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Supraharmonic mitigation in microgrid and electric vehicle charging station through multilevel converter

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ABSTRACT

The problem of supraharmonics (SH) in a microgrid (MG) system connected to an electric vehicle (EV) charging station is discussed in this work. SH, or high-frequency harmonics which occur beyond the typical harmonic spectrum, can cause problems with power quality (PQ) and equipment failure. A multilevel converter (MLC)-based solution is proposed together with a frequency domain analysis method to lessen this issue. Using frequency domain methods like the fast fourier transform (FFT), the suggested method precisely measures and examines the SH content in the MG and EV charging station. Based on the findings, an MLC control method that actively lowers the SH is created. The efficiency of the suggested strategy in lowering SH levels and ensuring PQ is assessed through experimental validation. The development of SH analysis and mitigation techniques as a result of this research makes it easier to safely and effectively integrate the infrastructure for EVs with renewable energy sources (RES).

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1. INTRODUCTION

The increase in the price of fossil fuels and in the rate of increase of carbon dioxide (CO2) emissions have led to a surge in the popularity of electric vehicles (EVs) in recent years. EV charging stations add to the strain on the utility grid and the distribution side load demand since they use the same power source. Higher stability, power conversion efficiency, easy interface with renewable energy sources (RES), and incorporation of energy storage units (ESU) make direct current (DC) MG-based EV charging [1]. Managing the demand on the utility grid may also be accomplished via the use of local ESU storage of electricity supplied by RES. Furthermore, energy control and management techniques should properly charge the EV battery charging unit to keep the EV charging demand within the levels of the MG. The ESSs are already playing a crucial part in the emerging smart grid paradigm, and they may play an even more important role if last-generation EV fast charging stations are integrated into smart grids, allowing the storage to perform peak shaving, power quality (PQ), and charge-time-reducing tasks [2]. The subject of disturbances propagating through supply lines below 2 kHz has been studied for a long time in the field of electrical engineering. When applied to distortions in voltage and current waveforms between 2 and 150 kilohertz, the term supraharmonics (SH) was established [3]. Power electronics (PE) devices are often utilized for greater powers due to their efficiency in converting DC to alternating current (AC) and AC to DC. Several large-scale impacts on the grid are introduced by this and these devices emit in this frequency range, leading others to be concerned. The SH emission is a major problem, particularly for isolated MGs, due to the growing prevalence of distributed generation and the integration of various electronic loads [4].

New regulations and standards have been established in response to the rise in MG implementation and the need to guarantee the reliability and safety of the electricity it generates. PQ problems, standards, and risk reduction approaches for MG have not, however, been thoroughly examined. Standards and regulations pertaining to PQ in MG are also not well addressed, despite the fact that there have been some evaluation studies on various grid codes (GC) and standards involving technical integration difficulties including voltage and frequency profiles. No coverage or standard exists for SH since it is a novel PQ occurrence brought up by MG development. Consequently, Alkahtani *et al.* [5] presents a current analysis of worldwide GCs, rules, standards, and regulations pertaining to PQ concerns. Because of the presence of electrical interfaces for power in MG systems, the SH is studied in terms of its features, causes, effects, and measurements as a novel phenomenon requiring extensive research. SH emission measurements provide a number of difficulties, as discussed in [6]. Accurate, sensitive, and wide-bandwidth sensors are needed for the measurements. It is possible for emissions to be much greater at the equipment ports than at the point of delivery. To provide an accurate depiction of emission levels across the power grid, measurements should be taken at a number of different points. The short-time fourier transform (STFT) has been used in [7] to measure the SH emissions and to investigate the time-frequency fluctuations of these emissions. Preventing or addressing SH issues in the design stages is the first line of mitigation in power grid protection. A previous decision to estimate the degree of emission compared with immunity is necessary for minimizing or avoiding SH emissions at the immunity level [8].

The hybrid active power filter (APF) is introduced in [9] for reducing SH. Although standard pulse width modulation (PWM) filters are effective for harmonics below the switching frequency, they have difficulty dealing with thosebeyond. One major drawback of existing techniques is their inadequacy in dealing with SH, particularly at higher frequencies and higher costs. Technology for multilevel converters (MLCs) developed as an advanced implementation of the voltage divider rule and used for mitigation of SH in [10]. Therefore, regular low-voltage switchgear is connected in series to generate a moderate voltage. This innovation allowed power semiconductors to function at a fraction of their rated voltage. Passive filtering, active filtering, and resonant-based existing methods are only some of the methods offered for reducing SH. Harmonic filters and high-frequency filters are two examples of passive filters used to reduce the volume of incoming sound [11]. However, owing to their narrow bandwidth, they are generally ineffectual in dealing with SH. APFs and hybrid filters are two examples of active filtering systems that may improve performance by actively injecting compensating currents to cancel out harmonics and certain SH. These methods may be effective, but they can be difficult to implement and expensive [12].

Fast fourier transform (FFT) and other frequency domain analytic methods have emerged as useful instruments for describing harmonic components in power systems in recent years [13]. The research investigates and analyzes stochastic harmonic distortion in multi-converter-based MG power systems. Uncertainties, like those generated by design parameter choices or changes to system parameters, may make it difficult to predict the quantity of harmonic distortion produced by multiple voltage source converters (VSCs) [14]. SH analysis and mitigation using frequency domain analysis have received less attention, though.

Problem and main contribution: in terms of SH distortions and their effects on PQ, MG systems integrated with RES and EV charging stations face significant problems. Existing research on SH in MG systems has shed light on their sources, effects, and possible solutions. The primary investigators have investigated several mitigation strategies, such as passive filters and active filters. Nevertheless, there are still issues that need to be resolved and places where the mitigation of SH in MG systems might be improved. The problem in this research is the MG systems' reduction of SH.

This study's major contribution is the suggestion and evaluation of aneutral point clamped (NPC)-based MLC as an effective reducing method. The goal of the study is to determine how well this converter architecture performs in lowering SH and enhancing PQ. The efficacy and benefits of the suggested approach will be shown through experimental evaluation and comparative research.

The remainder of this paper is organized as follows. Methodology, including frequency domain analysis through FFT and MLC for SH reduction, is presented in section 2. The experimental procedure and results are discussed in section 3. At last, the study summarizes in section 4.

2. METHOD

Maintaining PQ, especially in terms of SH, is difficult when MGs include RES and EVs. This study suggests a new method for analyzing and reducing SH in MGs that are linked to EV charging stations. The system features an MLC and employs a frequency domain method based on FFT analysis to efficiently reduce SH. Distributed energy resources (DERs) and manageable loads are the energy components that make up a DC MG, which is a low-voltage network. The emissions produced and electricity transmission losses experienced are both decreased by the standalone system. Solar photovoltaic (PV), wind turbine and energy storage systems (ESS) make up the system under investigation. EVs are included in the system's manageable loads. Using DC-DC converters and a charging regulatory control method, electricity is transferred from the DC MG to the EVs. The battery bank serves as both a generator and a load in the system, switching roles depending on the output from the wind turbine and solar panels. Maximum power point tracking (MPPT) was used to regulate the DC-DC converter that linked the PV to the DC MG. The DC MG is linked to the wind generator through AC-DC and DC-DC converters. The bidirectional converter charges and discharges the battery bank from the DC MG. A standalone DC MG powering an EV charging station, as described in [15], is shown in Figure 1.

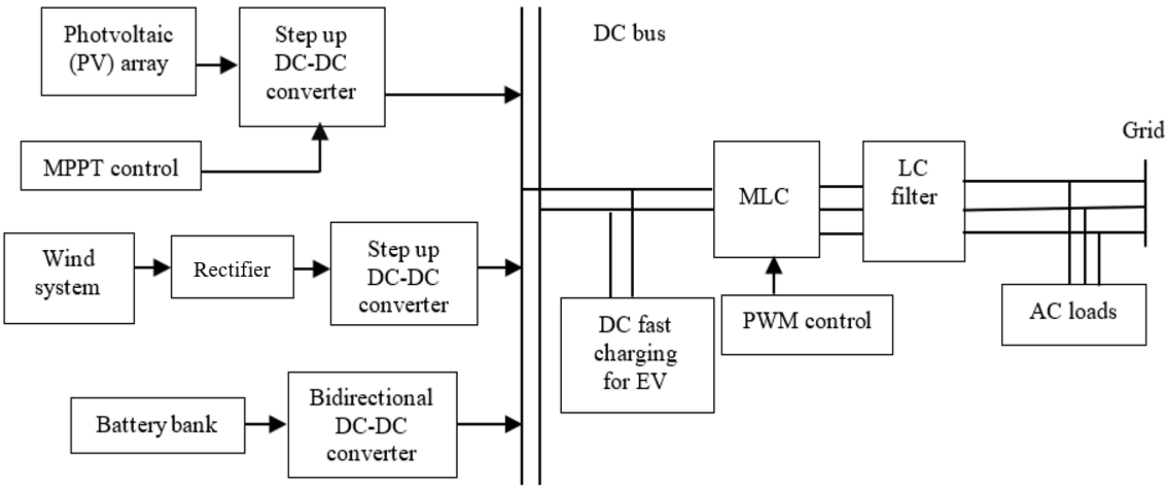


Figure 1. The architecture of the proposed MG-based EV charging station

2.1. SH in MG system

Most MG generators provide DC power, which must be integrated into the existing AC grid. Some devices can only run on power. Therefore, a DC conversion is needed at the very end of the system. On the other hand, the AC MG's DC-AC-DC energy conversion diminishes efficiency and results in energy losses. DC MG is intended to solve the problem with AC MG, and it takes the high DC voltage functioning as a point of reference. By using fewer converters in the same MG system process, DC MG may provide significant energy savings as compared to AC MG. To connect the DERs, the storage devices, and the loads, converters are needed in this category. In a power system, a variety of electromagnetic occurrences are often referred to as PQs. PQ concerns have been the subject of several studies and regulations in recent years because of the high level of integration of the MG system with the power network [16]. The PQ may be enhanced using distributed generation and the incorporation of DER in the form of MG. Due to the existence of nonlinear and unstable loads, which make up a bigger fraction of the overall load, PQ is a significant problem in small-scale islanded systems.

SH used to be in the traditional PQ frequency range (0-2 kHz). However, the rise of PE-based equipment, including MG sources, raises concerns about high-frequency noise over 2 kHz, particularly SH, which is between 2 and 150 kHz. SH is often found in the higher frequency end of the spectrum. In this context, the word "SH" refers to any distortion of the voltage and current waveforms occurring between 2 and 150 kHz. It is commonly accepted that the term "SH" refers to distortions in waveforms in the frequency range of 2-150 kHz. The top limit of the conventional PQ standards, which covers up to the 40th harmonic, is assumed to be identical to the lower limit (2 kHz). Since only a few standards cover this frequency range, this description is not entirely accurate. IEC 61000-4-19 provides a summary of the restrictions in those particular standards [17]. There aren't as many standards addressing this frequency range as are present for harmonics, but this frequency range may still be covered by national or military standards.

2.1.1. Effects of SH

Traditional assessments were made for line-commutated converters. However, self-commutated converters may readily reach considerably higher frequencies and produce emissions unrelated to the fundamental frequency. SH emissions come from several places, and as a result of the transition from AC to DC or vice versa, every device with converter-based PE generates a certain amount. The voltage sine wave is abruptly chopped by semiconductor switching devices when they flip between the cutoff and conducting states, producing massive harmonics like SH. For instance, the usage of inverter circuits is famous for producing harmonics. Such huge harmonics can decrease the lifespan of the equipment by causing the failure of electronic components, especially touch technologies, noise from mechanical resonance stimulation, or increased thermal stress. The PLC systems and power-electronic converter units are the two primary sources of SH in the grid. SH may have a variety of consequences on the PQ and overall system performance when they are present in an MG.

2.2. EV charging station

2.2.1. Charging station standards and levels

The society of automotive engineers (SAE), depending on charging cables and chargers, develops charging stations based on various standards. The communication protocol, electrical, and physical specifications are defined by two standards: the American standard SAEJ1772 and the international electro technical commission IEC 61851. Regulations for EV rectifying and constant voltage should be in accordance with SAE J1772. The SAWJ2293 criteria are adhered to when utilizing off-board chargers for utility- or MG-based charging. System integration communication requirements adhere to SAEJ 2836 [18]. The local grid's power level is taken into consideration while choosing the charging station's levels. DC level 1 (200-450 V, 80 A up to 36 kW), level 2 (200-450 V, 200 A up to 90 kW), and level 3 (200-600 V, 400 A up to 240 kW) EV chargers are divided into three categories based on voltage level. Levels 1 and 2 primarily specify on-board charging, whereas level 3 primarily covers off-board charging. The majority of level 3 charging powered by MG is used in the public sector. Table 1 presents the levels of DC charging stations.

Table 1. DC charging station levels

Levels	Charger type	Current range (A)	Voltage range (V)	Output power (kW)	Charging time
Level 1	Off-board	<80	200-500	40	22 min
Level 2	Off-board	<200	200-500	100	10 min
Level 3	Off-board	<400	200-600	240	30 min

2.2.2. Architecture of charging station

An AC-DC and a DC-DC power converter are contained outside and linked to the EV through EVsupply equipment, which comprises a power conversion system (PCS) in DC fast charging stations. It is essential for PCS to be able to provide a regulated DC output voltage of 100-800 V since this is the range required by the battery packs used in EVs as in [19]. Modular converters that can be stacked to give high power are preferred since the PCS requires a state of charge (SoC) of the battery to reach up to 80% within 30 minutes for a battery capacity of 20 kWh-40 kWh. Developing vehicle to grid (V2G) technology, in which electricity is fed to the grid from the EV, makes bidirectional power converters appealing. To further ensure safety, galvanic separation must be implemented between the electrical grid and the EV battery. A fast charging station for EVs may be set up in either an AC bus or a DC bus layout. The input side of a low-frequency transformer is linked to a central AC-DC rectifier in DC bus setups; PV sources, energy storage devices, and EVs are all coupled to the DC bus via the DC-DC converter. The increased adaptability of the system and the simplicity with which any grid-side anomalies may be avoided are both benefits of this design. Reducing the number of AC-DC rectifiers improves DC bus efficiency and makes implementing the control technique less complicated. DC charging station of EV from the grid is shown in Figure 2.

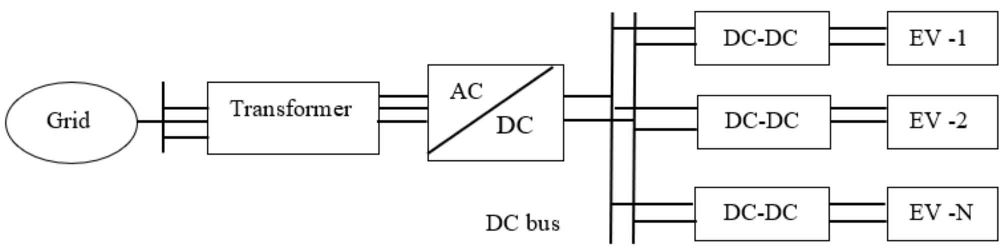


Figure 2. The architecture of the DC charging station

2.3. Measurements of SH in MG

The development of grid systems has raised the importance of SH measurement recently. New technologies like demand-side management, distribution generators (DGs), EVs and RESs are supported by the smart grid. Due to the presence of PE connections, these technologies have the ability to inject high frequency in the 2-150 kHz region, which in turn causes SH. Therefore, the advancement of smart grids or MG and the integration of RESs depend heavily on the discovery of an effective measurement for this kind of high-frequency emission. In addition to the basic 50 Hz component, the harmonic content of the spectra comparable to the distortion may be separated into three bands. First, there are frequencies in the low-order harmonics that are below 2 kHz, and then there are frequencies in the SH range that are between 2 kHz and 150 kHz. The third range is defined as frequencies greater than 150 kHz. Harmonic emission is often detected between the equipment under test (EUT) and the supply with a signal analyzer and a current transducer.

According to certain investigations of the measuring techniques on SH [20], the presence of other equipment in the circuitry has a significant impact on the current at the equipment terminals. In order to distinguish between the primary and secondary emissions, a differentiation must be established. The device's PEbased components mostly provide the primary emission, while sources from other devices produce the secondary emission. Numerous authors proposed a measurement technique that includes four stages for SH measurement [21], as seen in Figure 3. The components of the SH measurement shown are (a) a harmonic sensor, (b) a high-pass filter (HPF) and a low-pass filter (LPF), (c) an FFT analyzer with an interval of ten cycles, which is equivalent to 200 ms for a 50 Hz power frequency, and (d) a recorder.

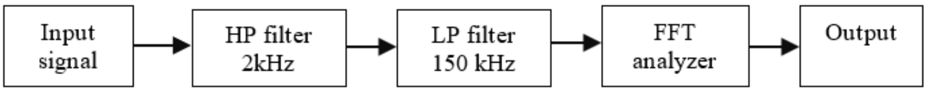


Figure 3. Measurement of SH emissions in accordance with IEC 6100-4-7 and 61000-4-30

The traditional method of measuring SH responds to the requirements provided by IEC 61000-4-30 for the time sample of the FFT measuring equipment. In accordance with that standard, the FFT interval measurements are ten cycles or 200 milliseconds for a 50 Hz power frequency. This is equivalent to 512 samples processed by the FFT device into 32 measurement subintervals. Due to MGs' extensive use of power-electronic interfaces, which include components like converters and charge controllers, worries about SH emissions have grown. The installation of the SH measuring device is another critical element to take into account throughout the evaluation process [22]. According to IEEE 519 (2014), it must be positioned among the grid and the switching converter.

2.4. Mitigation of SH using MLC

In order to boost the voltage and current-handling capacity and switching speed of power semiconductor devices (PSD), PE has become more popular. However possible, connecting a single power semiconductor switch straight to medium voltage grids remains challenging even in this modern day. By connecting low-voltage switching devices in series, a medium voltage may be synthesized with only a small portion of the voltage needed to be allowed by the power semiconductors. The solution's cost and size may be decreased by adding more low-voltage cells to each arm. As a result, the MLC technology may make more innovative use of these extra switches via unique modulation schemes, improving the output voltage and input current quality. Topologies of switching devices, often MOSFETs and IGBTs, in addition to auxiliary devices, including capacitors and diodes, make up a significant portion of multi-level voltage source converters (VSC) [23]. Creating a sinusoidal voltage waveform from a DC supply is the primary function of the converter. The waveform will change depending on the devices' carrier frequency and the number of levels. The voltage output may be divided into whatever many levels are present. Higher frequencies and levels bring the waveform closer to the standard. The most used multi-level inverter (MLI) topology is NPC. By connecting the grid neutral to a constant potential, the DC link capacitive divider maintains a constant potential for electricity between the PV cell and the ground. The fundamental benefit of this architecture is protecting a single-phase NPC from ground leakage currents [24] and circuit of NPC-MLI is shown in Figure 4.

By sequentially connecting PSD, the NPC MLC may produce a wide range of voltages. The output waveform may be shaped more precisely and SH can be effectively suppressed due to the wider voltage range. To mitigate the switching harmonics produced by PSD in traditional converters, the NPC MLC uses a clamping mechanism comprised of extra capacitors and diodes [25]. The voltage balancing between the clamping capacitors in an NPC-based MLC is essential for optimum operation and performance. The clamping capacitors in the converter are in charge of keeping the voltage levels at the intermediary clamping points, also referred to as the neutral points. The appropriate regulation of the switching states of the semiconductor devices inside the converter results in the voltage balancing process in an NPC converter [26]. Several capacitors and switches are used in the converter's operation to split the DC input voltage into different levels. Each clamping capacitor has two switches connected to it that are in charge of connecting the neutral point to the required voltage.

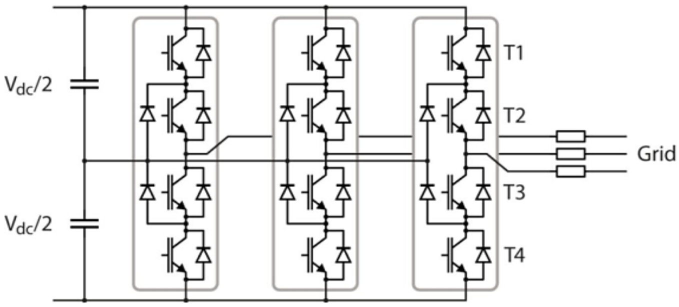


Figure 4. Circuit diagram of NPC-MLI

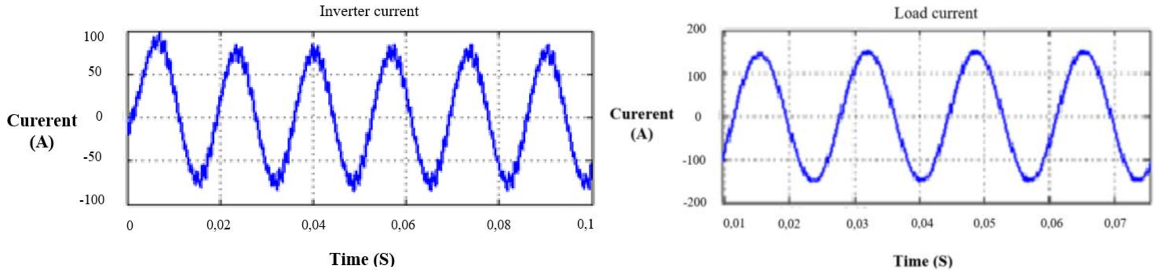
A control method is used to govern the switching states of the switches depending on the instantaneous voltage produced by the clamping capacitors in order to guarantee voltage balance. In order to balance the voltage distribution among the capacitors, the control algorithm continuously analyzes the capacitor voltages and modifies the switching states as necessary [27]. The NPC-based converter greatly decreases the SH content by decreasing these harmonics. MLCs, such as the NPC-based MLC, are often controlled by PWM. In the proposed work, the MLI is controlled by a PWM controller. The PWM method for controlling the shape of the output voltage waveform requires making adjustments to the converter's switching signals. PWM operates on the idea that the switching pulse width may be varied while the switching frequency remains fixed. The amplitude and waveform shape of the output voltage may be precisely regulated by the modulation of the pulse width.

Losses are produced by the capacitive discharging and charging of the clamping capacitors and the output capacitors at each switching transition. Due to the basic characteristics of the capacitor, a certain amount of energy is lost when the voltage that flows across the capacitors varies, leading to switching losses. Switching losses may be decreased by using snubber circuits, which include resistors and capacitors linked in parallel with the semiconductor devices, to assist in avoiding voltage spikes and ringing. The output voltage waveform may be precisely controlled using the PWM technique by continually altering the switching pulse width in response to the reference signal. By maintaining a constant switching frequency, which is often significantly greater than the fundamental frequency, a steady and stable output voltage may be maintained. The reference waveform that the inverter output must replicate is produced by the PWM controller. A high-frequency carrier waveform serves as the basis for PWM's switching pulse generation. The frequency and switching rate of the inverter is determined by the carrier waveform. Typically, the PWM controller produces a high-frequency triangle waveform. Overall, the PWM approach is an effective method for accurately regulating the electrical power given to the load in MLC, such as NPC-based converters, by controlling the waveform of the output voltage.

3. RESULTS AND DISCUSSION

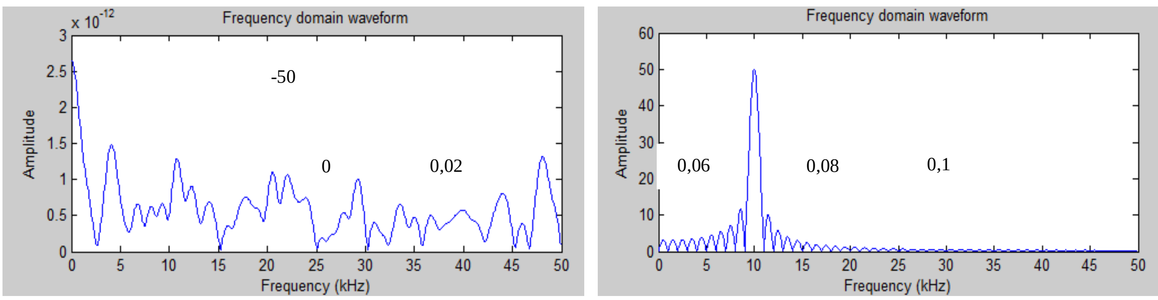
This section analyses and evaluates the experimental data from the proposed work on suppressing SH using an NPC-based MLC in an MG-connected EV charging station. The significance of the results in relation to the aims of the research is discussed in Figure 5. As part of integrating RES into the grid, an SH study of the MG was performed. SH of large magnitudes at a range of frequencies were detected by the measurements. Using methods of frequency analysis such as the FFT, the precise SH frequencies and their magnitudes were determined. The existence of SH in the data showed that the MG'sPQ was affected by the incorporation of RES. The current of the inverter with respect to time is 80 A. To address MG's SH problem, the recommended mitigation method employing an MLC was placed into operation. The converter's capacity to produce a wide range of voltages meant that complex voltage waveforms could be synthesized. The converter used a PWM method to precisely control the switching patterns, therefore lowering the MG's SH component levels. The inverter's time domain current waveform is presented in Figure 5. Figure 5(a) presents the occurrence of SH in the current waveform due to the integration of RES. Figure 5(b) presents the mitigated current waveform after employing NPC-MLC. The frequency spectrum with respect to the amplitude of the EV charging current waveform is presented in Figure 6. Figure 6(a) depicts the SH emission due to the EV charging station and Figure 6(b) shows the frequency suppression after using MLC.

Due to the PE converters employed in the charging infrastructure, SH emissions could occur when an EV station is connected to an MG for fast charging. Such emissions may spread throughout the MG and have an impact on other connected systems and devices. MLC is implemented to reduce SH emissions. Additionally, there are regulatory standards and rules in place to establish the allowed emission levels and guarantee the compatibility of various MG components. The frequency spectrum obtained before implementing the MLC reveals the presence of significant SH emissions. The illustration depicts an amplified SH component with increasing frequency up to 50 kHz. This observation aligns with the expected behavior due to the operation of the EV charging station, which generates nonlinear current waveforms. However, a notable decrease in SH emissions is seen once the MLC is added. The SH is considerably suppressed up to 10 kHz, and the graphical depiction demonstrates a significant decrease in amplitude beyond 50 kHz. This result indicates the effectiveness of the MLC in mitigating the SH emissions from the EV charging station. APQ analyzer is utilized that can record signals with a high frequency. If SH is being considered, connect the measuring device to the MG architecture. The current over a sufficient time is measured in order to pick up fundamental and harmonic frequencies. The frequency structure of the collected waveform data may be examined by performing a fourier transform. In order to determine the presence and magnitude of harmonics and SH, the fourier transform transforms the waveform from the time domain to the frequency domain. The frequency spectrum of the MG's inverter signal is shown in Figure 7. Figure 7(a) presents the SH emission due to RES integration and the suppression of SH using MLC is presented in Figure 7(b).



(a) (b)

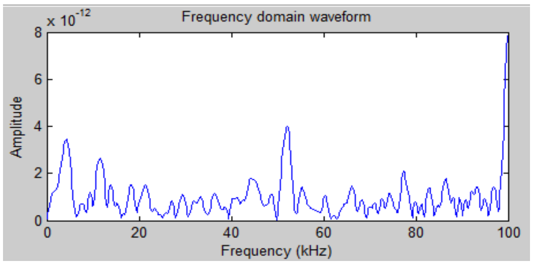
Figure 5. Inverter's time domain waveform (a) SH produced by RES system and (b) using NPC-MLC



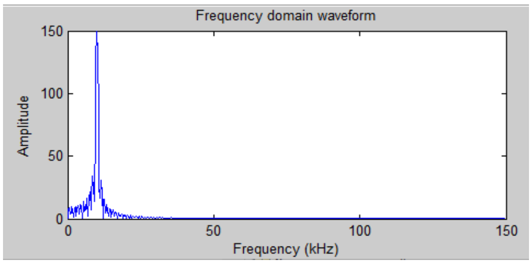
(a) (b)

Figure 6. Frequency domain waveform (a) high frequency due to EV charging station and (b) suppression of frequency after using MLC

Figure 7(a), the frequency ranges between 2 and 100 kHz which indicates the SH in the system. This SH might result from nonlinear loads or from the way the grid interacts with RES. The graph in Figure 7(b) indicates the reduction of the frequency range up to 8 kHz.This reduction demonstrates the extent to which the mitigation strategy attenuated the SH. A comparison experiment was done after the MLC was put into operation to see how well SH reduction worked. The SH measurement results post-mitigation showed a significant reduction in the magnitudes of SH compared to the pre-mitigation scenario. The SH at frequencies of 5th, 7th, and 11th harmonics were dramatically reduced by 85% after using the MLC-based mitigation approach in an MG system integrated with RES and an EV charging station and enhancing the MG's PQ.



(a)



(b)

Figure 7. Frequency domain waveform (a) indicating SH and (b) SH mitigation using MLC

4. CONCLUSION

The SH challenges with an MG system coupled with RES and an EV charging station have been effectively solved in this research. The suggested MLC-based mitigation strategy has proven successful in lowering SH and enhancing the system's overall PQ, as shown by the extensive analysis and experiments. The main goal was to reduce SH and its adverse effects on the MG system. SH amplitudes at certain frequencies have been significantly reduced by 85% using the MLC and the PWM technique. The analysis of the frequency domain waveform was reported in the findings and discussion section, emphasizing the successful reduction of SH and the corresponding improvement in PQ. The compatibility between the predicted and the actual results paves the way for more study and application possibilities, assuring ongoing progress in this area and allowing the deployment of future MG systems that are more effective and dependable. It is possible to have a thorough knowledge of the advantages, disadvantages, and performance characteristics of the different modulation strategies used in MLCs by performing future research that compares and assesses them.

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