

Design and performance evaluation of multilevel inverter for solar energy systems and electric vehicle charging with multi output active clamp forward converter

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Abstract. This paper addresses the challenges of achieving efficient and high-quality power conversion in solar energy systems and electric vehicle (EV) charging applications by introducing a Multi-Output Active Clamp Forward Converter (MOACFC). The proposed system is designed to generate symmetrical and asymmetrical DC voltage configurations for a Multilevel Inverter (MLI) topology. Traditional MLI topologies often require numerous switches and DC sources, leading to increased complexity and reduced efficiency. To overcome these limitations, the MOACFC delivers multiple output voltages from a single solar generation input, effectively reducing the number of switches and DC sources required. This study also highlights the application of a Recurrent Neural Network Incremental Conductance (RNN-INC)-based Maximum Power Point Tracking (MPPT) algorithm to optimize power extraction from photovoltaic (PV) arrays. The MLI system's fundamental module can produce 9-level, 21-level, and 31-level outputs, with the Nearest Level Control Pulse Width Modulation (NLCPWM) and Level Shifted Pulse Width Modulation (LSPWM) techniques employed to minimize Total Harmonic Distortion (THD). The results demonstrate significant improvements in power quality, with THD levels reduced to 3.77% in voltage and 0.99% in current for EV charging applications – substantially better than conventional 2-level and 3-level inverters. The findings indicate that the proposed MOACFC-MLI system is a more efficient and reliable alternative, offering enhanced power quality and reduced electrical stress on EV battery systems.

Keywords: Solar generation, Recurrent neural networks, Incremental conductance, Multilevel inverter, Active clamp forward converter, Total harmonic distortion, Nearest level control pulse width modulation (NLCPWM).

1 Introduction

The increasing global population, coupled with the ever-growing demands of businesses and daily necessities, has placed significant emphasis on power generation. To meet these demands, numerous power plants have been established over time, with the majority relying on traditional energy sources. In India, approximately 75% of the country's energy is generated through thermal power stations that primarily use coal and fossil fuels. This heavy dependence on fossil fuels has resulted in a considerable rise in carbon emissions, which in turn has had a profound impact on atmospheric and climatic conditions. These ongoing environmental changes have sparked concerns about the long-term sustainability of such energy production methods [1].

As a result of these concerns, there has been growing interest in the development and utilization of sustainable energy sources such as solar and wind power. These renewable energy sources are classified as eco-friendly and non-traditional alternatives to conventional fossil fuel-based power generation. The increasing focus on renewable energy has become a significant area of research, particularly in the fields of power electronics and power systems. Researchers aim to expand the applications of these sustainable energy sources to reduce the heavy reliance on weather-dependent power generation and enhance the overall reliability of the energy supply. The concept of Multilevel Inverters (MLIs) was first introduced in relation to the 3-level converter, marking its inception in the late 20th century. MLIs have since evolved to include a greater number of voltage levels compared to standard inverter configurations. This increase in the number of levels has led to improvements in power rating and a reduction in the number of required devices

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[2]. MLIs offer numerous advantages over traditional voltage source inverters (VSIs) and current source inverters (CSIs), such as increased efficiency in buck-boost operations and Quasi-Z-Source Inverters (Q-ZSIs). These operations are more efficient than those performed by conventional VSIs and CSIs, making MLIs an attractive option for high-power applications [3].

One of the key features of MLIs is their ability to maintain power delivery even during the maintenance or failure of one of the converters. This capability was demonstrated in a study [4], where a novel 5-level fault-tolerant MLI topology is proposed, designed to tolerate both single and multiple-switch open-circuit faults. This topology can generate all required voltage levels while maintaining capacitor voltage balancing even when one or two switches fail. Particularly, the output power remains preserved in all faulty scenarios. However, one drawback of this topology is its increased complexity in control and implementation, which may require more advanced and costly control systems to effectively manage fault tolerance and ensure reliable operation under all conditions. MLIs are particularly well-suited for demanding applications and high-power evaluations. They consist of various power electronic devices arranged in a specific configuration that works in conjunction with DC-connected voltages to generate higher levels of output waveforms [5]. The adoption of MLIs is driven by their numerous inherent advantages, including reduced switching stress, minimized dv/dt impact on switches, enhanced reliability, cost-effectiveness, simplified design complexity, reduced Total Harmonic Distortion (THD), and increased efficiency across a wide range of applications [6].

MLIs play a crucial role not only in renewable energy applications but also in the context of electric vehicles (EVs). MLIs are known for their ability to generate a stepped waveform that closely approximates a sine wave by utilizing advanced power electronic switches. This capability makes MLIs a preferred choice for producing significant output, particularly in solar power generation systems [7]. The stepped waveform produced by MLIs helps reduce the harmonic content in the output, which is essential for maintaining power quality in renewable energy systems.

In the realm of MLI topologies, a distinctive hybrid MLI configuration has been introduced in [8], combining symmetrical and asymmetrical features. This innovative architecture is designed to reduce the number of devices and sources required, making it particularly suitable for applications in solar photovoltaics (PV) and motor drives. The hybrid topology leverages the advantages of both symmetric and asymmetric configurations, delivering high performance with fewer components, thereby improving efficiency and reducing costs in renewable energy systems.

In [9], a modified topology that integrates the Cascaded H-Bridge (CHB) MLI with the cascaded three-phase 2-level VSI topology is developed. This combination achieves higher voltage levels using fewer components compared to conventional MLI topologies of the same level. By directly connecting these two topologies, the need for line-frequency transformers is eliminated, thereby reducing the overall system cost and removing the associated drawbacks of

transformers. However, a notable drawback of this approach is the increased complexity in the control strategy, which may require more sophisticated algorithms to maintain stable operation and ensure proper voltage balancing across the levels.

In [10], the proposed MLI topology features an asymmetrical configuration utilizing five Insulated Gate Bipolar Transistor (IGBT) switches and two DC sources per phase, which is favored for its efficiency. The DC sources are optimized through the application of the Level Shift Pulse Width Modulation (LSPWM) control method. The operation and control of the three-phase, 9-level MLI in grid-tied mode with synchronverter control are thoroughly analysed. However, a drawback of this configuration is its increased complexity in the design and implementation of the control strategy, which may require more precise tuning and monitoring to ensure stable grid synchronization and effective fault handling.

In the context of EV charging systems, inverters are of paramount importance, serving both wired and wireless configurations. Various MLI designs have been developed to meet the specific needs of EV technology, especially when integrated with renewable energy sources (RES) [11, 12]. This integration is particularly valuable in systems that support vehicle-to-grid (V2G) operations, where power flow is bidirectional. In such systems, renewable energy sources are harnessed not only to power the vehicle but also to feed energy back into the grid. This approach enhances battery longevity and optimizes the states of charge (SOC) and discharge (SOD), thereby improving the overall efficiency and sustainability of EV operations.

In [13], a solar PV system featuring a 53-level MLI combined with a single-input, multiple-output DC-DC boost converter is described. The system utilizes the Perturb and Observe (P&O) method for Maximum Power Point Tracking (MPPT) to optimize energy extraction from the solar panels. The DC voltage generated by the solar panels is fed into the single-input, multiple-output boost converter, which increases the voltage to the required level before supplying it to the 53-level inverter. In [14], a new single-phase 7-level PWM inverter is introduced, designed to minimize the number of power components required for both standalone and grid-integrated PV systems. This innovative inverter achieves improvements in efficiency, footprint, and cost by reducing the component count. The MLI is comprised of two distinct circuits: the main circuit, which is a straightforward H-bridge inverter responsible for controlling the output voltage polarity, and the auxiliary circuit, which uses a combination of switches to generate the output voltage. Additionally, a boost converter is integrated within the PV array to facilitate MPPT at the input stage of the 7-level inverter.

In another MLI topology [15], DC voltage sources are connected in series to create various voltage combinations and can also be configured in parallel to achieve the desired output voltage. This arrangement, known as the Switched Series/Parallel Sources (SSPS) MLI, offers greater flexibility in obtaining different output voltage levels. An alternative architecture [16], called Series-Connected Switching Sources (SCSS), introduces a novel approach for generating

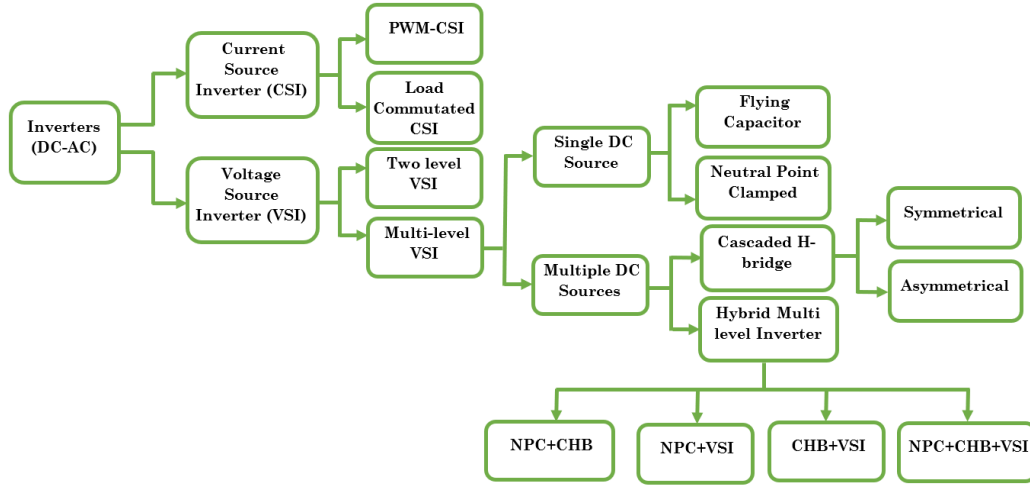


Fig. 1. Classification of MLI.

diverse converter configurations for various voltage levels. This design is notable for its ability to reduce THD using two perpendicular space vectors. The core idea of this architecture is its capacity to produce a unique set of 133 output space vectors, allowing for incremental adjustments of the root mean square (RMS) voltage. This method provides enhanced precision and control over the output voltage, making it particularly effective in applications where power quality and efficiency are crucial.

Classification of MLIs is shown in [Figure 1](#). The NPC (Neutral Point Clamped) and FC (Flying Capacitor) configurations of MLIs face challenges related to maintaining a balanced neutral point, which necessitates additional circuitry. Although researchers have proposed solutions to address this issue, these often involve incorporating more components into the existing systems, thereby increasing complexity [\[17–19\]](#). In contrast, CHB (Cascaded H-Bridge)-based MLIs have gained popularity due to their modular architecture, reduced need for capacitors, and simplified control. This design approach is widely adopted in various applications, including solar systems, storage batteries, and EVs [\[20\]](#).

In [\[21\]](#), a method is proposed for controlling a PV cascaded H-bridge MLI that addresses issues with failed cells and varying meteorological conditions in large-scale grid-connected applications. The controller is developed through an analysis of the interaction between the inverter's common-mode and differential-mode quantities, using both time-domain and space vector representation analyses. A notable drawback of this approach is that it may not fully account for the complexities introduced by rapid fluctuations in environmental conditions, which could impact its robustness and effectiveness in real-world scenarios.

In [\[22\]](#), a new single-phase pulse-width modulated 7-level inverter architecture is proposed for PV systems that support home-grid integration and EV charging. This inverter design features a reduced number of power components and passive elements, leading to lower output voltage THD and achieving unity power factor operation. Additionally, the inverter benefits from simplified control and

switching strategies compared to more recent topologies. However, a drawback of this design is that the limited number of levels increases the THD compared to higher-level inverters, potentially affecting power quality.

In [\[23\]](#), a novel capacitor-based boost multilevel inverter (CB-MLI) topology is introduced, designed specifically for EV and hybrid electric vehicle (HEV) applications. This topology can generate an 11-level waveform using just eleven switches, three capacitors, and a single isolated source. Its unique self-balancing capacitor feature sets it apart from other designs. The control strategy employs a constant carrier PWM approach for switching the IGBTs. However, a drawback of this topology is that the complexity of balancing the capacitors might introduce challenges in maintaining consistent performance under varying operating conditions.

In [\[24\]](#), a bidirectional single-phase, 3-level stacked neutral-point-clamped (3L-SNPC) converter for charging station (CS) applications is analysed. This converter can function as either a rectifier or an inverter, depending on the direction of power flow. The study proposes a 3L-SNPC topology specifically for EV charging stations. Additionally, it describes a potential CS architecture that facilitates the integration of utility grids and renewable energy sources, such as PV and wind systems, allowing for surplus energy to be fed back into the AC grid and supporting distributed generation. However, a drawback of this approach is that the complexity of the 3L-SNPC topology may increase the overall system cost and control complexity, potentially offsetting some of the benefits of its bidirectional capability.

In [\[25\]](#), a novel grid-tied system for PV applications is introduced, featuring an enhanced flyback DC-DC converter paired with a new switched-capacitor (SC) based MLI. This design addresses a significant issue in capacitive switching inverters – the problem of impact currents during capacitor charging – by incorporating an inductor with a parallel diode in the capacitive charging current path. This approach improves the efficiency of the converter and mitigates charging current stress on the capacitors. However, a drawback of this system is that the added components (inductor and diode) may increase the overall system

complexity and cost, potentially impacting the practicality of the design for some applications.

In [26], a charging architecture for the Reconfigurable Cascaded Multilevel Converter tailored for EV powertrain applications is presented. The innovative aspect of this design is the direct connection between the AC system and the powertrain converter through an inductor filter, while the required galvanic isolation for onboard chargers is managed within the Electric Vehicle Supply Equipment (EVSE) control box. However, a potential drawback of this approach is that the reliance on an external EVSE for galvanic isolation might complicate the integration process and increase system costs. In [27], a novel grid-connected modular inverter is proposed for an integrated bidirectional charging station aimed at residential applications. This system supports the electrical grid by providing buffering services and enhancing grid stability. The proposed modular bidirectional inverter can also function as an EV charger. However, a notable drawback is the high THD associated with this design, which can adversely affect power quality and system efficiency.

This paper presents the design and implementation of a Multi-Output Active Clamp Forward Converter (MOACFC) aimed at generating both symmetrical and asymmetrical DC voltage configurations for a MLI topology specifically tailored for solar energy generation systems. The proposed MLI topology can produce 9-level, 21-level, and 31-level voltage outputs. A key feature of this design is the significant reduction in the number of components required, utilizing only eight switches, which is considerably fewer than those used in conventional MLI systems. This reduction in components not only simplifies the overall design but also leads to a decrease in conduction and switching losses, thereby enhancing the overall efficiency of the system. The MOACFC plays a critical role in this system by providing multiple output voltages simultaneously from a single solar generation source. This is particularly important in MLIs where different voltage levels are required to create the stepped waveform that approximates a sinusoidal output. The ability of the MOACFC to generate these multiple voltage levels from a single input source simplifies the power conversion process and reduces the need for additional converters or complex circuitry. To maximize the power output from the PV arrays, the MOACFC is operated using a Recurrent Neural Network Incremental Conductance (RNN-INC)-based MPPT algorithm. This advanced MPPT algorithm is designed to efficiently track the maximum power point of the PV arrays, ensuring that the solar energy system operates at its highest possible efficiency. RNNs are particularly well-suited for this task because of their ability to learn from and adapt to changing conditions over time, which is a common challenge in renewable energy systems due to the dynamic nature of environmental factors such as irradiance and temperature.

Unlike traditional INC algorithms, which rely on predefined, fixed control rules that may not be optimal under all conditions, the RNN-based approach offers a more flexible and adaptive solution. The RNN can continuously learn and adjust its control strategy based on the current

operating conditions, potentially leading to improved performance in real-world scenarios where conditions are constantly changing. This adaptability makes the RNN-INC MPPT algorithm a promising tool for enhancing the efficiency and reliability of solar generation systems, particularly in dynamic environments.

The main objectives of this work are summarized as follows:

- Introducing the MOACFC as a novel approach for generating symmetrical and asymmetrical DC voltage configurations for MLIs in solar generation systems.
- Demonstrating the capability of the MOACFC-enhanced MLI to produce 9-level, 21-level, and 31-level voltage outputs, thus reducing the complexity of traditional MLI topologies.
- Proposing the integration of the MOACFC with an RNN-INC-based MPPT algorithm to efficiently track maximum power output from PV arrays.
- Rigorously testing the combined performance of the MLI and MOACFC in dynamic environments with EV charger as the load.
- Evaluating the output voltage and current waveforms of various inverters using LSPWM, highlighting the achieved levels of THD for each configuration.

The paper is planned as follows: [Section 2](#) provides an explanation of the MLI configuration, [Section 3](#) covers various modulation strategies, [Section 4](#) explains the MOACFC with a solar generation system, [Section 5](#) presents the EV charging application and closed loop control, [Section 6](#) presents simulation results, and [Section 7](#) discusses experimental results before concluding.

2 MLI configuration

In this section working of MLI and its switching states are explained. For simplicity, constant voltage sources are employed and replaced with solar generation systems in further sections. [Figure 2](#) depicts the MLI configuration discussed in this work [2]. This architecture consists of four interconnected units that play a pivotal role in establishing voltage amplitude levels. Additionally, the setup includes four supplementary switches responsible for controlling the polarity of these voltage levels. Each unit is composed of essential components: a direct current (DC) source, a controlled switch utilizing IGBTs technology, and an uncontrolled switch (diode). When utilizing symmetric or equal DC sources set at a magnitude denoted as ($V_1 = V_2 = V_3 = V_4 = V_{dc}$) the system can generate nine distinct voltage levels across the designated load.

To have more voltage levels in the load, it is advisable to consider using DC sources that are not equal or symmetrical. By incorporating four distinct DC sources characterized by magnitudes of ($V_1 = V_{dc}$, $V_2 = 2V_{dc}$, $V_3 = 3V_{dc}$ and $V_4 = 4V_{dc}$), the resulting configuration can generate a total of 21 output voltage levels. By applying another combination of four voltages ($V_1 = V_{dc}$, $V_2 = 2V_{dc}$, $V_3 = 4V_{dc}$

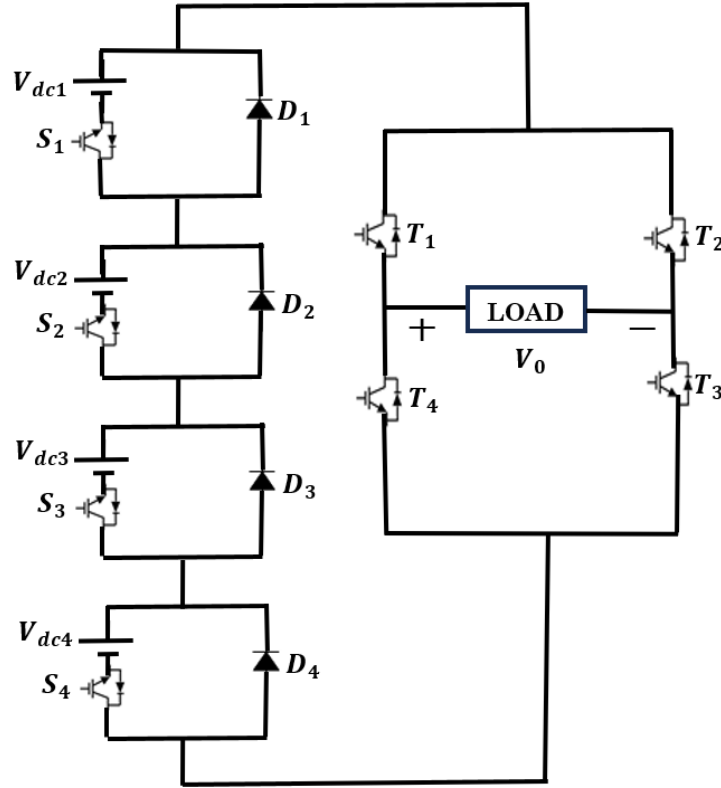


Fig. 2. Multilevel inverter with four units.

and $V_4 = 8V_{dc}$), the configuration can produce a total of 31 discrete output voltage levels.

S_1, S_2, S_3 and S_4 are the four switches in four units for voltage levels and T_1, T_2, T_3 and T_4 are the four switches for output voltage polarity. Table 1 illustrates the switching combinations of 8 switches required to achieve 31 levels. In this representation, “1” signifies the switch is in the on state, while “0” denotes that the switch is in the off state.

Figure 3 presents a detailed depiction of the complex relationship between switching states and their corresponding current flow directions in a 31-level configuration. Each switching state, distinguished by specific combinations of semiconductor switches, governs both the path and magnitude of current within the system.

For a 9-level voltage at the output with equal or symmetric DC sources, the number of DC sources required is N_{dc} given as

$$N_{dc} = 4.$$

The number of levels and the number of DC sources are related as

$$N_{level} = 2 \times N_{dc} + 1.$$

The number of switches and the number of DC sources are related as

$$N_{sw} = N_{dc} + 4.$$

And number of levels is given as

$$N_{level} = 2 \times N_{sw} - 7.$$

For 21-level output voltage with unequal or asymmetric DC sources, the number of DC Sources is equal to

$$N_{dc} = 4.$$

The number of levels and the number of DC sources are related as

$$N_{level} = N_{dc}(N_{dc} + 1) + 1.$$

Then the number of switches and the number of DC sources are related as

$$N_{sw} = N_{dc} + 4.$$

And number of levels is given as

$$N_{level} = (N_{sw} - 4)(N_{sw} - 3) + 1.$$

For 31-level output voltage with unequal or asymmetric DC sources, the number of DC Sources is equal to

$$N_{dc} = 4.$$

The number of levels and the number of DC sources are related as:

$$N_{level} = 2^{(N_{dc}+1)} - 1.$$

Then the number of switches in terms of the number of DC sources is given as

Table 1. Switching combination for 31-Level.

Levels	S1	S2	S3	S4	T1	T2	T3	T4
+15 V	1	1	1	1	1	0	1	0
+14 V	0	1	1	1	1	0	1	0
+13 V	1	0	1	1	1	0	1	0
+12 V	0	0	1	1	1	0	1	0
+11 V	1	1	0	1	1	0	1	0
+10 V	0	1	0	1	1	0	1	0
+9 V	1	0	0	1	1	0	1	0
+8 V	0	0	0	1	1	0	1	0
+7 V	1	1	1	0	1	0	1	0
+6 V	0	1	1	0	1	0	1	0
+5 V	1	0	1	0	1	0	1	0
+4 V	0	0	1	0	1	0	1	0
+3 V	1	1	0	0	1	0	1	0
+2 V	0	1	0	0	1	0	1	0
+1 V	1	0	0	0	1	0	1	0
0 V	0	0	0	0	1	0	1	0
0 V	0	0	0	0	0	1	0	1
-1 V	1	0	0	0	0	1	0	1
-2 V	0	1	0	0	0	1	0	1
-3 V	1	1	0	0	0	1	0	1
-4 V	0	0	1	0	0	1	0	1
-5 V	1	0	1	0	0	1	0	1
-6 V	0	1	1	0	0	1	0	1
-7 V	1	1	1	0	0	1	0	1
-8 V	0	0	0	1	0	1	0	1
-9 V	1	0	0	1	0	1	0	1
-10 V	0	1	0	1	0	1	0	1
-11 V	1	1	0	1	0	1	0	1
-12 V	0	0	1	1	0	1	0	1
-13 V	1	0	1	1	0	1	0	1
-14 V	0	1	1	1	0	1	0	1
-15 V	1	1	1	1	0	1	0	1

$$N_{sw} = N_{dc} + 4.$$

And number of levels is given as

$$N_{level} = 2^{(N_{sw}-3)} - 1.$$

The number of devices required to achieve the voltage levels is presented in Table 2.

Figure 4 provides a detailed comparison between the proposed configuration and the configuration presented in the literature, focusing on the number of switches and the number of levels employed in each design.

2.1 Losses and efficiency

The proposed MLI's overall losses are sum of switching losses (P_S), and conduction losses (P_C).

Switching losses occur due to the inherent delay in changing the state of a switch, whether it is transitioning from the on to off position or vice versa. These losses are visible in both controlled and uncontrolled switches. A switch or diode with a shorter recovery time results in reduced switching losses. The switching losses during the closed state of the switch depend on the ON state resistance of the switch. The ON and OFF state switching losses of each IGBT are given as

$$P_{S_ON} = \frac{f_s t_{ON} V_{OFF} I_{ON}}{6}$$

$$P_{S_OFF} = \frac{f_s t_{OFF} V_{OFF} I_{ON}}{6}$$

t_{ON} and t_{OFF} are turn-on time interval and turn-off time interval individually, f_s is the switching frequency, V_{OFF}

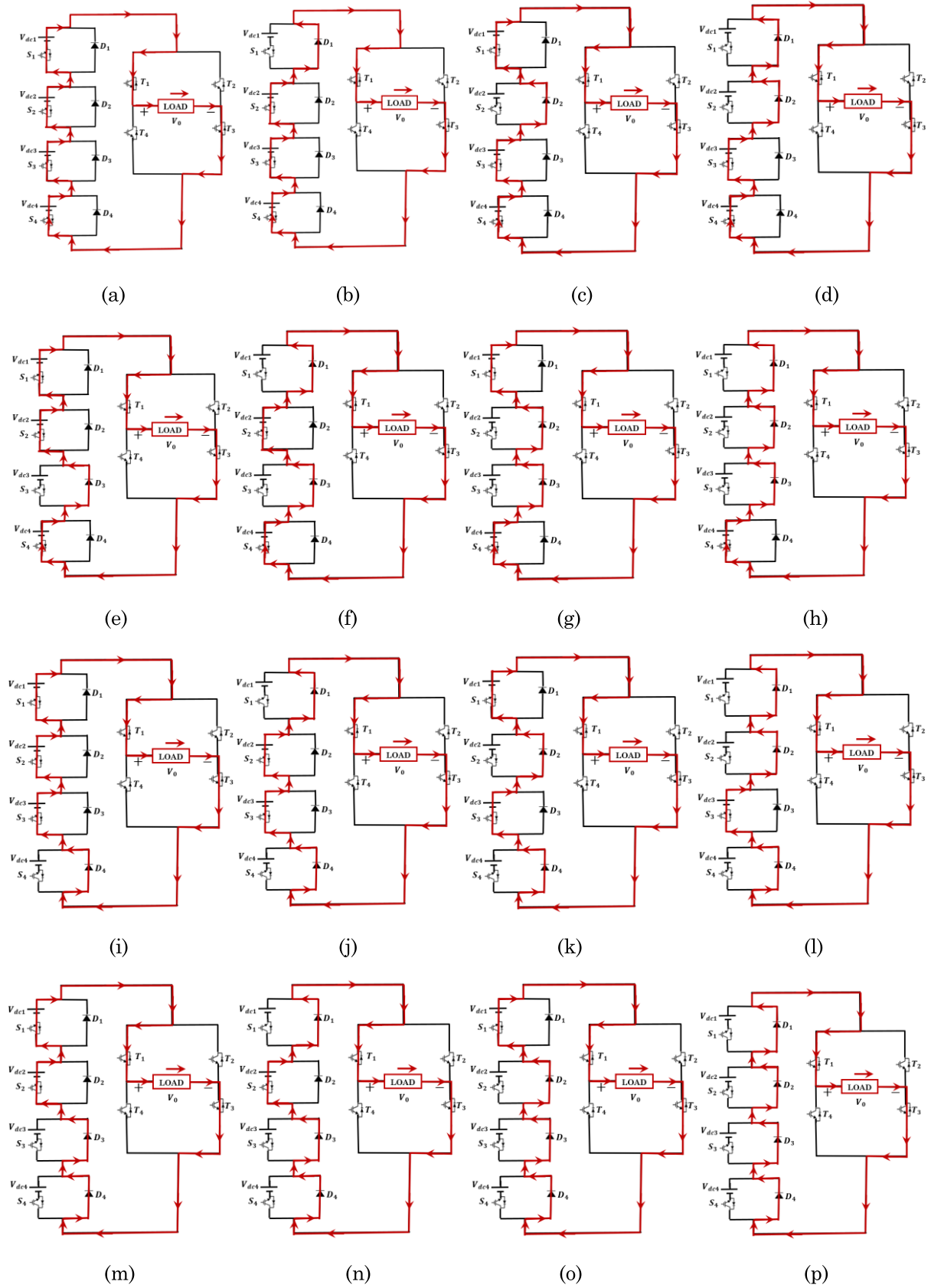
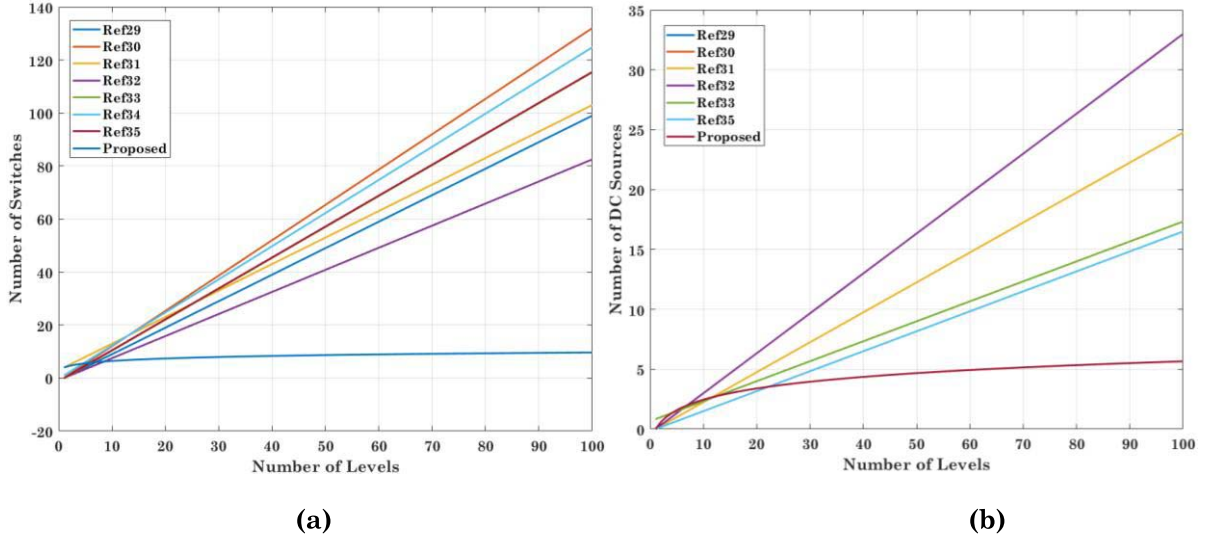


Fig. 3. Switching states to generate different positive and zero levels with $V_1 = V_{dc}$, $V_2 = 2V_{dc}$, $V_3 = 4V_{dc}$ and $V_4 = 8V_{dc}$; (a) $V_o = +15V_{dc}$; (b) $V_o = +14V_{dc}$; (c) $V_o = +13V_{dc}$; (d) $V_o = +12V_{dc}$; (e) $V_o = +11V_{dc}$; (f) $V_o = +10V_{dc}$; (g) $V_o = +9V_{dc}$; (h) $V_o = +8V_{dc}$; (i) $V_o = +7V_{dc}$; (j) $V_o = +6V_{dc}$; (k) $V_o = +5V_{dc}$; (l) $V_o = +4V_{dc}$; (m) $V_o = +3V_{dc}$; (n) $V_o = +2V_{dc}$; (o) $V_o = +1V_{dc}$; (p) $V_o = 0$.

Table 2. The number of devices and respective voltage levels.

No. of levels N_{level}	Symmetric N_{sw}	First asymmetric N_s	Second asymmetric N_d
7	7	3	3
15	11	7	7
31	19	15	15
63	35	31	31
127	67	63	63
255	131	127	127

**Fig. 4.** (a) Number of levels against the number of switches, (b) Number of levels against the number of DC Sources.

switch rated voltage and I_{ON} average current through the switch.

Switching losses of the diode are given as

$$P_{\text{S-D}} = \frac{f_s t_B V_{\text{RM}} I_{\text{RM}}}{6}$$

t_B is the reverse current time delay, V_{RM} is the maximum reverse recovery voltage, and I_{RM} the maximum reverse recovery current.

The total switching losses of MLI are given as

$$P_{\text{S-T}} = \sum_{m=1}^{N_{\text{sw}}} \left(\sum_{n=1}^{N_{\text{ON}}} (P_{\text{S-ON-}mn}) + \sum_{n=1}^{N_{\text{OFF}}} (P_{\text{S-OFF-}mn}) \right) + \sum_{m=1}^{N_d} \left(\sum_{n=1}^{N_{\text{OFF}}} (P_{\text{S-D-}mn}) \right)$$

N_{ON} and N_{OFF} are number of active and inactive states of the switches within a fundamental cycle.

Conduction losses primarily result from two main factors. First, there is ON state resistance in each semiconductor device, and second, there is the voltage drop across this resistance. These factors together contribute to the conduction losses across the semiconductor devices.

$$P_{\text{C-SW}} = V_{\text{ON-SW}} I_{\text{SW-ave}} + R_{\text{ON-SW}} I_{\text{SW-RMS}}^2$$

$$P_{\text{C-D}} = V_{\text{ON-D}} I_{\text{D-ave}} + R_{\text{ON-D}} I_{\text{D-RMS}}^2$$

V_{ON} and R_{ON} are the active state resistance of the IGBT and diode. I_{RMS} and I_{ave} are the RMS and average current of IGBT and diode.

The efficiency of the MLI is expressed as.

$$\eta = \left(\frac{P_{\text{out}}}{P_{\text{out}} + P_{\text{loss}}} \right) \times 100$$

$$= \left(\frac{\frac{(V_{\text{out(RMS)}})^2}{R_{\text{Load}}}}{\frac{(V_{\text{out(RMS)}})^2}{R_{\text{Load}}} + P_{\text{S-T}} + P_{\text{C-SW}} + P_{\text{C-D}}} \right)$$

3 Modulation strategies

The efficacy of various modulation strategies can be assessed by analysing the smoothness of the output current and voltage waveforms, along with the absence of distortions within them. To enhance the primary voltage component in the inverter's output, a reduction in THD is

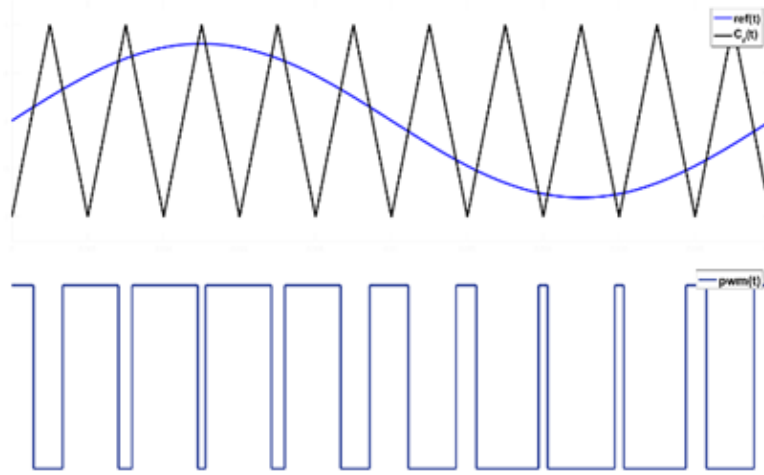


Fig. 5. Triangular carrier-based modulation scheme.

important. Increasing the fundamental voltage component in the output leads to increased load efficiency, enhanced power factor, protection of sensitive loads, and ultimately, an improvement in power quality at the receiving end. Therefore, the selection of modulation techniques must prioritize the minimization, or ideally, elimination of THD from the inverter's output.

3.1 Carrier-based PWM

In Figure 5, a modulation scheme utilizing a triangular carrier signal is depicted. Figure 5a displays both the reference sine wave and the triangular carrier wave, while Figure 5b presents the resultant PWM output.

The mathematical representation of the resulting pulse width modulation can be formulated as follows:

$$\begin{aligned}
 pwm(t) = & S + \frac{m_i}{2} \cos(\omega_1 t + \theta_1) \\
 & + \sum_{n=1}^{\infty} \frac{2}{n\pi} J_o\left(\frac{n\pi m_i}{2}\right) \sin(Sn\pi) \cos[n(\omega_c t + \theta_c)] \\
 & + \sum_{n=1}^{\infty} \sum_{p=\pm 1}^{\pm \infty} \frac{2}{n\pi} J_n \frac{n\pi m_i}{2} \sin\left(\frac{(2Sn+p)\pi}{2}\right) \\
 & \times \cos(n(\omega_c t + \theta_c) + p(\omega_1 t + \theta_1)).
 \end{aligned}$$

The modulation index is denoted as m_i , the carrier waveform frequency as ω_c , the fundamental frequency of the reference waveform as ω_1 , and Bessel functions J_o and J_n are also involved in the expression.

The modulation index m_i defines the degree to which the fundamental frequency component in the output voltage of an MLI can be controlled.

$$m_i = \frac{V_{ref}}{V_{c_r}}.$$

The peak value of the source wave is denoted as V_{ref} , and the peak value of the carrier wave is represented as V_{c_r} .

The frequency modulation index, known as m_f is characterized by the following definition:

$$m_f = \frac{\omega_c}{\omega_1}.$$

In a 2-level inverter, the operating frequency of active switches within the inverter can be computed as fundamental frequency ω_1 multiplied by the modulation factor m_f . However, in the context of a MLI, the switching frequency of active switches is affected by the number of levels integrated. When the carrier wave aligns with the reference wave, the modulation strategy is termed synchronous PWM. Conversely, if the carrier frequency remains constant and irrelevant to the reference wave, the resulting PWM is referred to as asynchronous PWM. This type of PWM might give rise to typical harmonics.

In LSPWM, the carrier waveforms are arranged in a sequence and then compared to the fundamental reference waveform. This process aims to generate a stepped multi-level output voltage from the MLI. If we denote the carrier waveform as $c_r(t)$, then the stacked carrier waveforms can be expressed as follows: $2c_{rm} + c_r(t)$, $2c_{rm} - c_r(t)$, $4c_{rm} + c_r(t)$, $4c_{rm} - c_r(t)$ and so forth, where c_{rm} signifies the highest value of the carrier waveform.

The positive slope of carrier signal $c_r(t)$ is given as

$$c_{r(ps)} = 2c_{rm}f_c - \frac{c_{rm}}{2}.$$

Positive slope of carrier signal $c_r(t)$ is given as

$$c_{r(ns)} = -2c_{rm}f_c + \frac{c_{rm}}{2}.$$

LSPWM is classified into three distinct types: APD-LSPWM, POD-LSPWM, and PD-LSPWM. In the PD-LSPWM approach, the carrier signals undergo level shifting while remaining in the same phase. Conversely, in POD-LSPWM, positive carrier signals experience a 180-degree phase shift relative to the negative carrier signals. In the instance of APD-LSPWM, alternating carrier signals are

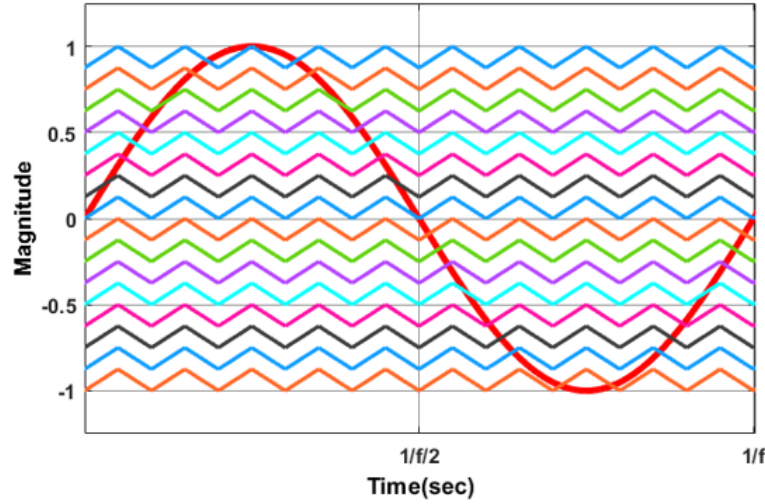


Fig. 6. PD-LSPWM.

subjected to a 180-degree phase shift. Figure 6 offers a visual representation of PD LSPWM. If the total of output voltage levels, involving the zero level, in a MLI is denoted as N_{level} , then the required count of carrier waveforms is equivalent to $N_{\text{level}} - 1$.

3.2 Nearest level control PWM

The fundamental principle at the core of this pulse width modulation is to establish an association between the reference voltage and the output voltage, typically by choosing the adjacent level. The ascending transition of the output signal is divided into two parts, known as the upper level and lower level, each having equal magnitudes. This approach is illustrated in Figure 7. To handle floating-point numbers, a rounding function is employed to determine the nearest even number.

Two methods can be employed to estimate the angles at which levels are changed.

1. Half height method

$$\theta_i = \sin^{-1} \left(\frac{i - 0.5}{n} \right)$$

where $n = \frac{N_{\text{level}} - 1}{2}$ and $i = 1, 2, 3, \dots, n$.

2. Half equal phase method

$$\theta_i = i \left(\frac{180}{2(n + 1)} \right)$$

where $n = \frac{N_{\text{level}} - 1}{2}$ and $i = 1, 2, 3, \dots, n$ and modulation index is given as $m_i = \frac{V_{\text{ref}}}{(N_{\text{level}} - 1) V_{\text{dc}}}$.

Within these two PWM strategies, there is a decrease in switching frequency, resulting in minimized power losses across the inverter and an enhancement in overall efficiency.

4 Multi-output active clamp forward converter (MOACFC) with solar generation system

A MOACFC is a specialized power electronics circuit used in DC-DC power conversion. It is an advanced variation of the conventional forward converter, which is a widely utilized configuration in numerous applications where efficient voltage conversion is required. The MOACFC, however, is distinct in its ability to provide multiple output voltages simultaneously from a single input voltage source, making it particularly useful in complex systems where various voltage levels are needed. The converter operates by taking a single input voltage, which, in this context, is typically supplied by a PV array. To generate the asymmetric DC voltages required by the proposed MLI, the MOACFC incorporates a transformer. The transformer is a critical component in the system, responsible for either stepping up or stepping down the input voltage to achieve the necessary output voltage levels. By adjusting the turns ratio of the transformer, the converter can produce the desired voltage levels across multiple outputs, ensuring that the inverter receives the appropriate voltage inputs for its operation.

The term “active clamp” in the name of the converter refers to a specialized circuit integrated into the design to improve efficiency and reduce voltage stress on the primary switch, denoted as S_Q . The active clamp circuit plays a key role in managing the energy stored in the transformer’s leakage inductance when the primary switch is turned off. By absorbing this energy, the active clamp circuit prevents voltage spikes that could otherwise damage the switch or lead to inefficient operation. Additionally, this circuit helps to minimize switching losses, thereby enhancing the overall efficiency of the converter and ensuring reliable performance under various operating conditions. Each output voltage produced by the MOACFC has a corresponding diode located on the secondary side of the transformer. These diodes are responsible for rectifying the voltage, and converting the AC waveform generated by the transformer into a DC output. To ensure that the rectified voltages are stable and free of ripples, output capacitors, and

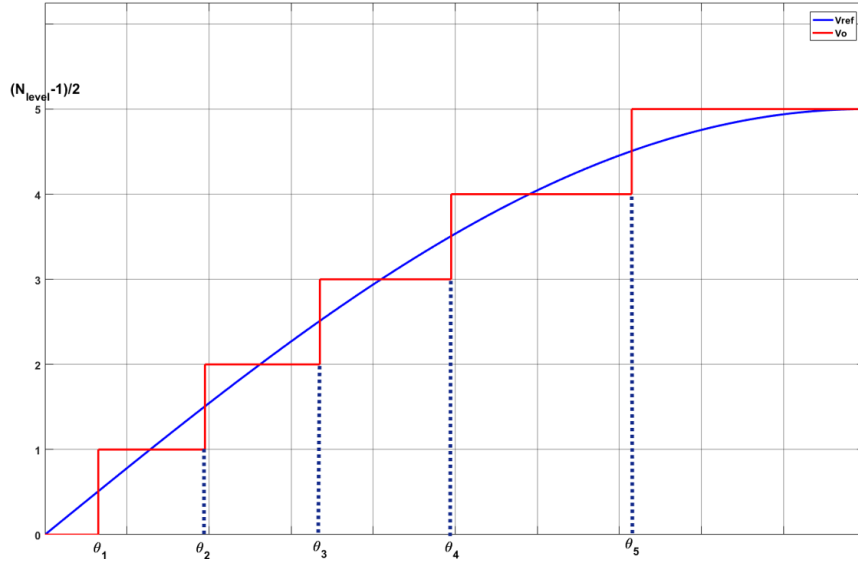


Fig. 7. Nearest level control PWM.

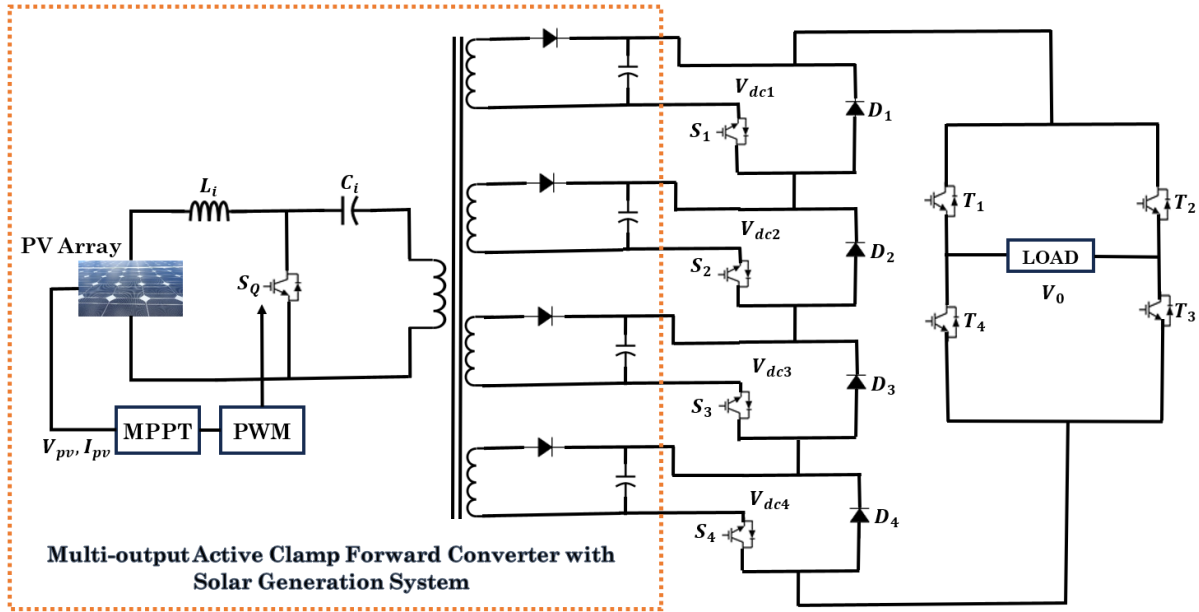


Fig. 8. MOACFC with Solar generation system for proposed MLI.

inductors are employed as filters. These components work together to smooth the DC output, providing steady and reliable voltage levels that are crucial for the proper functioning of the connected loads or subsequent stages of the power conversion system.

Figure 8 illustrates a typical MOACFC integrated with a solar generation system for the proposed MLI.

The Active Clamp Forward Converter (ACFC) is a versatile power electronics circuit capable of providing multiple

regulated output voltages, making it particularly suitable for applications that require several voltage rails. This capability allows the ACFC to replace multiple separate converters that would otherwise be needed to generate different voltage levels, thereby achieving a more compact design with a reduced component count. This reduction in components not only simplifies the overall system design but also enhances reliability by minimizing potential points of failure. The efficiency of the ACFC is significantly

improved by the active clamp circuit, which plays a crucial role in reducing switching losses and alleviating voltage stress on the primary switch. When the primary switch turns off, the active clamp circuit effectively manages the energy stored in the transformer's leakage inductance, preventing harmful voltage spikes that could damage the switch or lead to inefficient operation. By reducing these losses, the active clamp circuit enhances the overall efficiency of the converter, making it an attractive choice for high-performance applications.

Additionally, the active clamp circuitry contributes to a faster transient response when there are changes in load conditions. This quick adaptation to varying loads ensures that the output voltages remain stable and within desired levels, which is crucial for maintaining the performance and reliability of the system. This fast transient response is particularly important in dynamic environments where load demands can fluctuate rapidly. The design of the transformer within the ACFC is tailored to meet the specific voltage requirements of the MLI it supplies. The turns ratio of the transformer, denoted as $N_p:N_{s1}:N_{s2}:N_{s3}:N_{s4}$, is configured according to the desired output voltage levels of the MLI. For instance, to generate a 9-level output voltage, the transformer turns ratio is set to 1:1:1:1:1, providing equal voltage levels across all outputs. For a 21-level output voltage, the turns ratio is adjusted to 1:1:2:3:4, creating a range of voltage levels that support the higher number of output stages in the MLI. For a 31-level output voltage, the turns ratio is configured as 1:1:2:4:8, producing the necessary voltage steps required for the more complex multi-level structure. These specific turns ratios ensure that the ACFC can efficiently supply the correct voltage levels needed by the MLI, whether for 9-level, 21-level, or 31-level configurations. By carefully selecting the appropriate turn ratio, the converter is optimized to deliver the precise voltage outputs required, ensuring optimal performance of the MLI and the overall system.

4.1 RNN MPPT

For regulated voltage at the primary side of the transformer V_p and to track the maximum power after the PV array, switch S_Q is operated by using MPPT. An RNN-INC-based MPPT algorithm is adopted to operate the switch S_Q . INC is a popular algorithm used in MPPT systems for PV solar panels and other renewable energy sources. MPPT is crucial for optimizing the power output of a solar panel. It achieves this by continuously adapting the panel's operating point to maximize the power it produces, even in the face of fluctuating environmental conditions, such as variations in sunlight intensity and temperature [28].

A Neural Network (NN) is a computational model that draws inspiration from the organization and functionality of biological neurons found in the human brain. It is capable of learning complex relationships between input and output data, making it a versatile tool for approximating and predicting outputs based on given inputs. In this research, a RNN was utilized to forecast the required adjustment in the duty cycle when a PV system encounters abrupt changes in solar irradiance.

A RNN is an artificial NN specifically crafted to process sequential data and capture temporal dependencies inherent within the data. Contrasting traditional feedforward NNs, in which information streams in one direction, RNNs have networks that form instructed cycles, permitting them to demonstrate dynamic temporal behavior. The key feature of RNNs is their capability to preserve an internal memory state, or "hidden state," which enables them to process sequences of inputs while retaining information about previous inputs. At each time step, the hidden state is recalculated using both the current input and the previous hidden state. This recurring pattern enables RNNs to proficiently represent sequences of varying lengths.

Mathematically, the computation performed by an RNN at each time step can be described as follows:

$$h_t = f(W_{hx}x_t + W_{hh}h_{t-1} + b_h),$$

$$y_t = g(W_{yh}h_t + b_y).$$

Where:

- x_t is the input at time step t .
- h_t is the hidden state at time step t , representing the network's memory of previous inputs.
- y_t is the output at time step t .
- W_{hx} and W_{hh} are weight matrices that control the transformations of the input and hidden state, respectively.
- W_{yh} is the weight matrix that maps the hidden state to the output.
- b_h and b_y are bias vectors.
- f and g are activation functions, typically non-linear functions like the hyperbolic tangent or the rectified linear unit (ReLU).

During training, the parameters of the RNN are learned by backpropagation through time (BPTT), a modification of backpropagation that unfolds the network over time and computes gradients through the entire sequence. This allows the RNN to learn from sequential data by adjusting its parameters to minimize a given loss function, mean squared error.

The MPPT used in this paper employed the RNN as an auxiliary tool to improve the tracking accuracy of the conventional INC algorithm. The developed RNN specifically targets the estimation of the necessary change in the duty cycle (ΔD_m). The duty cycle of the maximum power point (D_m) is predominantly determined by solar irradiance (G). The variation in the maximum power point (MPP) duty cycle is dependent on both the change in solar irradiance and the previous value of solar irradiance. Likewise, the change in MPP current (ΔI_m) is influenced by the difference between the current solar irradiance reading and the change in solar irradiance. The proposed basis for training the RNN is the relationship $\Delta D_m = f(\Delta I_m, I_m)$. In this model, the RNN's input layer includes ($\Delta I_m, I_m$) as variables. Through training, the NN aims to predict the required variation in ΔD_m , which forms the output layer.

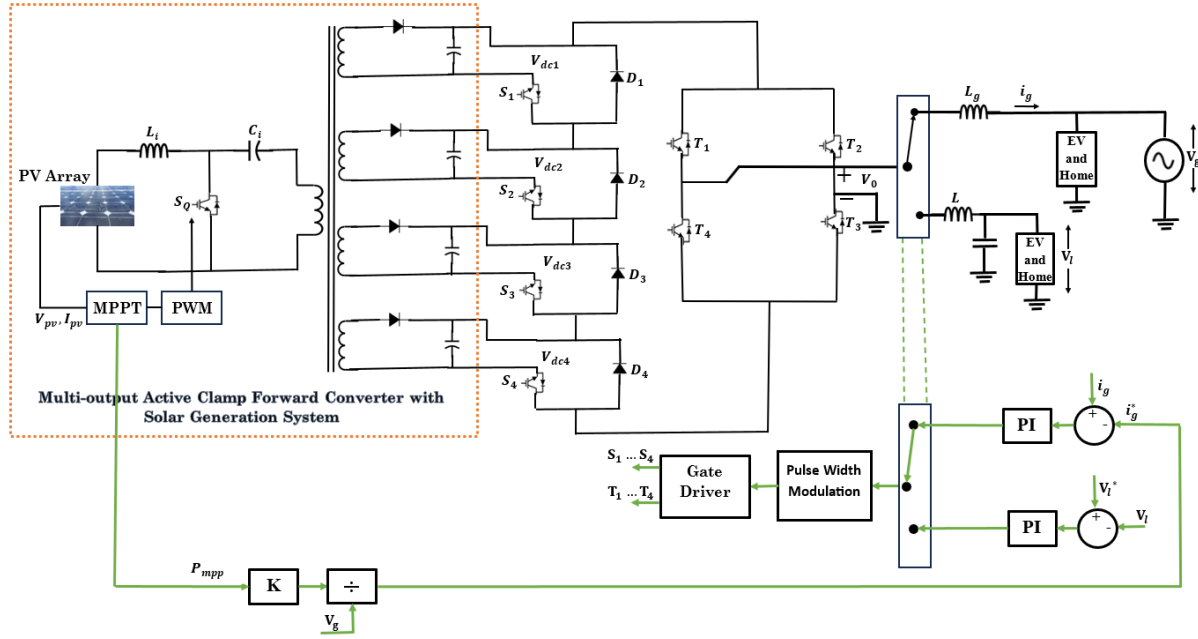


Fig. 9. Configuration of MOACFC-MLI with closed-loop control for EV charger.

Training a RNN in MATLAB for MPPT in a PV generation system involves following steps

- Prepare the dataset consisting of input-output pairs. For each time step, provide the current MPPT value, the change in MPPT current, and the corresponding change in duty cycle.
- Define the architecture of RNN model using MATLAB's neural network toolbox by specifying the number of input features, hidden units, and output units.
- Normalize the input data to a range suitable for RNN training. This step helps in improving the convergence and stability of the training process.
- Choose Mean squared error (MSE) as an appropriate loss function for regression task.
- Train RNN model using the prepared dataset. Specify the training options such as the maximum number of epochs, learning rate, and mini-batch size.
- Evaluate the trained model using a separate validation dataset to assess its performance.

5 MOACFC and MLI for EV charging

The proposed MOACFC integrated with a MLI and enhanced by a RNN-based MPPT algorithm is meticulously designed to optimize the performance of solar generation systems, suitable for both stand-alone and grid-integrated operations. This advanced configuration is pivotal in enhancing power quality and efficiency, addressing the demands of modern solar energy systems. The system's

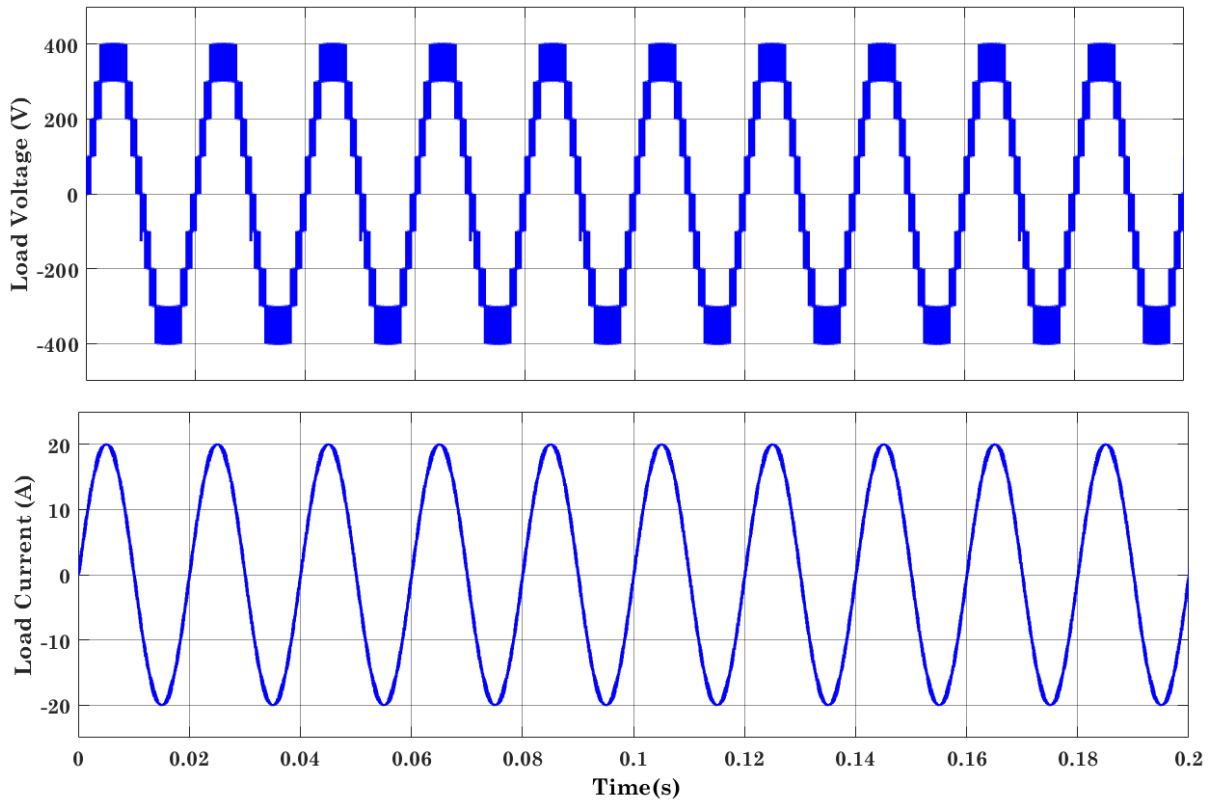
control scheme, depicted in Figure 9, provides a comprehensive framework for effective energy conversion and management. At the heart of this system lies the MOACFC, a crucial power conversion component that efficiently transforms the DC output from solar panels into multiple usable DC voltages. This converter is specifically engineered to handle various output voltages simultaneously, catering to diverse power requirements within the system. The ability to manage multiple voltages ensures that the system can accommodate different load demands while maintaining high conversion efficiency, making the MOACFC an essential element in both stand-alone and grid-tied applications.

Following the DC-to-DC conversion by the MOACFC, the MLI plays a critical role in converting the DC output into AC power, which is suitable for grid integration or supplying local AC loads. The multilevel structure of the inverter is particularly advantageous in reducing harmonic distortion, thereby improving the overall quality of the AC output. By minimizing harmonic distortion, the system ensures that the AC power delivered to the grid or local loads is of high quality, which is essential for maintaining system reliability and efficiency. A single choke coil is employed as a current filter within the system, serving a vital function in smoothing the current. This choke coil effectively ensures that the output voltage and current are sinusoidal, which is particularly important when interfacing with the grid. By smoothing the current, the choke coil helps to maintain power quality and minimize harmonic distortion in grid-connected operations, thereby ensuring that the system meets stringent grid standards and operates efficiently under various load conditions.

The RNN-based MPPT algorithm is implemented to maximize the power output from the solar PV array. Unlike traditional MPPT methods, the RNN-based approach

Table 3. Specifications of the system.

Parameter	Value
PV panel	Amerisolar AS-6M24-190 W
Maximum power	3 kW
Open circuit voltage, V_{oc}	29.8 V
Short-circuit current, I_{sc}	8.2 A
Voltage at maximum power point, V_{mp}	25 V
Current at maximum power point, I_{mp}	7.62 A
Temperature coefficient of V_{oc}	-0.36695%/°C
Temperature coefficient of I_{sc}	0.03922%/°C
Series-connected modules per string	4
Parallel strings	4
MOACFC	
Inductor	100 mH
Capacitor	15 μ F
Transformer turns ratio	
Symmetric configuration	100:100:100:100:100
Asymmetric configuration-1	100:40:80:120:160
Asymmetric configuration-2	100:25:50:100:200

**Fig. 10.** Voltage and current across the load for 9-level symmetric configuration with PD LSPWM.

excels in handling the non-linear and dynamic characteristics of solar power generation. It is highly responsive to rapid changes in environmental conditions such as

irradiance and temperature, ensuring that the system continuously operates at its maximum power point. This dynamic adaptability makes the RNN-based MPPT

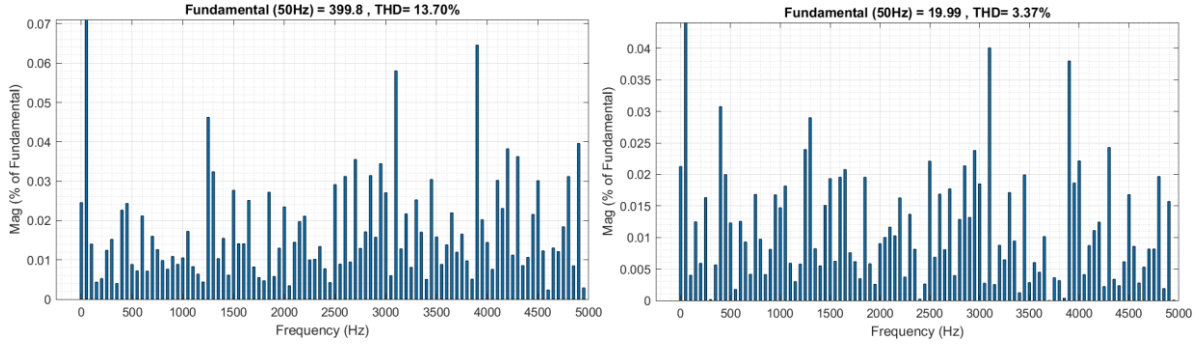


Fig. 11. THD of voltage current across the load for 9-Level symmetric configuration with PD LSPWM.

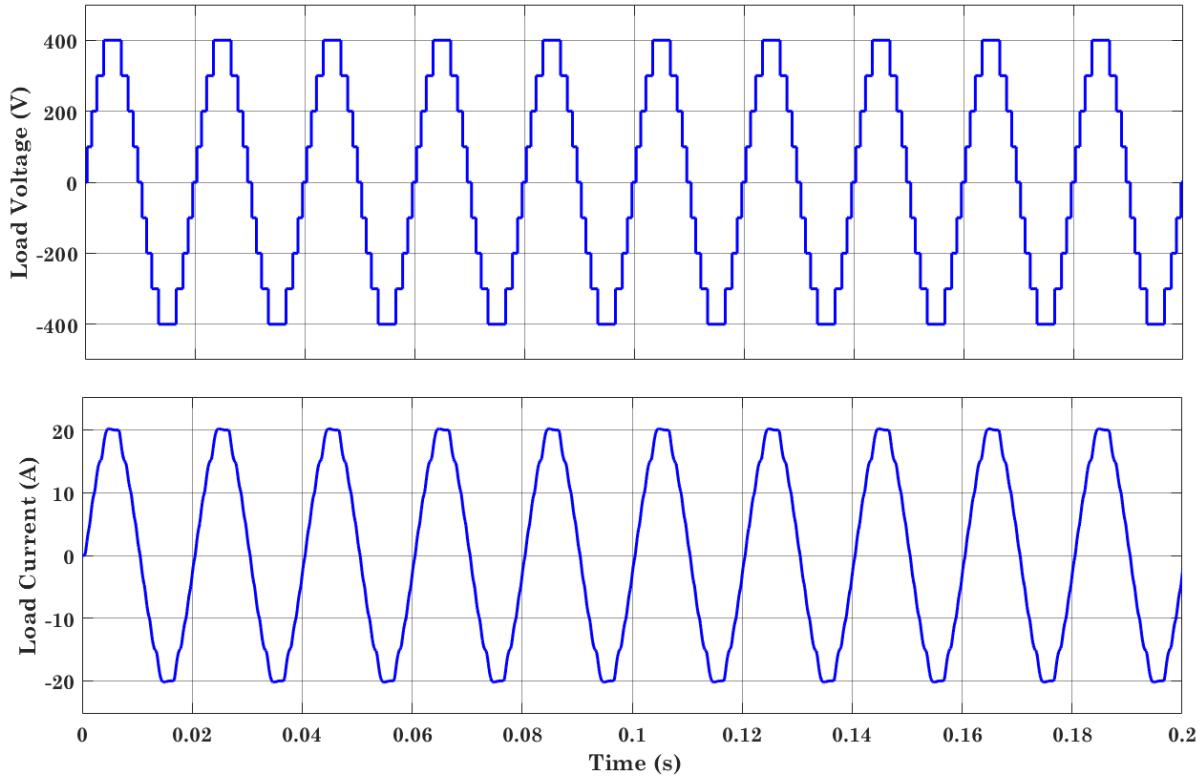


Fig. 12. Voltage and current across the load for 9-level symmetric configuration with NLC PWM (half-height method).

algorithm a superior choice for optimizing power extraction in both stand-alone and grid-connected solar systems. The control strategy illustrated in Figure 9 ensures optimal power extraction and efficient energy conversion in all operating modes. The MPPT algorithm is central to this strategy, incorporating a constant factor K that defines the system's tracking efficiency. This factor ensures that the system consistently operates at its maximum power point, dynamically adjusting to changing environmental conditions to maximize energy capture. While various linear and non-linear controllers could be employed to regulate load voltage or grid current, this work utilizes a conventional Proportional-Integral (PI) controller due to its simplicity and effectiveness. The PI controller is well-suited

for maintaining system stability and achieving desired performance outcomes with straightforward implementation, making it an ideal choice for the control of the MOACFC and MLI system.

In grid-integrated operation, the system's reference set point is the sinusoidal grid voltage. This approach ensures that the PV system operates at a unity power factor by aligning its power output with the grid voltage. To achieve this, the reference sinusoidal grid current is generated by dividing the power output from the PV system by the grid voltage. This method effectively synchronizes the PV system with the grid, ensuring that the injected power is in phase with the grid voltage, thereby maintaining a unity power factor. The process is illustrated in Figure 9, which

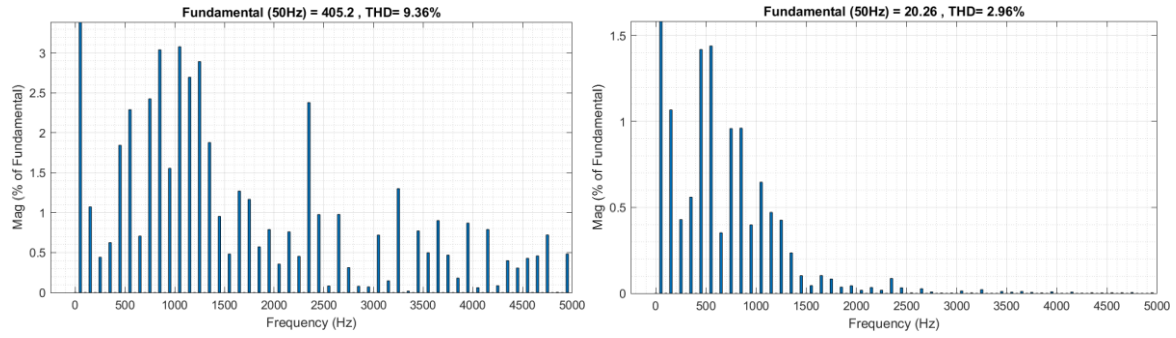


Fig. 13. THD of voltage and current across the load for 9-Level symmetric configuration with NLC PWM (half-height method).

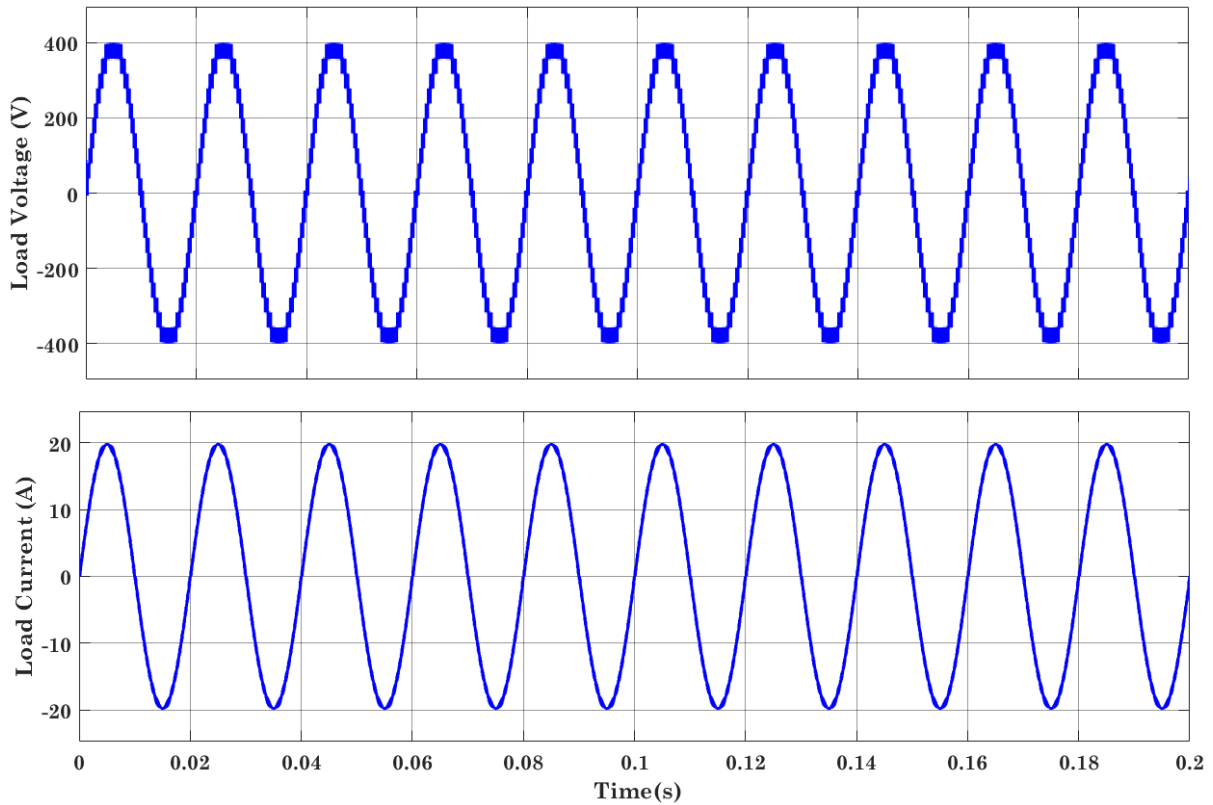


Fig. 14. Voltage and current voltage and current across the load for 21-level asymmetric configuration with PD LSPWM.

shows the alignment between the PV system's power output and the grid voltage for seamless integration.

In stand-alone operation, the reference set point differs from that in grid-connected mode. Here, the reference is a sinusoidal waveform that corresponds to the desired load voltage, ensuring that the generated power accurately meets the load requirements. This approach allows the system to provide stable and reliable power to the load, regardless of whether it is connected to the grid or operating independently. The system's ability to maintain the desired load voltage is crucial for the stability and performance of the stand-alone operation, ensuring that the power needs of the load are consistently met.

A closed-loop current control mechanism is employed to ensure that the actual current injected into the grid, denoted as i_g , follows the reference current i_g^* . This is a critical aspect of the control strategy, as it ensures that the system's output is consistent with the desired operational mode, whether grid-integrated or stand-alone. The conventional Proportional-Integral (PI) controller plays a central role in this regulation process. It ensures that the actual current injected into the grid or supplied to the load closely follows the reference current, thereby maintaining system stability and performance.

The reference current i_g^* is generated based on the desired operation mode. In grid-integrated mode, the

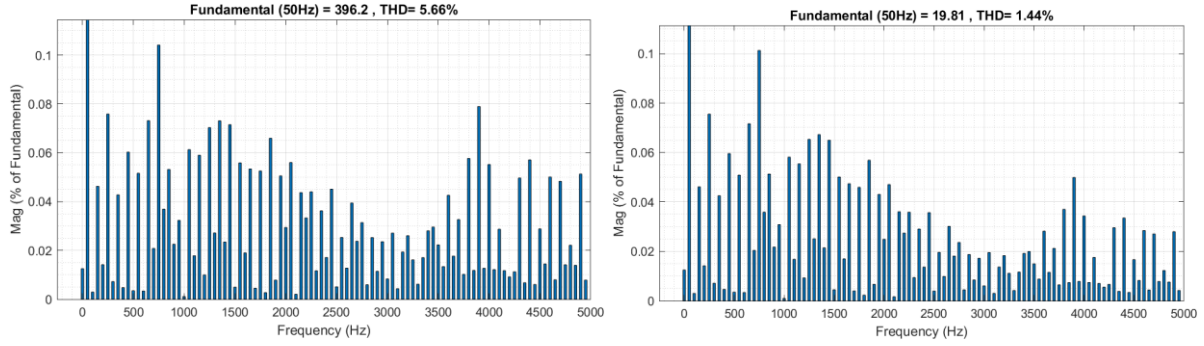


Fig. 15. THD of voltage and current across the load for 21-level asymmetric configuration with PD LSPWM.

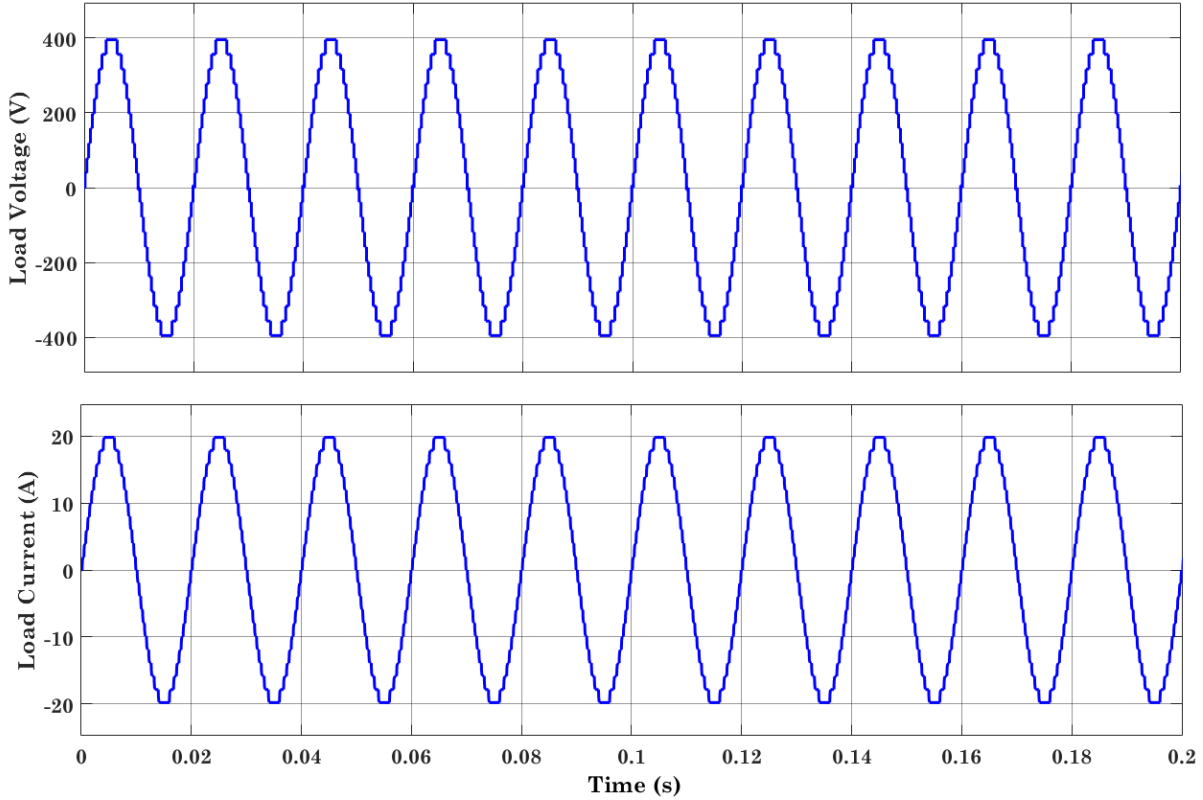


Fig. 16. Voltage and Current across the load for 21-level asymmetric configuration with NLC PWM (half-height method).

reference current is obtained by dividing the PV power by the grid voltage, resulting in a sinusoidal waveform that serves as the target for the system's output. The PI controller then processes the error between the reference current i_g^* and the actual injected current i_g . By minimizing this error, the PI controller adjusts its output to ensure that the actual current closely follows the reference, maintaining optimal performance.

The output signal from the PI controller is treated as the modulation index signal M_a , which is crucial for generating the correct gating pulses for the converter and inverter stages. This modulation index signal is compared with carrier waveforms to produce the gating pulses S_1, S_2, S_3, S_4 and T_1, T_2, T_3, T_4 . These pulses control the switching

of the converter and inverter devices, ensuring that the power conversion process is optimized. By carefully controlling the switching actions, the system can maintain efficient and accurate power conversion, whether supplying the grid or a stand-alone load.

6 Simulation results

To assess the working of the configuration depicted in Figure 8, a simulation model was established using the MATLAB/Simulink environment. Table 3 presents the specifications of the PV system, MOACFC, and MLI adopted in simulation.

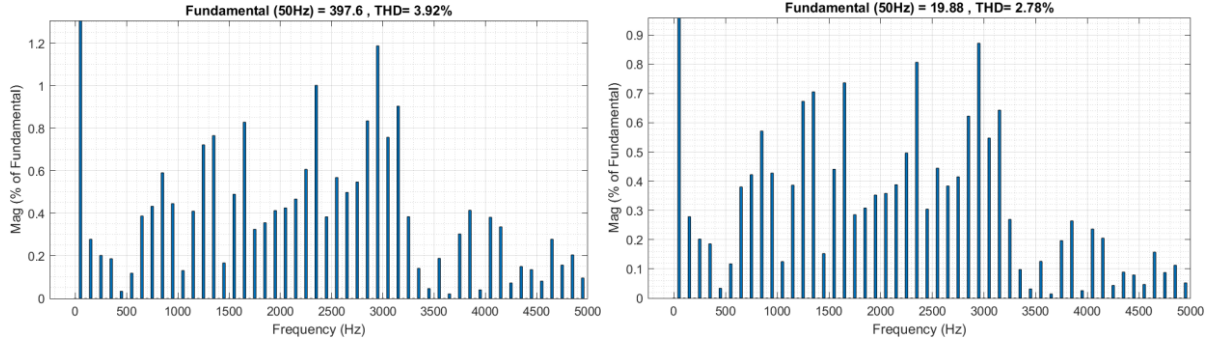


Fig. 17. THD of voltage and current across the load for 21-Level asymmetric configuration with NLC PWM (half-height method).

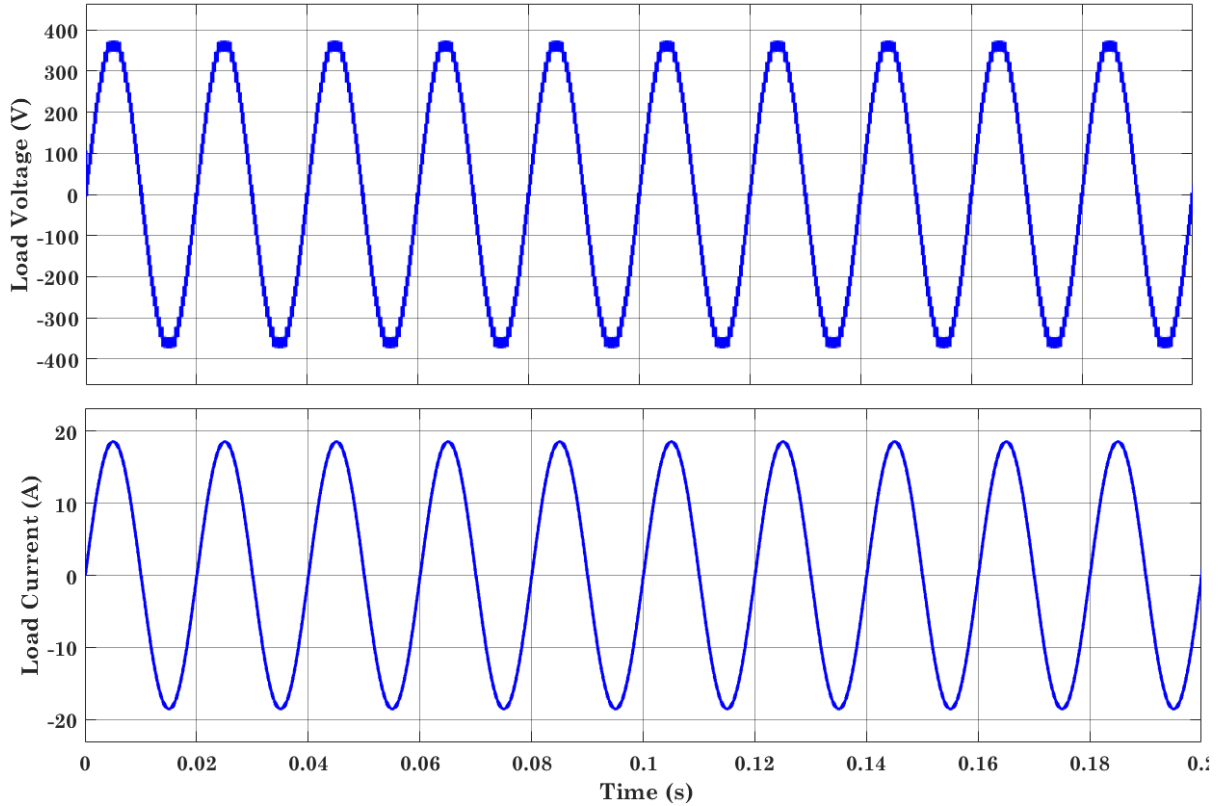


Fig. 18. Voltage and current across the load for 31-level asymmetric configuration with PD LSPWM.

6.1 Case 1: Constant irradiance with RL load

In the initial phase of the study, constant irradiation and constant temperature are considered to assess the efficacy of the proposed MOACFC-MLI configuration. Parameters of the PV array, number of series, and parallel connected modules are presented in Table 3. As the voltage at MPP from each PV module is 25 V and the number of series-connected modules are four hence possible voltage across the primary of the multi-winding transformer is 100 V. The number of achievable output levels at the output depends on the turns ratio of the transformer as presented in Table 3. In the scenario of a symmetric configuration,

there are nine potential output levels. For the first asymmetric configuration, twenty-one levels are attainable, and for the second asymmetric configuration, thirty-one levels are attainable.

With symmetric configuration, four voltages of 100 V each generate a 9-level output voltage across the load of $20\ \Omega$ and 2 mH. Figure 10 exhibits the voltage and current waveforms across the load, emphasizing their response when subjected to PD LSPWM modulation at a switching frequency of 10 kHz. Figure 11 provides the THD in the 9-level load current and voltage when employing PD LSPWM modulation. Figure 12 showcases the load current voltage when Nearest Level Control Pulse Width

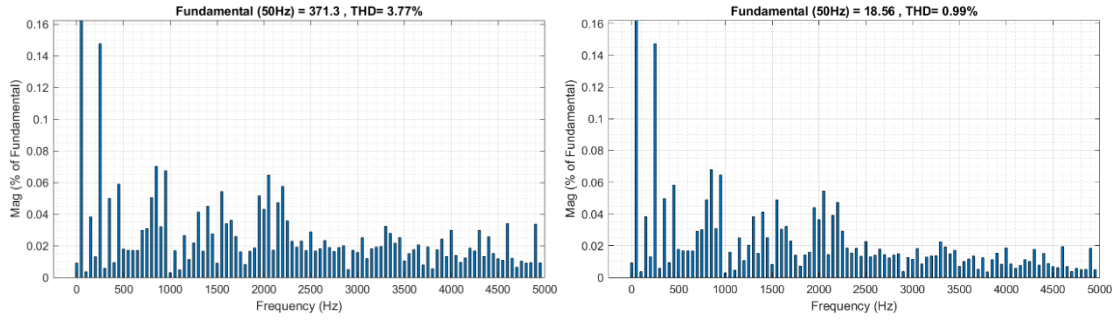


Fig. 19. THD of voltage and current across the load for 31-Level asymmetric configuration with PD LSPWM.

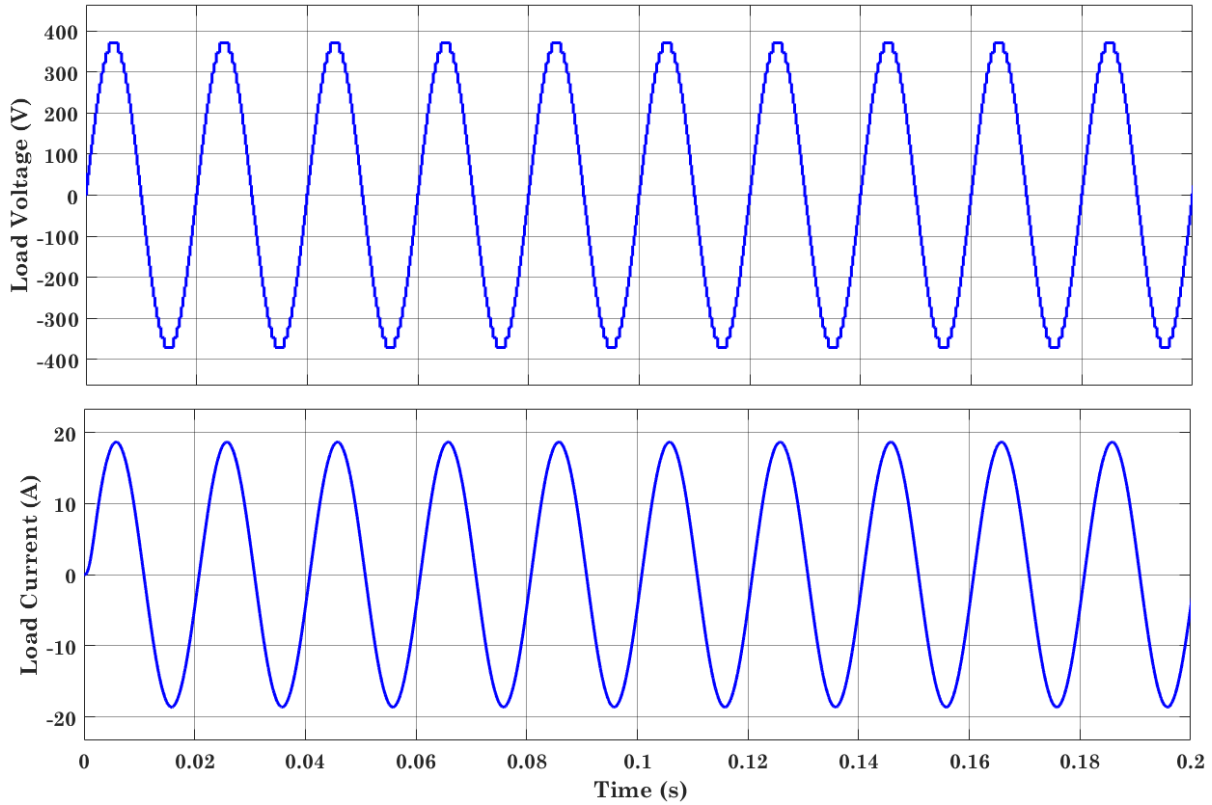


Fig. 20. Voltage and current across the load for 31-level asymmetric configuration with NLC PWM (half-height method).

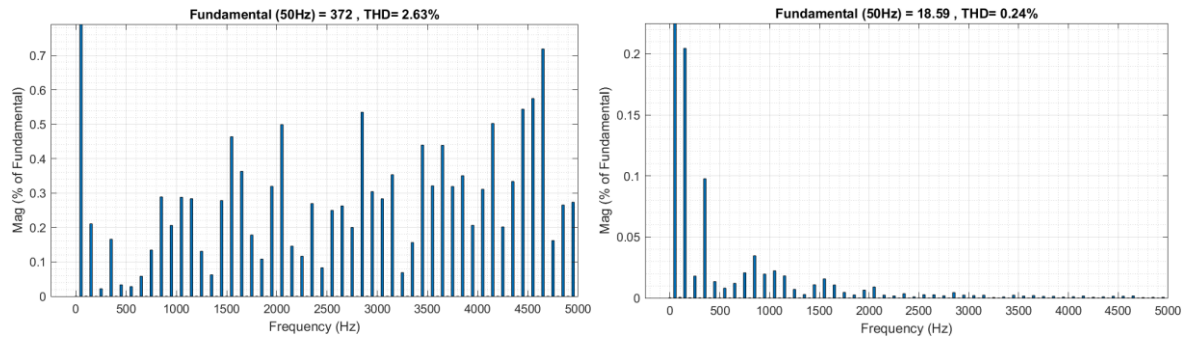
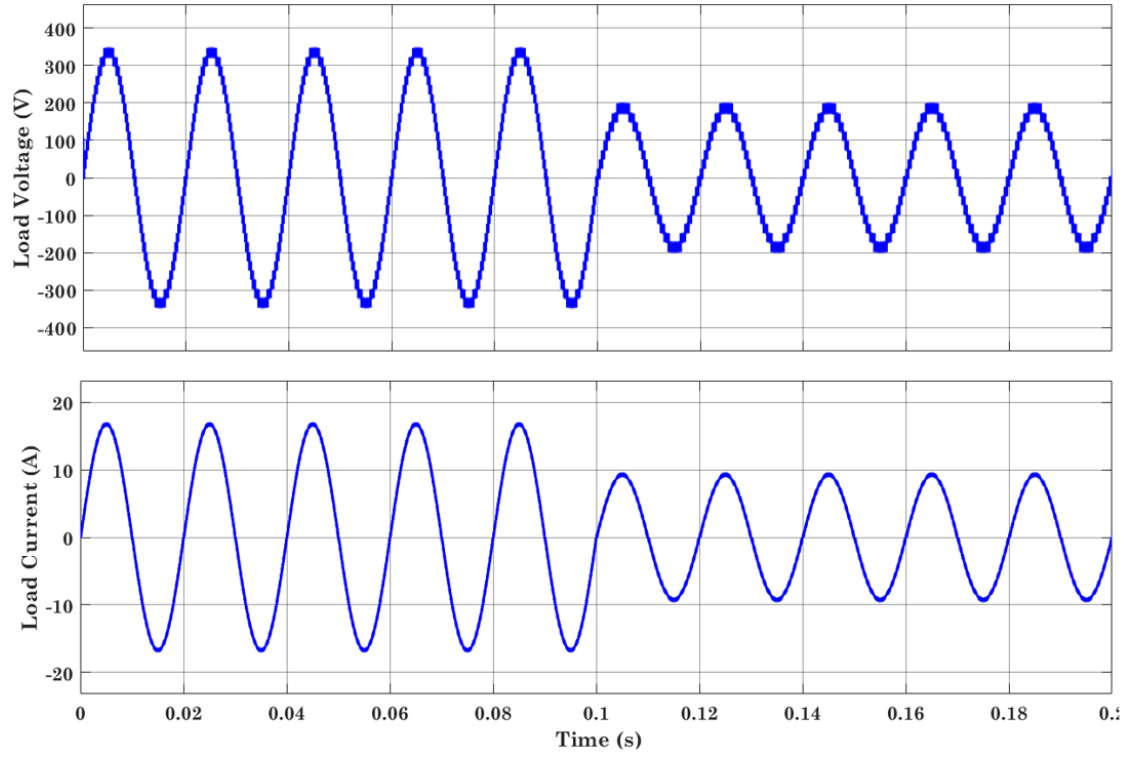
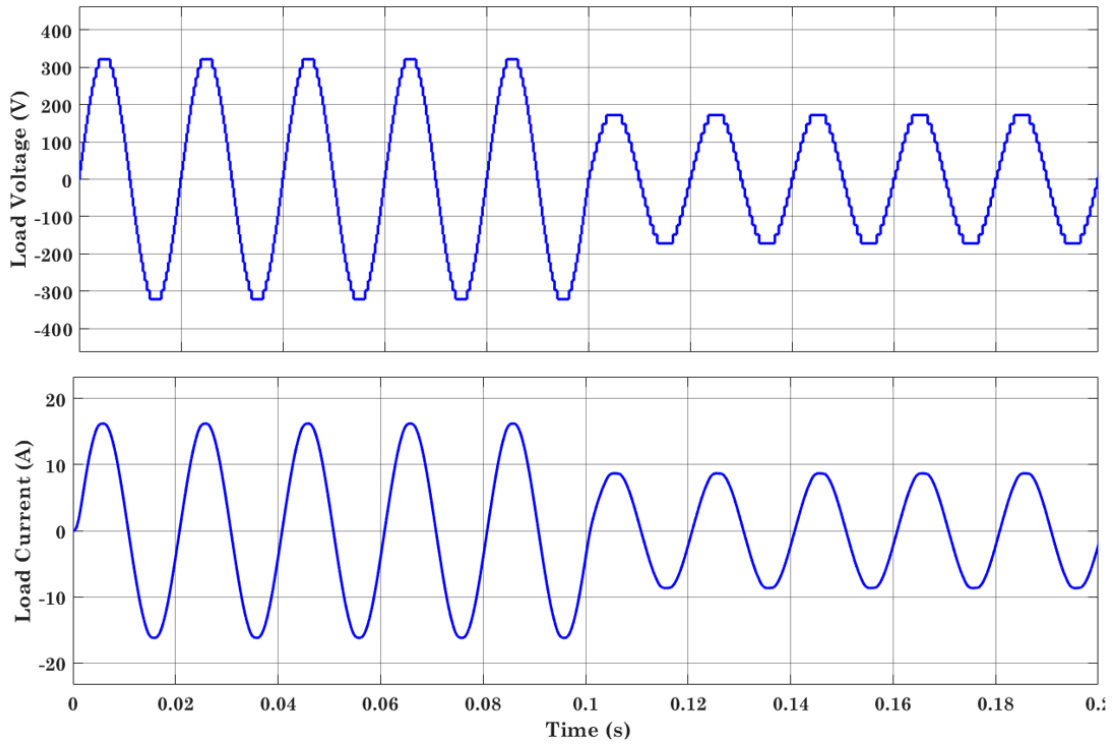


Fig. 21. THD of voltage and current across the load for 31-Level asymmetric configuration with NLC PWM (half-height method).

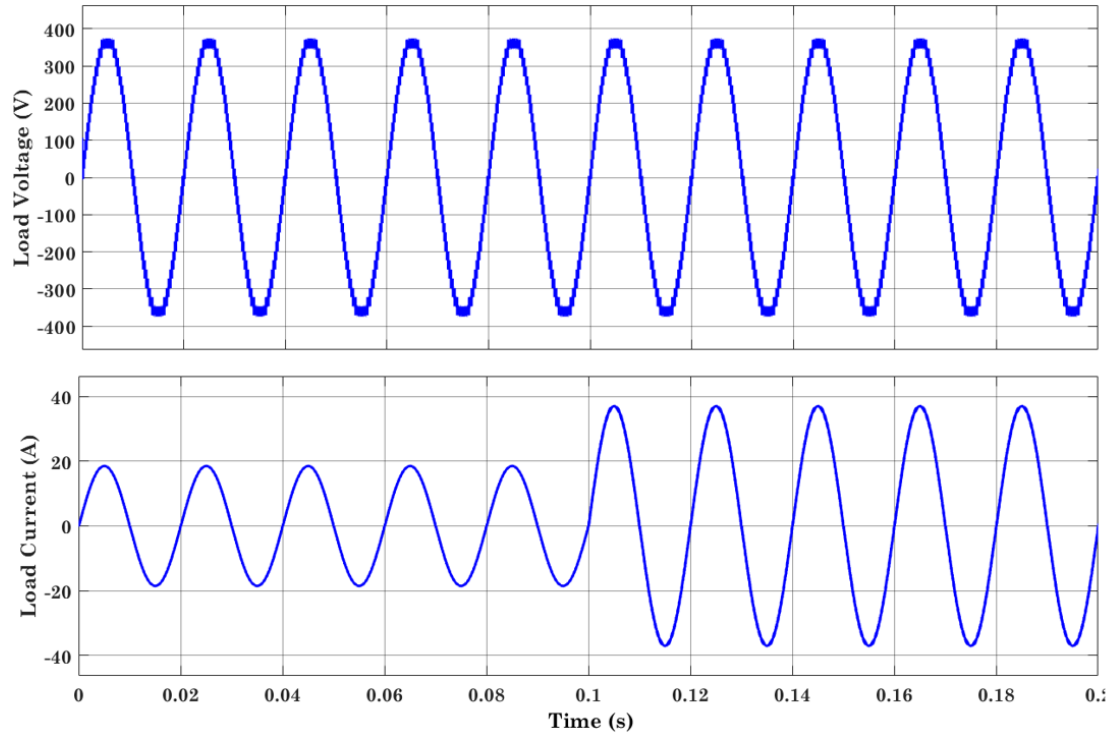


(a)

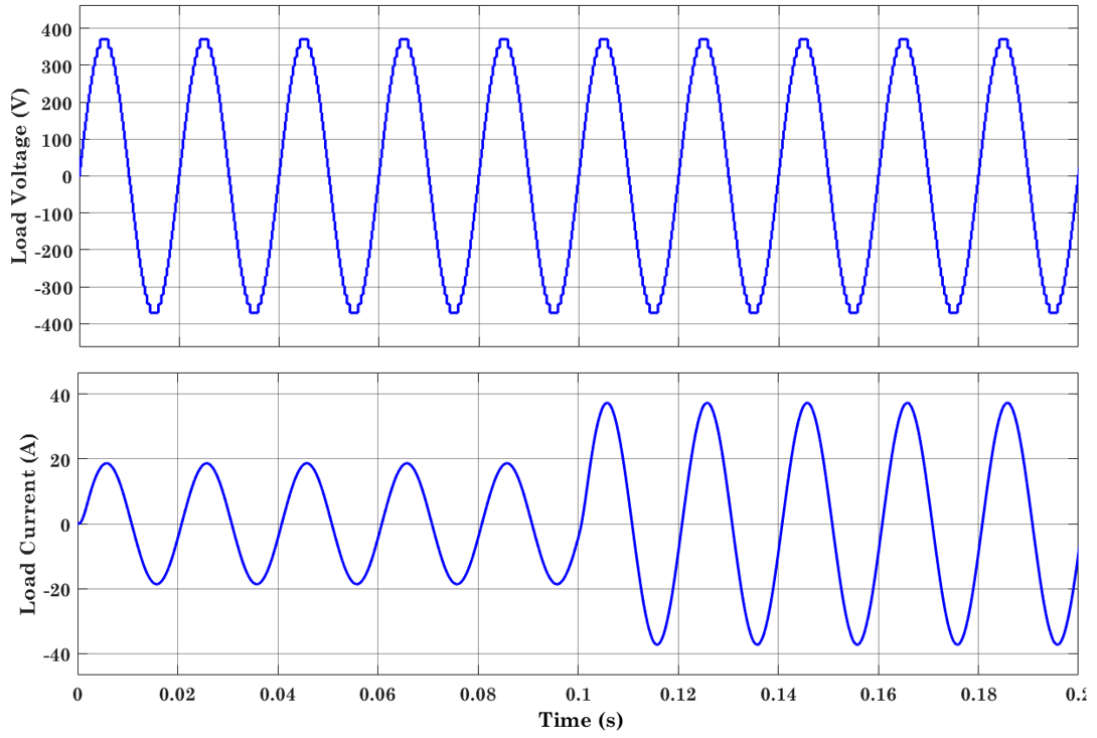


(b)

Fig. 22. Voltage and current across the load for 31-level asymmetric configuration when modulation index is changed from 0.9 to 0.5. (a) PD LSPWM; (b) NLCPWM.



(a)



(b)

Fig. 23. Voltage and current across the load for 31-level asymmetric configuration when load is changed (a) PD LSPWM (b) NLCPWM.

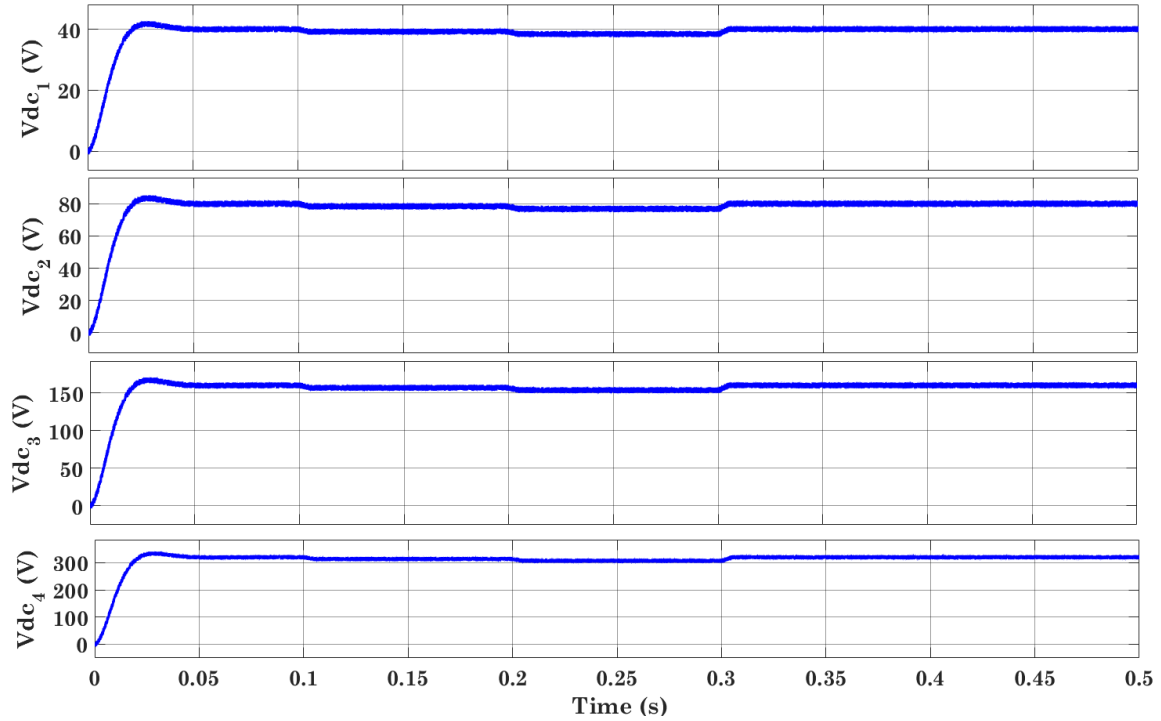


Fig. 24. DC voltages applied to the MLI with PV generation system.

Modulation (NLCPWM) modulation, using the half-height method, is employed in the same system. In Figure 13, the THD of the 9-level load voltage and current signals is presented for the NLCPWM modulation configuration. Utilizing an asymmetric configuration with the same number of levels makes it possible to raise the possible voltage levels. In asymmetric configuration-1, to achieve a 21-level output voltage, the required voltages across the secondary of the transformer are 40 V, 80 V, 120 V, and 160 V. The cumulative impact of these sources enables the system to reach a maximum voltage of 400 V at the output. In Figure 14 the 21-level voltage and current waveforms across the load when subjected to PD LSPWM modulation at a carrier frequency of 10 kHz is presented. Figure 15 provides the THD in the 21-level load voltage and current with PD LSPWM modulation. Figure 16 demonstrates the voltage and current across the load when NLCPWM modulation, employing the half-height method, is utilized. Figure 17 subsequently exhibits the THD of the 21-level load voltage and current when subjected to NLCPWM modulation.

To achieve an even higher number of levels, specifically 31 levels, a modification is made to the magnitudes of the available DC voltages across the secondary. These voltages are 25 V, 50 V, 100 V, and 160 V with the turn's ratio given in Table 3. With these adjusted voltages, the system can achieve a maximum voltage of 375 V. Figure 18 presents the 31-level voltage and output current waveforms across the load when subjected to PD LSPWM modulation at a carrier frequency of 10 kHz. Figure 19 offers the THD in the 31-level load voltage and current employing PD LSPWM modulation. Figure 20 portrays the voltage and current characteristics across the load when NLCPWM

modulation is applied, utilizing the half-height method. Subsequently, Figure 21 showcases the THD of the 31-level load voltage and current influenced by NLCPWM modulation.

Figures 22a and 22b display the load voltage and current waveforms in a 31-level asymmetric configuration for a modulation index variation of 0.9–0.5 at 0.1 s. It is important to note that as the modulation index decreases, the levels of the converted voltage decrease accordingly. Consequently, this reduction in voltage levels leads to an increase in the THD in both voltage and current signals. Figures 23a and 23b depict the behavior of load voltage and current when the load is increased at 0.1 s.

6.2 Case 2: Variable irradiance with RL load

Variable irradiance is considered in this case to check the efficacy of the proposed configuration during sudden atmospheric conditions. The 31-level MOACFC-MLI is considered with the turn ratio of the second asymmetric configuration given as 100:40:80:160:320. This configuration is obtained to deliver a maximum voltage of 600 V across the load while achieving the 31-level output inverter voltage waveform. To harness the maximum available power from the PV panels, the ACFC is regulated using an RNN-based MPPT algorithm. This algorithm ensures that the converter operates at the point where the PV panels generate the highest power output.

The valuation of MLI performance in conjunction with a PV generation system is conducted by considering varying irradiance levels, shifting from 1000 w/m² to 800 w/m² at 0.1 s, then from 800 w/m² to 600 w/m² at 0.2 s,

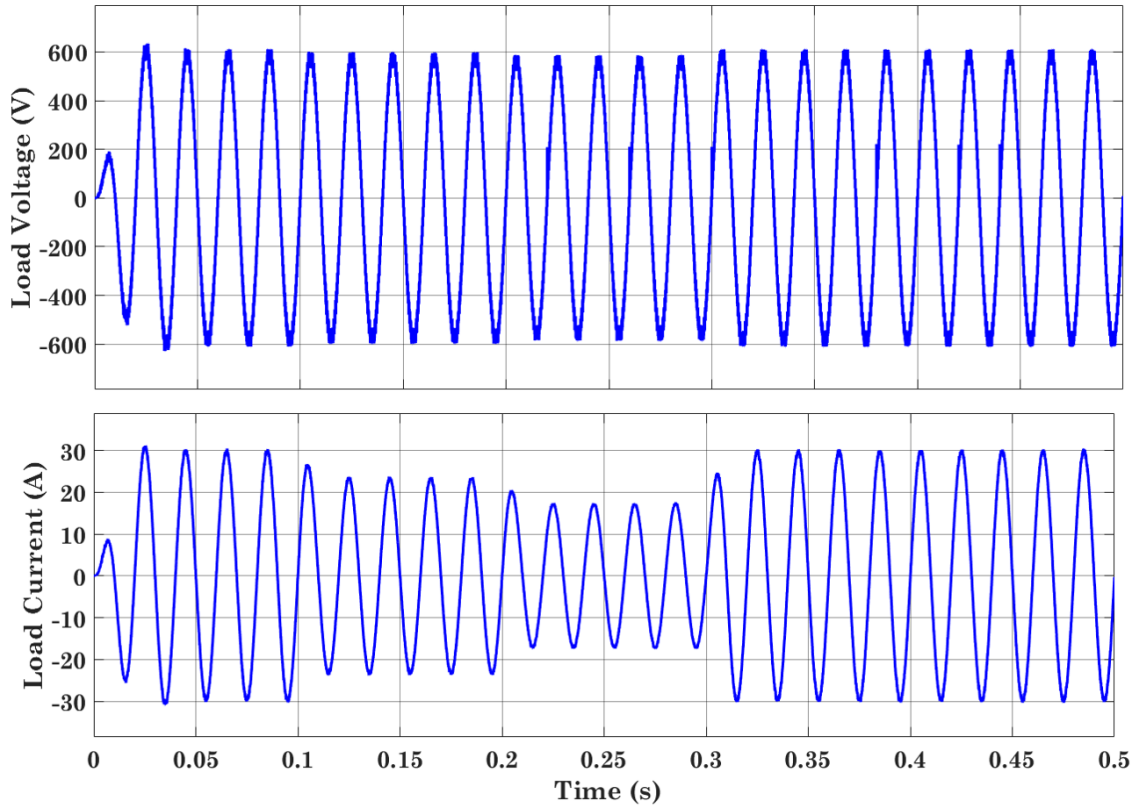


Fig. 25. Load voltage and load current with variable Irradiances.

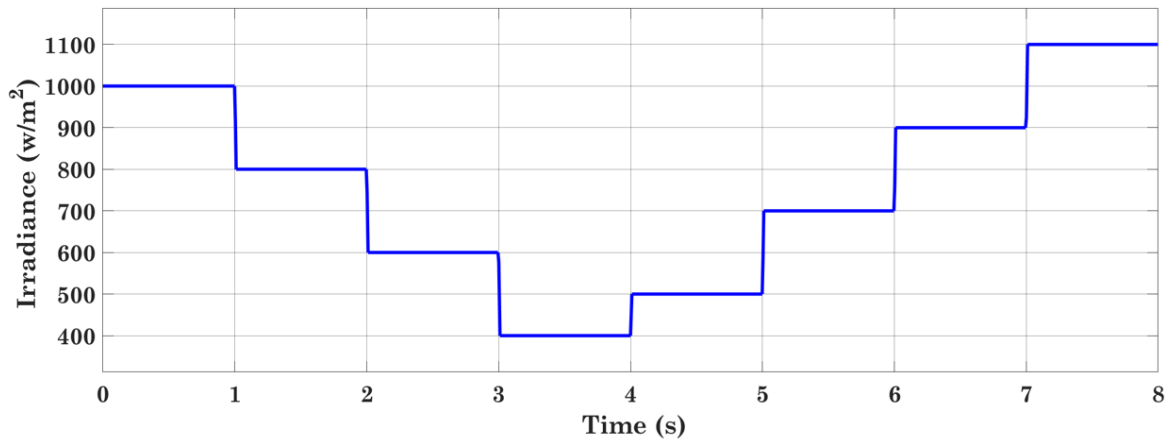


Fig. 26. Irradiance variation in w/m^2 .

and finally from 600 w/m^2 to 1000 w/m^2 at 0.3 s. Figure 24 illustrates the DC voltages available at the output of the ACFC. Load voltage and load current with PDLSPWM modulation are presented in Figure 25.

6.3 Case 3: Variable irradiance with EV charger

The proposed 31-level MOACFC integrated with a MLI for solar generation systems is designed to efficiently charge an EV. This system is simulated using MATLAB/Simulink to evaluate its performance under varying conditions.

The parameters of the PV panel used in the simulation are presented in Table 3. For the PV array, a configuration of 1 series-connected module and 32 parallel-connected modules is chosen, resulting in a total power rating of 6 kW. This configuration is designed to match the power requirements for charging the selected EV.

The EV chosen for this study has a battery capacity of 2.71 kWh and a nominal voltage of 51.1 V. This specific configuration ensures that the charging system can efficiently manage the power delivery to the EV battery. The 31-level MOACFC-MLI is designed with a turn ratio

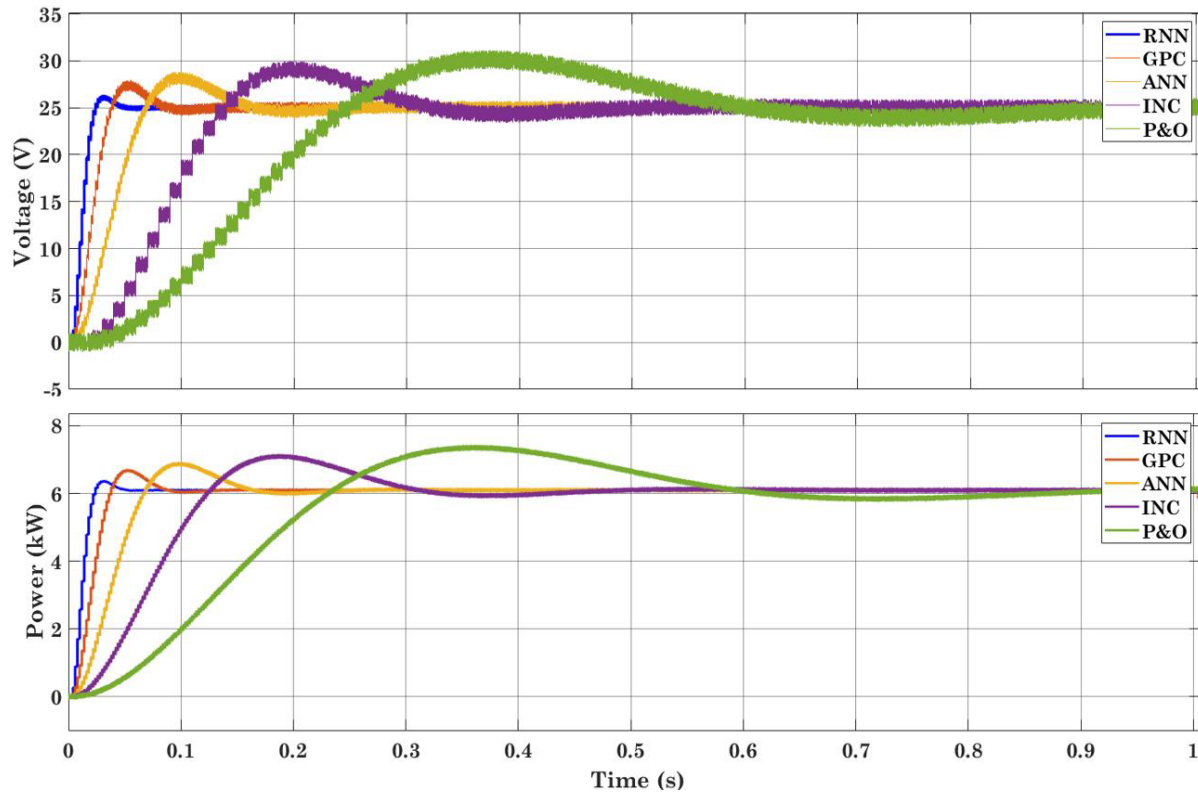


Fig. 27. PV voltage and power at the primary of the transformer.

Table 4. Comparison of different MPPTs for voltage.

MPPT	Peak overshoot (V)	Rise time (s)	Stability time (s)	Ripples (%)
Proposed RNN	26.379	0.0140	0.071	1.01
GPC	27.941	0.0242	0.108	2.11
ANN	28.828	0.0480	0.32	4.29
INC	29.956	0.0901	0.612	5.43
P&O	31.131	0.1701	0.99	7.82

of 25:25:50:100:200 for the second asymmetric configuration, achieving a maximum output voltage of 375 V. This high voltage level is essential to match the specifications of the EV charger. The simulation considers both islanding mode and grid-connected mode. Figure 26 illustrates the variation in irradiance for these two modes.

Figure 27 provides a comparative analysis of the PV voltage and power at the terminals on the primary side of the transformer, showcasing the performance of various MPPT algorithms. Figure 27 highlights the proposed RNN-based MPPT algorithm alongside several established MPPT methods, including the Giza Pyramid Construction-based MPPT [30], Artificial Neural Network (ANN)-based MPPT [31], INC [32], and P&O [33] algorithms. The comparison depicted in Figure 27 demonstrates that the proposed RNN-based MPPT algorithm outperforms the other MPPT strategies in multiple critical performance metrics. These include peak overshoot, rise time, settling

time, and the level of ripples in the PV power and voltage output. Specifically, the RNN-based MPPT exhibits a faster response time with reduced overshoot, enabling quicker and more stable convergence to the maximum power point. This enhanced performance is particularly significant in dynamic conditions, where rapid changes in irradiance or temperature can challenge the stability and efficiency of power extraction.

The superiority of the RNN-based MPPT in maintaining minimal fluctuations and ripples in the output not only ensures more efficient power conversion but also contributes to the longevity and reliability of the solar generation system. The detailed comparative data, which further quantifies these performance differences, is systematically presented in Table 4, offering a comprehensive evaluation of each algorithm's strengths and weaknesses. This detailed analysis underscores the advantages of employing the RNN-based MPPT algorithm in solar power systems, especially

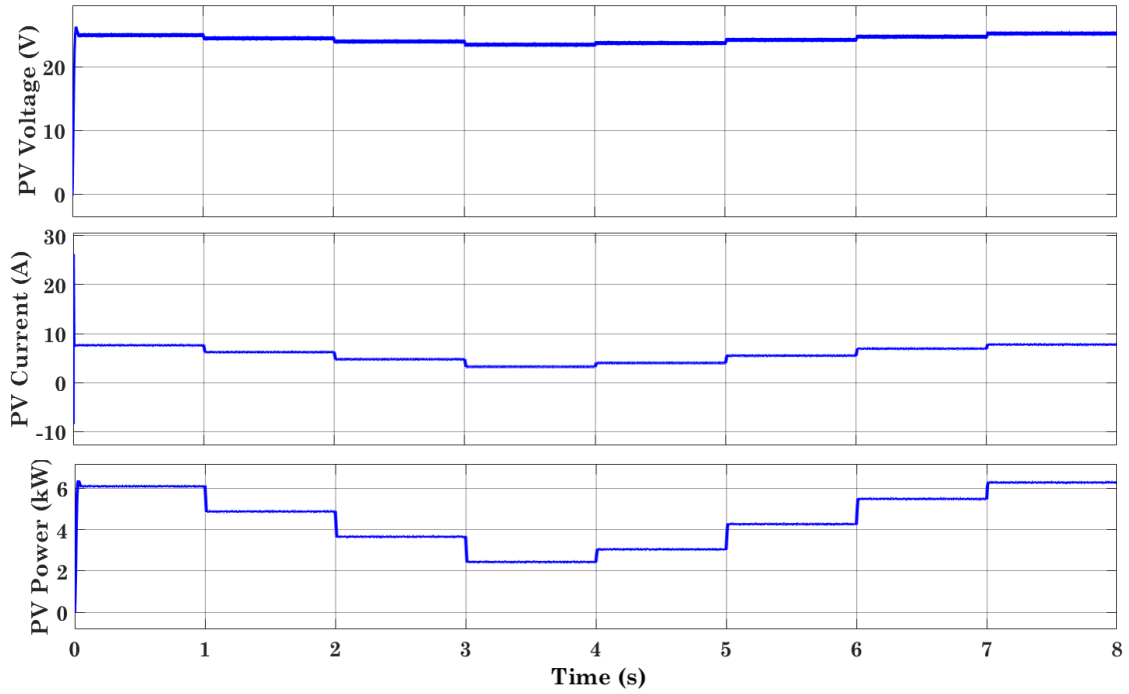


Fig. 28. PV panel voltage, PV panel current, and total output power from the PV array.

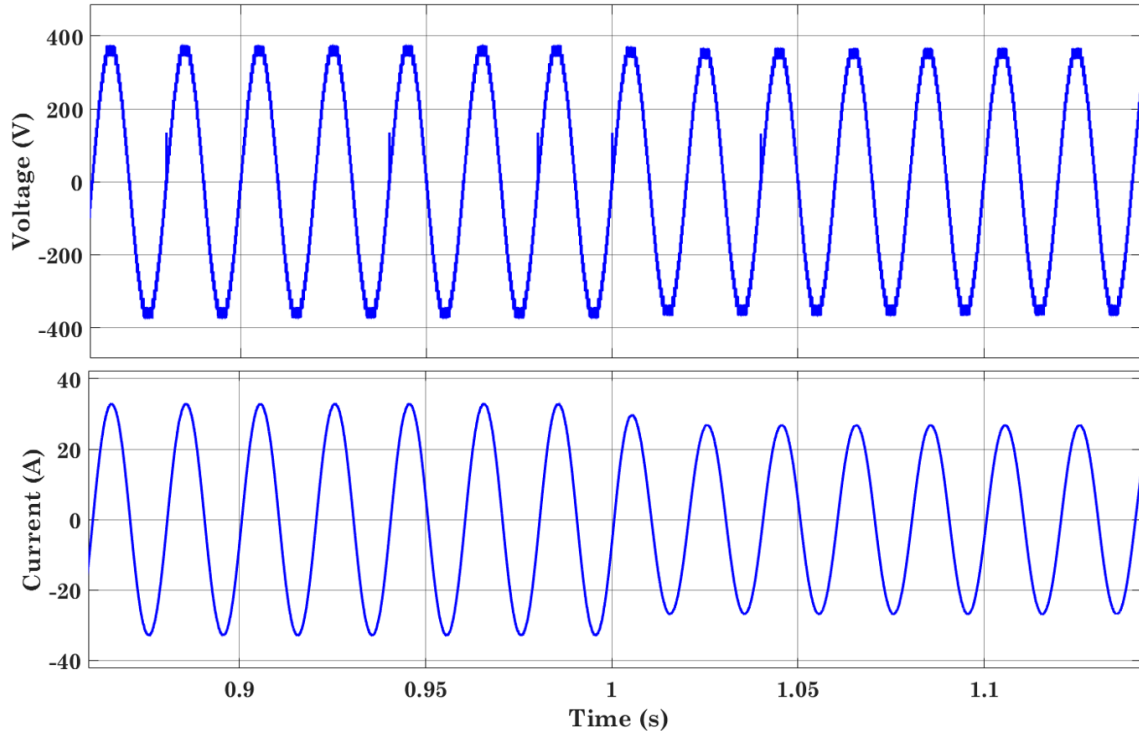


Fig. 29. Output voltage and output current of the proposed configuration of MLI.

in scenarios demanding high precision and stability under varying environmental conditions.

Initially, the system operates in islanding mode. As the irradiance changes, the PV panel's voltage, current, and

total power output are monitored. These parameters are presented in [Figure 28](#). The voltage ripples at the output of the PV array are determined to be 1%, indicating a stable and efficient power conversion process. As the

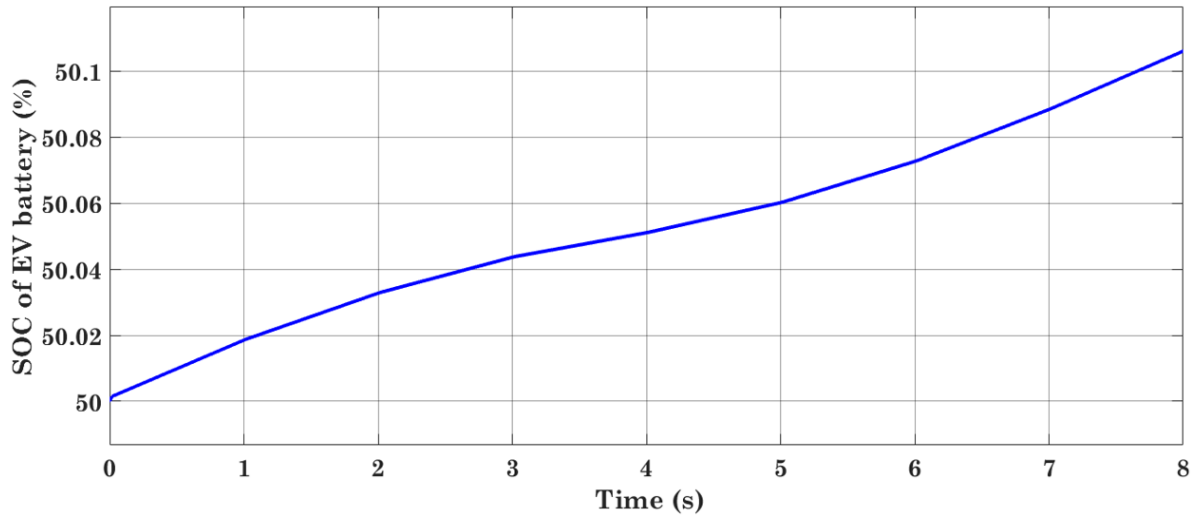


Fig. 30. SOC (%) of the EV battery with initial charge of 50% during islanding mode.

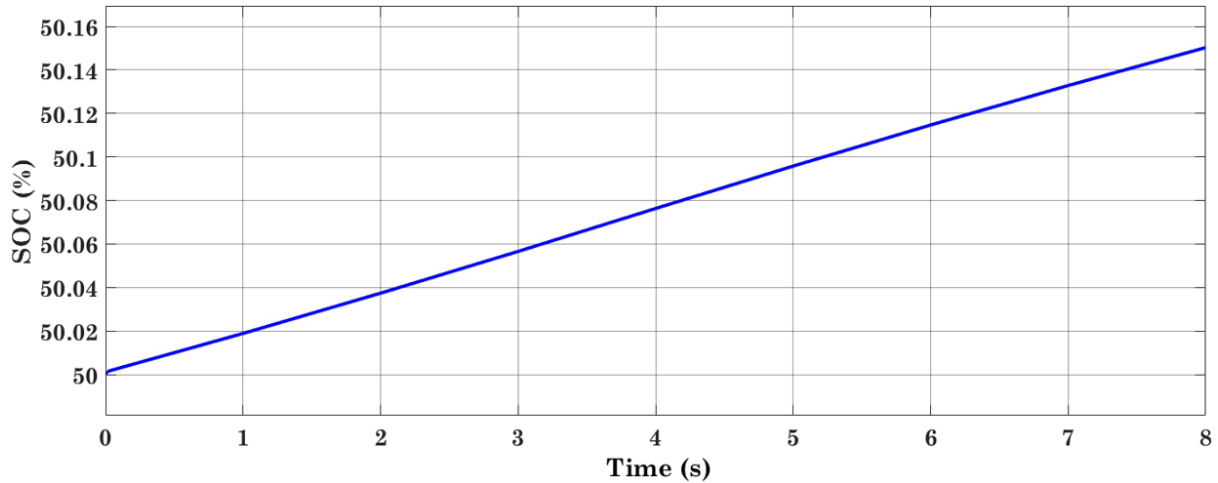


Fig. 31. SOC (%) of the EV battery with initial charge of 50% during grid connected mode.

irradiance varies, the output power from the PV array changes proportionally. This variation is crucial for understanding the system's dynamic response to environmental changes.

Figure 29 presents the 31-level output voltage and current of the MLI. The 31-level output ensures a high-quality AC waveform with reduced harmonic distortion, which is beneficial for the EV battery. Figure 30 shows the SOC of the connected EV battery, starting from an initial charge of 50%. Within 8 s, the SOC increases from 50% to 50.1%. This rapid charging rate demonstrates the efficiency of the proposed MOACFC-MLI system. To fully charge the battery from 0% to 100%, the proposed system requires 2 h and 14 min. This duration is 26% less than the charging time required by a conventional two-level inverter, highlighting the significant improvement in charging efficiency.

The stable output voltage and current of the MLI ensure that the EV battery is charged efficiently and safely.

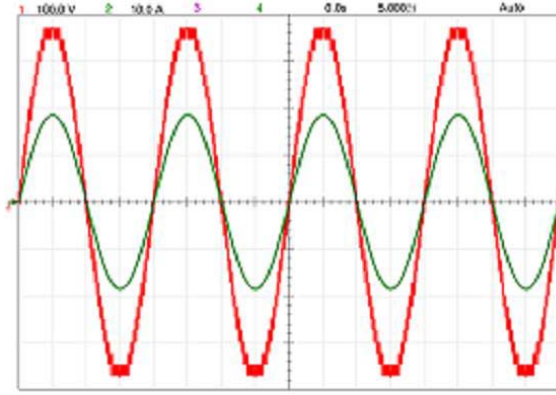
The reduction in voltage ripples to just 1% at the PV array output contributes to the overall stability and efficiency of the system. The significant reduction in charging time compared to conventional systems demonstrates the effectiveness of the 31-level MOACFC-MLI in handling high power densities and delivering efficient power conversion. This improvement can lead to faster turnaround times for EV charging, making the system more practical for real-world applications.

Figure 31 presents the SOC of the EV battery during grid-connected mode. In this mode, the system leverages both the PV array and the grid to charge the EV battery, resulting in a more efficient charging process.

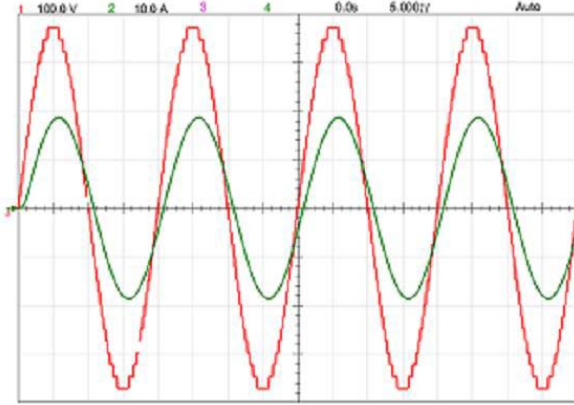
Initially, the SOC of the battery is at 50%. Within the first 8 s of operation in grid-connected mode, the SOC increases from 50% to 50.16%. This rapid increase indicates the effectiveness of the grid-assisted charging process, which supplements solar power with grid power to achieve faster

Table 5. Comparative analysis of inverter topologies.

Parameter	2-level inverter	3-level inverter	7-level topology [29]	Proposed 31-level MOACFC-MLI
Output voltage THD (%)	15.63	10.3	5.6	3.77
Output current THD (%)	3.5	2.1	1.8	0.99
DC voltage ripple (%)	5	3.2	2.5	1.05



(a)



(b)

Fig. 32. Load voltage and current for 31-level asymmetric configuration with (a) PD LSPWM (b) NLCPWM.

charging rates. The analysis extends to determine the total time required to fully charge the battery from 0% to 100% in grid-connected mode. The proposed system requires 1 h and 24 min to achieve a full charge under these conditions. This is a significant improvement over the charging time required in islanding mode and conventional charging systems.

The integration of grid power with the PV array in grid-connected mode significantly enhances the charging efficiency. The combined power sources provide a more stable and continuous supply of power, reducing the dependency on solar irradiance and ensuring a consistent charging rate. In grid-connected mode, the system maintains high power quality by synchronizing with the grid voltage.

The reference set point for the charging process is the sinusoidal grid voltage, which ensures that the power factor remains close to unity. This results in efficient power transfer and minimal losses during the charging process.

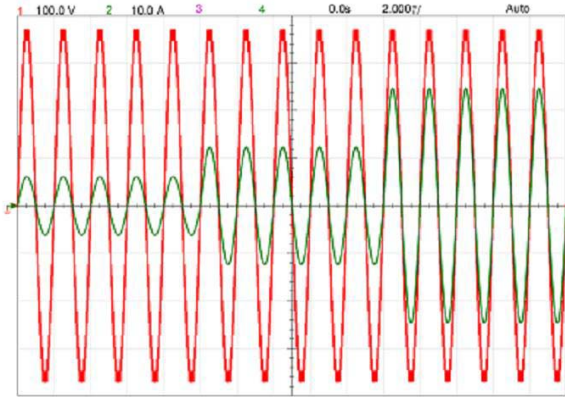
Total harmonic distortion is a crucial parameter in evaluating the quality of power delivered by the inverter. Lower THD values indicate better power quality, which is essential for both grid integration and efficient EV charging. The THD of the output voltage in islanding mode is measured at 3.77%. This relatively low THD value indicates that the proposed system produces a high-quality AC voltage output, which is vital for ensuring the efficient operation of the connected load or grid.

The THD of the output current in islanding mode is 0.99%. This exceptionally low current distortion highlights the effectiveness of the proposed inverter in delivering a clean current waveform, crucial for minimizing losses and improving the overall efficiency of the system. The voltage ripple at the DC side of the inverter is maintained at 1.05%. This minimal ripple ensures stable DC voltage, which is critical for the reliable operation of the inverter and the subsequent AC power conversion.

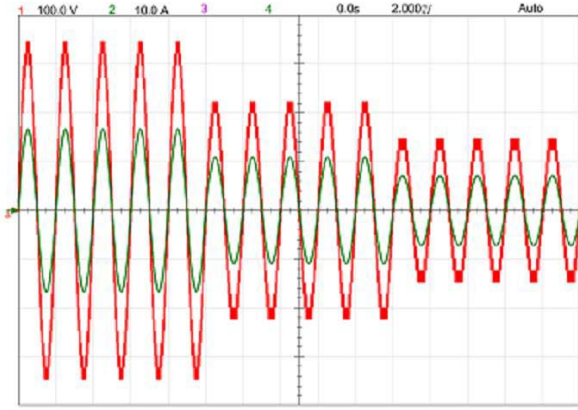
To comprehensively assess the performance of the proposed 31-level MOACFC-MLI system, compare it against conventional 2-level, 3-level inverters, and a 7-level topology as presented in [29]. The comparison is summarized in Table 5.

7 Experimental results

A prototype of the proposed single-phase MLI configuration was assembled to validate the reliability of the simulation results. In this study, to balance simplicity with acceptable accuracy, a PV emulator employing the physical single-diode PV model is utilized. This configuration operates with a DC voltage of 100 V applied across the primary of the transformer, with voltages distributed across four secondary windings ($V_{dc1} = 25$ V, $V_{dc2} = 50$ V, $V_{dc3} = 100$ V, and $V_{dc4} = 200$ V). The designed circuit can generate staircase waveforms with a maximum output voltage of 375 V. To achieve this, IGBT switches were employed, specifically the BUP306D 1200 V 23 A type for level generation and the BUP314D 1200 V 42 A type for the H-bridge. During the experimental phase, the inverter powered at a line frequency of 50 Hz and was subjected to RL loads. Both PD LSPWM and NLC PWM strategies are used. A switching frequency of 10 kHz is adopted for PD LSPWM and for NLC PWM switching frequency of switches is equal to the fundamental frequency. The MLI runs its switches at the line frequency and is engineered to minimize the count of conducting switches for a specified current path. As a result,



(a)

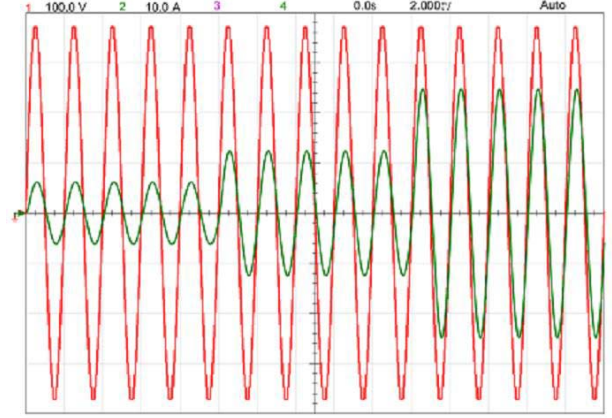


(b)

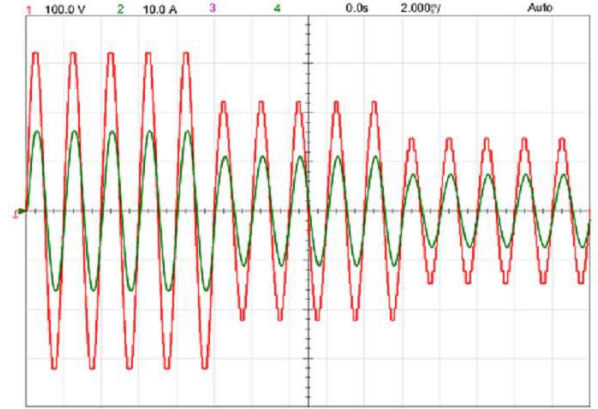
Fig. 33. Load voltage and current for 31-level asymmetric configuration with PD LSPWM (a) Load Change (b) Modulation Index Change.

this design approach significantly reduces both switching losses and conduction losses, ultimately enhancing the overall efficiency of the MLI when used in conjunction with NLC PWM control.

The IGBT switching signals were generated using both PD LSPWM and NLC PWM strategy, as detailed in [Section 2](#). These signals were interfaced with a TMS320F28335 digital signal processor board, which is a 32-bit C2000 processor manufactured by Texas Instruments. Real-time gate signals obtained from the digital input/output of the TMS320F28335 Digital Signal Controller (DSC) chip were isolated and amplified through TLP-250H optocouplers, serving as drivers for the IGBTs. To avoid potential short circuits in the DC link caused by the switches, a delay time of 6 μ s was implemented between the gate signals of complementary switch pairs. For measuring the circuit current, a Swiss LEM LA55-P current sensor was employed. The maximum temperature limit for the heat sinks was set at 70 $^{\circ}$ C to ensure proper thermal management. The proposed inverter had a rated output power of 800 W. Subsequently, a series of tests were conducted on the prototype to assess the performance of the proposed topology.



(a)



(b)

Fig. 34. Load voltage and current for 31-level asymmetric configuration with NLC PWM (a) Load Change (b) Modulation Index Change.

[Figure 32](#) presents experimental outcomes illustrating the load voltage and load current characteristics for a 31-level MLI. The MLI is subjected to two modulation techniques: PD LSPWM and NLC PWM. These modulation techniques determine how the inverter generates its output voltage and current waveforms. In [Figure 33](#), the load voltage and current profiles are displayed as the load conditions are varied, and the modulation index is adjusted using PD LSPWM. [Figure 34](#) showcases similar load voltage and current characteristics, but in this case, the load conditions are varied, and the modulation index is adjusted using NLC PWM.

8 Conclusion

This study introduces a MOACFC integrated with a MLI topology designed specifically for solar energy systems and EV charging applications. The proposed system features innovative symmetrical and asymmetrical configurations to produce 9-level, 21-level, and 31-level voltage outputs, which significantly reduce the number of switches and DC

sources compared to traditional MLI topologies. This efficient design is complemented by an RNN-INC-based MPPT algorithm that optimizes power extraction from PV arrays. Through rigorous simulation and hardware testing, the proposed system demonstrated exceptional performance under dynamic conditions. The 9-level, 21-level, and 31-level inverters exhibited THD values of 9.36%, 3.92%, and 2.63%, respectively, using Nearest Level Control Pulse Width Modulation (NLCPWM). For EV charging applications, the proposed configuration achieved voltage and current THD reductions of 3.77% and 0.99%, respectively. These values significantly outperform conventional 2-level (15.63% voltage and 3.5% current THD) and 3-level inverters (10.3% voltage and 2.1% current THD). The reduced THD not only enhances power quality but also improves charging efficiency and reduces electrical stress on the EV battery system. This is crucial for extending battery life and ensuring reliable operation. The modular design of the MLI and the versatile output of the MOACFC facilitate scalability and ease of maintenance. The system's ability to handle varying grid conditions and dynamic load demands with high precision and reliability underscores its practicality for real-world applications. The implementation of the RNN-INC-based MPPT algorithm ensures maximum power extraction from PV arrays, contributing to overall system efficiency. The combination of the MLI and MOACFC provides a robust solution for delivering high-quality power for both stand-alone and grid-integrated operations. The proposed MOACFC-MLI system offers a significant advancement in solar generation and EV charging technology, presenting a more efficient and reliable alternative to conventional inverter topologies. The system's reduced THD, improved power quality, and enhanced efficiency make it a compelling solution for modern renewable energy applications, supporting the widespread adoption of sustainable energy practices. Future research should explore further optimization of thermal management and the integration of additional renewable energy sources to continue enhancing system performance and reliability.

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Conflicts of interest

The authors declare that they have no conflicts of interest.

Data availability statement

No data were used to support this study.

Ethics approval

All procedures performed in studies involving human participants were by the ethical standards of the institutional and/or national research committee. All applicable international, national, and/or institutional guidelines for the care and use of animals were followed.

Informed consent

Informed consent was obtained from all individual participants included in the study.

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