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Mitigation of PQ issues in EV charging station connected distribution system using novel RSMLI-based shunt APF

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ABSTRACT

In the present scenario, the significant use of electric vehicles (EVs) is growing rapidly in the automotive industry due to cheaper transportation, no fossil fuel required, low maintenance, no fuel cost, and low impacts on the environment over the formal internal combustion engine (ICE) vehicles. In actuality, these EVs are powered by batteries that are charged by a utility-grid-based charging facility. A power-electronic conversion-based charging device is used in this charging station to charge the battery packs in the EV system. The problem statement of this work is identified, these conversion devices in charging units proliferate the power quality of the utility grid. To overcome these problems, a classical square-wave inverter-based active power filter (APF) is employed. The major problems in classical inverters are high common-mode voltage, more harmonic profile, high dV/dt stress, high switching stress, and low efficiency. The contribution of this work is proposing the multilevel inverter (MLI) based APF for better compensation over classical inverters. In this approach, a novel reduced-switch MLI-based APF has been proposed for the mitigation of harmonic currents and also enhances the power factor in utility-grid-connected distribution systems. The effectiveness of the proposed reduced-switch multilevel inverter (RSMLI)-APF is validated by integrating the number of charging units with the MATLAB/Simulink tool, and simulation outcomes are shown along with comparisons.

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1. INTRODUCTION

In India, the use of electric vehicles (EVs) such as electric cars, electric bikes, and auto-rickshaws is quickly increasing, accounting for more than 38% of all vehicles registered up to December 2022 [1], [2]. In principle, an EV uses an electric motor driven by a battery energy storage system (BESS), and the batteries are charged via utility-grid-supplied charging stations. As the use of various EVs grows, so does the need for and construction of charging stations. EV charging stations require power-electronic converters to charge the batteries, which causes harmonic current distortions and spreads power quality in grid-connected distribution systems [3]. The emergence of power quality (PQ) issues causes severe issues in the distribution system, impacting supply terminal voltage, current, and fundamental frequency [4]. Current harmonics, unbalanced loads, low reactive power demand, and non-unity supply power factor are the primary issues with poor PQ in the distribution system.

A lot of researchers and power professionals are being compelled to develop modern mitigation devices using custom-power technology (CPT) [5]–[7]. Various custom-power (CP) technologies are available to alleviate relative PQ difficulties, leading to a distribution system that is sinusoidal in shape, well-balanced fundamental, and continuous. Static compensators, distributed static compensator (DSTATCOM) [8], [9], active power filter (APF) [9], and dynamical voltage restorer (DVR) [10] are examples of prominent CP devices. According to the research, the APF is the most effective compensating device for resolving current-related PQ issues when compared to traditional passive power filters [11], [12].

In general, APF is integrated as a shunt or parallel to EV charging station connected distribution network for elimination of harmonic current distortions and also enhance the power factor. It comprises three-phase voltage-source inverters (VSIs) powered with the DC-link common capacitor by means of line interface filters. In recent days, these classical 2-level or 3-level square-wave inverter modules have been replaced with multilevel inverter (MLI) topologies for medium-voltage and high-power applications [13]. The major problems raised in classical square-wave inverters are eliminated by employing the MLI topologies; it offers favorable merits such as good quality root mean square (RMS) voltage, reduced common-mode voltage, low harmonic profile, low dV/dt stress, and low switching stress, and increased efficiency. In general, the MLI topology generates staircase output voltage at load terminals from several input DC sources by regulating the switching action of respective switches using feasible switching pulses [14].

These MLI topologies are classified based on their input DC sources, which can be either single or multiple [15]–[17]. A novel reduced-switch multilevel inverter (RSMLI) has been generally preferable for higher voltage levels [18]–[20]. According to various literature studies, a single-phase 5-level RSMLI topology is proposed in [21], it utilizes the 7 switches for medium-voltage applications by using transformers. But this topology is not suitable for higher voltage levels because it requires more switches and high frequency transformers which increase the size and cost of overall topology. Based on the above problem statement, the major contribution of this work is proposing the novel RSMLI topology for MLI-APF for PQ enhancement in EV charging systems with fewer switching devices and it doesn't require any high-frequency transformers.

In this work, a novel 5-level RSMLI-APF has been proposed for enhancing PQ in EV charging systems by utilizing only 5 switches and controlled by novel instantaneous real-power theory with reduced-carrier pulse width modulation (PWM) technique. The methodology and performance of the proposed novel 5-level RSMLI-APF for PQ enhancement with instantaneous real-reactive power (IRP)-random carrier pulse-width modulation (RCPWM) technique has been validated with MATLAB/Simulink tool, simulation outcomes are illustrated with attractive comparisons.

2. PROPOSED CONCEPT

The block diagram of shunt connected 5-level RSMLI-APF for enhancing PQ in grid-based charging system is depicted in Figure 1. The operating principle of 5-level RSMLI-APF is well-committed based on the active-filtering technique for counteracting the harmonic current distortions coming from the EV charging system. It administers the source or passive containment cooling system (PCC) currents based on the in-phase opposition principle for harmonic current reduction, reactive power control, load balancing, and power-factor improvement. The viable line interfacing filters are used and connected after the RSMLI topology for the reduction of uneven notches in compensation currents furnished by the 5-level RSMLI topology. The block diagram representation of the proposed 5-level RSMLI topology is shown in Figure 2.

The proposed 5-level RSMLI topology requires only (N) switches connected as H-bridge shapes named S_{d1}, S_{d2}, S_{d3}, S_{d4}, and S_{d5}, respectively. Moreover, ((N-1)/2) input DC capacitors are required for energizing the 5-level RSMLI topology named C_{dc1}, C_{dc2} defined as the total input DC voltage of $V_{dc.c}$. The systemization of various output voltage V_o levels at load terminals is comprised of 5 voltage levels such as $0V_{dc}$, $+V_{dc}$, $+2V_{dc}$, $-V_{dc}$, and $-2V_{dc}$, respectively. The switching states of the proposed 5-level RSMLI topology are illustrated in Table 1. In that, "1" expresses the ON-state of the respective switch, and "0" expresses the OFF-state of a respective switch, accordingly. The operation of the proposed 5-level RSMLI-APF relies on the extraction of feasible reference currents through a significant control scheme, the IRP control theory is best suited for APF which extracts the reference currents from distorted currents through sensing devices.

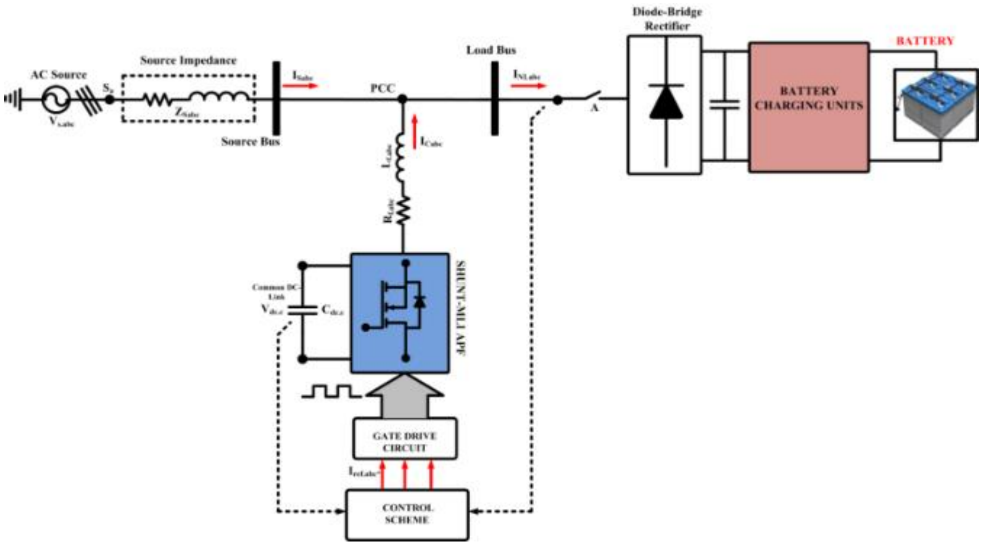


Figure 1. Block diagram representation of shunt-connected 5-level RSMLI-APF for PQ enhancement in EV charging system

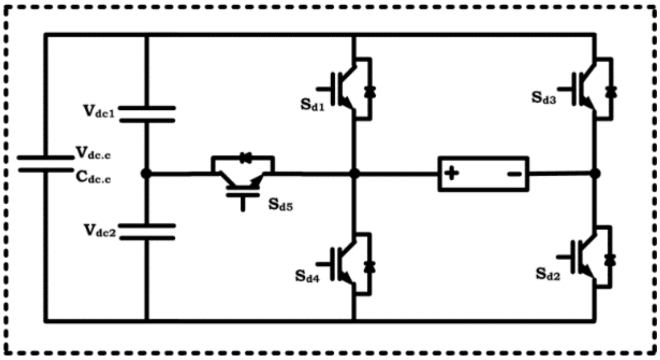


Figure 2. Block diagram of proposed 5-level RSMLI topology

Table 1. Switching states generation of proposed 5-level RSMLI topology

Levels	Output voltage (V_O)	Switching sequence				
		S_{da1}	S_{da2}		S_{da4}	S_{da5}
Level-1	0 V_{dc}	0	1	0	1	0
Level-2	+V_{dc}	0	1	0	0	1
Level-3	+2V_{dc}	1	1	0	0	0
Level-4	-V_{dc}	0	0	1	0	1
Level-5	-2V_{dc}	0	0	1	1	0

3. INSTANTANEOUS REAL-REACTIVE POWER CONTROL THEORY

Typically, the IRP controller utilizes Clarke's conversion technique for rotating standard abc into symmetric parameters in a stationary frame [22]–[27]. The (1) to (3) are used to calculate the instantaneous values of real and reactive powers in a symmetric frame.

$$p = v_{st.\alpha} i_{NL.\alpha} + v_{st.\beta} i_{NL.\beta} \tag{1}$$

$$q = -v_{st.\beta} i_{NL.\alpha} + v_{st.\alpha} i_{NL.\beta} \tag{2}$$

In a symmetric -frame, the affected non-linear load currents are defined as (3):

$$\begin{bmatrix} i_{NL.\alpha} \\ i_{NL.\beta} \end{bmatrix} = \frac{1}{\Delta_k} \begin{bmatrix} v_{st.\alpha} & v_{st.\beta} \\ -v_{st.\beta} & v_{st.\alpha} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} \tag{3}$$

where,

$$\Delta_k = v_{st.\alpha}^2 + v_{st.\beta}^2 \quad (4)$$

The resulting actual currents are then routed via a second-degree high-pass filter, allowing higher-level components to get specific signals that serve as references. The high-frequency sections are treated, resulting in a component loss denoted as ($P_{.Loss}$). In addition, by utilizing the suitable gains parameters for the PI controller that is located in the DC control section, which is coupled to the main controller, the DC voltage of the shunt-integrated RSMLI remains constant. The DC control section corrects errors induced by the variation of the real DC voltage ($V_{dc.a}$) and the standard DC voltage ($V_{dc.r}^*$). The results of the controlling component at the nth point are shown in (5) and (6).

$$V_{dc.er} = V_{dc.r}^* - V_{dc.a} \quad (5)$$

$$\Delta_{ia.dc} = K_{p.d} * \left(V_{dc.er(n)} - V_{dc.er(n-1)}\right) + K_{i.d} * \left(V_{dc.er(n)}\right) \quad (6)$$

Figure 3 depicts the schematic design of an IRP controller. As a result, as indicated in (7), the acquired reference currents ($i_{cr.\alpha\beta}^*$) in the $\alpha\beta$-frame are reverted into the initial abc frame via an inverted Clarke's transformation process, delivering the final reference current as ($i_{cr.abc}^*$).

$$\begin{bmatrix} i_{cr.a}^* \\ i_{cr.b}^* \\ i_{cr.c}^* \end{bmatrix} = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1 & 0 \\ 1/\sqrt{2} & -1/2 & \sqrt{3}/2 \\ 1/\sqrt{2} & -1/2 & -\sqrt{3}/2 \end{bmatrix} \begin{bmatrix} i_0^* \\ i_{c.\alpha}^* \\ i_{c.\beta}^* \end{bmatrix} \quad (7)$$

In fact, the proposed RSMLI topology is controlled by using the reduced-carrier PWM technique; it requires low carrier signals for the generation of required 5-voltage levels which decreases the complex drive circuitry over the hase-shifted pulse width modulation (PSPWM) and level-shifted pulse width modulation (LSPWM) techniques [28]–[33]. For generation of 5-voltage levels, the proposed RCPWM technique requires only 1 sinusoidal reference signal V_{ref} with a frequency of 50 Hz. Also, 2 triangular carrier signals are needed such as V_{c1}, V_{c2}, V_{c3}, and V_{c4}, with a carrier frequency of 3050 Hz which are vertically disposed and slight variations in magnitude of carrier signals. The switching pattern and switching pulses of the proposed RCPWM technique are depicted in Figures 4 and 5.

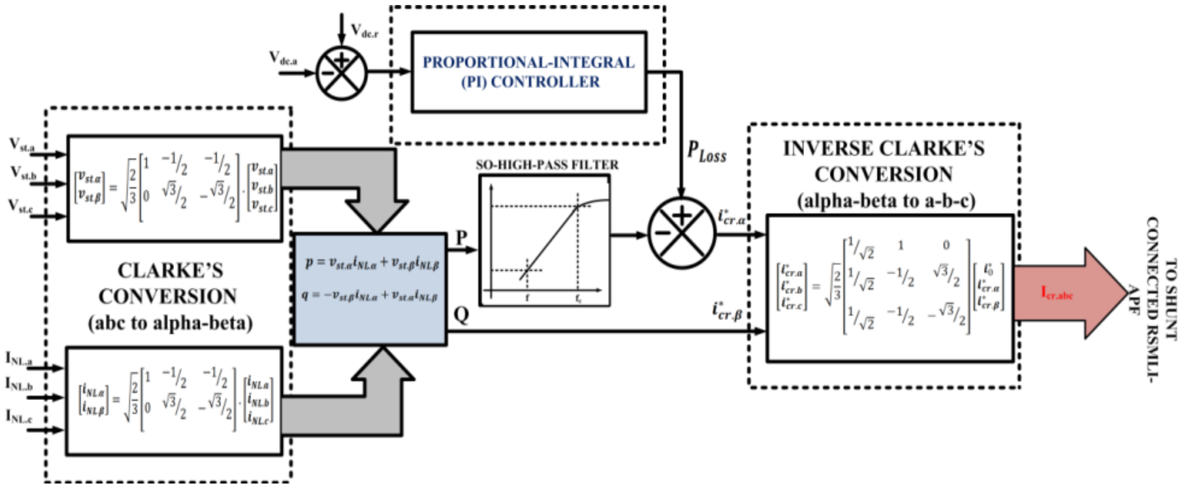


Figure 3. Schematic model of IRP control for shunt RSMLI of APF device

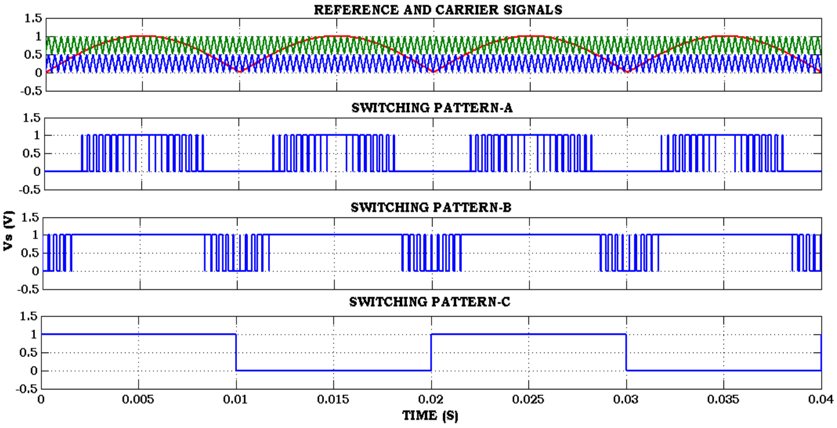


Figure 4. Switching pattern

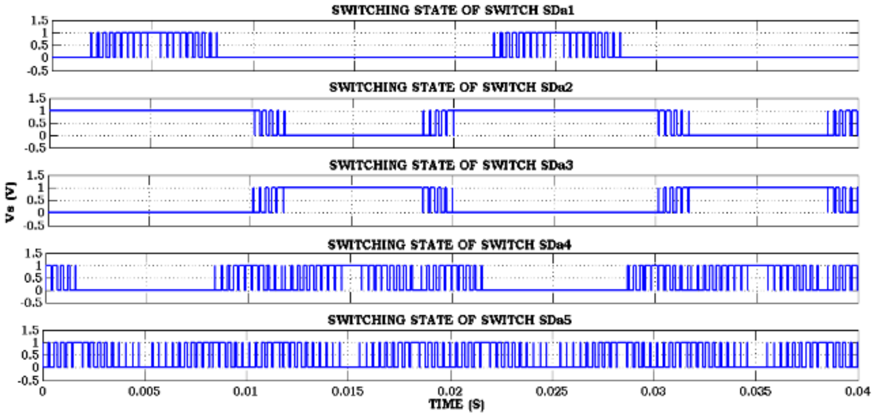


Figure 5. Switching states

4. RESULTS AND DISCUSSION

The effectiveness of the proposed RSMLI-APF is validated by integrating the number of charging units with the MATLAB/Simulink tool, and simulation outcomes are shown along with comparisons. Also, the specifications and values of the proposed concept are illustrated in Table 2.

Table 2. Specifications and values

S. No	System parameters	Values
1	Supply voltage	V_{sabc}-415 V and F_S-50 Hz
2	Supply impedance	Rs-0.1 Ω and Ls-0.9 mH
3	Non-linear load impedance	R_{NL}-30 Ω and L_{NL}-30 mH
4	DC capacitor	V_{dc}-880 V and C_{dc}-1500 µF
5	VSI's filter	R_f-0.1 Ω and L_f-5 mH
6	EV battery voltage	V_{bat}-400 V, I_{bat}-30 A, and P_{bat}-12 KW
7	PI controller	K_p-18.3 and K_i-4.3
8	RCPWM carrier frequency	Fc-3050 Hz

4.1. Performance of proposed novel 5-level reduced-switch multilevel inverter-active power filter for power quality enhancement under one electric vehicle charging connected system

Figure 6 shows the simulation results of the proposed novel 5-level RSMLI-APF for PQ enhancement under one EV charger-connected system. For driving the EV charger load, the three-phase distribution network is powered by a supply with a three-phase voltage of Vrms-415 V and a rated operating frequency of Fs-50 Hz. It comprises a 3-phase diode-bridge rectifier with an EV charging system as a non-linear load that produces harmonic fluctuations that impact the current quality at the distribution systems PCC. This non-linear EV charger loading uses approximately 30 A of rated current, distorting the supply or PCC current and causing significant heat loss and damage to other adjacent connected loads at the PCC level.

To reduce the harmonics of current at the PCC, a shunt-connected 5-level RSMLI-APF device governed by IRP control methodology was used. It injects the necessary in-phase compensation currents to compensate for the harmonics in the 30 A supply current. The shunt-integrated 5-level RSMLI-APF circuit consequently generates supply or PCC current that is sinusoidal in shape, linear in nature, fundamentally important, and well-balanced as seen in Figure 6(a). Thus, the supply or PCC current is in phase with the supplying voltage, resulting in a power factor of unity at the supply or PCC level, as shown in Figure 6(b). The calculated total harmonic distortion (THD) of the EV charger load current is 3.88%, while the calculated THD of the supply current is 2.58%, indicating that the supply current THD levels are under the IEEE-519/2014 standards, as illustrated in Figures 6(c) and (d).

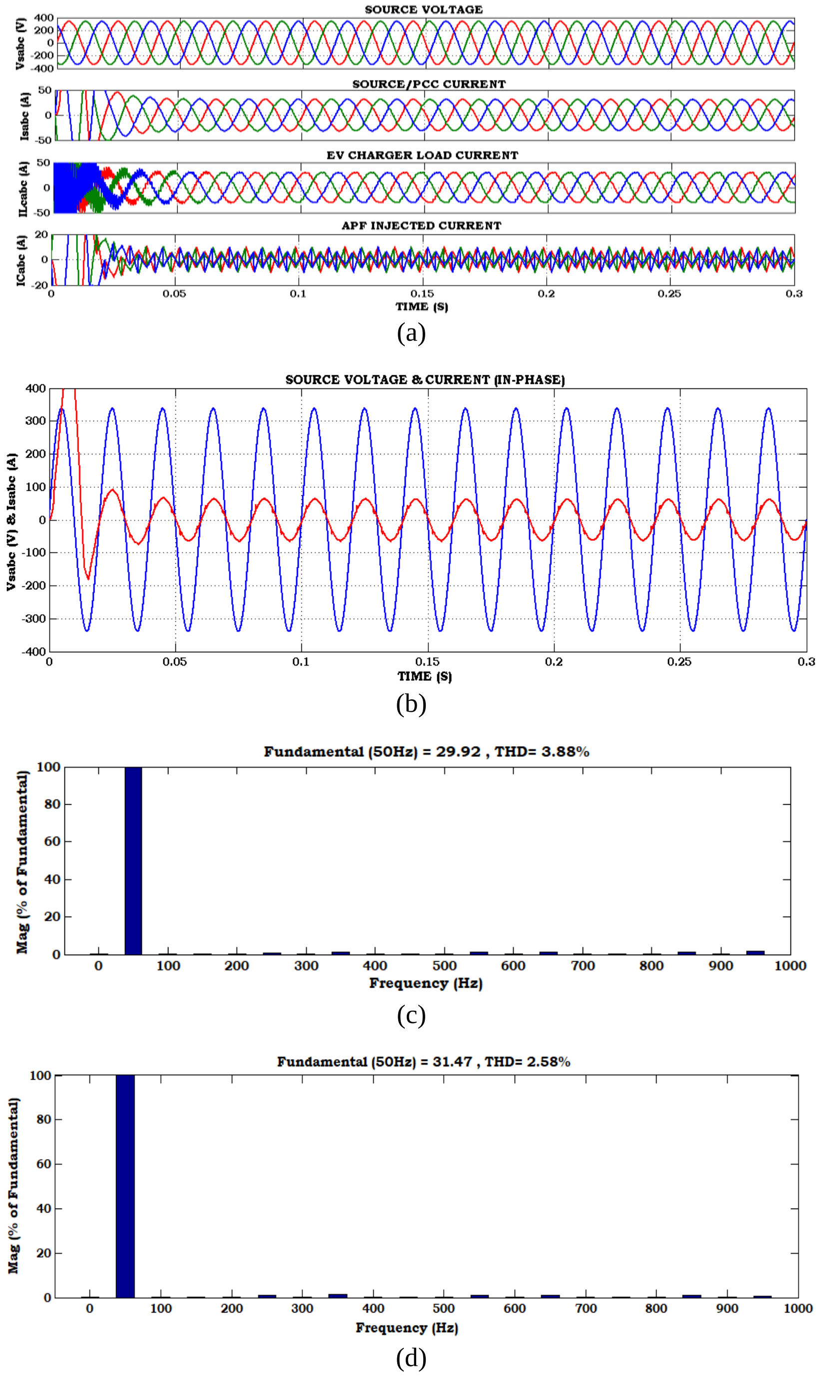


Figure 6. Simulation results of proposed novel 5-level RSMLI-APF for PQ enhancement under one EV charging connected system (a) harmonic current mitigation, (b) source voltage and current (in-phase condition, (c) THD of EV charger load current, and (d) THD of source or PCC current

4.2. Performance of proposed novel 5-level reduced-switch multilevel inverter-active power filter for power quality enhancement under three electric vehicle charging connected system

Figure 7 (in the Appendix) shows the simulation results of the proposed novel 5-level RSMLI-APF for PQ enhancement under three EV charger-connected systems. For driving the EV charger load, the three-phase distribution network is powered by a supply with a three-phase voltage of Vrms-415 V and a rated operating frequency of Fs-50 Hz. It comprises a 3-phase diode-bridge rectifier with an EV charging system as a non-linear load that produces harmonic fluctuations that impact the current quality at the distribution systems PCC. This non-linear EV charger loading uses approximately 30 A of rated current, distorting the supply or PCC current and causing significant heat loss and damage to other adjacent connected loads at the PCC level. To reduce the harmonics of current at the PCC, a shunt-connected 5-level RSMLI-APF device governed by IRP control methodology was used. It injects the necessary in-phase compensation currents to compensate for the harmonics in the 30 A supply current. The shunt-integrated 5-level RSMLI-APF circuit consequently generates supply or PCC current that is sinusoidal in shape, linear in nature, fundamentally important, and well-balanced as seen in Figure 7(a). Thus, the supply or PCC current is in phase with the supplying voltage, resulting in a power factor of unity at the supply or PCC level, as shown in Figure 7(b). The calculated THD of the EV charger load current is 11.57%, while the calculated THD of the supply current is 3.94%, indicating that the supply current THD levels are under the IEEE-519/2014 standards, as illustrated in Figures 7(c) and (d).

4.3. Performance of proposed novel 5-level reduced-switch multilevel inverter-active power filter for power quality enhancement under five electric vehicle charging connected system

Figure 8 (in the Appendix) shows the simulation results of the proposed novel 5-level RSMLI-APF for PQ enhancement under five EV charger-connected systems. This non-linear EV charger loading uses approximately 30 A of rated current, distorting the supply or PCC current and causing significant heat loss and damage to other adjacent connected loads at the PCC level. To reduce the harmonics of current at the PCC, a shunt-connected 5-level RSMLI-APF device governed by IRP control methodology was used. It injects the necessary in-phase compensation currents to compensate for the harmonics in the 30 A supply current. The shunt-integrated 5-level RSMLI-APF circuit consequently generates supply or PCC current that is sinusoidal in shape, linear in nature, fundamentally important, and well-balanced as seen in Figure 8(a). Thus, the supply or PCC current is in phase with the supplying voltage, resulting in a power factor of unity at the supply or PCC level, as shown in Figure 8(b). The calculated THD of the EV charger load current is 19.09%, while the calculated THD of the supply current is 3.81%, indicating that the supply current THD levels are under the IEEE-519/2014 standards, as illustrated in Figures 8(c) and (d). The simulation result of the suggested 5-level RSMLI architecture is shown in Figure 9 (in the Appendix). The suggested RSMLI topology's staircase 5-level output voltage is displayed in Figure 9(a) with a value of about 880 V and the THD spectrum of 5-level output voltage is presented in Figure 9(b), respectively. Table 3 and Figure 10 provide THD comparisons and a graphical perspective of the proposed novel 5-level RSMLI-APF for harmonic elimination based on the number of EV charging systems connected to the distribution network. Table 4 shows a comparison of the number of switching devices for standard MLI topologies and the proposed 5-Level RSMLI design. In comparison to traditional MLI topologies, the proposed RSMLI topology requires many fewer switching devices, reducing topology size, cost, and complexity.

Table 3. THD comparisons

THD (%)	EV charger load current	Source current
With one EV charging system	3.88%	2.58%
With three EV charging systems	11.57%	3.94%
With five EV charging systems	19.09%	3.81%

Table 4. Comparison of the number of switching devices for classical MLI topologies and proposed 5-level RSMLI topology

Topologies/	Classical 5-level MLI topologies			Proposed 5-level RSMLI
Switching devices	DCMLI topology [15]	FC-MLI topology [16]	CHBMLI topology [17]	topology
Main switches	8	8	8	5
Input DC sources	4	4	2	1
Clamping diodes	12	0	0	0
Body diodes	8	8	8	5
Balancing capacitors	0	6	0	0

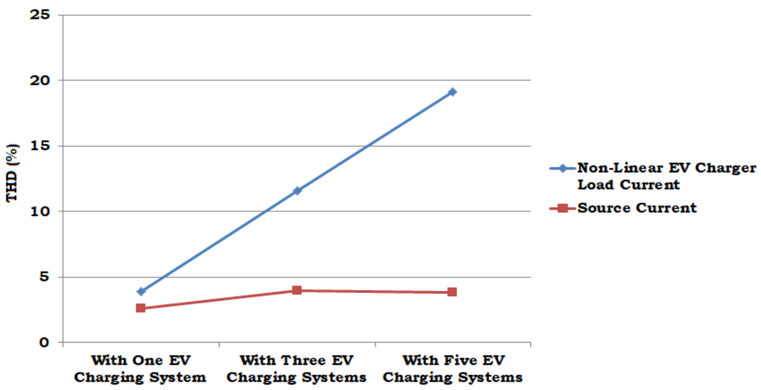
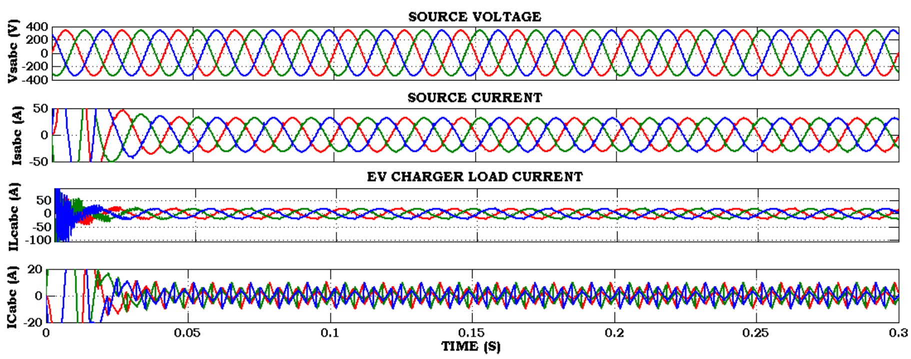


Figure 10. Graphical view of proposed novel 5-level RSMLI-APF for harmonic elimination under a number of EV charging systems connected to the distribution network

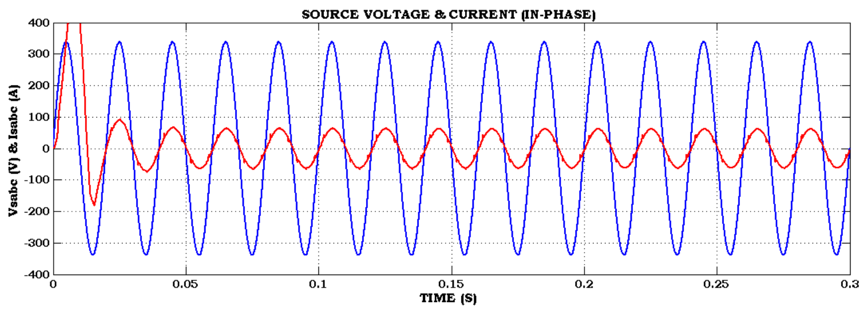
5. CONCLUSION

In this work, an efficient 5-level RSMLI-PWM has been proposed for the compensation of harmonic currents and power-factor correction in EV chargers connected distribution system. The shunt-connected 5-level RSMLI-APF enhances the power-quality features in the distribution system as a result; the system has a well-balanced, linear, and fundamental character. Over the classical 5-level MLI topologies, the key merits of the proposed 5-level RSMLI topology have fewer switches, compact size, good quality RMS voltage, reduced common-mode voltage, low harmonic content, low dV/dt stress and switch losses, and increased efficiency. Also, the proposed RCPWM technique requires only 2 carriers for the generation of required switching pulses to novel 5-level RSMLI topology among the PSPWM and LSPWM techniques, which reduces the computational delay, and complex gate-pulse generation unit. Therefore, the proposed novel 5-level RSMLI topology requires very less switching devices and no need for any high-frequency transformers which reduces the size, cost, and complex control circuitry. The THD spectrum of source current in all EV charger-connected systems is well maintained as per IEEE-519/2014 values.

APPENDIX



(a)



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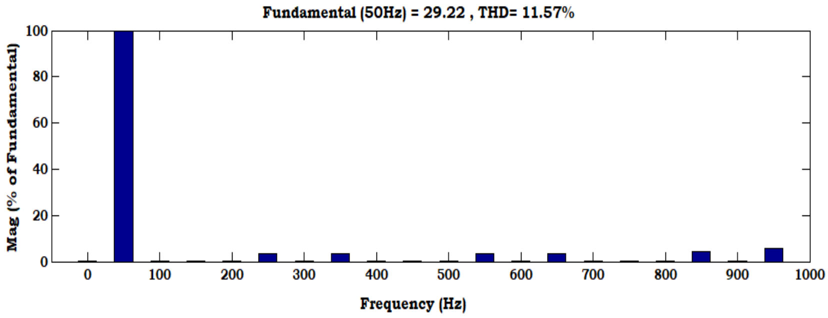

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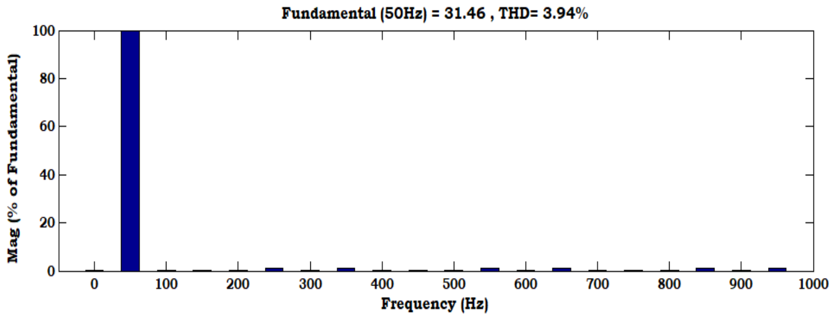
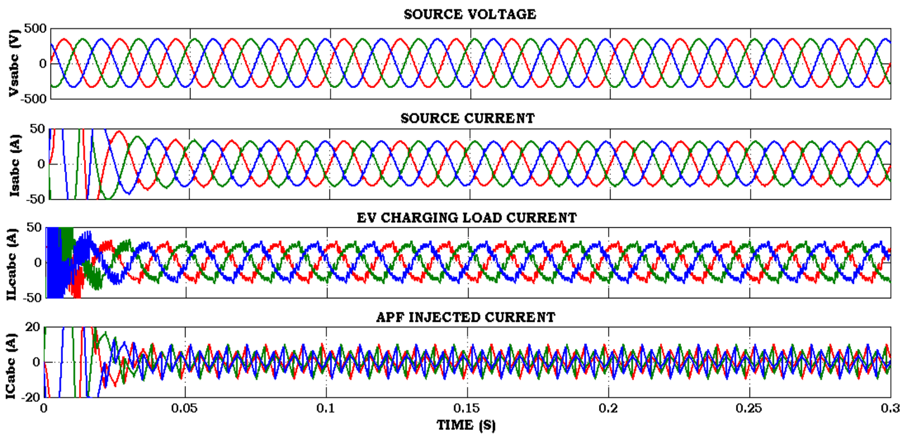


(d)

Figure 7. Simulation results of proposed novel 5-level RSMLI-APF for PQ enhancement under three EV charging connected systems (a) harmonic current mitigation, (b) source voltage and current (in-phase), (c) THD of EV charger load current, and (d) THD of source or PCC current



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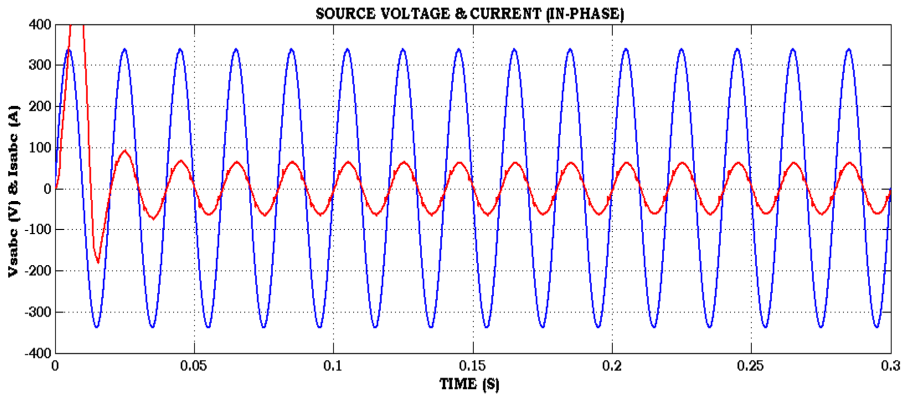

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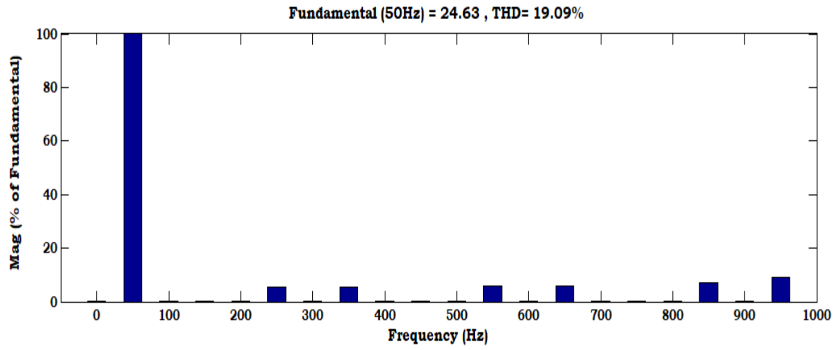

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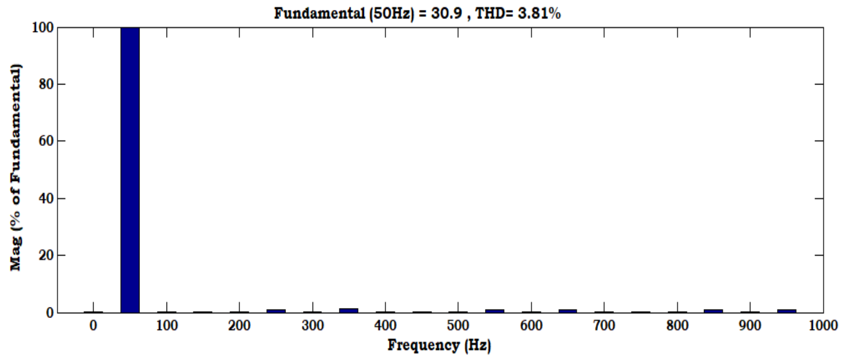
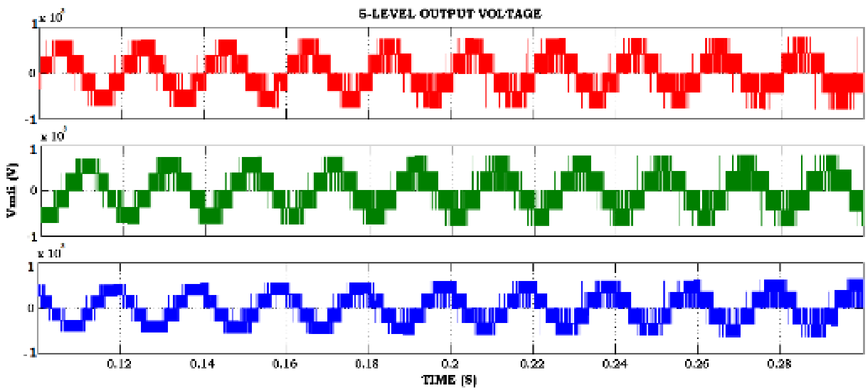
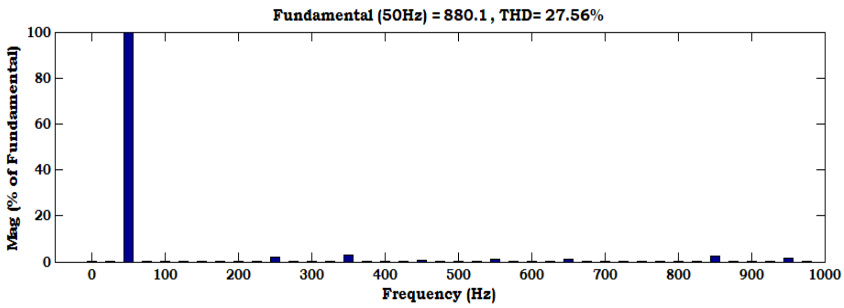


(d)

Figure 8. Simulation results of proposed novel 5-level RSMLI-APF for PQ enhancement under five EV charging connected systems (a) harmonic current mitigation, (b) source voltage and current (in-phase), (c) THD of EV charger load current, and (d) THD of source or PCC current



(a)



(b)

Figure 9. Simulation result of proposed 5-RSMLI topology (a) output 5-level voltage and (b) THD of output 5-level voltage

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