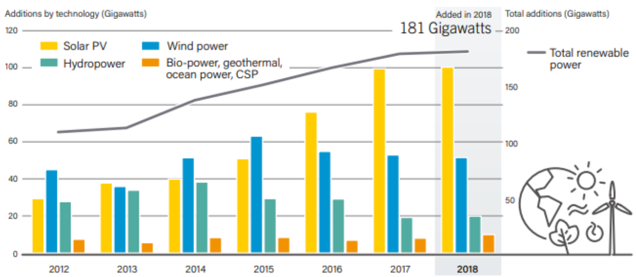


FIGURE 1. Annual power generated from RESs worldwide in recent years [1].

I. INTRODUCTION

The rapid growth of the global energy consumption is the key reason for high fossil fuel usage and rising greenhouse gas emissions. Relevant concerns have encouraged the renewable power generation sector to conduct extensive research to determine how to replace traditional fossil fuels and decrease environmental problems. For this reason, the installation and integration of renewable energy sources (RESs) into the current power system have grown dramatically in recent years, as illustrated in Fig. 1. For grid-connected RESs, hydropower no longer accounts for half of the cumulative renewable power capacity in operation, falling below 48% by the end of 2018. Wind power rose to compose roughly 25% of the installed renewable power generation capacity, while solar PV exceeded 20% for the first time. Overall, renewable energy has grown to account for more than 33% of the world's total installed power generating capacity [1]. However, due to their dependence on weather conditions, types of fuel (i.e., fuel cell), and the small amount of power they generate, RESs are combined with existing distribution generators (DGs) and energy storage systems (ESSs). Furthermore, many countries encourage connections of RES-based DGs to a distribution network known as distributed energy sources (DESs). Therefore, the concept of microgrid (MG) is developed, which is defined as a set of DESs and interconnected loads within clearly delineated electric boundaries that perform as a single grid [2].

As a result of the rapid expansion of the power grid and their complex structure due to the wide area of DESs, MG can be considered the most intelligent solution for optimal operation [3]. It has been developed to overcome the RESs' limitation and improve the operation of power systems by enhancing the voltage profile and reducing the distribution feeders' energy losses, enhancing system reliability, minimizing environmental pollution, and reducing electricity bills [4]. The technologies that are currently designed for DG systems are focused on RESs (photovoltaic [PV] and wind turbine [WT]) and low-emission DGs (microturbines and fuel cells). Thus, large-scale deployment of MG contributes significantly to the reduction of CO_2 emissions and helps mitigate climate change. However, one of the most related technical challenges with the control and operation of either standalone or grid-connected MG systems is power quality (PQ) issues. These challenges are a major concern in the MG system due to the structure, operating mode (standalone or grid-connected), and performances of DESs in MG [5]. Some of the PQ problems caused by the high penetration of DGs are current harmonics, voltage harmonics, voltage swell or sag, fluctuation, unbalance, malfunction of protective devices, overloading, and failure of electrical equipment [6]. MG sources highly depend on power electronics devices such as converters; thus, a high-frequency emission will lead to new phenomenon, namely, supraharmonics (SH) emissions. SH emissions can be characterized as the injection of harmonic by grid devices into an installation by grid devices with a 2–150 kHz frequency range. Emissions in such a frequency range have raised concerns because of the increasing existence of power electronic interfaces, which include devices such as DC/AC converters, electric vehicles, and heat pumps, in addition to the charge controllers of PV and wind systems [7].

With the increase in MG installation and to ensure high quality of its output power, some standards and requirements have been developed recently [8], [9]. These standards cover different issues related to the integration of technical problems and PQ issues, which are investigated and reviewed extensively in ýthe literature [10]–[13]. Standard and grid code (GC) requirement compliance verification has to be performed during the advancement of RES integration. In this regard, some studies have made an effort to give proof of compliance and verification with the technical regulation that is already listed in modern GCs and other standards. For instance, a mitigation technique for voltage sag in MG according to IEEE standards is proposed in [14] and according to German GC in [15]. Compliance with the frequency and voltage regulations based on the German GC was evaluated for an MG linked main grid in [16]. Moreover, on the basis of recent standards, the swell, unbalance, fluctuation, and harmonics issues are mitigated in MG systems by using external devices such as static synchronous compensator (STATCOM) [17], [18], dynamic voltage restorers (DVR) [19], static VAR compensator (SVC) [20], [21], and unified PQ conditioner (UPQC) [22].

The DVR is used to mitigate voltage sag and swell to improve the PQ in MG that contains PV and batteries, showing good performance [23]. Another study introduced the DVR to address voltage fluctuation and disturbances [24]. The outcomes of this study showed that the DVR improved the performance of critical or sensitive loads connected to a MG that is sensitive to voltage fluctuation. Moreover, DVR is used to reduce the harmonics produced by converters of MG units, as introduced in [25]. As a conventional power device, STATCOM is used to overcome the voltage sag and swell and thus enhance voltage stability in [26], reduce harmonics in [27], mitigate unbalance in [28], reduce power fluctuation in MG, and increase the voltage regulation and system power factor [29]. The SVC is developed to solve various critical PQ problems in MG systems [20], [21], [30]. For the same purpose, other custom power devices such as UPQC are used. The authors in [31] proposed a design of MG with a suitable UPQC to handle harmonic distortion according to IEEE 519-1992 standards.

The UPQC is also used in [22] to mitigate sag and swell in an MG that consists of a hybrid PV/wind system via injection or absorbing reactive current. These custom power devices can mitigate the PQ incidence in MG to some degree. However, they can increase the cost and complexity of the MG system. Optimization methods and new control strategies are developed to overcome the limitations of the above-mentioned devices. For instance, particle swarm optimization efficiently achieves optimal voltage unbalance compensation in a MG [32] and mitigates MG voltage fluctuation [33]. Other optimization strategies such as model predictive control (MPC) were utilized in MGs for bus voltage unbalance and harmonics compensation by [34], while [35] used fuzzy logic controller to mitigate the voltage sag in an MG that consists of PV and wind systems. Other controllers are also used, such as coordinated control of dual-interfacing converters in [36] to compensate for MG voltage unbalance and current harmonics.

Although the PQ issues are mitigated using various methods as discussed above, a comparative overview of PQ issues and mitigation strategies in MG has not been described so far. Furthermore, many studies reviewed the PQ for conventional power systems, such as [37], [38]. Others reviewed various MG applications, including MG stability [39], MG energy management [40], planning and operation of MG [41], MG protection [42], and control strategies of MG systems [43]. However, no comprehensive review has been conducted for PQ issues, standards, and mitigation strategies for MG. In addition, some review studies have been conducted on different GC and standards concerning technical integration issues such as voltage and frequency profiles; however, standards and regulations concerning PQ in MG are not sufficiently covered. Furthermore, on the basis of [4], the PQ problem in MG may increase its power cost by 10%. SH, as a new PQ phenomenon due to MG advancement, is not covered and no standard exists yet in this regard. Hence, this research introduces an updated review of international GCs, rules, standards, and regulations with respect to PQ issues. Furthermore, an in-depth analysis is conducted in terms of the issues and mitigation methods of PQ that are already applied to achieve high-quality of MG output power. Moreover, the SH is investigated in terms of characteristics, causes, consequences, and measurements as a new phenomenon that needs much attention because of the existence of power electronic interfaces in MG systems. Finally, the possible recommendations for future research related to PQ on MG, including SH, are presented. This work considerably adds to the existing literature with regard to research trends in the field.

II. OVERVIEW OF MICROGRID

In 1882, Thomas Edison installed the first electric power system in Manhattan; this system was an as-yet undiscovered MG [44]. The global energy demand has increased dramatically in recent years. Therefore, a trend of evolving MG in the electrical sector is taking place around the world [45]. MG, in general, is a small-scale electrical system with a load cluster and DESs that work together via software and devices for energy management. The MG is designed to provide the efficiency of a local community's power supply. It is always connected at low-voltage levels but sometimes at the medium voltage level associated with some DESs such as microturbines, fuel cells, and PVs together with storage tools (e.g., flywheels, batteries, and energy capacitors) and flexible loads [46]. Fig. 2 illustrates the structure components of MG, which consists of RES, ESS, DG, and loads.

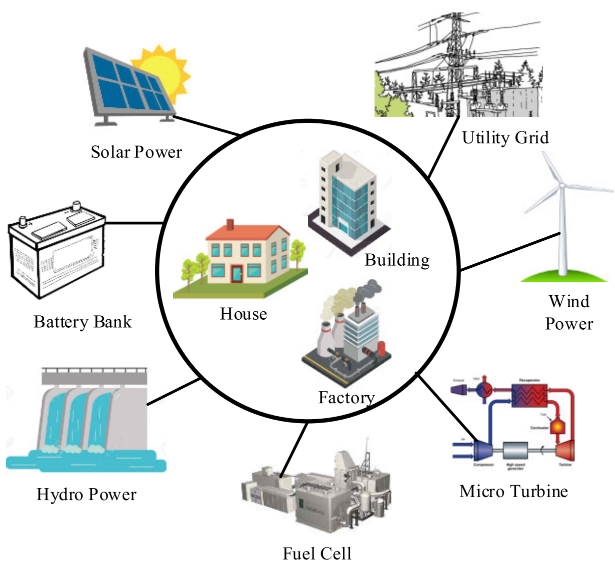


FIGURE 2. Structure of MG.

Recent years have seen a dramatic increase in world energy demand. Therefore, MG development in the power system, mainly in Asia and North America, has increased [45]. In this context, according to the latest report of MG growth tracker (the 16th edition of Navigant Research's global MG database) and in terms of MG capacity, Asia has recently emerged as the global leader with 40%, followed by North America with 34%. The total power capacity of MGs by region is shown in Fig. 3 [47].

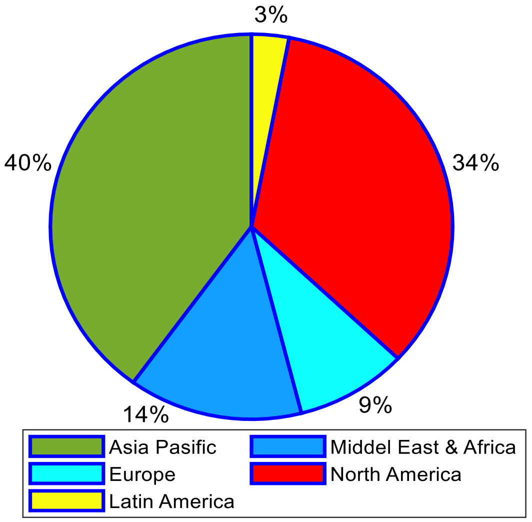


FIGURE 3. **Total power capacity of MG by region.**

MG adoption has several advantages from the technological and economic points of view, such as cost savings during the construction of new transmission lines, flexibility at the site of the plant, diversification of energy sources, minimization of power network losses, and enhancement of system reliability and stability. From a constructional and technical point of view, various forms of DGs combined in MG can be classified as conventional and non-conventional generators, as shown in Fig. 4.

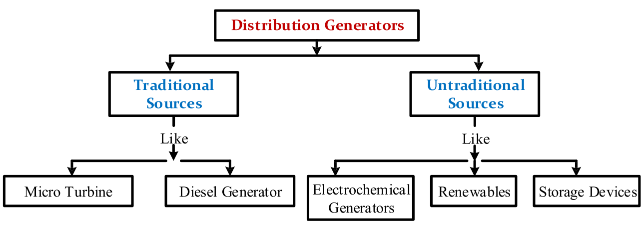


FIGURE 4. **DG types and technologies.**

A. LOW-VOLTAGE RIDE-THROUGH CAPABILITY REQUIREMENT TOWARD VOLTAGE SAG MITIGATION

Overall, electricity generation in MG comes mainly from hybrid distribution sources of energy incorporating various sources such as traditional sources, RESs, energy battery storage, and load aggradation in one system, as illustrated in Fig. 5. The power generated from some of these sources (i.e., PV and WT) cannot be utilized directly due to the characteristic of the energy formed. In such a case, an electronic power interface is required for energy conversion to regulate the local power and voltage [48]. Nonetheless, the intermittency of RES will impact the MG operation. Therefore, ESS is implemented in MG to store extra power produced from RES and supply stored energy to the grid once the power supply is unable to meet the load demand requirement [49]. The MG can work in either standalone or grid-connected mode. Table 1 shows a comparison between these different structures in terms of operation type.

B. AC MICROGRIDS

MG can be classified as AC, DC, and hybrid AC/DC. Fig.6 shows the typical AC MG. In this system, all DGs that include storage devices and loads are constantly linked to the AC busbar network either with a converter or not. Generally, AC generators such as microturbines, diesel, and WTs could be linked to the AC busbar directly without converters. Alternatively, for DC power supplies such as battery, ESS, and PV systems, a DC/AC inverter is essential. Therefore, the loads are connected in a straight line to the AC busbar. AC MG has many drawbacks, and such a network involves complex control and synchronization issues. However, this network is still widely used nowadays [50].

In AC MG, as the power interface among the main power grid and MG, the point of common coupling (PCC) is implemented as shown in Fig. 7. Commonly, the three-phase AC bus is utilized as PCC and in between the main power grid and MG, a fast switch is implemented as a cut-off point [51]. Under normal conditions, the DG will have the power for the load, and the excess power produced will be sent to the power grid. Once the output power generated by the DGs is lower than the demand for load, the main grid will regulate and send the power required to the AC MG. An important detail to mention is that the regulation of PQ in AC MG is regulated based on the conventional distribution system and the operation mode [52].

C. DC MICROGRIDS

The majority of MG generators produce DC power, which should be converted to AC power to fit the current AC network. DC conversion is required at the end of the system because some equipment requires SC power to operate. However, the DC-AC-DC energy conversion in AC MG reduces efficiency and causes energy losses. With the high DC voltage operation taken as a reference point, DC MG is designed to address the issue in AC MG. A DC MG structure is shown in Fig. 8. Compared with AC MG, DC MG can offer considerable energy savings by decreasing the number of converters in a single MG system process [53]. This category requires converters to interface the DESs, storage devices, and loads.

The authors in [54] claimed that DC MGs are more suitable for distribution systems in residential areas than AC distributed grids and that they cause few PQ issues. One of the best advantages of DC MG is that it overcomes some control problems in the MG, making DG synchronization no longer necessary and ensuring that the controls are largely dependent on DC bus voltage. Moreover, the primary control is considerably simpler due to the absence of reactive power flow management. Furthermore, many modern devices run on DC power and have no power electronics devices that

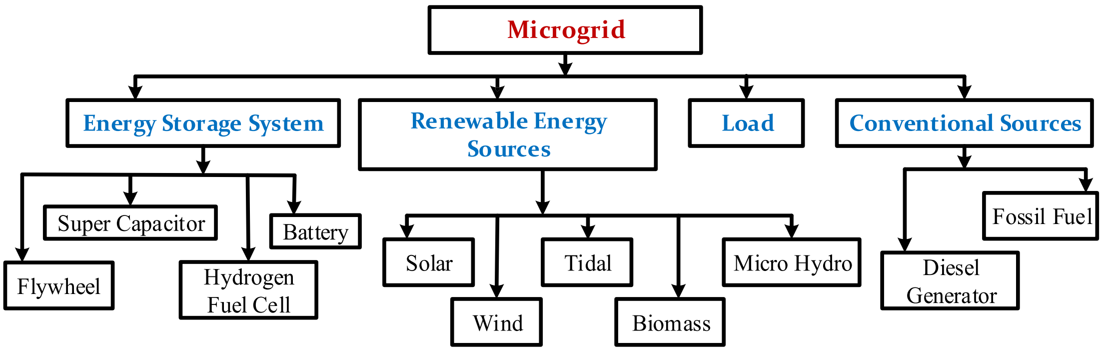


FIGURE 5. Type of hybrid distributed energy sources used in MG.

TABLE 1. Comparison between different structures of MG.

TYPE	DC MG	AC MG	Hybrid-MG
Integration	-It can be easily integrated with WTs, PV cells, and fuel cells (FCs)	-It can only be integrated with DC-DG units through conversion levels -Synchronization is required for AC integration	-It can be directly integrated -Appropriate for DC-based generation (e.g. PV, electric vehicle [EV], energy storage, and FCs) -No need for power converters
Voltage conversion	-DC/AC and DC/DC bidirectional power converter linked to busbar	-Voltage transfer stability is achieved through the use of AC/DC/AC converter -AC load is connected directly to the bus line -An AC-DC converter is needed for DC loads	-A transformer is employed for the AC side for the voltage conversion. However, DC-DC converter is used for the conversion of DC side voltage
Protection scheme	-Utility protection and fuses -Power circuit breaker (CB) -Molded case CB -Isolated case CB -Static switch	-Miniature CB -Sectionalizes CB -Overcurrent relays -Reclosers -Fuses	-The AC and DC connected via two transformers and two four-quadrant
Pros	-A direct link between DC loads and DC buses can be formed -Fewer power converters are needed	-Easily reconfigurable via existing grids -DG unit synchronization is necessary	-Directly connected to grids -DG unit synchronization is not needed -Minimizes power losses -Simplified controls
Cons	-Voltage is not standardized -Extra power storage is needed -Not reconfigurable from the current grid -Security is difficult	-With the host grid, synchronization is difficult -Low reliability and efficiency -Complex controller and architecture	-Complex management and controller, especially in islanded mode -Low reliability -Low efficiency

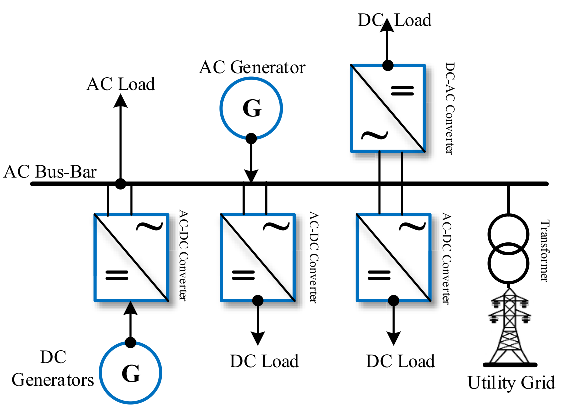


FIGURE 6. Typical structure of AC MG: single line diagram.

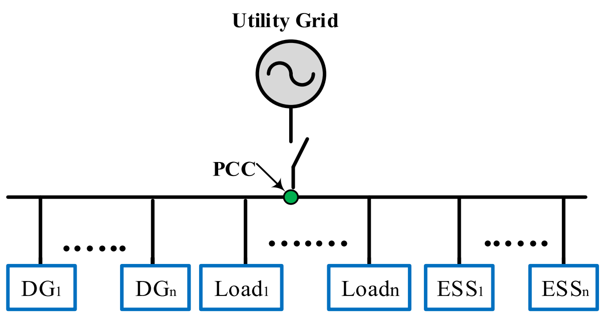


FIGURE 7. Simple configuration of the interface between AC MG and utility grid.

cause harmonics. Moreover, the conversion level in DC MG is low because it skips the AC stage in the middle of the process [53]. The operating DC MG is smoother than AB MG because phase monitoring and frequency are not taken into account [55].

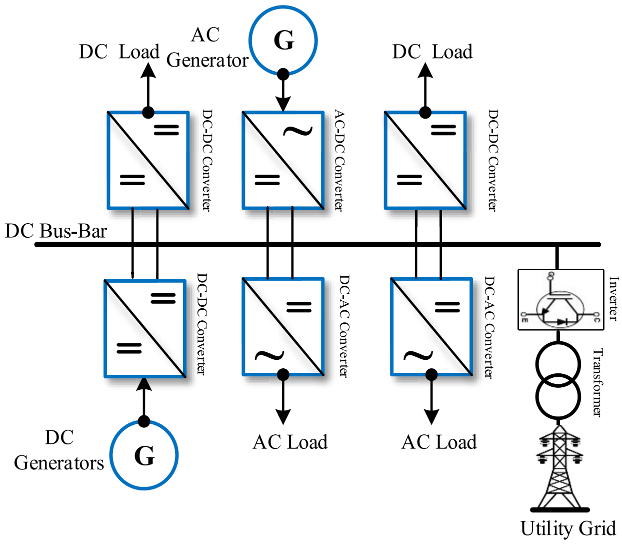


FIGURE 8. Typical structure of hybrid DC/AC MG: single line diagram.

D. HYBRID AC-DC MICROGRIDS

Hybrid MGs consist of AC and DC networks linked together by large-scale multi-bidirectional converters. This system could decrease conversion stages (DC-AC-DC and AC-DC-AC) in individual DC or AC MG and thus reduce the occurrence of PQ events. In this type, AC sources and loads are linked to the AC MG busbar, while the DC sources and loads are linked to the DC busbar. The storage system can be linked to either of the MGs. Fig. 9 illustrates the single line diagram of a hybrid AC/DC MG [54], [56].

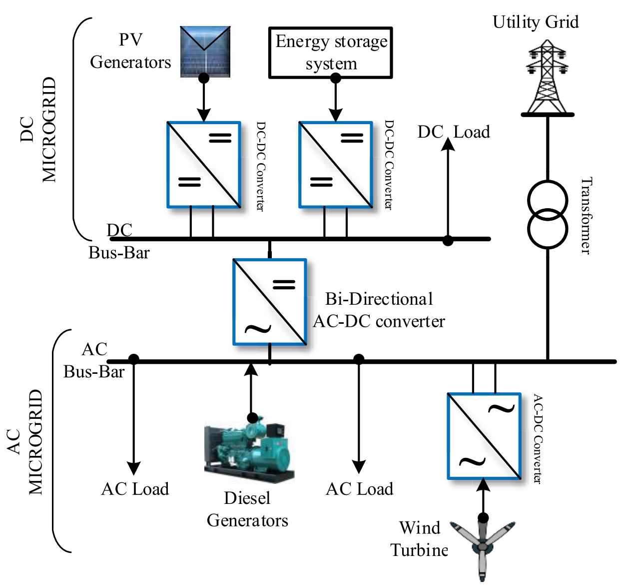


FIGURE 9. Typical structure of hybrid DC/AC MG: single line diagram.

In the grid-connected operation mode, the MG will supply or employ the power from the main grid to meet energy generation and load demand requirements. When maintenance or disturbances occur, the MG must isolate itself from the main grid and work in autonomous mode. In the operation mode, the MG performs efficiently to assure that the critical load supply is not compromised. The transient that occurs during the switching phase must be well controlled to prevent device destruction in the MG. Thus, PQ issues need more investigation in this case [57].

III. OVERVIEW OF MG POWER QUALITY AND STANDARDS

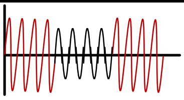
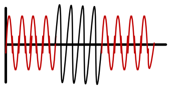
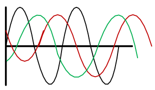
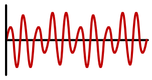
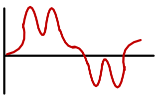
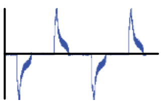
The MG has its own individual conduct and PQ problems that are unlike those of conventional systems. The challenges of MG PQ are due to its unique structure, operating mode (connected grid or standalone), type, and configuration of MG distribution resources [58]. The issues of MG PQ can generally be divided into four major types [5]. The first type is the operating conditions of the MG DESs (fluctuation of output power generated from RESs such as PV and WT). The second type is the current and voltage harmonics caused by the power electronics devices of the DESs. Moreover, the voltage and current harmonics can be generated by nonlinear loads in the MG system are third type. The fourth type is MG voltage unbalance. The unbalance problem is normally generated by unbalanced three-phase loads and the presence of single-phase loads in the MG. Furthermore, as the integration of MG increases dramatically year after year, some GCs have started to apply strict requirements for PQ issues such as voltage sag and voltage swell concerning the integration of MGs into the main power grid. The universal RESs, MGs, and smart grids standard-setting group are increasingly becoming aware of SH, which is the distortion of harmonics in the frequency range between 2 to 150 kHz [7]. Therefore, this paper will focus on SH issues in MG systems as a new phenomenon that needs more investigation.

A. MG PQ ISSUES

The term PQ is typically used for a wide range of electromagnetic events in an electrical power system. With the high integration of the MG system into the power network, many studies and regulations concerning PQ issues have been published in recent years [8]. By means of DG and integration of DES in the form of MG, the PQ can be improved. PQ issues have recently become important given the need for reliable power to meet the needs of customers and the presence and extensive usage of different kinds of electronic and electrical gadgets in the commercial and industrial sectors. Table 2 lists and summarizes the PQ problems concerning MG operation, including its indicators, brief description, and potential causes and effects.

PQ is a major concern in small-scale islanded systems because of the presence of nonlinear and unbalanced loads, which forms a larger proportion of the total load. This situation creates voltage problems such as distortion, fluctuation, and voltage sags/swells in a relatively weak system [59]. In the islanded mode, disturbances such as distortion and voltage unbalance are most likely to occur because of the very high impedance and the more uneven load distribution compared with the grid-connected mode. In the grid-connected mode, disturbances such as unbalanced utility voltages and

TABLE 2. Most important PQ issues related to MG.

PQ Problem	Brief Description	Indicators	Causes	Effects
 Sag	The voltage levels decrease at the nominal frequency by 10% to 90% of the nominal RMS voltage over a period ranging from 0.5 cycle to 1 min	-Magnitude -Duration	-Abrupt load rises -Faults -Motors starting -Energization of a heavy load	-Can damage the MGs' power electronics devices -High power losses -Damage sensitive load equipment -Speed loss for motors -Extinguishing of lighting lamps
 Swell	The voltage levels increase at the nominal power frequency over the period not exceeding 1 cycle and less than 1 min	-Magnitude -Duration	-Abrupt load reduction -De-energization of a heavy load	-Breakdown of components on the power supplies of the equipment -Control problems and hardware failure -Overheating
 Unbalance	A variation of voltage in the three-phase system where the difference between phase angle and magnitude is not equal	-Phase shift -Magnitude	-Variations in the load -Large single-phase loads -Unequal load distribution	-Reduce equipment's life -Increase cable losses -Inject more harmonic currents -Phase faults -Poor inverter efficiency
 Fluctuation	Voltage changes up or down from its rated supply voltage	-Magnitude	-Using equipment or devices that require a higher load -Repeated ON/OFF of electrical motors -oscillating loads	-Changes in torque and slip in motors -Harmful to household appliances and electrical and electronic appliances of MGs - Lights flicker or glow more brightly
 Harmonics	The distortion of current or voltage sinusoidal waveform than its pure sinusoidal shape because of the harmonics	-Peak magnitude -Frequency	-Nonlinear loads -Electronic inverter -Computer drives -Variable speed motors	-Reduced performance of energy generation in MG's units -Distort the MG's output AC sine wave -Inefficiencies in equipment operations and overheating -Higher line losses ($I^2 \times R$)
 Supraharmonics	The distortion of voltage and current waveforms with a frequency range from 2 to 150 kHz	-Frequency	-Switching of power electronics devices, especially inverters -Modern sources	-Inverter instability for MG units -Lost connection with smart meters -Increase power losses -Failures in protection devices -Damaged power supply

voltage sag are the most frequent problems [60]. The voltage generated from the sources such as wind, solar and fuel cells are highly intermittent and thus these sources cannot be connected directly to the grid. Table 3 shows the PQ problems introduced in different DG units [61].

TABLE 3. PQ issues related to generation units of MG.

PQ problem	Solar	Wind	Small-hydro	Diesel
Voltage (sag/swell)	×	✓	✓	✓
(over/under) voltage	×	✓	×	✓
Voltage unbalance	✓	×	×	×
Voltage transient	×	✓	×	×
Voltage harmonics	✓	✓	✓	×
Flicker	✓	✓	×	✓
Current harmonics	✓	✓	✓	×
Interruption	✓	✓	×	×

The PQ incident is analyzed based on the development of standards for measuring PQ. This idea means that one of the major factors that influence the analysis of PQ is the development of its standards. Two international standards exist, namely, IEC and IEEE, and different countries with high RES installation, such as Germany and the US, have improved their GCs with new standards [22], [62]–[67]. PQ standards have been employed by many researchers, and these PQ standards define the acceptable levels of distortions and deviations in various electrical quantities such as current, voltage, and power factor. Table 4 lists some of the standards to specify the PQ parameters.

TABLE 4. List of some standards for PQ parameters.

Standard	Description
IEEE Stand. 519-92	Suggested harmonic requirements and specifications in the power system
IEEE Stand. 1159-95	Suggested power quality requirements and specifications in the power system
IEEE Stand. 1100-99	Suggested specifications and requirements for grounding and powering sensitive electronic devices
IEEE Stand. 1250-95	Guide for the operation to the sensitive equipment from momentary voltage distribution
IEEE Stand. 1366-2012	Reliability indexes for the distribution of electric power
IEC 61000-2-2	Compatibility rates of low frequency conducted disturbances as well as signalling in power supply systems
IEC 61000-2-4	Compatibility rates for low frequency induced disruptions in industrial plants
IEC 61000-3-2	Harmonic current emission limits
IEC 61000-4-15	Flicker and fluctuation meters – Functional requirements and configuration specifications
IEC 50160	Characteristics and specifications of the distribution systems voltage

IEEE Standard 1159-2009, which is a revision of IEEE Standard 1159-1995, presents the recommended PQ requirements and specifications for power systems. All the terms and PQ indices are clearly defined and specified. This standard includes some PQ limits and requirements, such as voltage sag and swell over-voltages [69].

B. SAG/SWELL ISSUES IN MG

The sag (dip) event is among the most serious PQ challenges that are caused mainly by faults and lead to instability of the power sector. Voltage sag frequently disrupts the operation of sensitive electronic devices, which is typical in DES systems that consist of MG [22]. Swell, the behavior of which is opposite that of sag, is another serious PQ issue; however, it rarely occurs [70]. As the integration of DES and MG increases, many standards and GCs are imposing new regulations, such as low-voltage ride-through (LVRT) and high-voltage ride-through (HVRT) in case of sag and swell, respectively. Such regulations require the MG sources to disconnect from the grid in case the sag or swell lasts for a specified time [71]. In the case of sag event, the German standard applies LVRT, in which the MGs have to stay connected and support the system by providing reactive power even though the voltage decreases to 0% from its nominal value for 0.15 s; otherwise, disconnection is compulsory. In the case of a swell event, the German standard applies HVRT, in which the MG has to stay connected even though the voltage increases to 120% from its nominal value for 0.1 s; otherwise, disconnection is compulsory [72], [73]. The voltage level and time duration for sag and swell differ from one GC to another. Table 5 shows the limits of voltage and time duration allowed according to different countries' GC and regulations in case of sag and swell events [8].

TABLE 5. Voltage sag/swell requirements.

Country	*Voltage Swell*		*Voltage Sag*	
Requirement	*Voltage Rise*	*Time*	*Voltage Drop*	*Time*
Denmark	120%	0.1 s	20%	0.5 s
Germany	120%	0.1 s	0%	0.15 s
China	-	-	20%	0.625 s
Spain	130%	0.25 s	0%	1.5 s
Italy	125%	0.1 s	0%	0.2 s
UK	-	-	15%	0.14 s
USA	140%	1 s	15%	0.6 s
Japan	-	-	15%	1.0 s
Australia	130%	0.06 s	0%	0.45 s
South Africa	120%	0.15 s	0%	0.15 s

C. HARMONICS

The nonlinear loads, electronic inverters, computer drives, and variable speed motors that generate harmonics are applicable for MGs. Most electrical systems handle harmonics until a specific amount; however, once it becomes large, it will result in communication failures, excessive line losses, overheating, and trip of the circuit breaker [74]. Many studies are conducted on low-voltage systems to analyze PQ on the basis of the harmonics problem. MGs are a low-voltage network; thus, PQ is a significant problem for this type of system, and it needs to be investigated and addressed [75]. MG sources mainly consist of RESs with a power electronics device that produces harmonics to the system. Thus, MG systems have to reduce harmonics emission according to certain standards and new GC requirements [76].

As MG integration specifications into the grid advance, various harmonic distortion criteria are implemented to ensure that the voltage and current waveform are compatible with the grid as much as possible. Therefore, some requirements have been imposed on the individual and total harmonics distortion (THD) limits for DES and MG connected to the main power grid [79], [80], [84]. For current THD (I_{THD}), all requirements, standards, and GCs are similar, in which the I_{THD} should be less than 5%. UK standards (EREC G83) are more strict, requiring $I_{THD} < 3\%$ [81]. Concerning voltage THD (V_{THD}), the literature indicates most countries follow either IEEE or IEC standards [85], in which the V_{THD} must not exceed 5% at a low and medium voltage where the MG can take place. Table 6 presents the limits of current and voltage in terms of harmonics that should be achieved at PCC.

TABLE 6. Current and voltage harmonics distortion limits of the MG system.

	Standards	*Harmonics order*	*limit*	*THD*	*Ref.*
Current harmonics	IEEE 1547, AS 4777.	3 ≤ h < 33 (odd)	<(4%–0.3%)	<5%	[77] [78]
		2≤ h ≤ 32 (even)	<(1%–0.5%)		
	IEC 61000-3-2	3 ≤ h ≤ 39 (odd)	<(0.3%–0.6%)	<5%	[79, 80]
		8 ≤ h ≤ 40 (even)	<0.2%–1.6%)		
	UK (EREC G83 Stds.)	3≤ h ≤ 35 (odd)	<(2.3%–0.15%)	<3%	[81]
		8 ≤ h ≤ 40 (even)	<(0.23%–0.3%)		
	GB/T, ECM	1 ≤ h < 33 (odd)	<(4%–0.3%)	<5%	[82, 83]
		2≤ h ≤ 30 (even)	<(1%–0.5%)		
	Standards	**Voltage level**	*Harmonics limit*	*THD*	*Ref.*
Voltage harmonics	IEC Standards	(V >161) kV	1%	1.5%	[80]
		(69 ≤ V ≤ 161) kV	1.5%	2.5%	
		(2.3 ≤ V ≤ 69) kV	3%	5%	
	IEEE 519	(V >161) kV	1%	1.5%	[76, 77]
		(69 ≤ V ≤ 161) kV	1.5%	2.5%	
		(1 ≤ V ≤ 69) kV	3%	5%	
		(V ≤ 1) kV	5%	8%	

D. VOLTAGE UNBALANCE AND FLUCTUATION

Voltage unbalance is the most frequently occurring PQ phenomenon. Voltage unbalance factor (VUF), which is a ratio of positive to the negative sequence of voltage components, is used to measure the degree of unbalance [86]. Voltage unbalance can have adverse effects on MG power electronics and power system devices. Power systems will suffer more losses and will be less stable under unbalanced conditions; thus, having a balanced system, especially with the diversity of MG sources, is paramount [87]. Therefore, certain GCs and standards criteria have been established to ensure stable and balanced integration of MGs and other DESs to limit the VUF. For example, IEEE Std[84] does not allow VUF to exceed 3%. The IEC standard requires all DGs to maintain the VUF below 2% [80]. Chinese and German requirements state that the VUF should not exceed 2% [82], [88], [89]. The Canadian Standards Association (CAN/CSA-C61000-2-2) set 2% as the highest permitted limit of VUF; in case of unbalanced loading, 3% is allowed [90]. Generally, the global standards indicate that the acceptable VUF limit should be within 1% and 2% [88], [91].

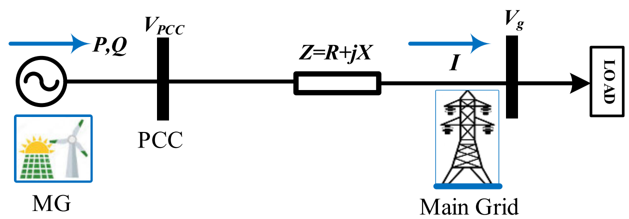


FIGURE 10. Equivalent circuit of grid-connected MG.

The fluctuations in MG are known as slow voltage variations at switches or steady operations. Typically, the fluctuation of voltage in MG occurs due to changes in solar irradiation, wind speed, battery charge/discharge, and load variations [16]. An essential detail to mention is that voltage fluctuations can be caused by sources whose output power changes widely with time. Fig. 10 shows the equivalent circuit of grid-connected MGs sources. The voltage between DESs that build MG and the main grid is the Z impedance voltage and the current is $I = P\text{-}jQ/V_{pcc}$. Then, the voltage change is $\Delta V = V_g\text{-}V_{pcc} = IZ= (P\text{-}jQ/V_{pcc}).Z.$ Thus, on the basis of these formulae, active power or reactive power variations delivered into the grid create voltage fluctuations of the main utility grid [92]. As imposed by IEC standards, voltage fluctuations can vary by ±10% of its nominal value [80], [93]. According to the European Standards (EN 50160), ±10% nominal voltage is permitted in 10-minute intervals, but ±15% is sometimes allowed [94]. In general, most GCs follow IEC standards. Thus, fluctuation limits need to be investigated, because, similar to MG, wind and solar energy are an example of DESs that generate power that varies randomly based on weather conditions, thereby leading to increased fluctuation.

IV. SUPRAHARMONICS

SH was previously within the classical PQ frequency range (i.e. 0–2 kHz). However, the ongoing increase in power electronics-based devices such as MG sources makes high-frequency noise beyond 2 kHz, specifically SH, which is within the range of 2–150 kHz, a subject of concern. In general, SH is present at the further end of the frequency spectrum. In this regard, the term SH refers to any kind of voltage and current waveform distortion in the frequency range of 2 to 150 kHz [95]. Semiconductor switching devices produce large harmonics of voltages, as they suddenly chop waveforms of voltage during their transmission from conductive to cut-off states. Inverter circuits generate harmonics and are widely used. They can cause electronic device failure, especially with touch technology, noise due to mechanical resonance excitation, or additional thermal stress, which may reduce the equipment's lifetime. In general, electronic converter units and power line communication systems are two major sources of SH in the grid [96].

The use of cancellation effects between various equipment systems was a major factor behind the harmonics emission standards in IEC 61000-3-2 some 16 years ago [97]. Many standards and GCs have issued requirements concerning harmonics, especially for MGs and RESs, as discussed in Section 3.3. However, recent times have seen an increase in the number of equipment that implements technologies based on high frequencies, which cause SH; such equipment includes PV and wind converters, EV chargers, and computer power supplies. So far, no standards or limits exist with regard to SH in the power system in general. Therefore, more investigation is needed to organize the SH emission in the power sector toward high-quality production of power.

A. CONSEQUENCES OF SUPRAHARMONICS

This family of disturbances is becoming an increasing concern in the industry, especially with the growth of distributed and embedded generation using inverters. The large number of distributed RESs with fluctuating power infeed can have an increasingly negative influence on the electricity supply system. High-frequency emissions in future grids and the impact on connected consumers are expected to increase [98]. SH are receiving attention because of their possible impact on other devices connected to a network [99]. In this regard, SH can increase capacitive currents that can damage the power supply, increase the neutral current, and thus increase the safety risk. Furthermore, it can cause (*a*) faults in touch-controlled operator components and lamp dimmers; (*b*) reduction in the service life of LED lamps; (*c*) communication problems (for example, PLC communications); (*d*) overheating of transformers and capacitor banks; (*f*) failures in protection devices; (*g*) lost connections with intelligent meters; and (*h*) interruptions in domestic appliances, medical equipment, semiconductor manufacturing equipment, and even transportation control systems. Moreover, SH distortions caused by nonlinear loads increase power losses and thus have an adverse impact on the distribution systems and components of electric utilities. Finally, SH are known to cause instability in weak networks with inverters of MG systems, with the consequent spurious tripping of inverters [100]–[102]. Therefore, the effects of SH are hazardous if not taken seriously.

B. CHARACTERISTICS OF SH

The effort to increase the power factor and decrease the harmonic content in the lower-frequency range of the output current of inverters used in grid-connected devices has led to increased SH emission [103]. In this case, SH originates from the inverter switching circuits and is then pumped into the grid for as long as the inverter operates. When the inverter is not operating or producing output, the device can become

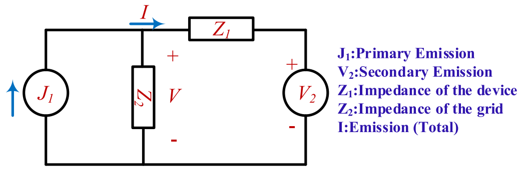


FIGURE 11. Primary and secondary emissions.

a sink for SH [104]. For the harmonic current at the interface of a device or a complete installation, the basic principles are the same and the MG or main grid depends on sources inside and outside of the device [96]. Sources of MG using inverters as output can be both a source and a sink of SH. Two driving forces exist for the currents at the interface between the grid and the inverter. The resulting currents are referred to as primary emission and secondary emission [7]. Primary emission is the part of the harmonic or SH current driven by power electronic or other sources in the device or installation (driven by I_1 in Fig. 11). Secondary emission is the part driven by sources outside of the device or installation (driven by V_2 in Fig. 11). The current measured at the device-grid interface, I, is the total of the secondary and primary emissions. V_2 plays a much larger role for SH than for lower-frequency harmonics [105].

C. MEASUREMENTS AND MITIGATION OF SH

Smart power grids have made SH emissions relevant [106]. These grids support the use of emerging technology, such as demand-side management, EVs, DGs, and RESs. The effect of MG resources on PQ, which is linked to higher-frequency injection, is due to the existence of power electronics interfaces. The number of generating units in the system affects emissions within the frequency range from 2 kHz to 150 kHz, thus causing SH emission. Therefore, analysis of higher-frequency emissions is important because such emissions may have an impact on the PQ of the MG system and the electrical grid. Recently, some researchers studied the possible measurement and mitigation methods and devices for SH. The authors in [102] suggest that the signal sampling rate must be chosen as per the rules of signal analysis so that components up to 9 kHz can be measured. However, in transforming the data utilizing the FFT, the number of samples should be processed by a power of two; thus, the total sampling will be 20.48 kHz. The proposed method is shown in Fig. 12. With the frequency resolution of 5 Hz taken into account, the calculation of a single FFT of 4,096 samples is recommended. Finally, FFT components with a 5 Hz resolution are divided into 200 Hz bands.

Another type of SH measurement emissions in a smart grid or MG is shown in Fig. 13, as proposed in [107]. This system constitutes four-channel acquisition configurations. The first two channels are used for the measurement of voltage, and the other two channels are used for the measurement of current. These channels calculate the components of fundamental and SH harmonies individually such that the dynamic range of the recording device is maximized. Channel 1 comprises a step-down transformer. A second-order high-pass RC filter is used to filter the fundamental, and lower-order harmonics in the signal is placed in channel 2. This channel also contains a varistor, a Zener diode series connection, and a voltage divider to regulate the voltage. An isolation transformer is used to ensure user safety. The electrical circuit of this type of test is illustrated in Fig. 14 [107].

The same current is measured by using two Rogowski coil sensors. The first Rogowski coil has a bandwidth ranging from 23 Hz to 1 MHz, and the other one has high sensitivity and a bandwidth ranging from 150 Hz to 6 MHz. In channel 3, the current signal is obtained via the first Rogowski coil. The fundamental component of the current is derived from this acquisition. The second coil filters the basic component of the measured current. Therefore, on the second Rogowski coil output, a first-order RC high-pass filter is used to filter out the harmonics of lower order. On channel 4, the filtered signal can be displayed and received. Better sensitivity helps in measuring low-amplitude emissions at higher frequencies.

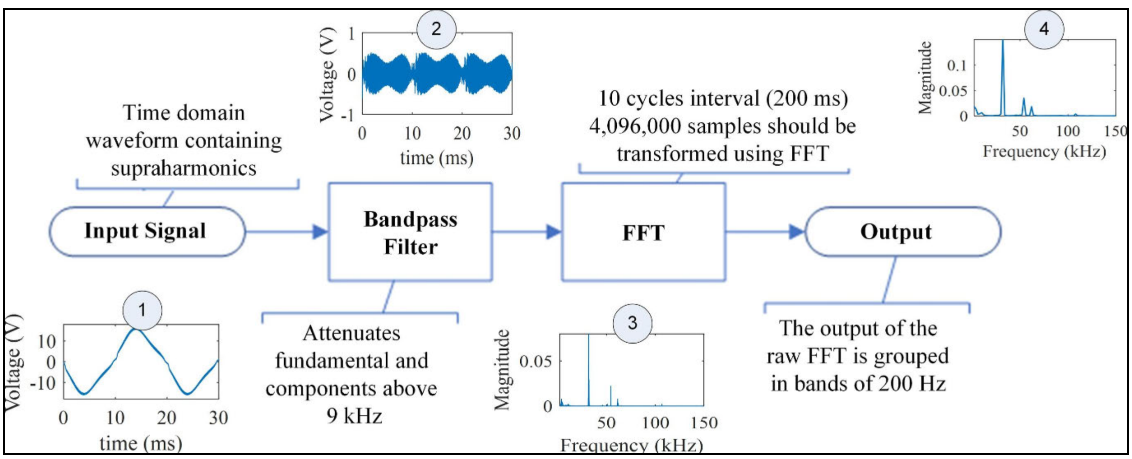


FIGURE 12. SH emission measurement method [102].

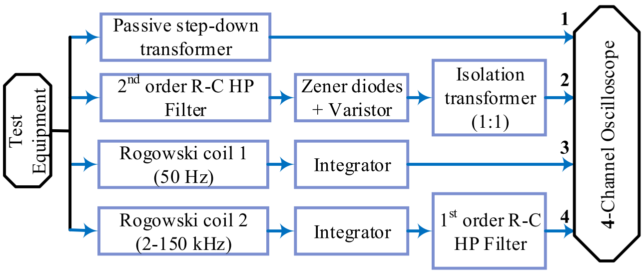


FIGURE 13. System design block diagram for measuring SH emissions.

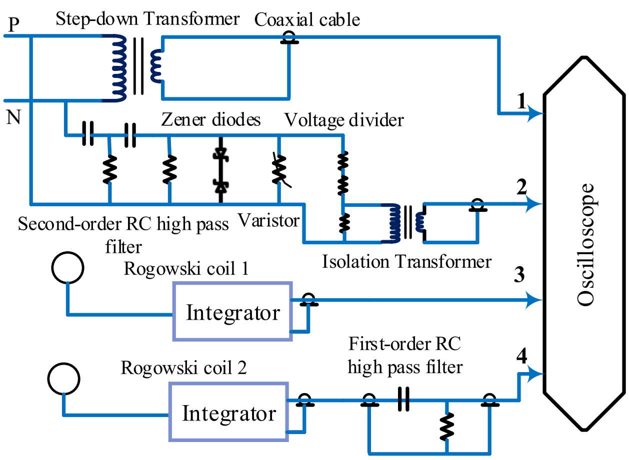


FIGURE 14. Electrical circuit of SH emission measurement [107].

High-pass filtration is important to achieve a better dynamic range between the largest and smallest quantities during measurement due to the very small amplitude of the SH components [60], [107], [108].

The up-to-date technology in measuring SH emission is a single device that performs all the required stages of detection, filtering, and recording. This device, which is shown in Fig. 15, should be mounted between the switching converter and the grid [109], [110]. The authors in [111] proposed a method to access the SH with sampling reduction on the basis of compressive sensing and analog filter bank. This strategy has shown good results in terms of SH analysis, enabling sampling rate reduction and good frequency estimation. A key detail to mention is that the SH mitigation techniques are not covered yet possibly because of the lack of relevant accurate measurements and standards. Therefore, careful attention and rapid solutions are required for the high integration of MG that has different sources that cause SH emission.

V. POWER QUALITY MITIGATION DEVICES, METHODS, AND CONTROL STRATEGIES IN MG

PQ problem mitigation in MG has attracted a great deal of interest in the last decade due to the increasing involvement of renewable energy sources in the low-voltage grid. Various devices and control methods could assist in mitigating the risk of PQ in the power system in general. Such methods have been developed for MG integration into the power utility grid.

A. DYNAMIC VOLTAGE RESTORERS (DVR)

A DVR is used in MG system PQ mitigation, as shown in Fig. 16. The DVR is used to handle voltage sag and swell, thus improving the PQ of MGs that contain PV and batteries [23]. However, some limitations in terms of LVRT still exist. Therefore, [112] used an optimization technique to enhance the performance of the DVR in solving the sag problem in the MG system. The fuzzy logic-based DVR is used to overcome the sag and swell in an MG connected grid. MPC was applied by [113] to enhance the performance of the DVR and tolerate the sage and swell in an MG that consists of a PV, supercapacitor, and battery. The results show that the proposed DVR-based MPC system can compensate for sag/swell and thus keep the MG stable. For accurate sag detection and compensation for islanded MG, the DVR is applied in [114]. The results show the ability of DVR to mitigate the sag event during different types of grid fault. The voltage fluctuation in MG, including RESs, is mitigated using DVR. The results show the DVR's efficiency in overcoming the fluctuation of an MG that contains PV and wind systems, which depend on unstable sources. Wind/PV/fuel cell and main grid voltage unbalance and harmonics at the AC bus are tolerated by using DVR efficiently, as proposed in [115]. PQ mitigation using DVR based on the standard requirements is proposed by [21]. The effectiveness of this method reduced VUF to less than 1%, while current and voltage THD reduced to less than 5%, as stated in recent integration requirements. Overall, DVR is one of the best devices for mitigating PQ issues in the conventional power system and MGs.

B. STATCOM AND SVC

STATCOM and SVC are other devices used to solve PQ issues. These two devices, which are shown in Fig. 17, are flexible AC transmission system devices and have been used extensively in recent years to solve many PQ issues that are mainly due to RES integration, such as LVRT, to overcome the sag events in PV systems [116] and wind systems [117]. The authors in [117] compared the effectiveness of SVC and STATCOM in addressing the sag event and found that the STATCOM contributes more to the transient margin compared with the SVC. In [118], STATCOM was used to mitigate voltage fluctuations in high penetration of DREs as MG. In addition, STATCOM was used for voltage fluctuation mitigation and reactive power compensation in MG in [119]. Another study showed the ability of STATCOM to reduce power fluctuation in MG and increase the voltage regulation and system power factor [29]. For harmonics mitigation and THD in MG that uses numerous sources such as WTs, diesel generators, fuel cells, microturbines, and PV arrays, STATCOM reduced the harmonics based on IEEE 1547 standards [120]. From the above studies, we can conclude that STATCOM has a high ability to mitigate voltage fluctuation and enhance the voltage profile in the MGs system while mitigating sag/swell events to a lesser extent. SVC was used

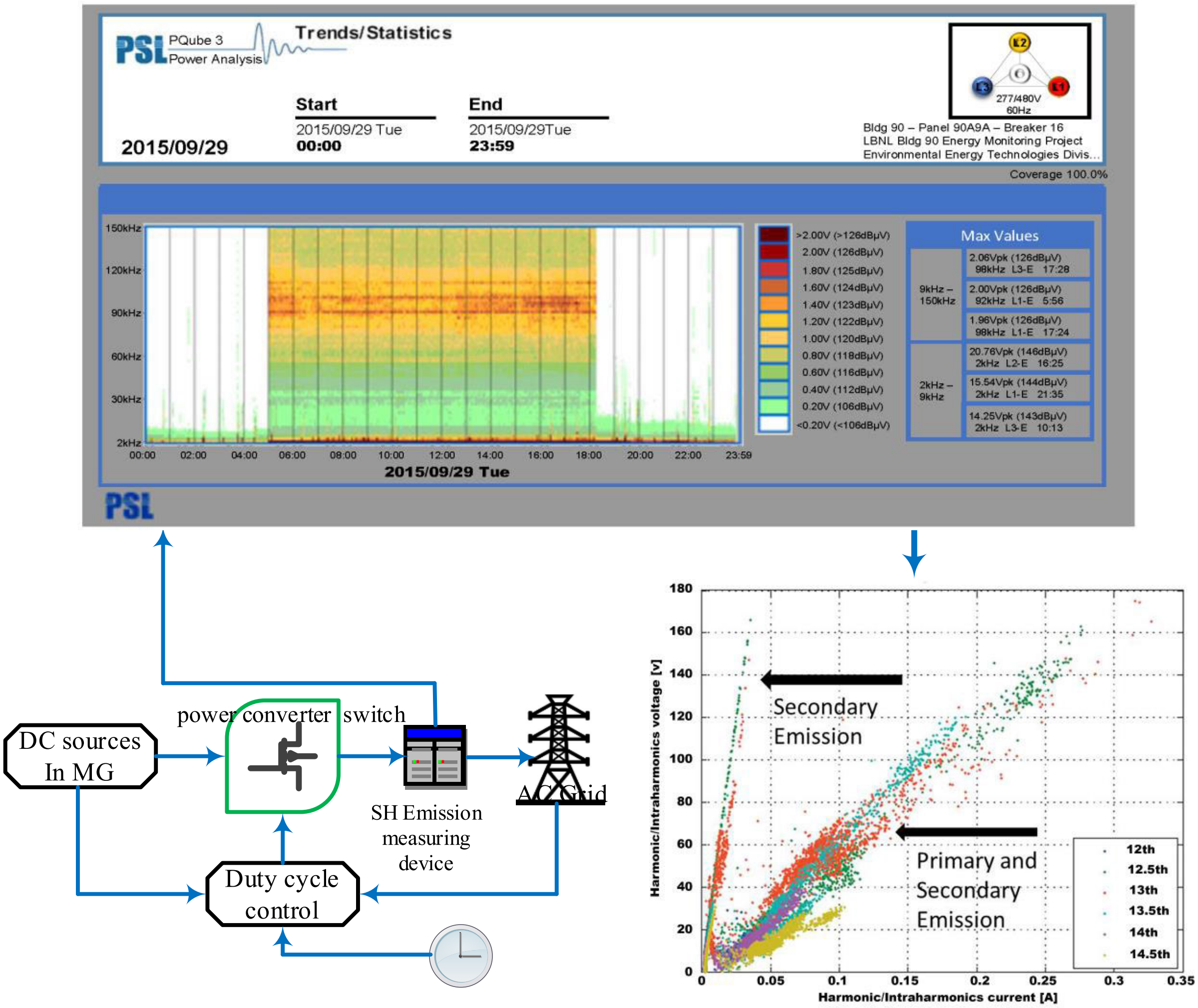


FIGURE 15. Single device measuring SH on-sit.

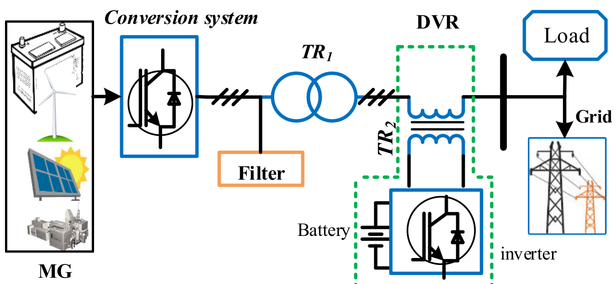


FIGURE 16. DVR-integrated MG system to mitigate PQ issues.

in MG to improve the quality of the delivered power and to increase system efficiency during voltage sag in [30]. It was used for the same purpose in islanded MG by the authors in [121] and showed good performance. However, during severe sag events, the SVC performs more poorly than DVR and STATCOM.

C. UNIFIED PQ CONDITIONER

UPQC is the complete configuration of hybrid filters and identified as a multifunctional power conditioner utilized to compensate for different voltage disturbances, correct voltage fluctuations, and prevent the entry of harmonic load current into the power system. It was designed to mitigate the disturbances that affect the performance of sensitive and/or critical loads and thus enhance the quality of the power system [92]. The UPQC is a combination of shunt and series controllers connected by a common DC bus, as Fig. 18 indicates. The shunt controller can generate or absorb reactive power at the connection point. However, the series controller is linked in series with the MG line to control the line parameters [122]. In [123], the fuzzy logic controller was implemented on UPQC to minimize the voltage and current harmonics. The results demonstrate that the overall harmonic distortion was reduced from 8.93% to 3.34%.

Reference [31] proposes a design of MG with a suitable UPQC to improve harmonic distortion. Results show that the measured voltage sag occurs from 0.2 to 0.3 s with a high THD (2.69%). Harmonic spectrum analysis of load current without UPQC shows a THD of 33.26%. The use of UPQC obtains a current THD of 3.11%, which meets the IEEE 519-1992 standards of less than 5% [31]. The UPQC is used in [22] to mitigate the sag and swell in an MG that consists of

TABLE 7. Comparison of various custom power devices.

Factors	DSTATCOM	SVC	DVR	UPQC
Rating	Low rating	Low	High rating	Higher ratings are available
Speed of operation	Less than DVR	Less than DVR	Fast	Faster
Compensation method	Shunt compensation	Shunt	Series compensation	Both series and shunt
Active/reactive power	Reactive	Reactive	Active/reactive	Both
Harmonics	Less	Less	Much less	Least
Problems addressed	Sag/swell	Sag/swell	Sag/harmonics/fluctuation/swell	Swell/sag/harmonics/transients/unbalance and flicker
Cost	Normal	Average	High	Higher
Complexity	High	High	High	Higher

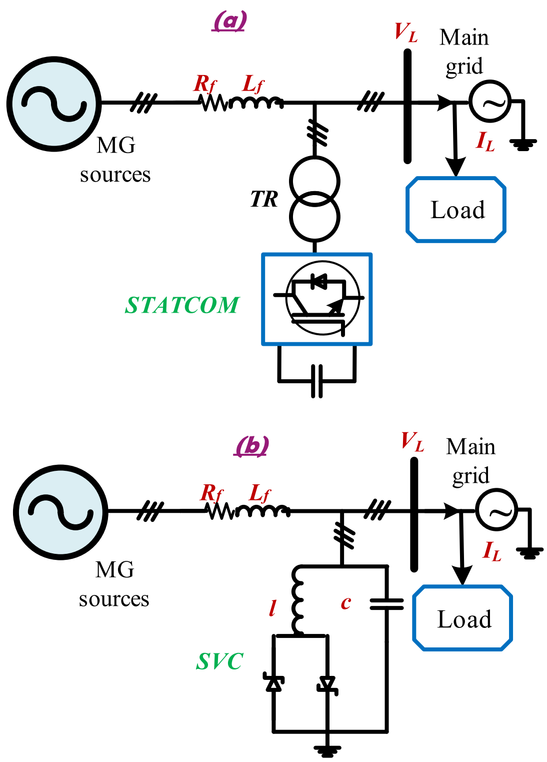


FIGURE 17. Typical configuration of (a) STATCOM and (b) SVC used for PQ mitigation in MG systems.

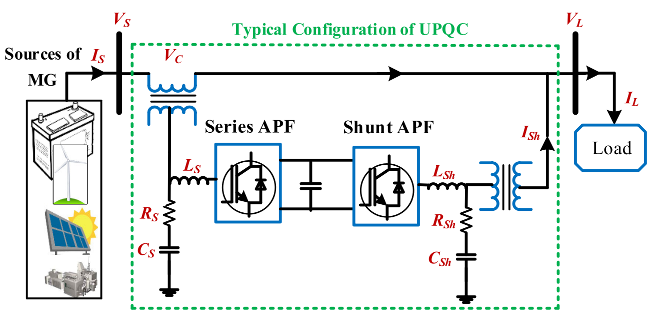


FIGURE 18. General configuration of UPQC used for PQ mitigation in MG systems.

a hybrid PV/wind system via injection or absorbing reactive current. Voltage sag mitigation and THD reduction using the UPQC device are improved by an adaptive neuro-fuzzy inference system (ANFIS) [124]. The results show that the sag and THD PQ issues were within the required limits, as stated by different standards and GCs. In [125], a UPQC is designed to improve PQ, and its performance was evaluated for various nonlinear loads. The results show that the UPQC reduced the I_{THD} and V_{THD} when ANN control techniques were used to enhance the overall performance. THD is reduced from 12.6% to 3.7% and from 73.4% to 3.7% for voltage and current, respectively. Although the UPQC is widely used to mitigate sag/swell/harmonics, the authors in [126] introduced the UPQC to mitigate the voltage unbalance in the MG system connected to the grid. The results illustrate that the UPQC can detect the unbalance incidence and reduce the VUF to less than 2%, as stated by standard requirements for MG integration.

Finally, on the basis of the literature, Table 7 illustrates a comparison between the most popular devices used to mitigate the PQ issues in MG. The comparison was made in terms of cost, rating, and different aspects of performance. Overall, DVR is superior to SVC and STATCOM in terms of addressing voltage sag, swell, fluctuation, and unbalance, while UPQC offers the best protection for sensitive loads from low-quality sources.

D. OTHER METHODS AND CONTROL STRATEGIES

During the advancement of MG installation, various PQ mitigation methods and control strategies that use optimization algorithms are developed. For instance, the authors in [127] proposed biogeography-based optimization to reduce the harmonics in MG systems to within the required limits. Some optimization methods were used to enhance the performance of custom power devices to mitigate PQ issues in MG. In [35], the fuzzy logic controller was used to mitigate the voltage sag in an MG that consists of PV and wind systems. SATACOM was optimized using genetic algorithms (GA) and bacteria foraging algorithm (BFA) by [128] to mitigate the MG voltage fluctuation. The results proved that the fluctuation at the end of the busbar is reduced by 10% and 15% for GA and BFA, respectively, which are higher than the 8% reduction achieved by a traditional controller. Artificial neural network (ANN) was used to optimize the SVC tuning for voltage and harmonics control in MG. The results of this study show the effectiveness of the proposed control, which reduced the voltage fluctuation to less than 1% from the specified voltage and maintained the THD below 5%,

TABLE 8. Summary of the devices, methods, and control strategies used to mitigate different PQ issues in MG.

Method	Issue mitigated	Outcomes	Limitations	Ref.
Biogeography-based optimization	Harmonics	-Reduced the harmonic within standard limits	-Increased the complexity. Some filters can achieve the same results	[127]
Fuzzy logic controller-based DVR	Voltage sag and swell	-Mitigated voltage sag up to 50% and voltage swell up to 150% -Faster detection rate than conventional method	-Not all types of sag are tested -Frequency fluctuation	[35]
Optimized STATCOM using GA and BFA	Voltage fluctuation	-Reduced voltage fluctuation at the end of the busbar by 10% and 15% for GA and BFA, respectively -Obtained better result than PI controller, which reduced the fluctuation to 8%	-Increased the cost and complexity -Long computational time of the optimization	[128]
ANN-based voltage source converter tuning	Harmonics and voltage fluctuation	-Reduced the voltage fluctuation to less than 1% -Maintained the THD below 5%	-Only the voltage harmonics is considered	[20]
Central inverter controller with MPC	Voltage unbalance	-Reduced the unbalance within acceptable values -Adjusted the negative sequence voltage	-The initial unbalance exceeded the specified limits	[129]
Adapted VSC control strategy	Voltage sag	-Injected reactive current to address voltage sag -Supported voltage stability during faults	-No GC requirements or standards are followed	[130]
DVR	Harmonics and voltage unbalance	-Reduced VUF to less than 1% -Reduced current and voltage THD to less than 5%	-Reactive power exchange between DG units is not eliminated	[21]
DVR	Voltage sag	-Mitigated the sag event during different types of a grid fault	-High complexity -High cost	[114]
STATCOM	Voltage fluctuations	-Eliminated voltage deviation and fluctuation	-Increased system complexity	[118]
DSTATCOM	Harmonics	-Reduced the harmonics based on IEEE 1547 standards	-Increased cost and complexity	[120]
SVC	Voltage sag	-Addressed all types of voltage sag -Support the voltage by reactive power injection during sag event	-Lower performance than DVR and STATCOM	[30]
UPQC	Voltage and current harmonics	-Reduced overall harmonic distortion from 8.93% to 3.34%	-Increased the cost and complexity of MG	[123]
UPQC	Voltage unbalance	-Reduced the VUF to less than 2%	-Other methods reduced the VUF to less than 1%, better than that of the proposed UPQC	[126]
ANFIS-based UPQC	Sag mitigation and THD reduction	-THD was within the required limits -Injected reactive power to address voltage sag	-Only three-phase fault is tested -Increased cost and complexity	[124]

consistent with the requirements of the IEEE Standard 519-2014 [20].

Furthermore, another optimization method was introduced in [129]. The authors in this study presented an MG central controller composed of two layers of model predictive controllers to compensate for voltage unbalance by adjusting the negative sequence voltage of their buses to keep the overall voltage unbalance of the network below the specified limits. To address the voltage sag event, the authors in [130] proposed an adapted voltage source converter control strategy. Table 8 summarizes the PQ devices, methods, and control strategies used to mitigate the different PQ issues in MG. No effective method or device currently exists to address the SH problem in MG systems; this matter needs more investigation in the future.

VI. CONCLUSION AND RECOMMENDATIONS

An MG network is an innovative power network that could be used to meet potential energy demand in the near future toward smart grid and green electricity. Several electricity sources in the MG network mainly depend on RESs. However, RES output is unstable and depends on weather conditions while needing many power electronics devices. Thus, the availability of PQ standards, measurement, and mitigation approaches are essential factors for the growth of MG. This research provided a detailed survey on the issues, standards, and mitigation of MG PQ. After providing an overview of the MG types, development, components, and configuration, this paper discussed the requirements, techniques, and schemes available for improving MG PQ issues such as voltage sag (LVRT), voltage swell (HVRT), voltage and current harmonic, fluctuation, and voltage unbalance in the MG system. The SH issue, which is considered a new phenomenon in the power industry, is highlighted in this study, along with its definition, standards, measurements, and available mitigation methods. The techniques and main devices used to mitigate the PQ issues in MG are discussed. Most of the PQ issues in MG and DERs are addressed by at least one reference standard; however, no standard for SH currently exists. Furthermore, research on SH mitigation is lacking. Among the devices used to mitigate the PQ issues in MG, UPQC and DVR are the best, followed by STATCOM and SVC. These devices are compared in terms of cost, rating, and different aspects of performance. Overall, DVR is superior to SVC and STATCOM in terms of addressing voltage sag, swell, fluctuation, and unbalance, while UPQC is the best protection device for sensitive loads from low-quality sources. The literature indicates that the best voltage balance was achieved by using a DVR.

From this review, some important and specific recommendations relevant to PQ issues, standards, and mitigations for further improvement are summarized as follows:

- Further studies should consider more RESs in MGs, such as hydropower, biomass, and geothermal, along with non-RES such as diesel generator to show the effects of a large diversity of sources on PQ.
- Although some PQ issues are regulated by GCs and standards, no standards exist for SH, whose effects can be hazardous if not taken seriously.
- SH mitigation techniques are not covered in research yet perhaps because of the lack of relevant accurate measurements and standards. Fast attention and rapid solutions are needed given the high integration of MG with different sources that cause SH emission.
- Devices such as DVR and UPQC should use a fast and accurate method for detecting PQ issues in MG.
- Generalized validation and benchmark methods for PQ mitigation in MG using an optimization method that takes uncertain weather conditions into consideration can be applied in the future.
- International system operators must adopt a constant or unique limit for every integration requirement to diminish dissimilarities between the current technical requirements and thus harmonize the PQ requirements in MGs.

The above recommendations can be the main contributors toward PQ improvement and mitigation of MG systems, especially with renewable sources, which are expected to dominate the energy market in the near future. Future studies based on this review output may also help address the drawbacks of current MG with respect to potential standards development and prevention of PQ issues such as SH.

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