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Original Article

Design and Performance Assessment of a Multilevel Inverter for Improved Standalone PV System Operation

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Abstract *- The design and performance assessment of a nine-level Multi-Level Inverter (MLI) for standalone Photovoltaic (PV) systems aim to increase the inverter's efficiency and decrease the usage of power switches. Multilevel inverters synthesize a sinusoidal output waveform from multiple voltage levels, which results in lower Total Harmonic Distortion (THD) and higher power quality. The nine-level multilevel inverter incorporates a variety of Pulse Width Modulation (PWM) techniques in this configuration to control the output voltage. The inverter can efficiently regulate power flow from the PV system to the load by optimizing the PWM control methods, resulting in a stable and dependable energy supply. The inverter experiences lower conduction and switching losses with fewer switches, resulting in enhanced overall efficiency. Furthermore, simplified circuitry can result in lower production costs and increased reliability. The performance analysis must examine this multilevel inverter's output voltage waveform, THD, efficiency, and power losses. It is possible to examine findings with the results of conventional inverters utilizing simulation modelling. The nine-level multilevel inverter can be an excellent option for standalone PV systems because it lowers THD and increases efficiency, enabling better system performance and greater use of renewable energy sources.*

Keywords *- Number of power switches, Modified MLI, Phase disposition PWM, PV system, THD.*

1. Introduction

Multilevel inverters have received much attention in recent years because of their ability to overcome the constraints of conventional two-level inverters, such as increased voltage stress on semiconductor devices and harmonic distortion. These inverters are appropriate for various applications in renewable energy systems, electric vehicles, and industrial drives because of improved voltage waveforms, decreased switching losses, and higher power quality. In standalone photovoltaic systems, a multilevel inverter is an essential component which transforms the Direct Current (DC) power supplied by solar panels into Alternating Current (AC) for use in various electrical appliances.

Standalone PV systems have been increasing in popularity in rural areas as the demand for clean, sustainable energy increases because they can produce dependable, eco-friendly electricity without a connection to the grid [1-3].

Due to voltage and harmonic distortion constraints, traditional two-level inverters are less effective for high-power applications. These weaknesses are fixed by multilevel inverters, which create AC waveforms from multiple voltage levels.

They achieve this by generating increased voltage outputs using a series of power semiconductor switches and capacitors, which reduces harmonic distortion, lowers switching losses, and improves overall efficiency.

Independent PV systems need a consistent and reliable power source because they are frequently used in remote or off-grid settings. Multilevel inverters are often used in such systems because they can create superior sinusoidal waveforms, lowering the possibility of harming delicate electronic devices. Additionally, multilevel inverters enable better voltage regulation, raising standalone PV systems' overall performance and dependability [4-8].

1.1. Literature Review

The neutral-point-clamped inverter, or diode-clamped MLI, is one of the most widely used multilevel inverter topologies. In order to produce various voltage levels across the output terminals, it is made up of numerous capacitors and diodes. Compared to other topologies, it requires more components because the voltage levels depend on the number of capacitors implemented. The cascaded H-bridge MLI is a different popular arrangement requiring utilising numerous H-bridge cells.

The inverter can achieve higher voltage levels by connecting more cells in series. Each H-bridge can produce three-level output voltages. Flying capacitors are used by the flying capacitor MLI to generate various voltage levels. It has fewer components than the diode-clamped MLI; however, it needs delicate voltage balancing of the flying capacitors, which is frequently complicated. In contrast to two-level inverters, it provides better voltage levels and lower switching losses [9-14].

Pulse width modulation techniques have become essential in managing the switching patterns of semiconductor devices to maximise the potential benefits of multilevel inverters. This investigation of the available information evaluates the various PWM methods utilised by multilevel inverters, their characteristics, and how these individuals affect the overall effectiveness of such inverters. One of the fundamental methods used in multilevel inverters to produce a nearly sinusoidal output voltage is sinusoidal PWM.

PWM pulses closely resembling the reference waveform are produced by comparing a sinusoidal reference waveform with a high-frequency carrier signal. Although SPWM is relatively simple to establish, it features low voltage resolution and high harmonic content, especially at low modulation indexes. A more advanced method called selective harmonic elimination PWM intends to reduce specific harmonics in the output voltage waveform.

The modulation indexes for the fundamental and a few chosen harmonic frequencies can be found by solving a series of nonlinear equations. Although the computational difficulty of this method rises with the number of desired harmonics to be removed, it provides better control over the harmonic content. In multilevel inverters, particularly in three-phase applications, Space Vector PWM is a common approach.

In contrast with SPWM, it generates a nearly sinusoidal output voltage with a higher voltage resolution. SVPWM enhances power quality, lowers voltage THD, and lowers common-mode voltage. However, its implementation necessitates more sophisticated control algorithms and mighty computing power.

Hybrid PWM techniques combine the advantages of various PWM techniques to enhance performance. As an illustration, combining SPWM and SHEPWM can improve harmonic performance while keeping the implementation process simple. Individual PWM strategies have some drawbacks, which hybrid techniques can help to offset, resulting in the development of more adaptable and practical multilevel inverter designs [15-19].

Seven- and nine-level multilevel inverters are voltage source inverters synthesising multiple output voltage levels by combining multiple DC voltage sources. The Cascaded H-Bridge (CHB) configuration is the topology these inverters use the most frequently. When using the CHB topology, each H-bridge module produces a portion of the overall output voltage, and the cumulative output is the sum of these portions. The Pulse-Width Modulation (PWM) technique manages the switches, producing the desired output voltage waveform [19-25].

The ability of multilevel inverters to lower THD in the output voltage waveform is one of their key advantages. Compared to traditional two-level inverters, they successfully minimise the distortion by synthesising a waveform that resembles a staircase and has a variety of voltage levels.

According to investigations, THD levels below 5% can be attained by seven-level and nine-level inverters, which is highly anticipated in the power grid and industrial applications. Efficiency is crucial for power electronic systems because it directly affects thermal performance and energy consumption.

Multilevel inverters are generally more efficient than conventional inverters, particularly at medium- to high output power levels. The higher efficiency of multilevel inverters results from the decreased switching losses brought on by the devices subjected to less voltage stress. The leading causes of power loss in multilevel inverters are switching losses during PWM operation and conduction losses in the switching devices. The overall power loss is significantly influenced by the switching frequency, control method, and switching device type choices [26-32].

The proposed nine-level multilevel inverter has benefits such as a lower harmonic content, less switch voltage stress, and better power quality. However, it also has certain limitations. Increased power semiconductor device and capacitor requirements lead to design complexity. To maintain stability and ensure proper voltage level balancing, control techniques become more complex.

Additionally, as levels are added, switching loss expands, decreasing efficiency. Power quality problems like voltage inconsistencies, harmonics, and electromagnetic

interference may occur, necessitating sophisticated filtering methods. Despite the advantages, implementing a nine-level multilevel inverter necessitates addressing these issues to achieve the highest levels of performance and dependability [33-36].

The proposed nine-level multilevel inverter has achieved the following objectives for standalone PV systems:

- Develop a multilevel inverter with optimum energy conversion performance and the least number of harmonic distortions suitable for standalone photovoltaic systems.
- Evaluate and enhance the voltage levels and switching devices in the multilevel inverter's topology to achieve the desired power rating and system specifications.
- Investigate control strategies and modulation techniques to change solar conditions while ensuring a reliable and smooth power transfer between the PV array and load.
- Employ computer-aided tools to simulate the designed multilevel inverter and validate its performance under various PV power levels and load conditions.
- Evaluate the benefits of the multilevel inverter in terms of efficiency, total harmonic distortion, and overall reliability in standalone PV systems.

2. Proposed Modified MLI and Operation

The proposed grid-connected PV power generation system effectively converts solar irradiance into usable electrical energy using a Nine Level Multilevel Inverter and a PWM control strategy. The system's main components are the PV panel, the multilevel inverter, a filter, and the grid/load connection. The PV panel is essential for converting solar radiation into direct current electricity. The PV panel's surface receives sunlight, which causes a current flow that is proportional to the amount of incident irradiance.

The temperature of the PV panel also has an impact on its performance, as higher temperatures can reduce the efficiency of the process of converting energy. A Nine Level Multilevel Inverter changes the PV panel's DC output into AC compatible with the grid. This type of inverter has multiple voltage levels, allowing it to generate a smoother and higher-quality output waveform compared to traditional two-level inverters.

Additionally, the multilevel inverter increases system effectiveness and lowers harmonic distortion. The PWM control strategy is utilised to manage the inverter's output voltage. The inverter can maintain the intended voltage output level and achieve Maximum Power Point Tracking (MPPT) by adjusting the duty cycle of the switching signals.A filter has been integrated into the system, ensuring the generated AC power is unambiguous and devoid of harmonic distortions. The filter reduces any high-frequency noise produced while the inverter switches, ensuring adherence to grid connection requirements and safeguarding delicate loads. When the PV panels produce more electricity than the connected loads need, the system can supply the excess power to the grid using the grid/load-connected operation. In addition, when a load requires more power than a PV panel can provide, the system uses additional power from the grid to satisfy the load's requirements.

The design for a modified multilevel inverter connected to solar panels is illustrated in Figure 1. The proposed nine-level multilevel inverter employs ten IGBT power components, a load (R and RL), and four symmetrical DC voltage sources to produce better voltage waveform quality and less harmonic distortion. The inverter generates nine voltage levels by carefully regulating the IGBTs' switching patterns, enabling finer voltage resolution and a smoother output waveform.

The connected load is less strained while the inverter's efficiency and performance improve. Additionally, the multilevel topology allows for lower switching frequencies, which reduces switching losses and boosts overall system efficiency. The inverter is appropriate for various applications, including grid-tie inverters, motor drives, and renewable energy systems, because it can generate high-quality AC voltage. Figure 2 illustrates the proposed nine-level multilevel inverter.

The proposed nine-level multilevel inverter is designed to operate with various voltage levels, including $-4V_{DC}$, $-3V_{DC}$, $-2V_{DC}$, $-V_{DC}$, $0V_{DC}$, $+V_{DC}$, $+2V_{DC}$, $+3V_{DC}$, and $+4V_{DC}$. This inverter topology offers increased voltage resolution and reduced harmonic distortion compared to conventional inverters. Utilizing multiple voltage levels can generate more accurate and smoother output waveforms, improving efficiency and lowering electromagnetic interference. The inverter's operation involves controlling the switching states of its power semiconductor devices to achieve the desired output voltage level.

The proposed MLI operates in a specific mode in which switches S1, S3, S5, S9, and S7 are turned on. In this configuration, dc voltage sources V1, V2, V3, and V4 are also utilised. This configuration leads to the inverter's output voltage being -4VDC. Figure 3 illustrates the operating mode of +4VDC output voltage.

A negative output voltage value results from the output voltage being inverted concerning the dc voltage Vdc, as indicated by the negative sign. The MLI is suitable for various power conversion applications because of this specific mode of operation, which enables the MLI to produce a controlled output voltage waveform with multiple voltage levels. The proposed MLI is operated in a specific mode by turning on switches S1, S3, S5, S9, and S10.

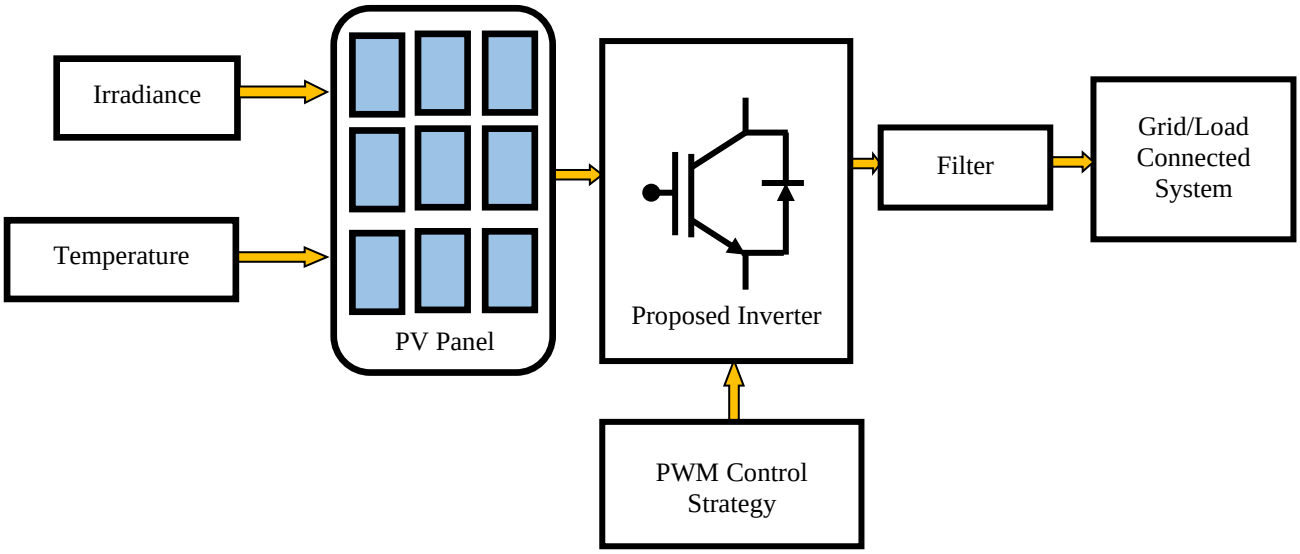

Fig. 1 PV interconnected modified MLI

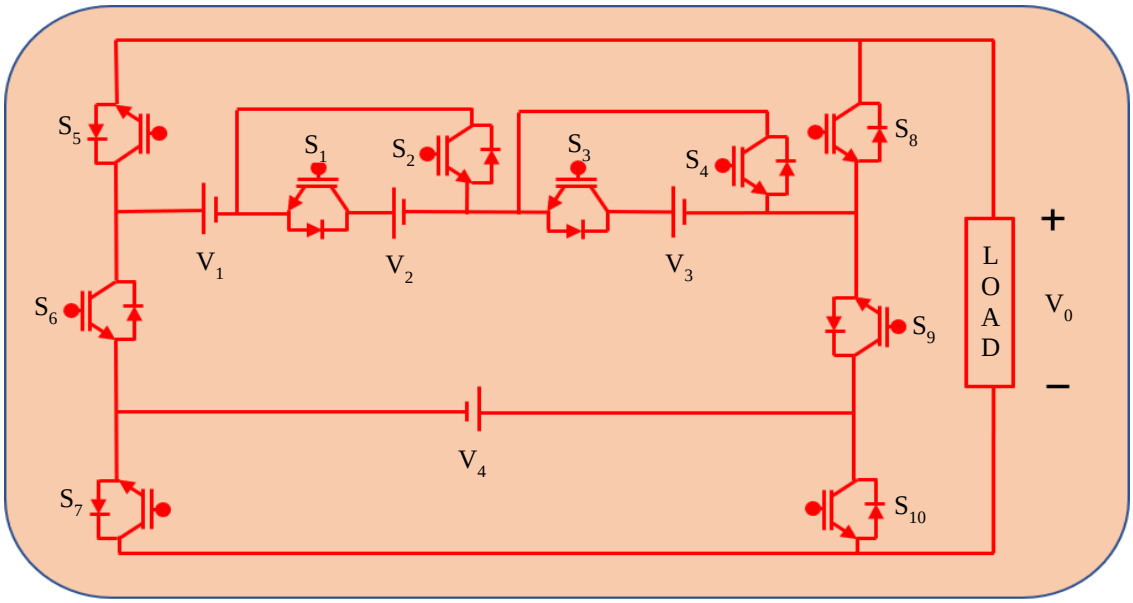

Fig. 2 Proposed nine-level multilevel inverter

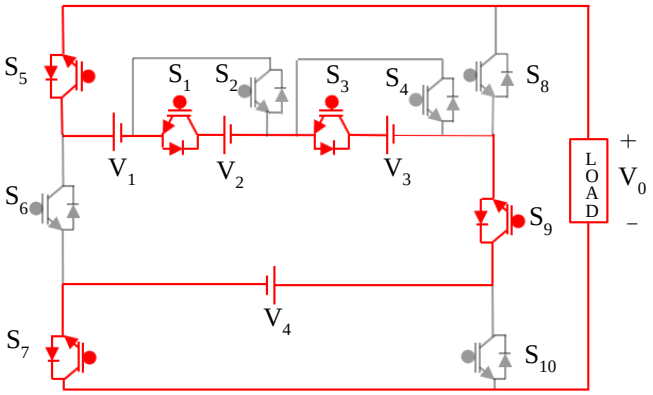

Fig. 3 +4V_{DC} output voltage

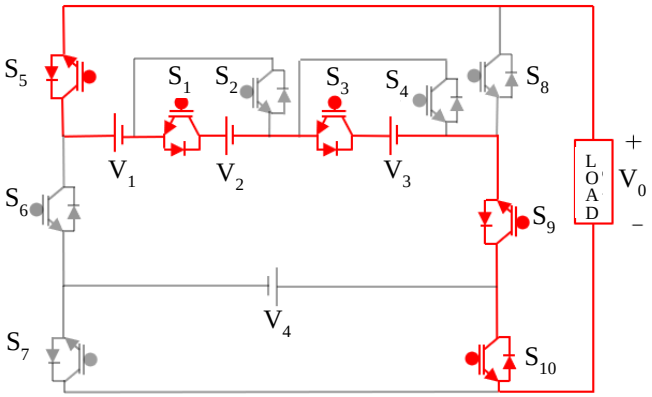

Fig. 4 +3V_{DC} output voltage

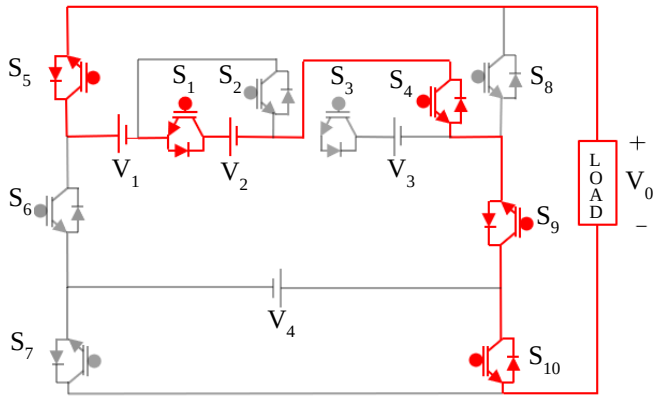

Fig. 5 +2V_{DC} output voltage

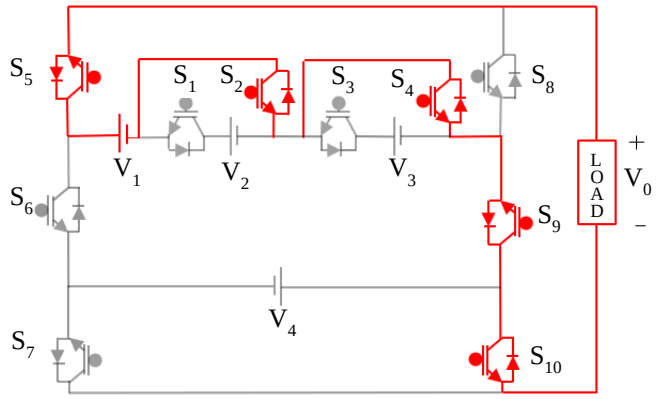

Fig. 6 +V_{DC} output voltage

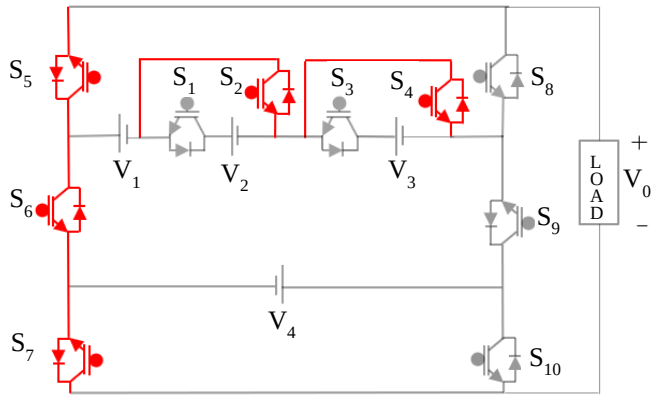

Fig. 7 0V_{DC} output voltage

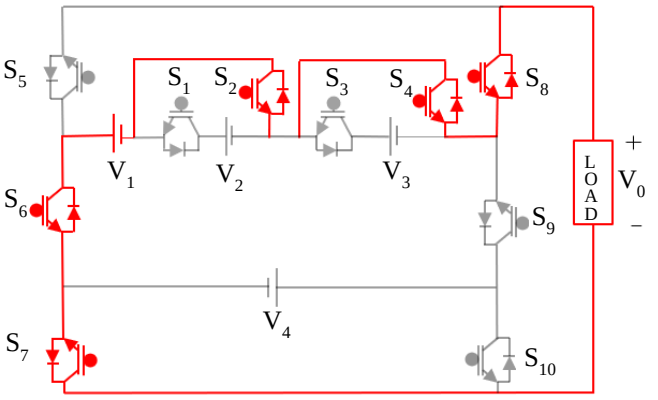

Fig. 8 -V_{DC} output voltage

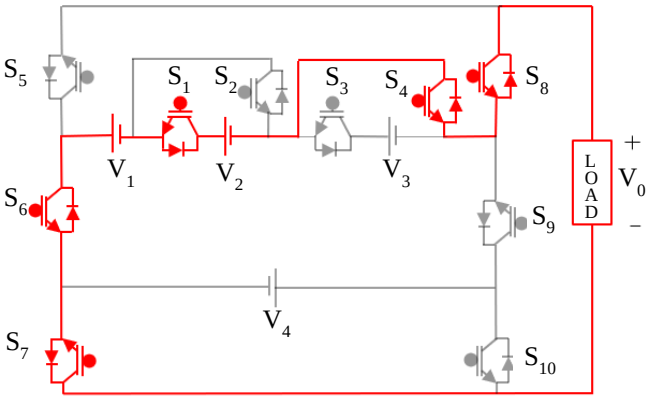

Fig. 9 -2V_{DC} output voltage

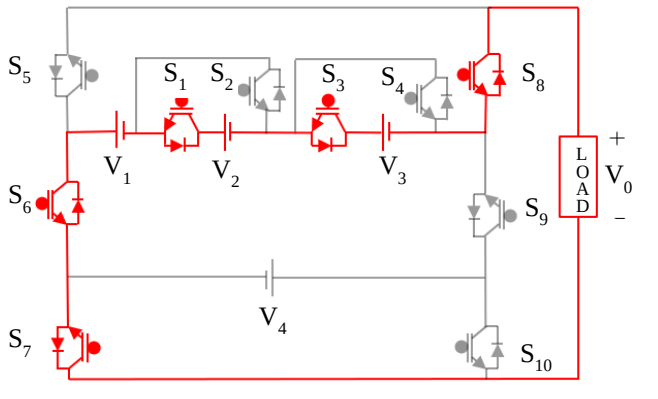

Fig. 10 -3V_{DC} output voltage

The MLI is powered by DC voltage sources V_1, V_2, and V_3. The MLI provides a -3V_{DC} output voltage in this configuration. This -3V_{DC} output voltage has to be utilised to power the connected load to the MLI.

Figure 4 illustrates the operating mode of +3VDC output voltage. The operation of an inverter entails converting a DC input voltage from sources V_1, V_2, and V_3 into an AC output voltage. The associated voltage sources are connected to the load when switches S_1, S_4, S_6, S_7, and S_8 are turned on.

Because of the particular combination of switches, the output voltage is negative (-2V_{DC}), indicating that the polarity of the AC waveform is inverted. Similarly, operating specific switches and DC voltage sources results in the output voltages -V_{DC}, 0, +V_{DC}, +2V_{DC}, +3V_{DC}, and +4V_{DC}. Figure 5 to Figure 11 depict the various operational modes of the proposed MLI. A reference sinusoidal signal and eight carrier waveforms are synthesised in the modulation technique called Pulse Width Modulation with Phase Disposition (PD-PWM).

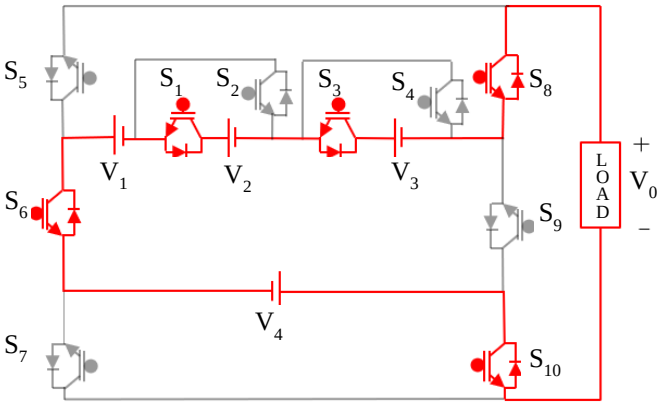

Fig. 11 -4V_{DC} output voltage

It attains effective signal transmission and control by different pulse widths of the carriers concerning the phase of the reference waveform. The instantaneous amplitude of a reference sinusoidal signal provides the basis for adjusting the pulse widths of each carrier, each of which corresponds to a particular phase angle. In addition to reducing power loss and improving overall system performance, PD-PWM maintains precise regulation. Figure 12 illustrates the pulse width modulation with phase disposition for the proposed nine-level inverter.

3. Results and Discussion

A proposed nine-level multilevel inverter is connected to a PV system in MATLAB/Simulink which, by Figure 1, operates at a temperature of 35°C and has an irradiance of 1000 W/m^2. Figure 13 illustrates the PV panel irradiance, and Figure 14 illustrates the temperature of the PV panel system. The boost converter must consider the PV panel voltage and maximum power in a solar power system. The input voltage range the boost converter has to handle is determined by the PV panel voltage.

It has to be suitable for the converter's operating range for effective energy transfer. The boost converter then increases the voltage to meet the system's needs, enabling the most efficient possible power transfer to the load or energy storage system. Solar energy is utilised efficiently and consistently when the voltage of the PV panels and the boost converter are proportionally correct. PV panel voltage of 288V and maximum output power are shown in Figures 15 and Figure 16, respectively.

The proposed nine-level inverter with a resistive load operates in a staircase mode, with voltage and current ratings of 230V and 10A, respectively. It achieves higher output harmonics, improved output waveform quality, and increased output voltage resolution. There is a higher harmonic distortion in the output current due to the resistive load. Figure 17 illustrates the output voltage and current waveform of nine-level inverters with resistive load. It attains staircase output voltage using a multi-level topology with a resistive and inductive load, maintaining a constant 230V and 8A current. This design significantly decreases output current harmonics, improving power quality and decreasing losses. THD is decreased due to improved voltage waveform approximation transformed possible by a higher proportion of voltage levels.

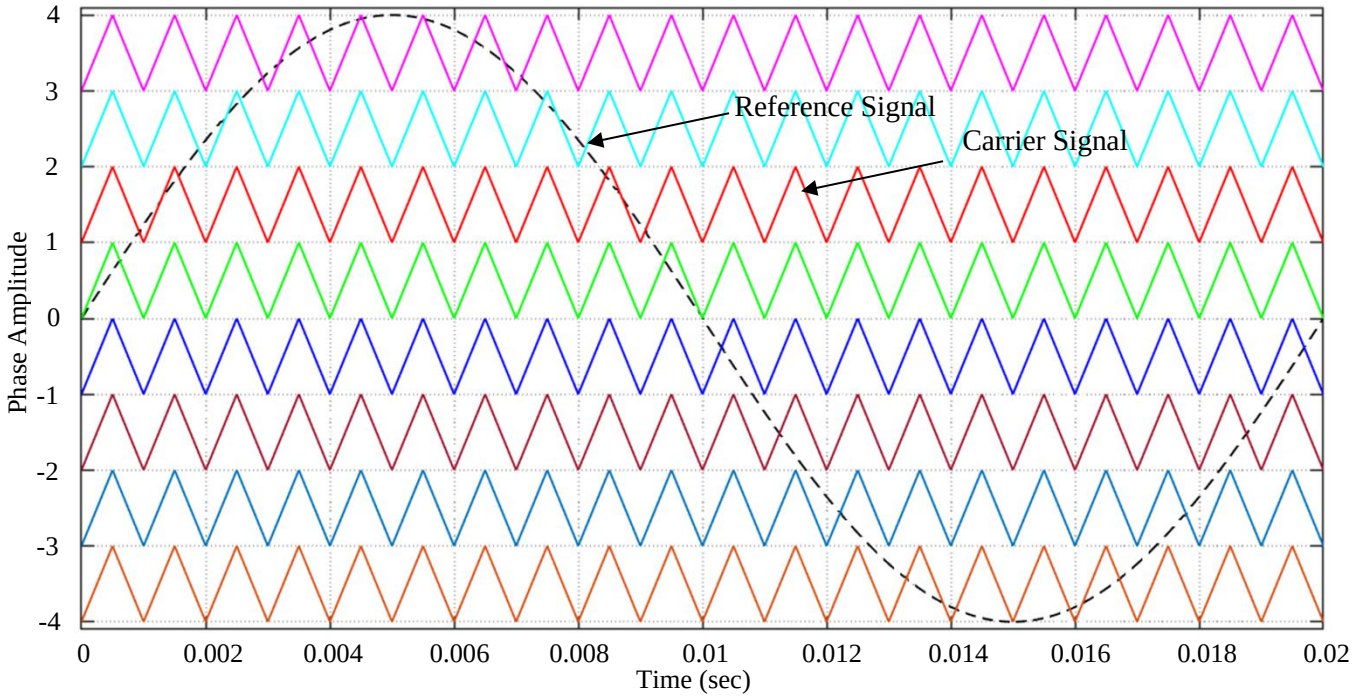

Fig. 12 Pulse width modulation with phase disposition

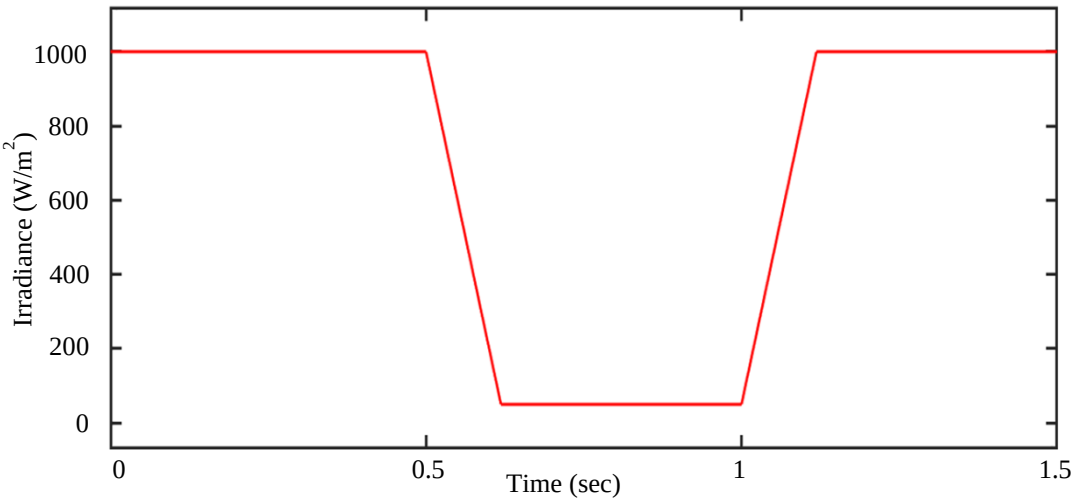

Fig. 13 PV panel irradiance

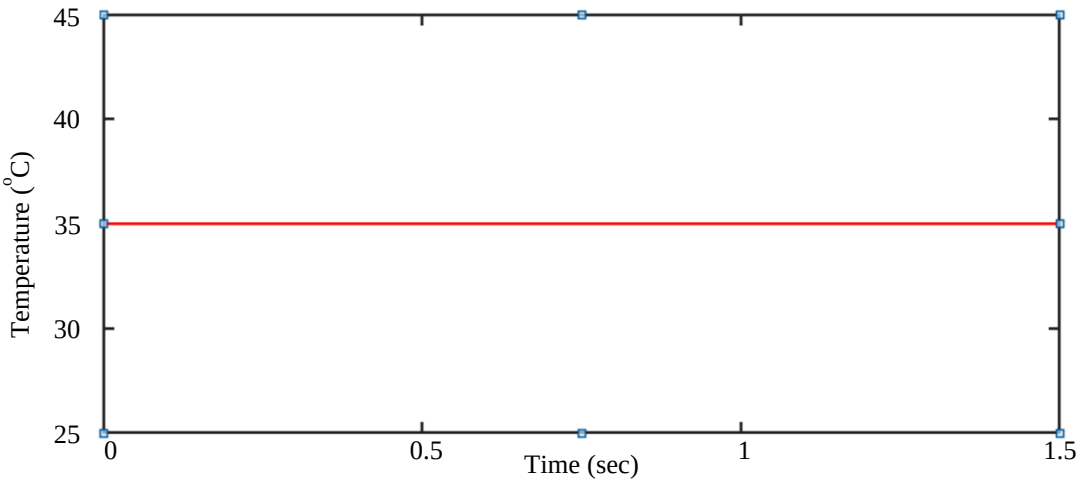

Fig. 14 PV panel temperature

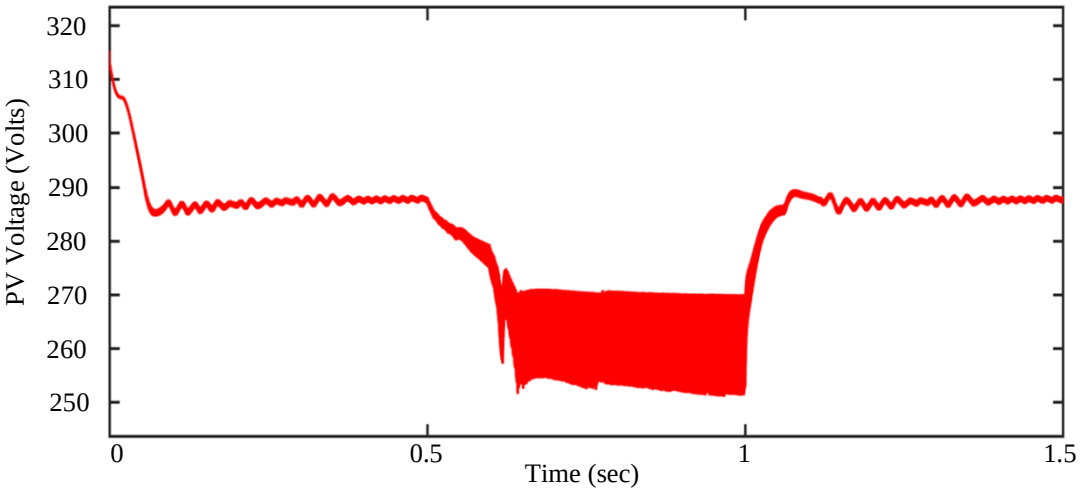

Fig. 15 PV panel voltage

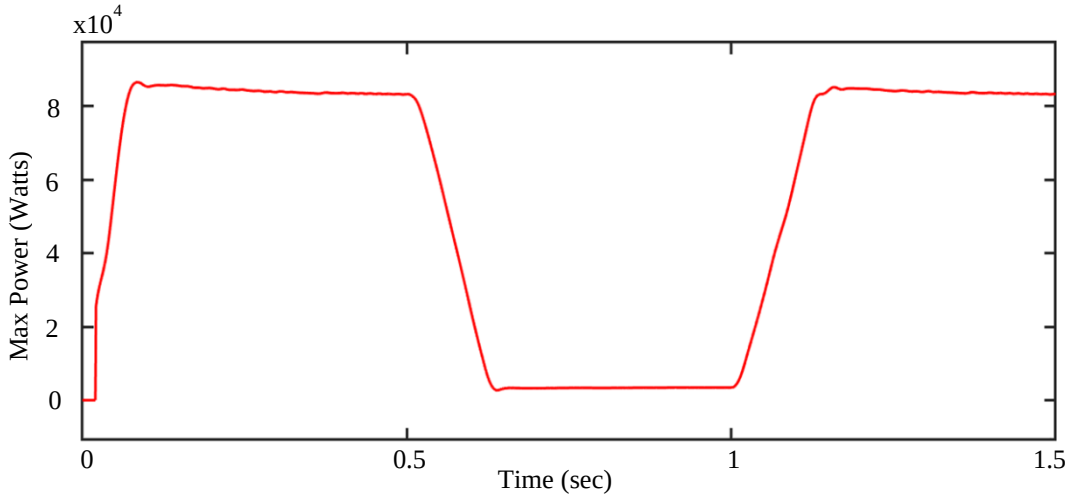

Fig. 16 PV panel maximum power

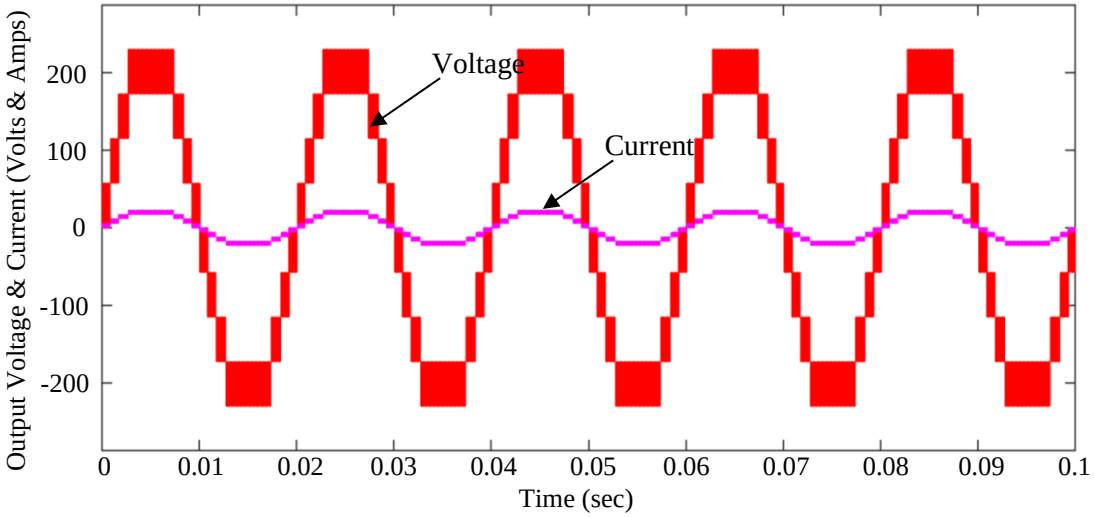

Fig. 17 Nine-level output voltage and current (R load)

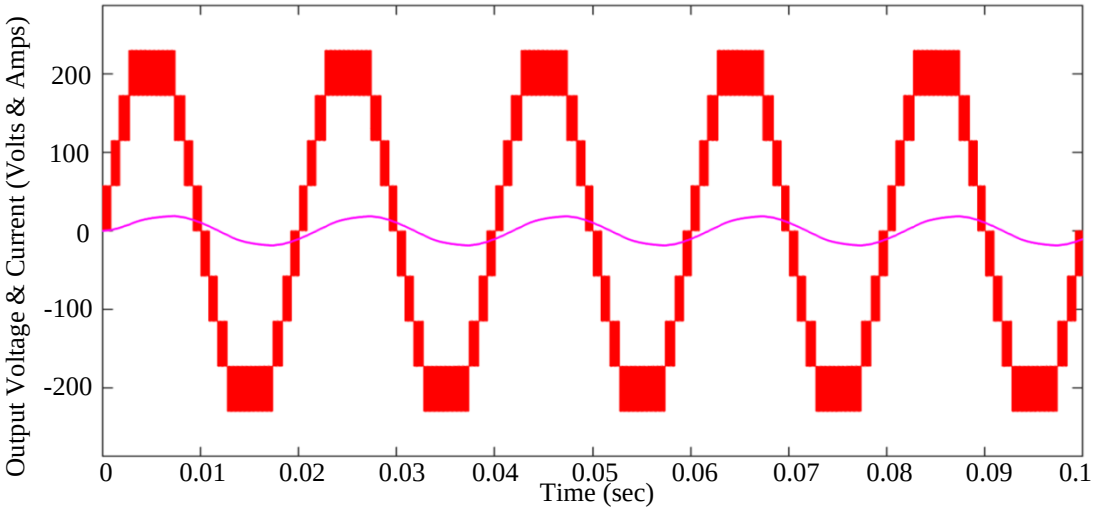

Fig. 18 Nine-level output voltage and current (RL load)

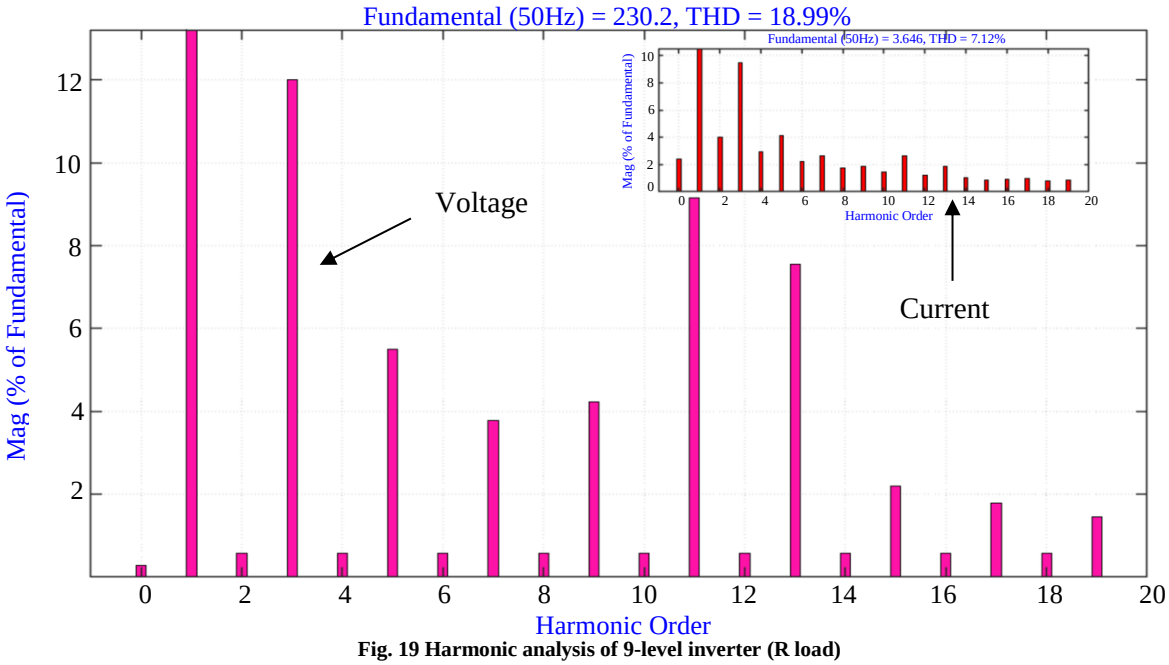

Fig. 19 Harmonic analysis of 9-level inverter (R load)

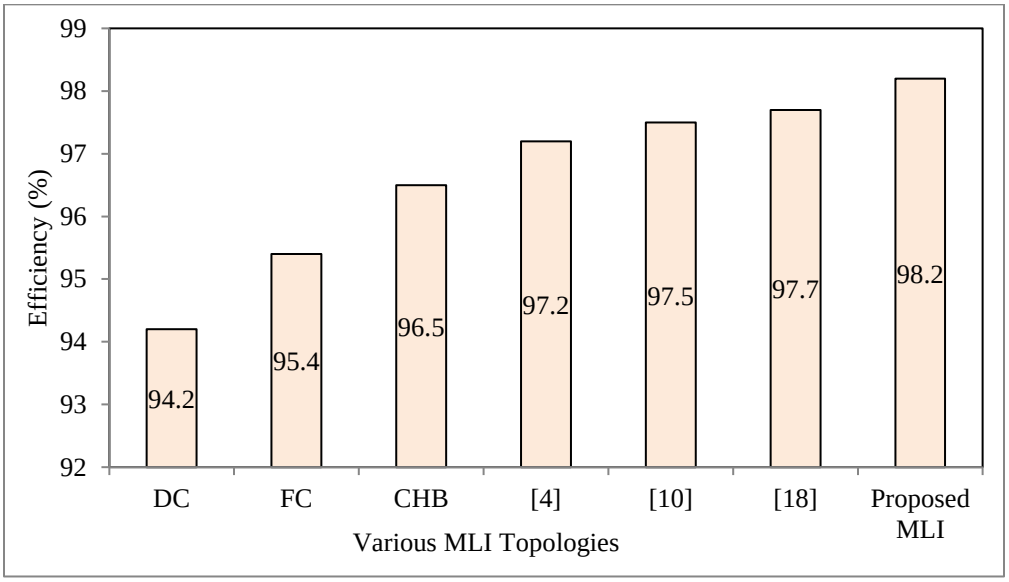

Fig. 20 Efficiency analysis of proposed and conventional MLI

Table 1. Comparison of proposed and conventional topology

S.No.	Parameters	DC MLI	FC MLI	CHB MLI	[4]	[10]	[18]	Proposed MLI
1	DC Sources	1	1	4	4	4	4	4
2	Power Switches	16	16	16	14	12	10	10
3	Power Diodes	24	-	-	-	-	10	-
4	DC Bus Capacitors	8	20	-	-	-	-	-
5	Balancing Capacitors	0	10	-	-	-	5	-

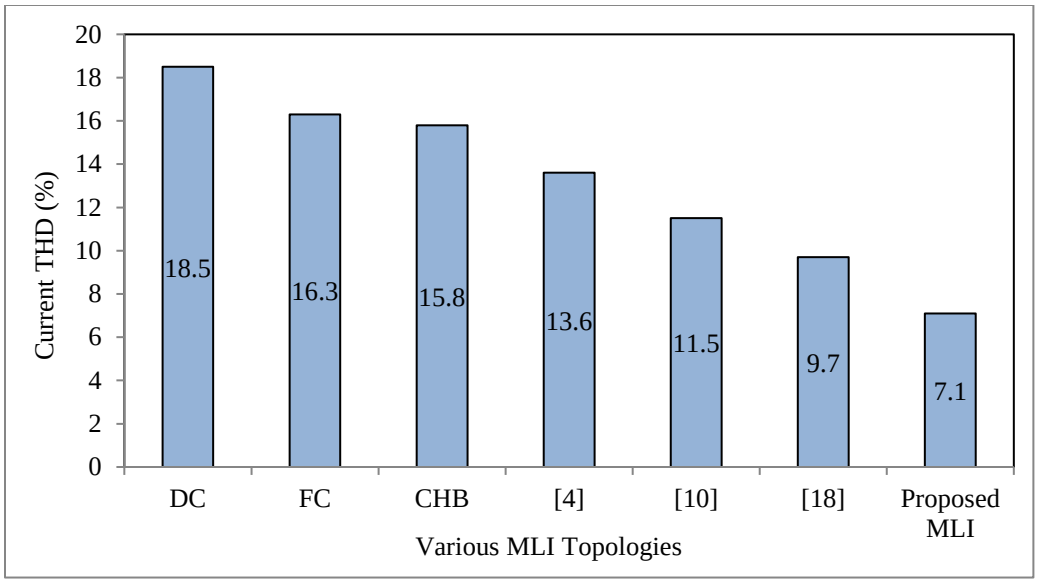

Fig. 21 Current analysis of proposed and conventional MLI

Table 2. Performance parameters proposed topology

S.No.	Parameters	Proposed MLI
1	No. of DC supplies	4
2	DC Voltage	60 V
3	RMS Voltage	240 V
4	No. of IGBTs	10
5	Driver Circuits	10
6	Carrier frequency	3 kHz
7	%THD (Current)	7.12 (RL load)
8	Switching loss	00.42 W
9	Conduction loss	41.31 W
10	Total loss	41.73 W
11	Efficiency	98.20 %

The ability of the inverter to produce lesser voltage steps reduces switching losses and improves efficiency. Figure 18 illustrates nine-level output voltage and current (RL load). The harmonic analysis of a 9-level inverter with an R load is shown in Figure 19. The output voltage waveform exhibits significant distortion, as indicated by the voltage Total Harmonic Distortion (THD), which is found to be 18.99%. Additionally, the output current waveform has a 7.12% current THD, which indicates the degree of distortion. These findings indicate that the proposed MLI outperforms traditional topologies regarding harmonic content. A comparison of the proposed MLI and the current conventional topologies is shown in Figure 20. The proposed MLI outperforms conventional topologies with an impressive efficiency of 98.2%. This demonstrates the improved energy conversion efficiency and reduced power losses the suggested MLI design provides. Figure 21 also compares recent research on the proposed MLI and traditional topologies. Comparing the proposed MLI to conventional topologies, the proposed MLI shows a lower current THD of about 7.1%. This suggests improved output power quality and current wave shaping, making the proposed MLI a good option for real-world applications. Overall, the findings exhibit that the proposed MLI has several advantages over traditional alternatives, including improved harmonic performance, increased efficiency, and current quality.

The configurations for handling DC sources, power switches, power diodes, DC bus capacitors, and balancing capacitors differ between the nine-level proposed and conventional MLI topologies are compared in Table 1. The proposed nine-level MLI requires fewer power switches to achieve additional intermediate voltage levels, which improves output waveform quality and lowers harmonic distortion. Conversely, traditional MLI typically operates with limited voltage levels, producing higher harmonic content. The proposed configuration improves system effectiveness, reduces stress on power devices, and offers increased voltage and power capability. The efficiency analysis of the proposed and conventional MLI is presented in Figure 20. The current analysis of proposed and conventional MLI is given in Figure 21.

The nine-level MLI that has been proposed performs effectively, with few losses and high output efficiency

overall. An efficient power conversion during switching operations is indicated by the switching loss of only 0.42 W. The conduction loss of 41.31 W shows that the inverter efficiently circulates current. Unexpectedly the total loss of 41.73 W shows exceptional system optimisation and minimal energy wasteful. The inverter's notable overall output efficiency of 98.20% highlights its capacity to convert input power into useful output power precisely. Table 2 illustrates the various performance parameters of the proposed MLI.

4. Conclusion

The proposed nine-level MLI performs admirably with ten power switches, with an exceptional total loss of only 41.73W. Its significant % efficiency rate of 98.20% demonstrates how much it can decrease energy consumption. Additionally, the 7.12% current THD according to load conditions ensures a stable and efficient operation, lowering the possibility of undesirable harmonics and enhancing the overall system reliability.

The advanced MLI design described here is a promising option for high-power applications because it balances performance and efficiency, promoting the efficient and sustainable use of electrical energy. It has the potential for effective renewable energy integration, advanced motor drives, and innovative grid applications due to higher voltage levels and reduced harmonics, opening up the possibility of a greener and more sustainable energy environment.

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