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Comparative harmonic elimination techniques for supraharmonic reduction in microgrid

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ABSTRACT

In order to reduce voltage distortion and supraharmonic (SH) emission in microgrid (MG) systems with electric vehicle (EV) charging stations, this research compares several harmonic elimination approaches. The increasing deployment of EVs has led to the integration of EV charging stations within MG systems, presents challenges in maintaining a high power quality (PQ). Voltage distortions and SH emissions are caused due to non-linear loads and the intermittent nature of EV charging, which have an effect on the performance and dependability of the MG. In order to solve these problems, multilevel converters (MLCs) are used to produce high-quality waveforms. MLCs use harmonic elimination methods to cut down on SH emissions, which improves the PQ overall. Sinusoidal pulse width modulation (PWM), selective harmonic elimination (SHE), space vector modulation (SVM), and random-PWM (RPWM) techniques are among the harmonic elimination methods compared and analyzed. The results will enable the selection of the most appropriate strategy for minimizing voltage distortion and SH emission in MG systems, while providing valuable insights into the effectiveness of each method.

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1. INTRODUCTION

There has been a lot of focus on methods to include electric vehicle (EV) charging stations into microgrids (MGs). However, owing to the existence of non-linear demands and the intermittent nature of EV charging, the integration of EV charging stations in MGs presents issues in maintaining a good power quality (PQ) as discussed in [1]. Non-linear circuit components are used into the designs of EVs. As a result, they contribute to the MG's harmonic current and they degrade the reliability of the MG’s electrical supply. In the context of direct current (DC) MGs, a critical analysis of the international PQ standards IEEE Std1159 and IEC 61000 are provided [2]. Voltage distortion and supraharmonic (SH) emission are serious problems for MGs that include EV charging stations. The non-linear features of EV chargers and other associated loads cause voltage distortion, which appears as a divergence from a perfectly sinusoidal waveform [3]. PQ difficulties may be made even worse by SH emission, which is the presence of high-frequency harmonics beyond of the typical harmonic spectrum. MG performance and reliability may be significantly impacted by voltage distortion and SH emissions, which can disrupt the functioning of sensitive equipment, introduce unnecessary losses, and cause interference with nearby power grids.

The merits and demerits of low-voltage DC (LVDC) MGs and alternating current (AC) MGs for the purpose of integrating low-carbon technology are provided [4]. Charging power levels' effect on decreasing the system's local self-consumption was also analyzed. High-frequency emissions, or so-called SHs, in the frequency range of 2-150 kHz, are one of the problems with power electronic systems. The interaction among a fixed frequency SH distortion and a piece of equipment requiring a non-linear current, which happens when the power supply frequency deviates from the ideal 50/60 Hz, is discussed in [5]. Interharmonic currents are introduced through the grid at lower frequencies as a result of this interaction. A photovoltaic (PV) inverter's (PVI) unintentional emission is mostly brought on by the pulse width modulation (PWM), which is utilized to produce the necessary AC voltage at the inverter bridge from the DC link voltage. A significant influence of the network impedance on the SH emission was additionally observed during the experiments [6]. When SH spreads across grids, it interferes with the components of power distribution and end-user equipment, causing things like light flicker, deterioration of capacitors and cable terminations, loud noise, and a disruption in EV charging. There is an increasing demand for recommendations that make it easier to diagnose issues associated to SH since these instances occur increasingly often. Different interferences are caused by various SH distortion characteristics. The rules for evaluating the effect of SH based on interference morphology are introduced in [7].

Standards must be significantly extended and improved in the SH range in order to adequately solve the issue of just addressing the harmonic interval. Additionally, it has been noted that certain situations involving EV chargers go above the permitted harmonic limits. As a result, it is important to better understand and assess the processes behind emission and distortion, as well as the interactions between pre-existing grid distortion and EV chargers [8]. A preliminary summary of the acoustic noise emissions from home appliances brought on by SH voltages is provided [9]. Nearly all contemporary home appliances have sources for mechanical oscillations, such as capacitors, coils, or transformers, and tests show that a large number of appliances create noise due to SH. A detailed description of the SH interaction between a number of devices and a low voltage grid in a representative setup is provided [10]. The flow of the currents between the grid and the devices, interactions between various devices and various grid impedances, and the ensuing effects on emission amplitude are studied.

The reduction of voltage distortion and SH emission in MG systems has been the subject of many research. The selective harmonic elimination (SHE) method is one strategy that tries to remove certain harmonics by creating suitable switching patterns for the multilevel converter (MLC) is discussed [11]. In MG systems, the SHE approach has shown good results in lowering harmonic distortion and enhancing PQ. However, further investigation is required to assess its efficacy, especially in the setting of MGs linked to EV charging stations. In MLCs, PWM approaches have also received a lot of attention. To reduce harmonic distortion, these methods require adjusting the converter's switching frequency and duty cycle [12]. Different PWM methods have been put forward and evaluated for their efficacy in lowering voltage distortion and suppressing SH emission, including sinusoidal PWM (SPWM), space vector PWM (SVPWM), third harmonic injection PWM, and random-PWM (RPWM) [13]–[16]. However, there is a lack of a thorough comparative examination of these methods in the context of MGs linked to EV charging stations. A thorough comparative analysis is required to determine the best strategy for reducing voltage distortion and SH emission in MG systems with EV charging stations, even though individual studies have looked at the effectiveness of different harmonic elimination techniques. Researchers and engineers would be able to make informed decisions on the development and operation of MG systems including EV charging stations with the help of such a study, which would provide useful insights into the performance, benefits, and limits of each approach.

2. METHOD

The suggested method focuses on employing MLC to reduce voltage distortion and SH emission in MG systems. An EV charging station, renewable energy resources, energy storage devices, and other pertinent parts make up the system. The MLC interfaces the EV charging station with the MG, playing a significant part in the system. With less harmonic content and better voltage stability, it is intended to produce high-quality waveforms. To provide optimum performance in reducing PQ concerns, the converter design and specifications are carefully specified.

2.1. System description

The proposed system is made up of the PV sources, a wind system, an energy storage system, a link to the grid, and a charging station for EVs, as illustrated in Figure 1 [17]. All of the DC MG's power generators are connected into a central DC bus. The renewable system's generated power is used mostly to charge EVs. Storage is an alternative energy source that may be used to power EVs or to absorb up surplus energy from PV systems. Because the grid is utilized as a backup, renewable sources may sell whatever energy they produce in excess. The extra power required to charge EVs comes mainly from the storage and subsequently the public grid if the renewable energy output is less than the power used by the EVs. Instead, the surplus power is used to charge the batteries and then sent back into the grid. The various PWM techniques are implemented for controlling the MLC as suggested in [18] and compared for better suppression of SH emission.

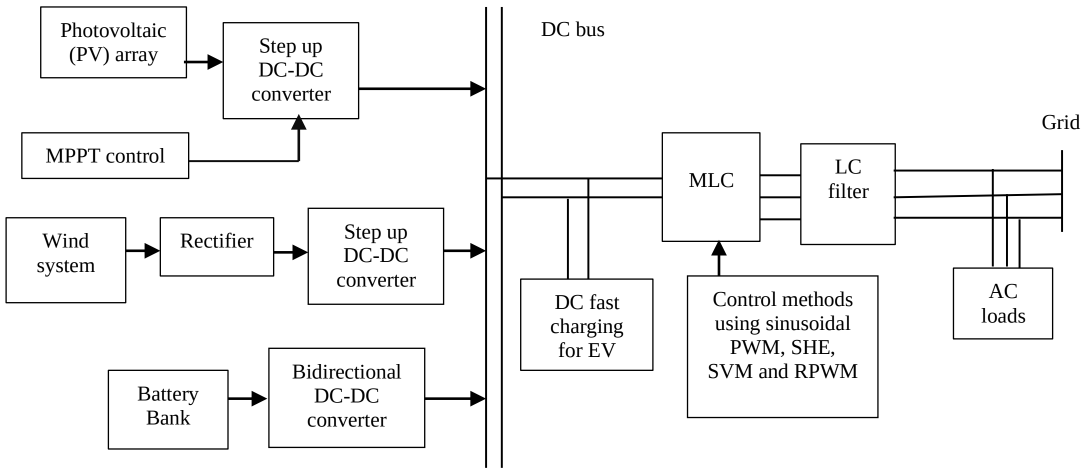

Figure 1. Comparative modulation techniques of MLC in the proposed MG

Energy storage units (ESUs) made up of rechargeable types of batteries are used for grid-connected applications because of their modular architecture, low energy density, and potential to absorb or give substantial power [19]. By adjusting the boost converter's switching pulse length, the maximum power point (MPPT) algorithm (incremental conductance approach) extracts the greatest amount of power possible from the PV array [20]. Power is transferred from the DC MG to the electrical network through the bidirectional DC-AC converter, which is responsible for reactive power regulation and grid synchronization. Maximum power conversion efficiency is achieved with minimal conversion losses when the DC-DC charging power converter feeds electricity at the correct voltage to the EV battery. However, the DC-DC converter's output voltage must correspond to the specified normal operating voltages.

2.2. Control of power converters

Power electronic converters' switching sequences are regulated using data collected from the direct DC bus and the vehicle connected to the charging station. The MPPT DC-DC converter on the PV side is regulated by the measured voltage and current from the PV devices. Battery charge level and current flow are used to regulate the buck/boost converter on the EV side.

2.2.1. Battery charging controller of electric vehicle

The battery in an EV gets charged by controlling the charging converter such that the voltage and current remain constant. The battery gets charged while the current flowing through it is greater than zero, when Ibatt > 0. The energy management system (EMS) controller is supplying the battery with a constant voltage that varies based on the direction of the battery current (Iref). The EMS of the charging station has been developed in order to give constant power to the charging point and their modes are operated as described in [21]. This was done depending on different factors of the charging station.

Whenever the vehicle fails to connect for charging, the goal of an EMS is to store the power generated by the PV panels and use less electricity as possible from the utility grid. Depending on the state of charge (SOC) and the sign of the reference current (Iref), the control signal switches the charging converter between constant-current mode (switch opened) and constant-voltage mode (switch closed), via the first setting utilized for constant-current charging and the other being used for constant-voltage charging. Constant-voltage charging is achieved with the outer voltage loop control, as shown in Figure 2, and rapid charging is achieved with the inner current loop control.

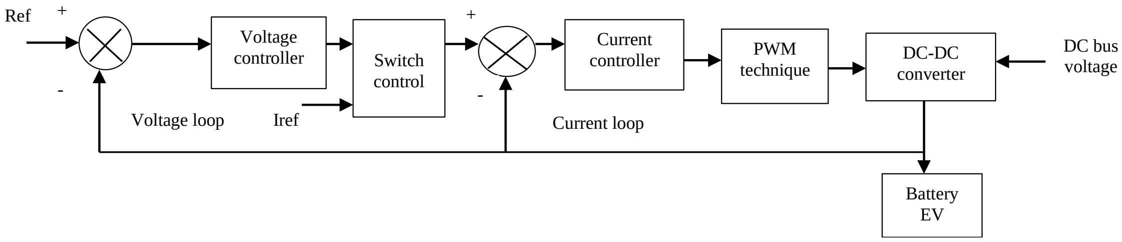

Figure 2. EV battery’s discharging and charging

2.3. Multilevel converter design

MLCs are structured such that the total DC voltage is distributed uniformly among the cascaded power semiconductors. Therefore, despite DC voltage balancing issues and sophisticated modulation, they are the most appropriate power converters for high-power uses. Neutral point clamped (NPC), flying capacitor, and cascaded H-bridge are the most researched and deployed MLC topologies. Despite the challenge of neutralpoint voltage balancing, the three-phase three-level NPC converter is the most popular of them as evaluated in [22]. Stepped waveform voltages are produced by the multilevel inverter's (MLI) collection of power semiconductors and capacitive voltage sources. Switch commutation allows large voltages from capacitors to be added at the output, whereas power semiconductors are only required to resist lower voltages. The following are some of the most appealing aspects of MLIs. First, they can provide low-distortion and low-dv/dt output voltages and take in low-distortion input current. It produces less common-mode (CM) voltage, which eases the burden on the motor's bearings. In addition, CM voltages may be cleared off with the use of advanced modulation techniques [23]. They are able to function at lower switching frequencies.

The switches reverse around between two states to regulate the power flow in the converter. This occurs in time for the converter's input and output node's inductors and capacitors to normalize or filter the switched signal. The required DC or AC with low frequency part is kept while the switched component is muted. Since the intended average value can be modified by varying the pulse width, this procedure is known as PWM. The low pulse number PWM options should adhere to the criteria of quarter and half wave symmetry and synchronization with the fundamental frequency. Assuring that the switching frequency fc is a multiple of integers of the synthesized fundamental frequency f1 is known as synchronization with the fundamental frequency. Thus, discrete frequencies that are fundamental frequency’s nf1 multiple, where n is an integer, will make up the frequency spectrum of the PWM waveform. It is guaranteed that there will not be any even harmonics in the output spectrum by quarter- and half-wave symmetry. The DC component is an essential even harmonic that is removed. There will not be any sub-harmonics, or components of frequency below the fundamental frequency. This is crucial because even a small-amplitude unwanted harmonic component at zero frequency may result in substantial current flows in inductive loads. According to switching frequency, the modulation techniques employed in MLI may be categorized. Power semiconductors may undergo a lot of commutations using techniques that operate at high switching frequencies within a single period of the basic output voltage.

2.4. Interaction of supraharmonic in microgrid

2.4.1. Distortion measurement and assessment

Rarely did the standards for harmonic and SH distortion that have been addressed up to this point define the processing techniques and parameters by which spectral components should be generated and their amplitudes assessed. The way time-domain signals are processed and evaluated is another factor that requests consideration in terms of the accuracy of the assessment of emissions. This factor includes not only the time period for providing averaged values (with reference to IEC 61000-4-7) [24], but also spectral leakage control and the impact on spectral amplitude estimate. The grid impedance is crucial for SH as well as low-frequency distortion (harmonics). Particularly, SH emissions from EV chargers will easily pass through the filters of other related equipment (such as electromagnetic interference (EMI) filters and PWM output filters of inverters), creating a low-impedance path among loads attached to the same grid up to a significant distance (hundreds of meters), which is an important part of the typical extension of the low voltage (LV) feeders coming from the secondary of a medium voltage (MV)/LV transformer.

SH contributes excess frequency components that vary from the ideal sinusoidal waveform when they occur in an electrical system. The voltage waveform may deviate or become distorted as a result of these extra frequency components, resulting in voltage distortion. However, it is crucial to remember that although lowering voltage distortion often results in a decrease in SH emission, it is not always possible to do so owing to system limitations or the existence of outside influences. The objective is to reduce emissions and their effects on PQ and system efficiency.

2.5. Harmonic elimination techniques

The voltage distortion is decreased by employing the harmonic elimination approach with an MLC and a suitable modulation strategy, which in turn aids in lowering the emission of SH. This is due to the harmonic elimination technique's emphasis on removing or decreasing certain harmonics and SH, which are significant sources of voltage distortion and emission. To accomplish such objectives, the following methods are used.

2.5.1. SPWM technique

The basic two-level SPWM with a triangular carrier and sine reference waveform serves as the basis for SPWM for MLI. The number of carriers utilized in multilevel SPWM is the only distinction between two level and multilevel SPWM. The inverter at the 'm' level makes use of the 'm-1' carrier. Diode-clamped and capacitor-clamped inverters rely on the interaction between a carrier and a reference to gate a particular complementary set of switches or a single cell within a multi-cell inverter. The carriers utilized in MLIs may be transferred vertically or horizontally. The benefit of the horizontally shifted carriers approach is that regardless of the quantity of the produced voltage, each module is turned on and off a fixed number of times every period. However, any digital controller can more readily construct a vertically shifted carrier system. Four carriers (C1–C4) split the entire modulation voltage into four regions (r1–r4) for a five level inverter [25]. By raising carrier frequency, lower order harmonics may be moved to higher order. However, without utilizing an output filter circuit, the overall harmonic distortion cannot be reduced. Switching losses are substantial in SPWM because the switching frequency is the same as the carrier frequency.

2.5.2. Selective harmonic elimination-pulse width modulation technique

The idea behind SHE-PWM approaches is based on the fourier theory division of the PWM current/voltage waveform, and it only relies on how the waveform is expressed and its characteristics. The amplitude and number of voltage levels as well as waveform features like symmetry are equally crucial to the analysis and play a crucial role in establishing the shape and complexity of the solution space. SHE-PWM exhibits a number of characteristics, including high efficiency with a small to fundamental frequency ratio. The removal of low-order harmonics, which prevents harmonic interference like resonance with external line filtering networks, which is often used in inverter power supplies. Low switching losses, tight harmonic control, and the flexibility to leave triplen harmonics unregulated allow three-phase systems to benefit from circuit architecture. Performance metrics like voltage/current total harmonic distortion (THD) that may also be improved for various quality factors. Since its introduction, SHE-PWM has generated a great deal of research interest and has been designed for a number of applications, mostly for high-voltage and high-power converters wherein switching losses are a significant issue and their reduction is of greatest importance.

2.5.3. Space vector pulse width modulation technique

The SVPWM modulation schemes have a significant impact on the capacitance values, ripple current rating, and voltage balancing of the DC bus capacitors. It is crucial to choose the modulation method based on the current control requirements since it affects the output voltage waveform's harmonic content. The benefit of this SVPWM approach is that the voltage output may be achieved with averaged values by employing the most nearby three vectors; this technique provides the greatest spectrum performance. A three-phase inverter system using SVM may adapt to a variety of switching characteristics. They are strong dynamic responsiveness, very low overall harmonic distortions for the resultant voltage, effective usage of DC voltage, and the ability to adjust the inverter efficiency for different load conditions.

This topology's efficient voltage vector is denoted by the symbol V1 (pnn). Vab, Vbc, and Vca are line voltage vectors that are 120 degrees apart in space as illustrated in Figure 3. The three legs or phases a, b, and c are either linked to the positive DC rail or the negative DC rail in this instance, as shown by the notation pnn. So, according to pnn, phase 'a' is linked to the positive DC rail, whereas phases 'b' and 'c' are linked to the negative DC rail. The clarks transformation may be used to represent the six non-zero voltage vectors (V1-V6) and the two zero vectors (V7, V8) that are referred to as state space vectors in the plane. Assuming that Ts, the sample period, is partitioned into T1, T2, and T0, the subintervals. Eight space vectors (Vn, n=0–7) are switched in order to simulate the sine wave line modulating signal Vs. The two non-zero vectors (Vn and Vn+1) along with a zero space vector (V0), however, should be employed to acquire the optimum load line voltage and reduce switching frequency if the modulating signal is between Vn and Vn+1. Figure 3 represents the three phase abc frame in αβ plane.

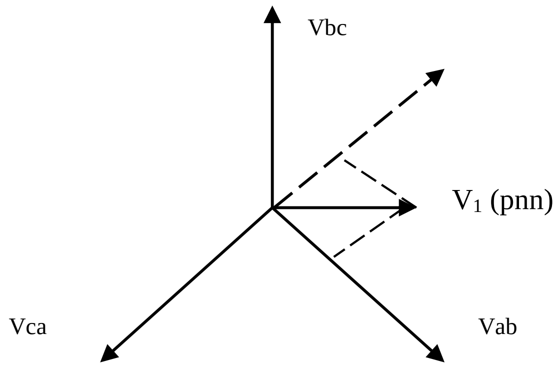

Figure 3. Three phase abc frame representation in αβ plane

2.5.4. RPWM technique

Hysteresis control and PWM, two different approaches, both aimed to lower emissions under 2 kHz. However, this causes emission between 10 kHz and 30 MHz, which is the PWM switching frequency. Self-switching converters are a crucial source of SH as a result. Electromagnetic interference (EMI) filtering and shielding are two mitigation approaches that are widely used and are effective, but because emissions still occur, it would be preferable to find a way to prevent them from occurring in initial stages. Spread spectrum techniques basically refer to dispersing a signal's energy across a broad frequency range to lower peak energy. The emergence of a random quantity is often included in these. Because the signal is nonperiodic, a nondeterministic switching method will have a continuous frequency spectrum. The average spectral power density of broadband emission may be severely constrained as a consequence. This technique might be used to eliminate the SH interference in a traditional PWM self-commutated Pstage. The fundamental characteristics of the various switching mechanisms are described [26]. The modification in carrier frequency is the first strategy among the several ones investigated to create randomness. This is a particularly efficient approach since the switching frequency cannot be fixed, causing a drop in the input and output spectra's spectral element at the initial switching frequency. To achieve this, a randomized method of gently bounding the signal between the two frequencies is used [16].

2.6. Comparative analysis

To effectively reduce voltage distortion in the suggested system, the above described harmonic elimination methods must be integrated into the MLC architecture. By adjusting the MLC's switching pulse width, PWM may be created. To create switching signals with the proper pulse widths, the reference waveform is compared to a carrier signal. To find the best switching angles for the MLC, SHE requires resolving a series of non-linear equations. The converter's appropriate control signals are then produced using these switching angles. The reference voltage space is divided using SVM, and the MLC's switching states are chosen accordingly. Based on the intended output voltage vector and the position of the reference vector inside the voltage space, switching states are chosen. Random time shifts are added to the switching pulses in the MLC using RPWM. These shifts in time distribute the energy throughout a higher frequency range, lowering the concentration at certain harmonics. The switching signals are generated while taking into account the random time-based shifts, which reduces the amount of SH emissions.

To lessen EMI while keeping waveform quality, the EV linked MG system could need excellent suppression of SH. RPWM is well-suited for applications where SH mitigation and reduced distortion in the current waveform are important. A smoother and less distorted current waveform is maintained by RPWM, which also improves power transfer efficiency and lessens the possibility of component failure or overheating. A steady and dependable operation is ensured by the wider frequency spectrum distribution obtained by RPWM, which helps alleviate resonance problems that may arise in the EV linked MG system.

3. RESULTS AND DISCUSSION

The effectiveness of four harmonic elimination strategies PWM, SHE, SVM, and RPWM for reducing voltage distortion and SH emission in an EV-connected MG system was examined in this research. THD and SH emission levels were the main performance indicators that the investigation focused on. A five level MLC is employed for SH reduction and the voltage output of the converter is indicated in Figure 4. In order to function at its most efficient, the time domain voltage waveform of the five-level MLC in the proposed system as shown in Figure 4(a) displays a number of distortions by generating 120 KHz. Figure 4(b) presents the frequency spectrum analysis of the distorted voltage waveform.

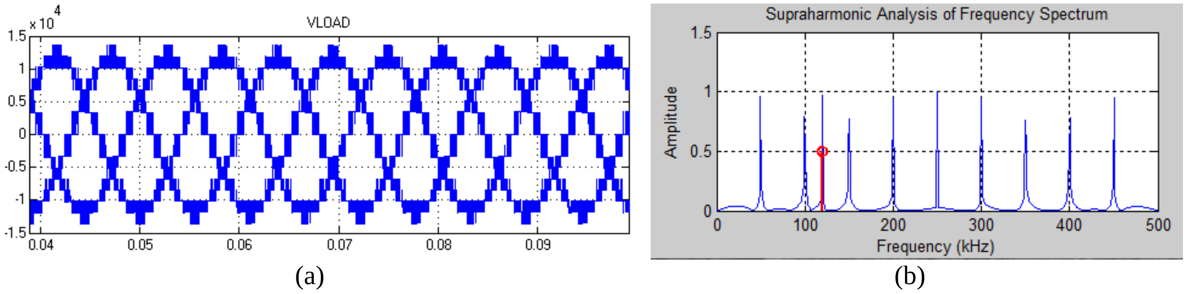

Figure 4. Five-level MLC: (a) MLC's output voltage waveform indicating voltage distortions and (b) frequency spectrum analysis of MLC voltage waveform

The waveform deviates from the ideal sinusoidal waveform due to severe harmonic distortions. Non-linear loads and switching transients inside the MG system are responsible for those harmonics. The SH analysis graph highlights the frequency spectrum with amplitude, highlighting the SH present in the voltage waveform of the five-level MLC. The distribution and strength of SH, which are harmonics with higher frequencies than the fundamental frequency, are well-illustrated in this graph. In the frequency spectrum, the SH frequency (120 KHz) will also show up as a peak. The intensity of the SH component in the signal will determine the peak's amplitude. Peaks with higher heights indicate SH with larger amplitude. The SH frequency component's amplitude is highlighted by the red stem line, making it simpler to see it in the spectrum. The voltage waveform also exhibits SH emissions, which are higher-frequency harmonics that might deteriorate the waveform's quality even further. These SH have the potential to perturb the system further and generate noise. To address the above issues, harmonic elimination techniques are implemented in the MLC through gate signals. Figure 5 presents the comparative SH analysis of frequency spectrum. Figure 5(a) presents the PWM technique, Figure 5(b) shows SHE-PWM technique, Figure 5(c) presents SVPWM technique, and Figure 5(d) presents the RPWM technique.

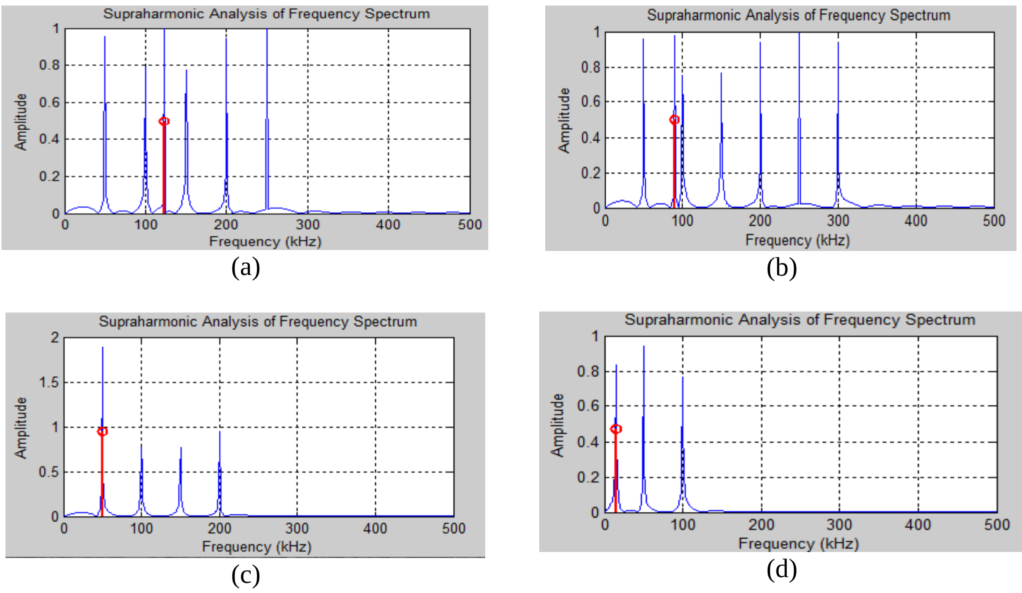

Figure 5. Frequency spectrum: (a) PWM technique, (b) SHE-PWM, (c) SVPWM, and (d) RPWM

A significant number of SH are dispersed over many frequencies (110 kHz) as shown in the frequency spectrum analysis graph for PWM in Figure 5(a). The SH's larger amplitudes show that the voltage waveform contains a significant amount of harmonic material. In contrast, the frequency spectrum analysis graph for SHE in Figure 5(b) shows less SH than for PWM and has a smaller amplitude, which shows that the SHE approach effectively suppressed the harmonics. In comparison to PWM and SHE, the frequency spectrum analysis graph for SVPWM in Figure 5(c) exhibits much less SH of frequencies at (50 kHz) and has lower amplitude, which proves that the SVM approach was effective in mitigating their harmonics. The best outcomes, however, are shown by the frequency spectrum analysis graph for RPWM in Figure 5(d). It shows very few SH of frequencies (5 kHz) with very less amplitude, indicating that the RPWM approach effectively suppresses higher-frequency harmonics.

The amount of harmonic content in the output voltage waveform is indicated by THD values. Better voltage distortion suppression is indicated by lower THD levels. A bar graph as shown in Figure 6 comparing the THD levels achieved by each technique (PWM, SHE, SVM, and RPWM) would provide a visual representation of their effectiveness in reducing harmonic distortion. The graph of Figure 6 displays the THD values on the y-axis and the different techniques on the x-axis.

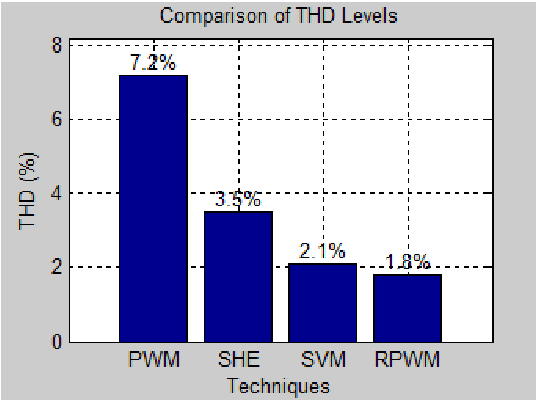

Figure 6. THD values of different techniques

Table 1 presents the comparative analysis of different techniques for SH reduction. The findings show that, of all the approaches, RPWM produced the lowest THD of 1.8%, demonstrating excellent harmonic suppression capacity. Additionally, RPWM demonstrated little SH emission, indicating successful higher-frequency harmonic reduction. RPWM stood out among the strategies tested for its significant advantages in reducing voltage distortion and SH emission. Because of the low THD that RPWM is able to accomplish, the output voltage waveform is clear and steady, satisfying the strict requirements for EV charging. The insignificant SH emission shows again the way RPWM works to reduce EMI and improve overall system performance. RPWM is shown to be the most advantageous strategy for reducing voltage distortion and SH emission in the suggested EV linked MG system based on the comparison study. It is a viable option for use in actual EV charging infrastructure due to its improved performance in terms of THD reduction and suppression of higher-frequency harmonics.

Table 1. Comparative analysis of harmonic elimination techniques for SH reduction

Technique	THD (%)	SH content (%)	Voltage distortion (%)	Voltage regulation
PWM	7.2	3	10	Fair
SHE-PWM	3.5	1	5	Good
SVPWM	2.1	0.5	3	Excellent
RPWM	1.8	0.2	2	Excellent

4. CONCLUSION

The study has successfully shown the suggested MLC with several harmonic elimination approaches, which reduces voltage distortion and SH in an MG connected with EV charging station. It is clear from the comparative examination of the frequency spectrum graphs that the RPWM approach works better than PWM, SHE, and SVM at reducing SH and enhancing voltage waveform quality. It displays the lowest amplitude of SH over the frequency range of interest. Utilizing the RPWM approach also considerably decreased the voltage distortion, which is indicated by the THD and the presence of SH. A significant increase in voltage quality can be seen in the THD measurement, which dropped from 7.2% to 1.8%. The cleaner and more stable voltage waveform indicated by the reduced amplitude of SH found in RPWM supports the compatibility between the study goal and the achieved results. In summary, the comparative analysis demonstrates that RPWM is the most suitable technique for mitigating voltage distortion and SH in the proposed system. Optimizing the RPWM method and investigating its scalability and usefulness in larger-scale MG systems could be the subject of future research. This study provides the foundation for future research into more sophisticated control techniques, grid integration, and the enhancement of voltage quality in MG with EV charging stations.

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