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Original Article

Performance Analysis of a Seven-Level Multilevel Inverter in Grid-Connected Systems

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Abstract *- This paper describes the design and analysis of a proposed seven-level multilevel inverter for integrating renewable energy sources into the power grid. Power conversion options that are efficient and trustworthy are crucial for effortless integration and effective use of renewable energy systems, which are becoming increasingly prevalent. Compared to conventional two-level inverters, multilevel inverters have several benefits, including less harmonic distortion, less voltage stress on the power devices, and improved power quality. A cascaded H-bridge structure combines the advantages of a modified phase-shifted pulse width modulation (PWM) control scheme in the proposed seven-level multilevel inverter topology. The design parameters and switching angles are optimised to achieve the highest power efficiency and least harmonic distortion. The proposed inverter is subjected to a thorough analysis, considering power losses, total harmonic distortion, and voltage waveforms. The proposed inverter's performance metrics and simulation results contrast the current multilevel inverter topologies. The proposed seven-level multilevel inverter offers better voltage quality, less total harmonic distortion, and lower power losses when compared to other existing topologies, according to simulation results. The suggested inverter also offers a superior output voltage waveform appropriate for the grid integration of renewable energy sources. The analysis and assessment provided in this paper confirm the viability and efficacy of the seven-level multilevel inverter suggested for integrating renewable energy, thereby advancing conversion technologies in the application of energy-efficient systems.*

Keywords *- 7-level, Efficiency, Multilevel inverter, Pulse width modulation, Total harmonic distortion.*

1. Introduction

Solar and wind power are examples of renewable energy sources that have attracted much attention recently because of how environmentally friendly and clean energy is. In place of conventional fossil fuel-based power generation, known to cause environmental pollution and global warming, these energy sources offer a practical substitute. However, effectively integrating renewable energy into the current power grid is extremely difficult due to these sources' intermittent and variable nature. Multilevel Inverters (MLIs), which provide enhanced voltage output quality, higher power efficiency, and improved harmonic effectiveness, can be used to approach these problems.

Due to their capacity to produce high-quality sinusoidal voltages with low harmonic content, multilevel inverters have become increasingly important in the combination of energy from renewable sources. These power converters accomplish this by synthesising the required final voltage waveform from multiple levels of DC voltages, typically obtained from renewable energy sources. Since fewer voltage steps exist when using multiple levels, the resultant pattern is more uniform and decreases the total harmonic distortion (THD). Additionally, inverters with multiple levels permit higher voltage functioning, lowering the current stress on the power devices and allowing the application of more minor and better-performing electronic parts for power generation [1-3].

2. Literature Review

A seven-level multilevel inverter requires an exploration of optimal modulation techniques, the choice of proper power electronic devices, and the design of control strategies. The recent seven-level multilevel inverter has been built using a variety of semiconductor components, including insulated-gate bipolar transistors (IGBTs), metal-oxide-semiconductor field-effect transistors (MOSFETs), and integrated gate-commutated thyristors (IGCTs). Various criteria, including switching speed, voltage rating, and power losses, are considered when selecting these devices [4-8].

In order to achieve precise output waveforms and regulate the power flow in multilevel inverters, strategies for modulating are essential. Pulse width modulation (PWM), selective harmonic elimination (SHE), and carrier-based modulation techniques are among the modulation strategies that have been researched for the proposed seven-level inverter. These methods seek to minimise switching losses, minimise harmonic content, and improve the inverter's performance in general. To compare the effectiveness of various modulation techniques, computational investigations and experimental verification have been carried out [9, 10].

Control strategies are created to manage power flow and preserve grid reliability to guarantee the effective integration of renewable energy sources. Numerous control algorithms have been suggested for the seven-level multilevel inverter, such as voltage control, current control, and hybrid control schemes. The abovementioned approaches use sophisticated control methods like fuzzy logic programming, model-based predictive control (MPC), and proportional-integral-derivative (PID) controllers. In order to compare how well different approaches to control manage in regards to grid synchronisation, power factor correction, and voltage regulation [11–13], research comparisons have been carried out.

Through computational and experimental examinations, the seven-level multilevel inverter has undergone extensive analysis and assessment. Total harmonic distortion, power losses, efficiency, voltage regulation, and transient response are among the important metrics of performance taken into account in the analyses mentioned above. The benefits and drawbacks of the proposed topology regarding cost, intricacy, and efficiency have been highlighted through comparisons with other multilevel inverter configurations, such as the five-level and nine-level inverters [14–16].

One of its drawbacks is the proposed seven-level multilevel inverter's [17] more complicated design than conventional two-level inverters. Multilevel inverters produce a more complicated circuit topology due to the need for more switches and capacitors, which are power electronic components. The inverter system's design, control, and maintenance may be complicated due to this higher level of complexity. The cost increases directly correlate with the degree of complexity of the seven-level multilevel inverter. Increased material costs, assembly costs, and overall system costs are caused by the additional power required by electronic components, as well as the complexities of the circuits. More specifically, in applications for integrating price-sensitive renewable energy, these higher costs may prevent the proposed multilevel inverter technology from being widely adopted [18–20].

In contrast to conventional two-level inverters, multilevel inverters require more complicated control. Advanced control algorithms and modulation methods are needed because the output waveform has more voltage levels. Higher computational resources and more advanced control hardware are needed to develop and apply such control strategies. The proposed multilevel inverter may be more challenging to establish in practice, particularly in real-time control applications [21–23].

Despite having advantages over two-level inverters, such as better voltage waveform excellence and less harmonic distortion, multilevel inverters continue to generate some harmonic distortion. In addition to interfering with other devices connected to the power grid, the output voltage waveform's harmonic content can negatively affect connected loads' performance. Harmonic distortion increases system complexity and costs and therefore has to be addressed with appropriate filtering and mitigation approaches [24–29].

Switches, capacitors, and diodes are among multilevel inverters' more common power electronic components. The durability and dependability of these components may impact the dependability of the entire system. The more parts there are, the more likely something will break or malfunction, necessitating routine maintenance and perhaps component replacement. The performance and availability of the system as a whole may be impacted by maintaining the components' dependability and accessibility throughout the system [30–32]. The scalability of the seven-level multilevel inverter may have restrictions. It can be challenging to scale up the multilevel inverter system to higher power levels and may call for alterations to the current circuit topology and control schemes. In order to guarantee an effortless integration into larger renewable energy systems, the system's capacity to grow has to be thoughtfully considered during the design process [33–37].

In order to integrate renewable energy, this work proposes the design and analysis of a seven-level multilevel inverter. For applications involving renewable energy, the proposed multilevel inverter has to take into account the following essential vital points:

- Examine and evaluate the proposed seven-level multilevel inverter modes of operations, which includes the standard cascaded H-bridge arrangement and the chosen control methods.
- Evaluate the seven-level multilevel inverter's output voltage attributes and determine whether it can produce high-quality, low-distortion voltage patterns which can be used to integrate renewable energy sources.
- Analyze the seven-level multilevel inverter's output current attributes and determine whether it can produce high-

quality, low-distortion voltage patterns which can be used to integrate renewable energy sources.

- Conduct simulations to evaluate the performance of the proposed multilevel inverter under different operating conditions, such as varying load conditions and different modulation indexes.
- In order to increase overall efficiency, evaluate the power losses in the proposed multilevel inverter, including conduction losses, switching losses, and other parasitic losses. Analyse the input and output power, considering steady-state and transient circumstances, to determine the multilevel inverter's efficiency. Then, examine it with other multilevel inverter topologies.
- Investigate the proposed multilevel inverter's responses to load modifications and capability to preserve constant output voltage and current under dynamic operating circumstances.

3. Proposed Seven-Level MLI and Modes of Operation

The proposed seven-level multilevel inverter with photovoltaic (PV) connected to the grid is intended to effectively utilise solar energy while seamlessly combining it with the grid. A PV module, a DC-DC converter, a multilevel inverter, a maximum power point tracking (MPPT) controller, and the grid are the components of the system. The PV panel converts solar energy into direct current (DC), subsequently introduced into the DC-DC converter.

The DC-DC converter regulates the voltage and current levels to meet the specifications of the multilevel inverter. It guarantees that the maximum power is transferred from the PV panel to the inverter. The multilevel inverter uses different voltage levels to generate a high-quality AC output waveform with low harmonic content. It accomplishes that by fusing various DC voltage sources and switching strategies. In order to maximise power generation, the MPPT controller continuously assesses the output of the PV panels and modifies the operating point. It ensures that the PV panel executes at its maximum power point, irrespective of the surrounding circumstances.

Furthermore, the multilevel inverter's alternating current output is synchronised with the grid voltage and fed into the grid. Figure 1 depicts the proposed seven-level multilevel inverter with a grid integration system for PV-connected systems. The proposed seven-level multilevel inverter employs IGBT switches. The inverter has several levels or voltage steps that allow for better output waveform quality and lower harmonics. The IGBT switches are combined to create each level of the inverter in a specific way, generally through the integration of series and parallel interactions. The inverter can produce seven different voltage levels, resulting in a higher resolution output waveform, by appropriately controlling the switching modes of the IGBT switches. Figure 2 depicts the proposed seven-level multilevel inverter with seven levels. A proposed seven-level multilevel inverter offers seven distinct modes of operation, enabling enhanced voltage output waveforms and improved power quality. This inverter utilizes multiple power electronic switches and DC sources to generate voltage levels beyond the traditional two-level inverters. The various modes of operation are illustrated in the sequence of $-3V_{dc}$, $-2V_{dc}$, $-V_{dc}$, $0V_{dc}$, $+V_{dc}$, $+2V_{dc}$ and $+3V_{dc}$ are mentioned below:

Mode 1: All power switches are turned off in this state, resulting in zero voltage output.

Mode 2: Only the first level power switch is activated; the others are left off. This results in a positive voltage at the output, as shown in Figure 3.

Mode 3: The second level power switch is activated, resulting in a negative voltage at the output, as illustrated in Figure 4.

Mode 4: The first and second-level power switches are turned on, resulting in an increased positive voltage at the output, as illustrated in Figure 5.

Mode 5: The third-level power switch is turned on, resulting in a doubled negative voltage at the output, as depicted in Figure 6.

Mode 6: Figure 7 illustrates mode 6, where the output voltage is tripled, and the first and third-level power switches have been absorbed concurrently.

Mode 7: The third and fourth level power switches are triggered in the final mode, resulting in a tripled negative voltage at the output illustrated in Figure 8.

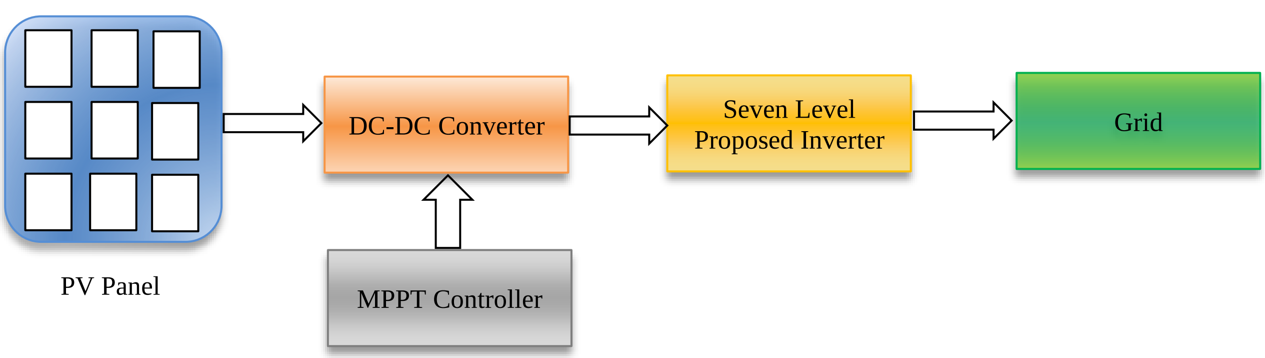


Fig. 1 PV connected the proposed seven-level multilevel inverter with grid integration

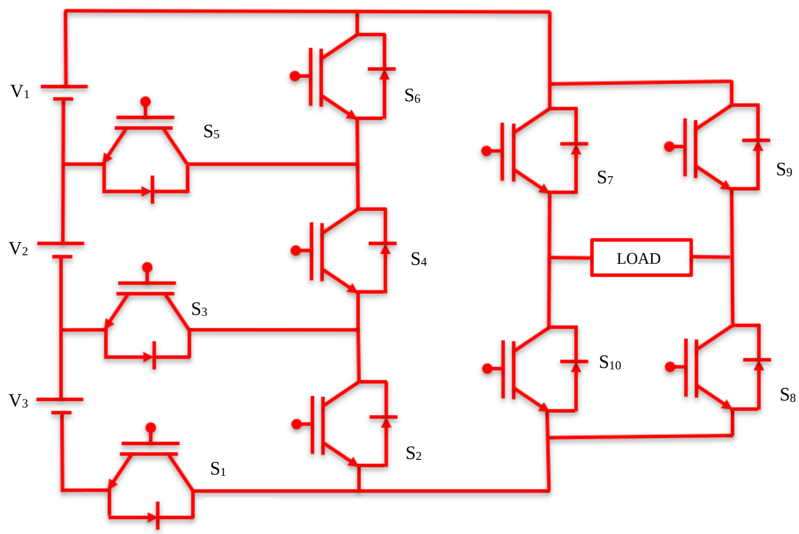


Fig. 2 Proposed seven-level multilevel inverter

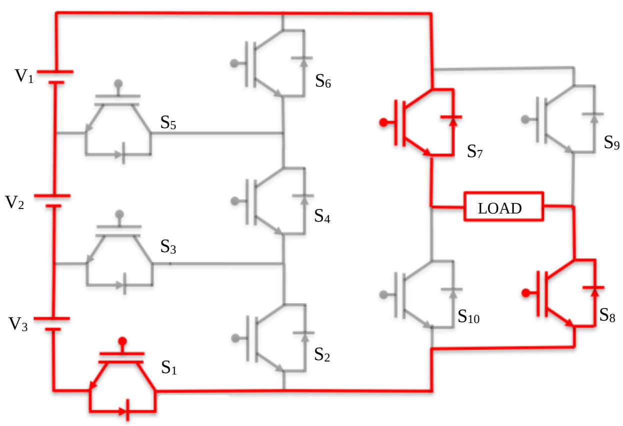


Fig. 3 +3V_{dc} Output voltage

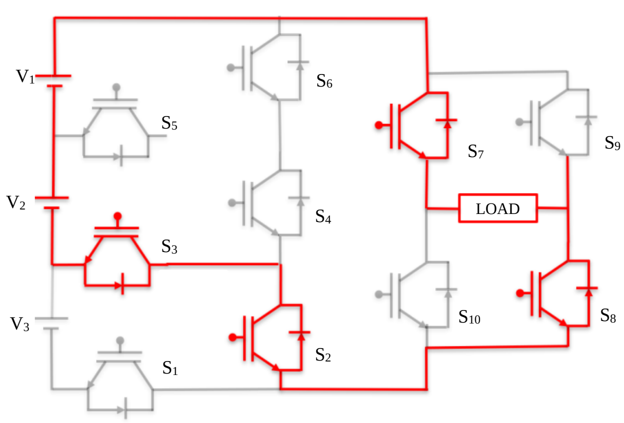


Fig. 4 +2V_{dc} Output voltage

Pulse Width Modulation with Phase Disposition (PWM-PD) controls a load's average voltage or power by varying pulses in an intermittent signal. The carrier wave and reference wave are two crucial elements in PWM-PD. A reference wave is a periodic signal symbolising the intended result or control signal. It has a specific frequency and is created in response to the input signal or control specifications. The reference wave determines the modulated signal's duty cycle or pulse width, which directly impacts the average power or voltage provided through the load.

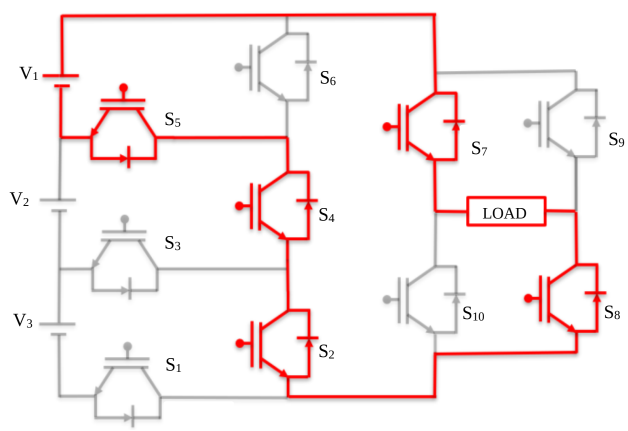


Fig. 5 +3V_{dc} Output voltage

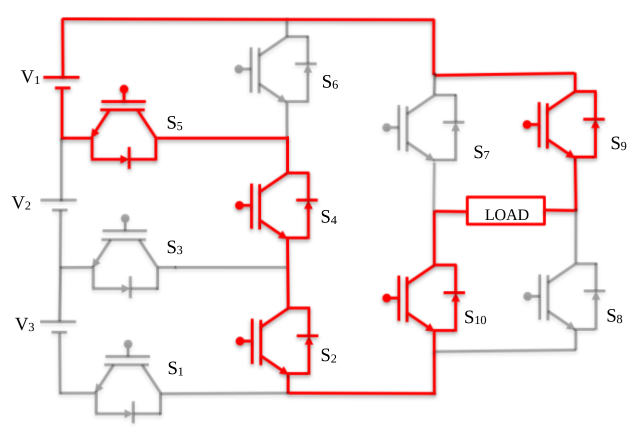


Fig. 6 -V_{dc} Output voltage

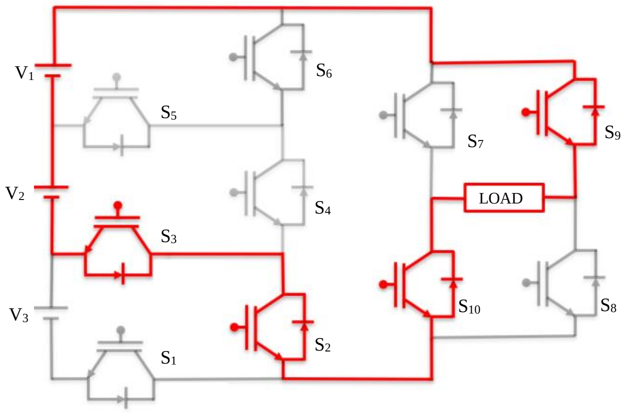


Fig. 7 -2V$_{dc}$ Output voltage

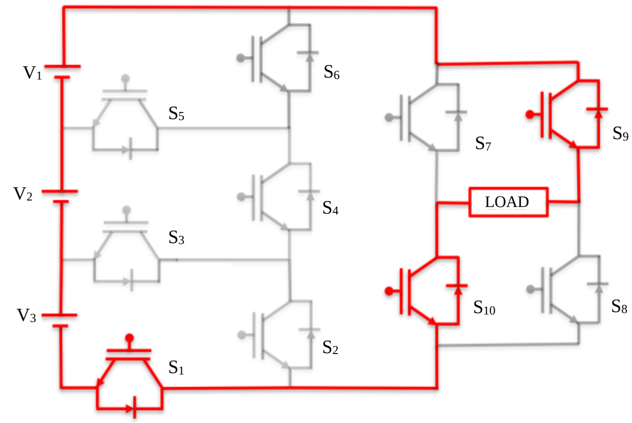


Fig. 8 -3V$_{dc}$ Output voltage

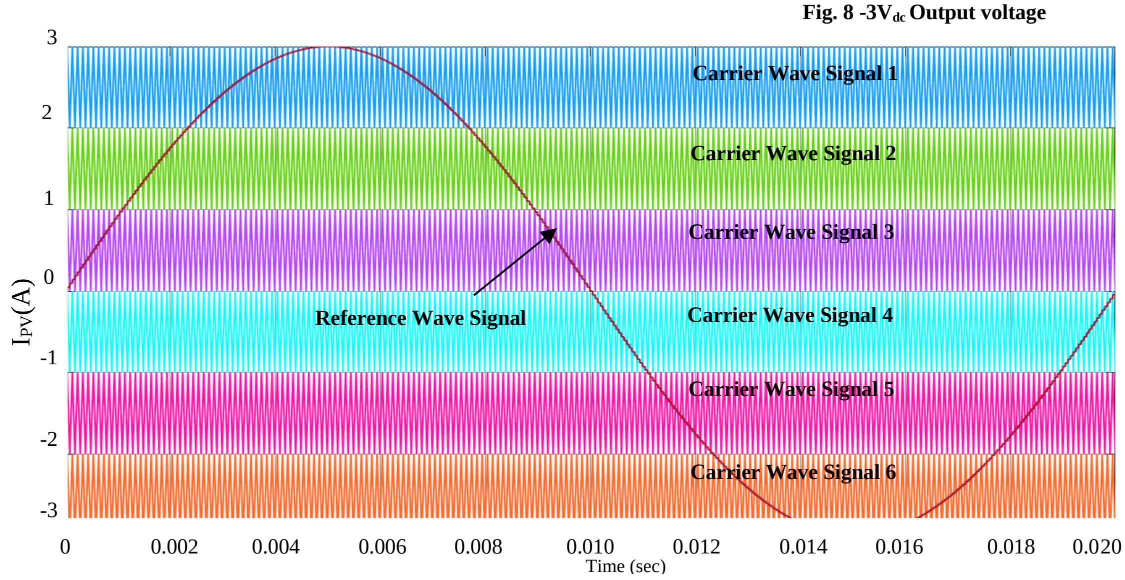


Fig. 9 Pulse width modulation with phase disposition

Conversely, the carrier wave is a high-frequency signals pattern that operates as the variation approach's carrier signal. It is usually much higher in frequency than the reference wave. An oscillator circuit generates the carrier wave, typically a square or sawtooth wave. It transports the information stored in the reference wave. The reference wave is compared to the carrier wave during the modulation process.

The pulse width or phase disposition of the carrier wave is modified by comparing the present values of the reference and carrier waves. As a result, there are pulses in the controlled pattern whose widths or phases match the values of the reference waves at any given moment. Figure 9 depicts pulse width modulation using a carrier and reference wave signal with phase disposition.

Expressions (1) and (2) regulate the amplitude and variation in the frequency of an MLI, respectively.

$$M_A = \frac{V_m}{V_c(m-1)} \tag{1}$$

$$M_f = \frac{f_c}{f_m} \tag{2}$$

To determine the total harmonic distortion (THD) of the recommended MLI's voltage, use the following equation (3). Similarly, the current THD value is computed.

$$THD = \sqrt{\frac{V_2^2+V_3^2+V_4^2+\cdots..+V_N^2}{V_1}} \tag{3}$$

Switching loss and conduction loss are two subtypes of total power loss in electronic components. Conduction loss happens whenever electricity passes through a resistive device, causing power dissipation. The resistance and magnitude of the current mainly determine this type of loss. Switching loss, conversely, is connected with the changes of a switch or semiconductor device between various states. It is caused by the energy lost during the switching process. Switching losses consist of turn-on and turn-off losses, which provide power dispersion. Minimizing conduction and switching losses is crucial for improving system efficiency and reducing wasted energy, especially in high-power applications like power electronics and inverters. The total power loss can be expressed as in equation (4),

$$P_{LOSS} = P_{Switching} + P_{Conduction} \quad (4)$$

However, several factors determine the efficiency of a multilevel inverter. To begin, switching losses associated with the semiconductor devices used in the inverter impact efficiency. Higher switching frequencies could result in higher losses. Second, conduction losses in power devices and losses in output filter elements impact efficiency. Furthermore, the control strategy used, such as pulse width modulation, can impact the efficiency of multilevel inverters. These variables can be customised to improve the overall efficiency of multilevel inverters in various applications. The efficiency of MLI is calculated by the following equation (5),

$$\text{Efficiency} = \frac{P_{Output}}{P_{Output}+W_{Loss}} * 100 \quad (5)$$

4. Results and Discussion

The seven-level multilevel inverter was simulated using a Matlab/Simulink with power electronic circuit modelling capacities. The topology of the inverter was three H-bridges connected in series, with each H-bridge consisting of four power switches and two capacitors. The signals that switched for the power switches were produced using the pulse width modulation technique. The simulation results showed the seven-level multilevel inverter's ability to generate high-quality output voltages. When the total harmonic distortion of the output voltage was examined, it was discovered to be considerably less than that in traditional two-level inverters. Reducing THD value is essential for applications dependent upon harmonic distortion, like motor drives and renewable energy systems.

Moreover, when contrasting with lower-level inverters, the seven-level inverter produced better voltage waveforms with fewer voltage steps. The simulation additionally verified the power switches' low voltage stress, which provides their durability and dependability. For starters, having more output voltage levels allows for better voltage resolution, which leads to better motor drive control. The decrease in voltage steps lowers the switching frequency, resulting in lower switching losses and higher efficiency.

Subsequently, the multilevel inverter can handle higher voltages, putting less strain on the power switches. By providing the voltage across multiple levels, the stress on each switch is decreased, which results in improved device dependability and lower power losses. This characteristic is especially useful in applications requiring considerable power where voltage and current are a significant concern.

The seven-level multilevel inverter also supports bidirectional power flow, making it ideal for applications including renewable energy sources and energy storage systems. The adaptability and dependability of these systems are improved by their capacity to switch between grid-connected and standalone operations with comfort. Figure 10 illustrates the PV array I-V characteristics of different power ratings. Figure 11 illustrates the PV array P-V characteristics of different power ratings according to the PV parameters listed in Table 1. Figure 12 illustrates the pulsed generating signal given to the boost converter.

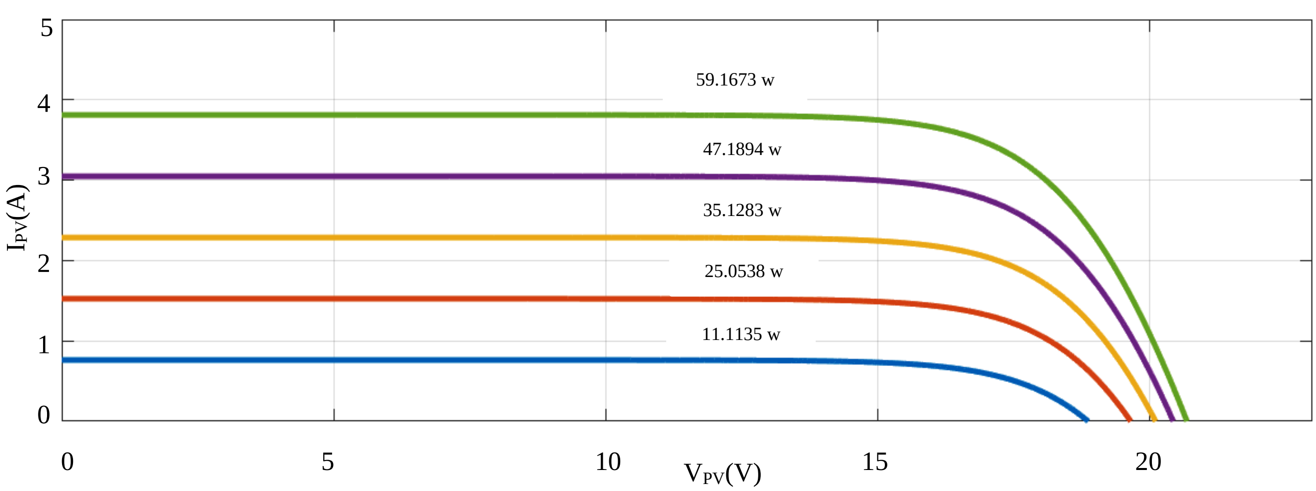


Fig. 10 PV array I-V characteristics

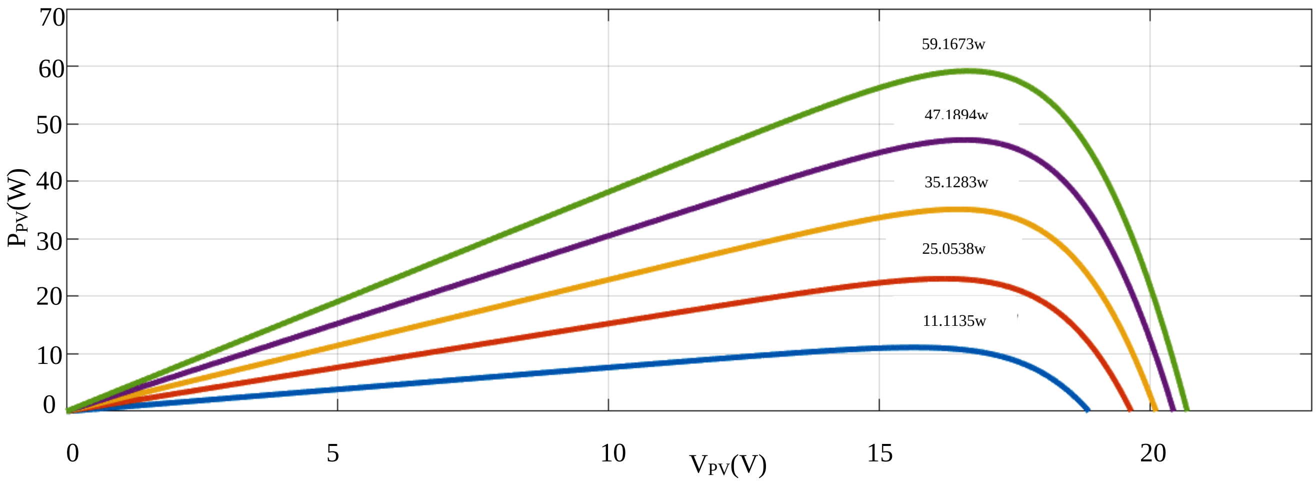


Fig. 11 PV array P-V characteristics

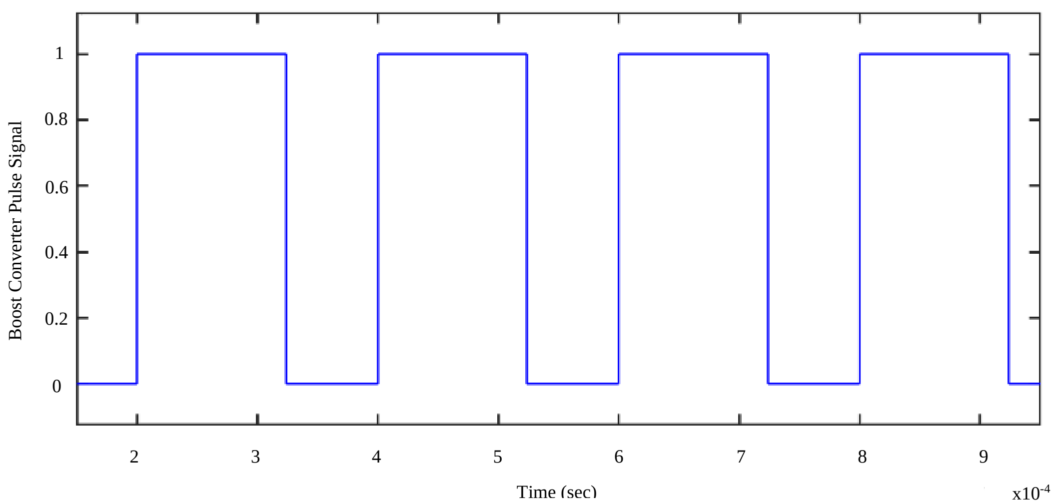


Fig. 12 Pulse signal to boost converter

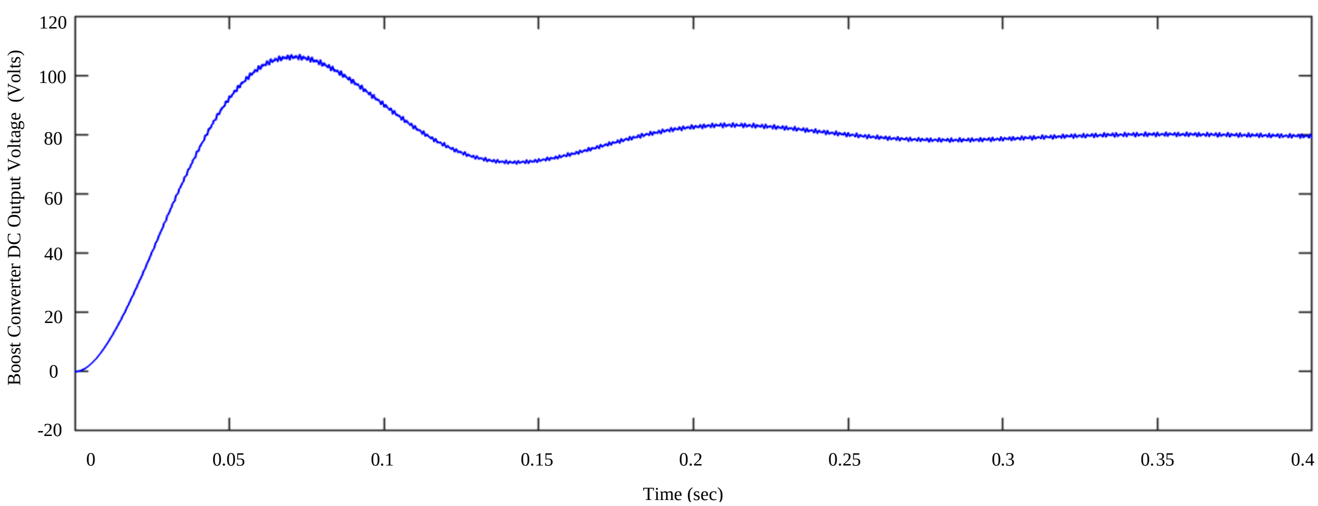


Fig. 13 Pulse width modulation with phase disposition

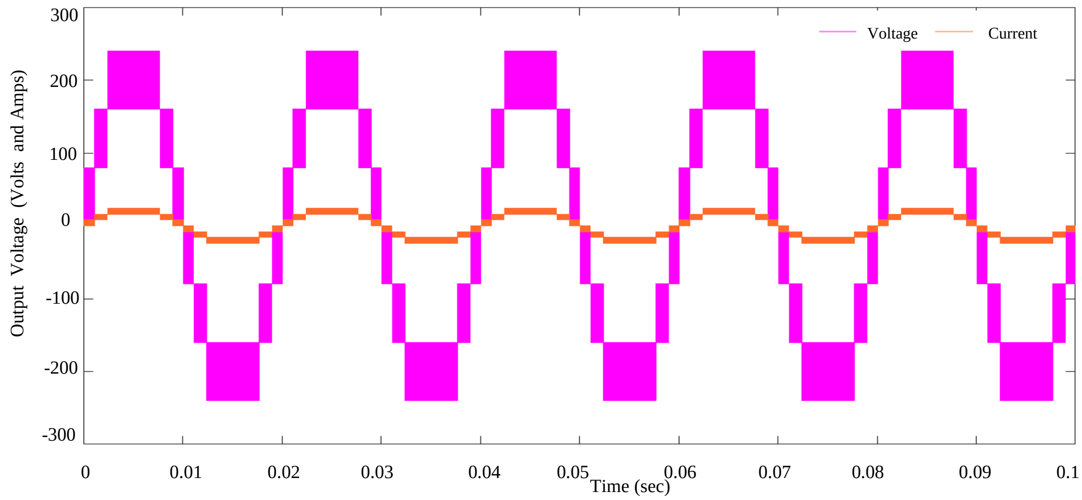


Fig. 14 Seven-level output voltage and current with R load

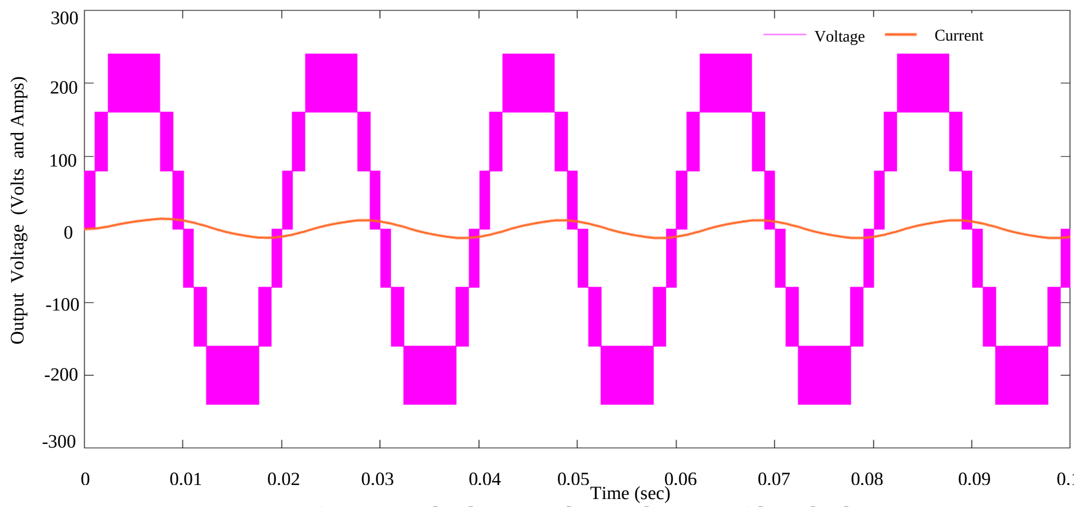


Fig. 15 Seven-level output voltage and current with RL load

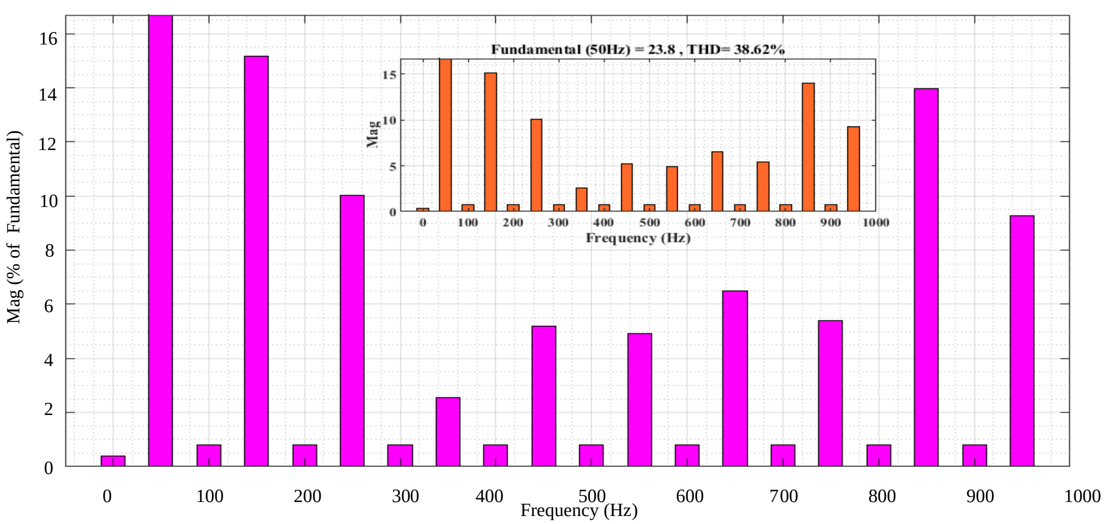


Fig. 16 Harmonic analysis of 7-level inverter for R load

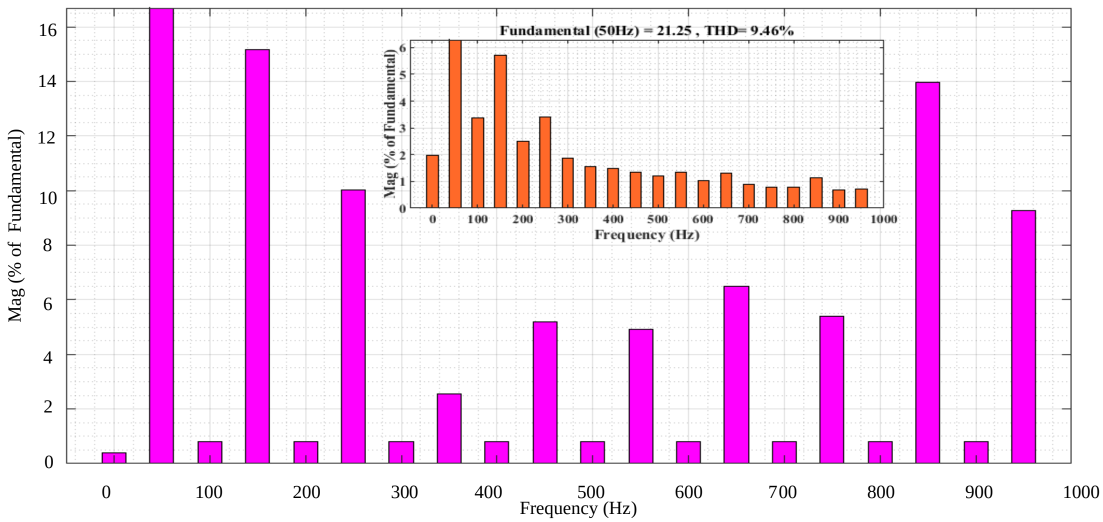


Fig. 17 Harmonic analysis of 7-level inverter for RL load

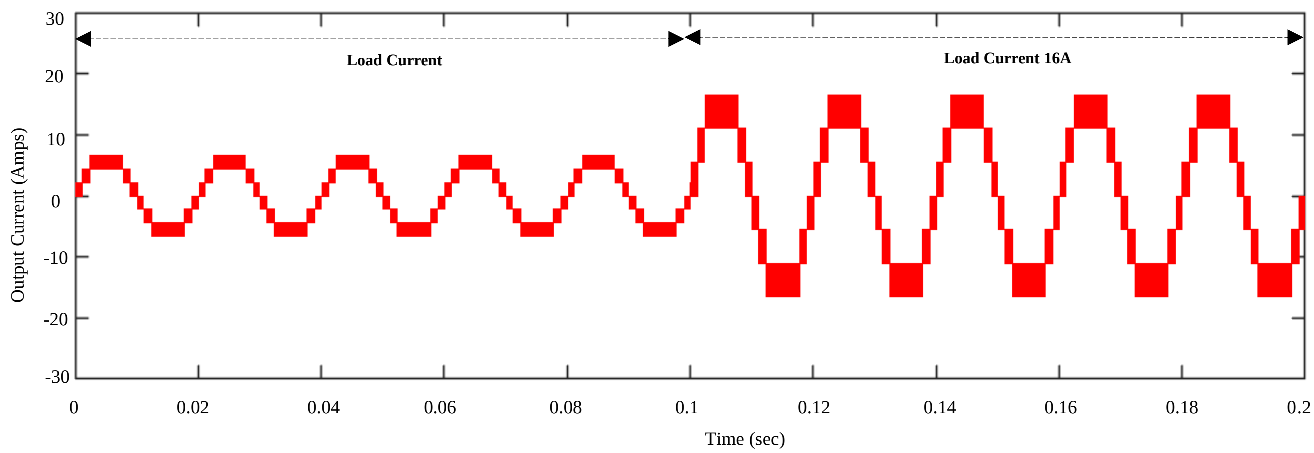


Fig. 18 Dynamic load change of resistive load from 6 A to 16 A

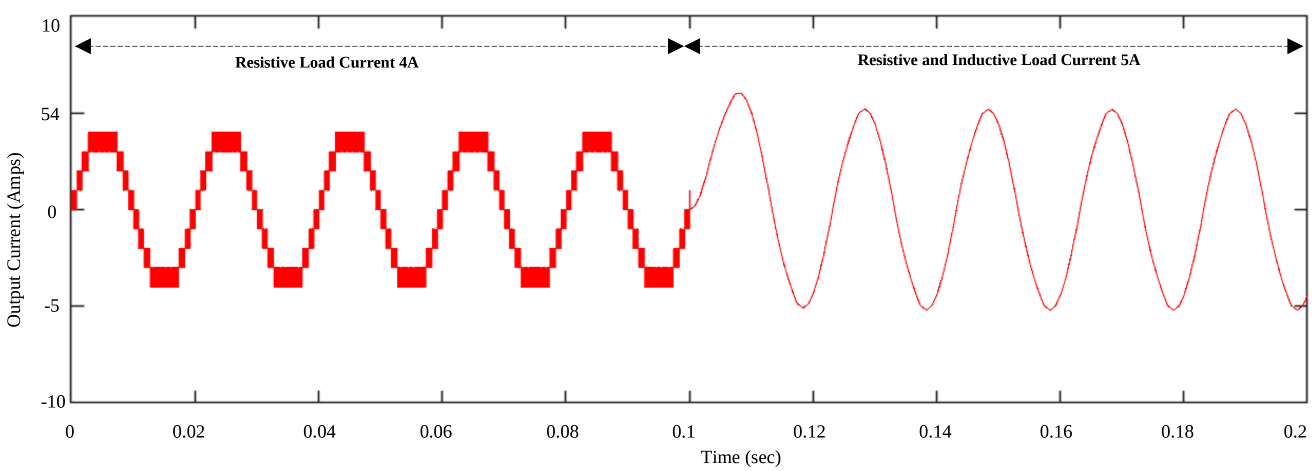


Fig. 19 Dynamic load change of R to RL load

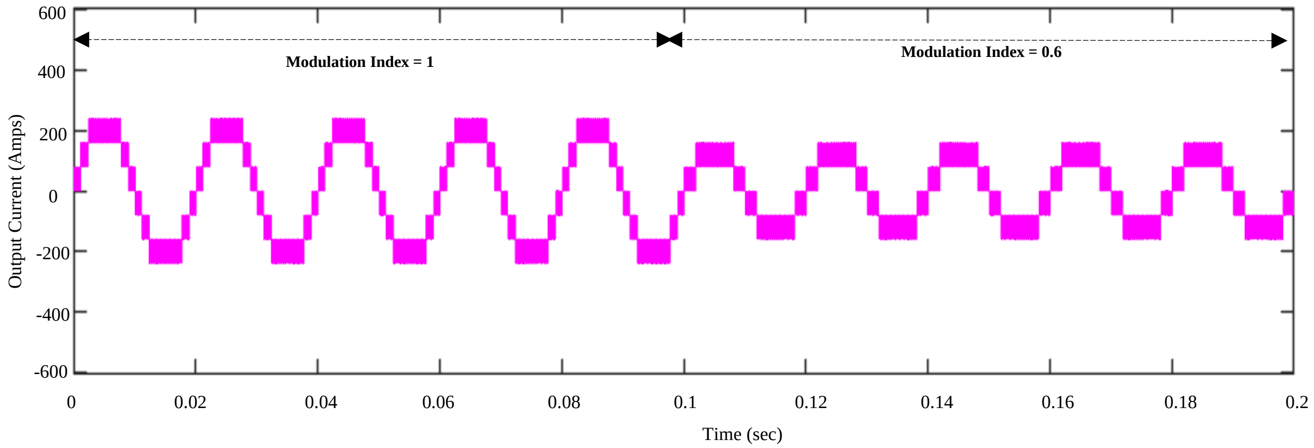


Fig. 20 Change in modulation index from 1 to 0.6

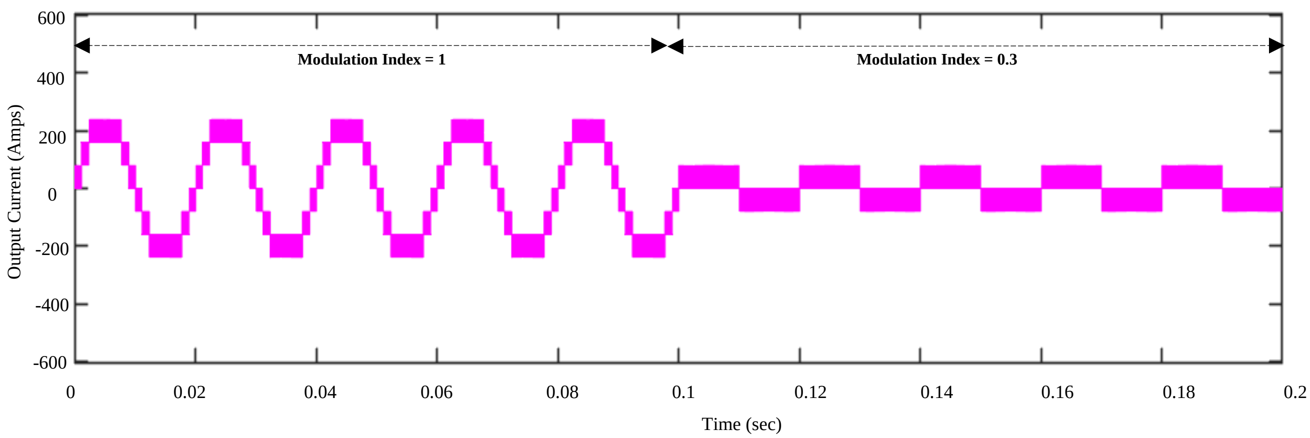
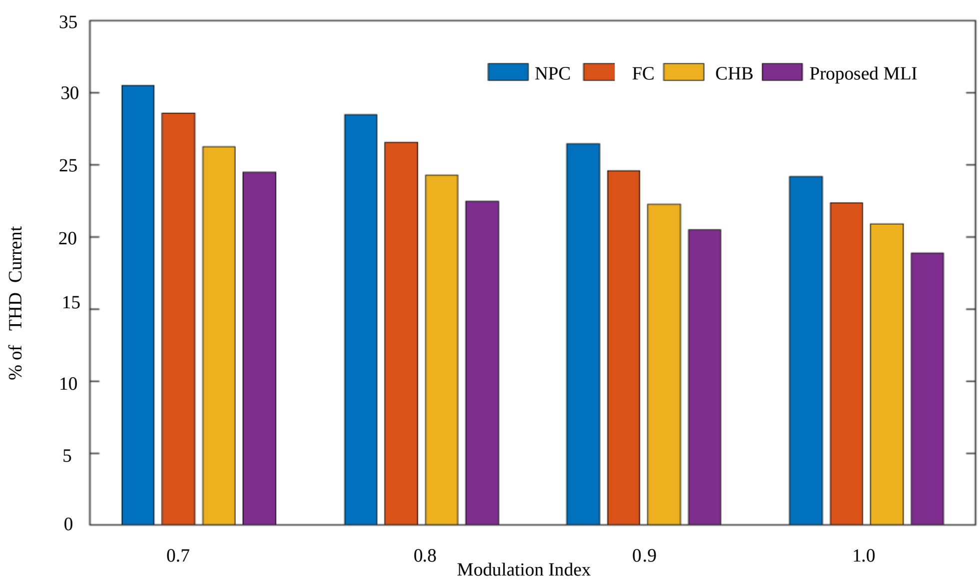


Fig. 21 Change in modulation index from 1 to 0.3



(NPC - Neutral Point Clamped MLI, FC - Flying Capacitor MLI, CHB - Cascaded H-Bridged MLI)
Fig. 22 Modulation index change of conventional and proposed MLI

Table 1. PV array parameters

S. No.	Parameter	Value
1.	Maximum power (P_{max})	200 W
2.	Open-circuit voltage/V_{oc}	32.4 V
3.	Maximum power voltage/V_{mp}	27 V
4.	Short-circuit current/I_{sc}	8 A
5.	Max power current/I_{mp}	7.41 A

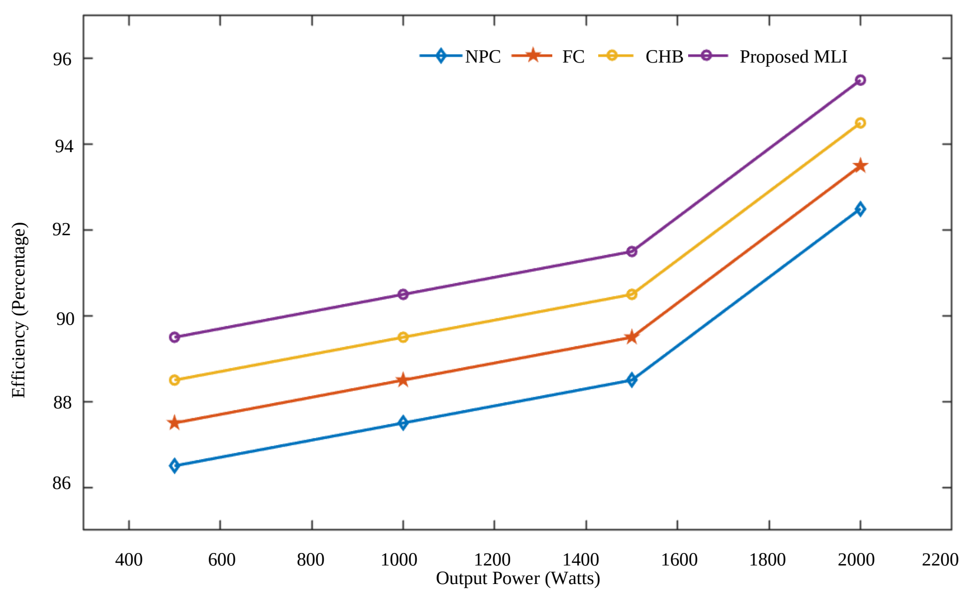
Table 2. PV with boost converters parameters

S. No.	Parameter	Value
1.	Irradiance	750-1000 W/m^2
2.	Temperature	25-45^{0}C
3.	DC link Voltage	80 V
4.	Grid voltage	230 V
5.	Frequency	50 Hz
6.	Switching Frequency	3780 Hz
7.	PV - Power rating	3500 W
8.	Filter inductance	2.18 mH
9.	Filter Capacitor	330 µF
10.	Parasitic Capacitance	100 µF

Table 3. Performance parameters of the conventional and proposed topology

Parameters	Conventional H-Bridged Topology	Proposed H-Bridged Topology
No. of DC Supplies	2	2
DC Voltage	80 V	80 V
RMS Voltage	240 V	240 V
No. of IGBTs	12	10
Driver Circuits	8	8
Carrier Frequency	2 kHz	2 kHz
%THD (Current)	17.23 (RL load)	9.46 (RL load)
Switching Loss	00.46 W	00.32 W
Conduction Loss	54.35 W	42.31 W
Total Loss	54.71 W	42.83 W
Efficiency	92.56 %	95.62 %

Table 2 illustrates the PV with boost converters parameters of irradiance and boosted DC link voltage. Figure 13 illustrates the boosted output voltage of 80 V from the PV array.



(NPC - Neutral Point Clamped MLI, FC - Flying Capacitor MLI, CHB - Cascaded H-Bridged MLI)
Fig. 23 Efficiency analysis of conventional and proposed MLI

Figure 14 illustrates the seven-level output voltage and current with R load, which further gives the output voltage of 240 V. It is filtered and given to the grid system. Figure 15 illustrates the seven-level output voltage and current with RL load; the inductive effect has achieved an almost pure sinusoidal waveform.

Figure 16 illustrates the harmonic analysis of a 7-level inverter for resistive load with a value of 38.62 %. Figure 17 illustrates the harmonic analysis of a 7-level inverter for resistive with an inductive load of 9.46 %. Figure 18 illustrates the dynamic load change of resistive load from 6 A to 16 A due to a sudden change in load resistor from 60 Ω to 150 Ω. Figure 19 illustrates the dynamic load change of the resistive-to-resistive inductance load combination. Figure 20 illustrates the change in modulation index from 1 to 0.6, which has reduced staircase output voltage from seven to five levels.

Figure 21 illustrates the change in modulation index from 1 to 0.3, which has reduced staircase output voltage from seven to three levels. Figure 22 illustrates the change in the modulation index of conventional and proposed MLI with different parameters. Figure 23 illustrates the efficiency analysis of conventional and proposed MLI, whereas proposed MLI has achieved 95.62 % due to fewer switches and power losses. Table 3 illustrates the performance parameters of the conventional and proposed topology.

5. Conclusion

A seven-level multilevel inverter has improved power quality and decreased THD compared to traditional inverters. The greater the output voltage levels, the better the voltage waveform approximated, leading to more velvety, sinusoidal-shaped output voltages. This results in improved power quality, lower voltage distortion, and lower harmonic content in the grid-connected system. A practical method for integrating PV into the grid has been demonstrated to be the seven-level multilevel inverter. The inverter can more easily adapt to the various DC voltage levels generated by the PV panels using multiple voltage levels. This enables the inverter to extract maximum power from the PV array and ensure efficient energy conversion. To maximise power extraction from PV modules, further reduce grid disruptions, and ensure effortless grid integration, future investigations can focus on improving the control methods for the inverter. Furthermore, investigate advanced modulation techniques and examine the inverter's response under different operating circumstances to establish more efficient and dependable grid-connected PV systems.

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