

Design and Performance Analysis of Reduced Device Count Cascaded Half Bridge Multilevel Inverter

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ABSTRACT

The demand for renewable energy, especially the PV system, is increasing day by day, but the efficiency of the system remains the main concern due to the increased power switches. This research is based on the design and analysis of a reduced switch cascaded half-bridge multilevel inverter (MLI) integrated with a PV system. The proposed inverter uses only eight power switches, where two switches serve as a polarity changer and four DC sources. A Perturb and Observe (P&O) maximum power point tracking (MPPT) algorithm is implemented to control the DC-DC boost converter to track the maximum power from the PV array under variable irradiances. The whole PV boost converter MLI system is implemented through Simulink feature of MATLAB. The computed results by the proposed protocol highlight the successful generation of the 13-level output with THD of 10.82%. This optimized design reduces the total number of components as compared to the conventional MLIs, leading to lower switching losses, reduced cost, simpler gate driver circuitry, and improved overall system efficiency. The proposed design confirms a practical and efficient approach for enhancing the performance of PV-based renewable energy systems.

1. Introduction

Renewable energy, especially solar energy, is the leading edge of the renewable energy transition due to the growing global demand for clean energy, which is fuelled by worries about air pollution, resource depletion, and climate change. Because solar photovoltaic (PV) technology directly turns sunlight into power without releasing greenhouse gases and because sunlight is a plentiful resource in many places, it has enormous promise. According to recent research, improvements in PV materials (such as perovskites) and system integration techniques are reducing costs and increasing efficiency, making solar energy more sustainable compared to traditional energy sources. Nevertheless, measuring the maximum power point under changing climatic conditions, controlling efficiency losses, and properly integrating solar systems into existing grids continue

to be challenging tasks, despite these encouraging advancements [1].

The development of fast-switching solid-state transistors has led to a rapid advancement in power electronics technology. Power electronics are now used in many different industries, from residential, commercial, to industrial applications. Because of all these latest advancements. Power electronic systems are now as efficient as 99%, mainly because of the switch mode operation of the semiconductor devices [2].

Because of their high efficiency, quick switching times, and affordability, power converters are essential parts of contemporary electrical systems. Their input and output kinds are used to categorize them: Rectifiers convert AC to DC, cycloconverters and AC voltage controllers convert AC to AC,

choppers convert DC to DC, and inverters convert DC to AC [3].

Multilevel inverters (MLIs) are an extremely effective family of DC-AC power converters. MLIs greatly reduce total harmonic distortion (THD) by synthesizing output voltage waveforms in several steps, in contrast to conventional two-level inverters. MLIs are especially appealing for medium to high voltage applications because of these capabilities. MLIs also have a number of benefits, including low costs, high efficiency, modular design, few installation requirements, and fewer semiconductor devices [4].

The capacity of MLIs to produce high output voltages without the need for large transformers while retaining low harmonic distortion is one of their most prominent characteristics. MLIs are therefore frequently utilized in photovoltaic (PV) systems and other renewable energy applications [5].

Multilevel inverters come in three primary types: Cascaded H-Bridge (CHB), Flying Capacitor or capacitor Clamped (C-C), and Diode-Clamped (D-C) or Neutral Clamped (NPC). In order to clamp diodes and balance capacitors, a number of devices are needed in the case of C-C and D-C MLIs, which increases the system's complexity and size [7]. The CHB inverter, on the other hand, is more straightforward and scalable, that uses fewer parts to provide the same output voltage levels. Nevertheless, the CHB architecture has a drawback in that it requires

several separate DC sources to function, which might make the overall system design more difficult in some situations. Researchers are currently attempting to improve MLI designs in order to minimize harmonic distortion and reduce power consumption while utilizing fewer switching devices and streamlining control circuits [8]. In order to do this, a number of innovative topologies have been developed that use fewer power switches while still generating multilevel output waveforms that closely mimic the ideal sinusoidal signal. These developments seek to enhance multilevel inverter system efficiency, cost, and performance for a variety of applications [9].

In summary, there have been many algorithms in literature, conventional as well as soft computing, for the maximum power point tracking in solar PV systems, while some studies focused on using new inverter topologies. There are also some studies in which both of these aspects are addressed simultaneously to improve the signal quality. This work focuses on utilizing the benefits of the conventional perturb and observe technique in PV systems by introducing a new methodology through reduced device count MLI. The proposed methodology and results sufficiently show that the efficiency is still guaranteed by the introduced new inverter topology, which reduces switches and achieves a stable output. The results are also better in terms of the number of devices compared with a few recent studies.

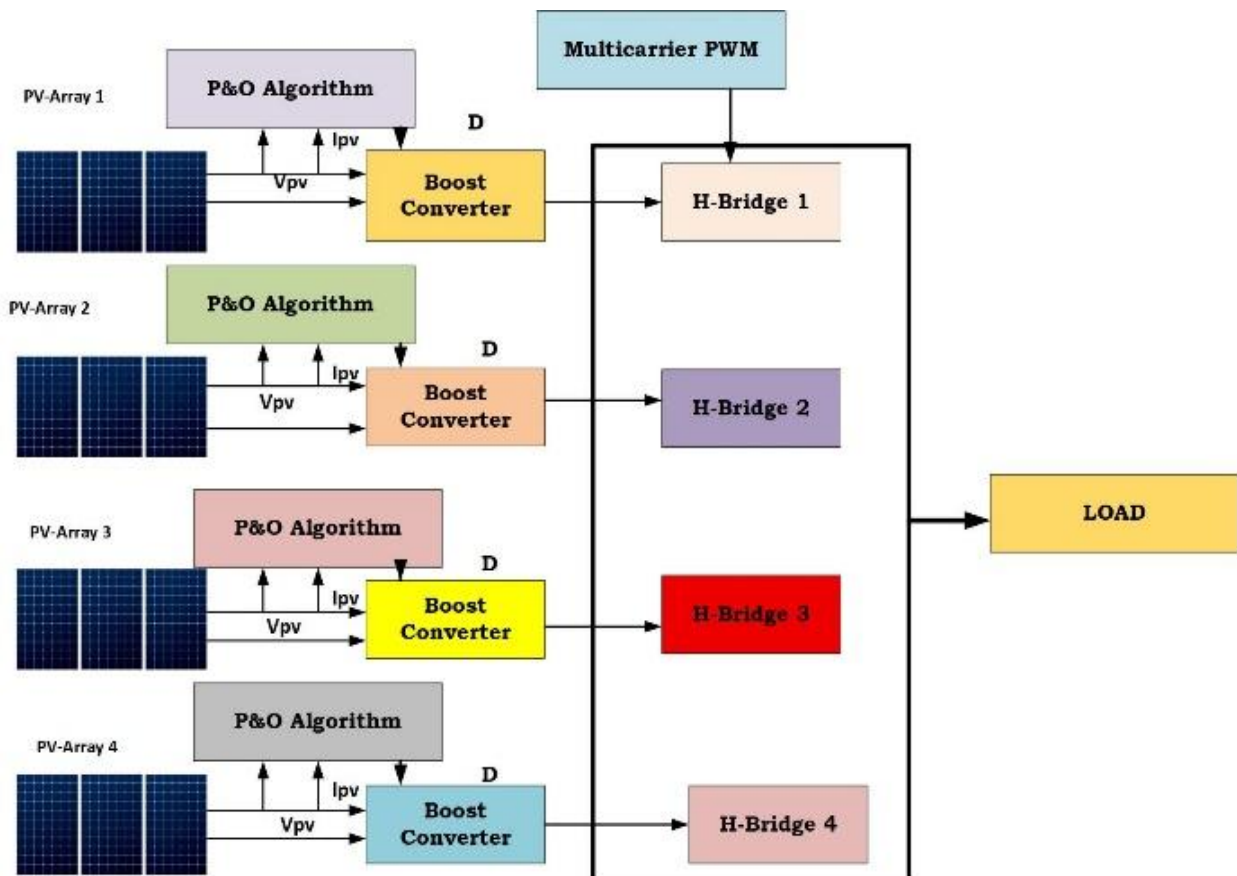


Fig. 1. Classification of Reduced Count MLI

2. Methodology

The steps and process used in the methodology to achieve the objectives have been presented here. A simulation of an MPPT system for PV Panels with the cascaded half-bridge multilevel inverters was created and implemented in the Simulink feature of MATLAB, integrated with the DC-DC boost converter and the Perturb and Observe (P&O) algorithm as a baseline. The model was designed using the level-shifted PWM techniques for the inverter control.

A P&O MPPT algorithm was implemented for its fine tuning. To evaluate the system performance, it was tested at different environmental parameter values of temperature and irradiance levels. In order to examine factors like total harmonic distortion (THD), output voltage quality, and Power Output.

In Fig. 1, we represent the proposed system protocol in the form of a block diagram containing four PV arrays, each connected to a hybrid MPPT algorithm incorporated boost converter. The boosted output is given into a cascaded H-Bridge multilevel inverter (CH-MLI) controlled by a multicarrier PWM technique to supply power to the load circuit diagram.

2.1 Proposed Topology

The Fig. 2 shows the circuit diagram of the proposed cascaded H-Bridge multilevel inverter topology. The proposed inverter topology is asymmetric, needing different DC sources, which has an impact on the performance. The benefit of using this asymmetric design is the obviously higher output levels, even at the cost of fewer components. The THD also decreases in this regard as compared to a symmetric design with the same voltage DC sources.

On the other hand, there is less switching loss and enhanced system efficiency in asymmetric designs. The proposed topology, consisting of four voltage sources (V_1 to V_4) with the values of $V_1 = 40$, $V_2 = 80$, $V_3 = 120$, and $V_4 = 240$ V with the reverse polarity, all the sources have to be linked with a full bridge (H-Bridge) inverter model formed by two switching devices and their associated anti-parallel switches. The switches from S_1 - S_6 correspond to three standard H-Bridges generating stepped output voltage levels.

The fourth model, is formed by the switches S_7 and S_8 , is configured as a reverse polarity (RP) cell, used to introduce a negative voltage level, as it will increase the number of output voltage levels and improve waveform quality. The combined output is delivered to the load side, achieving a multilevel voltage waveform.

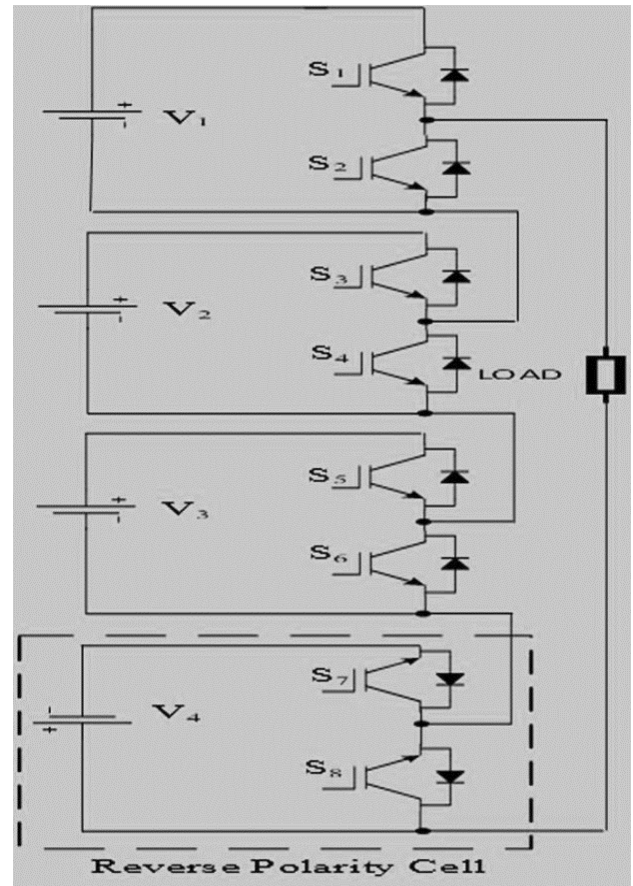


Fig. 2. Proposed Topology of Cascaded Half Bridge with Polarity Changer

2.2 Switching Operation

By activating the inverter switches in a proper way, various voltage levels can be produced at the load terminal, as shown in Table 1.

Table 1

Switching States of the Proposed Topology

M	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	Output Voltage	V
1	1	0	0	1	0	1	0	1	V	V_1
2	0	1	1	0	0	1	0	1	2V	V_2
3	0	1	0	1	1	0	0	1	3V	V_3
4	1	0	0	1	1	0	0	1	4V	V_1+V_3
5	0	1	1	0	1	0	0	1	5V	V_2+V_3
6	1	0	1	0	1	0	0	1	6V	$V_1+V_2+V_3$
7	0	1	0	1	0	1	0	1	0V	0
8	0	1	1	0	1	0	1	0	-1V	$-V_4+V_2+V_3$
9	1	0	0	1	1	0	1	0	-2V	$-V_4+V_1+V_3$
10	0	1	0	1	1	0	1	0	-3V	$-V_4+V_3$
11	0	1	1	0	0	0	1	0	-4V	$-V_4+V_2$
12	1	0	0	1	0	1	1	0	-5V	$-V_4+V_1$
13	1	1	0	1	0	1	1	0	-6V	$-V_4$

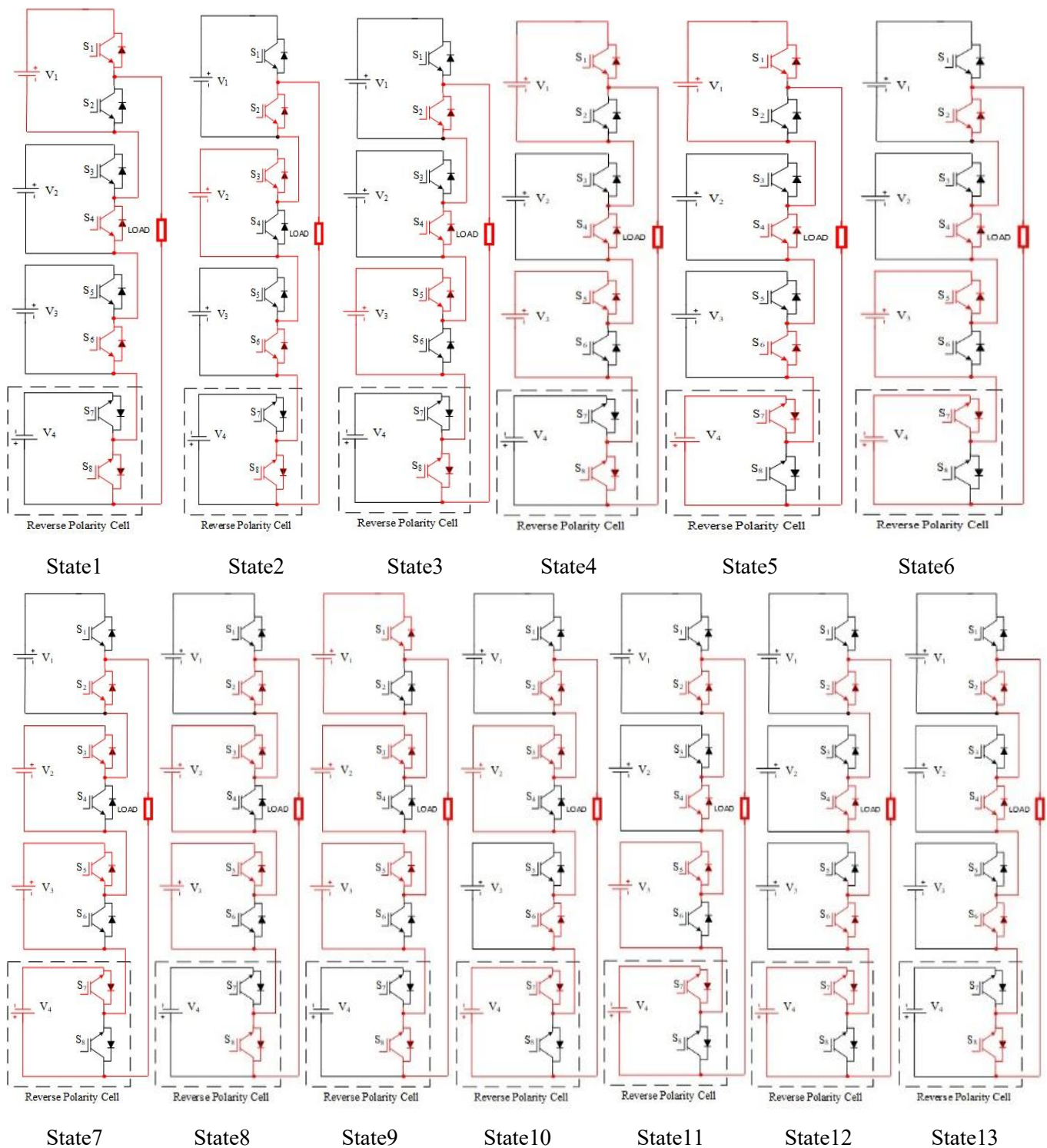


Fig. 3. Switching Sates (1-13)

The switching operation of the model is shown in Fig. 3. As shown in Fig.3 (state-1), when the switches S_1 , S_4 , S_6 and S_8 are turned on, the output voltage of positive 40V is generated on the load. As shown in Fig. 3 (state-2), activating the switches S_2 , S_3 , S_6 and S_8 generates the positive voltage 80V at the load side for a higher output level. Additionally, as shown in Fig. 3 (state-3), a 120V (positive) output can be obtained by activating the switches S_2 , S_4 , S_5 and S_8 , which connects the third DC source V_3 to the load.

S_1 , S_4 , S_5 and S_8 are turned on it generates positive voltage of 160V (positive) as shown in Fig. 3 (state-4). When switches S_2 , S_3 , S_5 and S_8 are turned on it gives positive voltage of 200V (positive) as shown in

Fig. 3 (state-5). Similarly, the combined voltage of the three sources $V_1 + V_2 + V_3 = 240V$ is supplied to the load when switches S_1 , S_3 , S_5 and S_8 are activated, resulting a 240V (positive) output voltage level as shown in Fig. 3 (state-6).

Similarly, for the negative cycle, as shown in Fig. 3 (state-8) the switches S_2 , S_3 , S_5 and S_7 generate -40V at the load side. As shown in Fig. 3 (state-9), switches S_1 , S_4 , S_5 and S_7 generate -80V. By activating switches as shown in Fig. 3 (state-10). S_2 , S_4 , S_5 and S_7 generate the -120V at the load side. As shown in Fig. 3 (state-11) switches S_2 , S_3 , S_6 and S_7 generate -160V. As shown in Fig 3 (state-12) switches S_1 , S_4 , S_5 and S_7 generate -200V. By combining the voltages of all three

sources $V_1 + V_2 + V_3 = 240V$, along with the polarity cell generates the $-240V$ at the load side as shown in Fig. 3 (state-13). The switching combinations presented in Table 1 describe the different operating conditions of the inverter for each output voltage level.

2.3 Multicarrier Pulse Width Modulation

To improve the output waveform quality and lower the THD, multilevel inverters (MLIs) use a variety of multicarrier pulsed width modulation (PWM) techniques, including selective harmonic elimination PWM (SHE-PWM), phase-shifted PWM (PS-PWM), level-shifted PWM (LS-PWM), and space vector PWM (SVPWM) [10-11]. These methods use a centralized reference waveform in conjunction with

(N_L-1) carrier signals, where N_L is the number of voltage levels with identical frequency and amplitude. Simple voltage control has been made easier by the PWM technique, which also suppresses lower-order harmonic components, simplifies filtering, lowers the power losses, and permits digital implementation. The suggested Cascaded H-Bridge Multilevel Inverter (CHB-MLI) uses LS-PWM to identify switching patterns using the eight carrier signals and one reference wave. Phase Disposition (PD), Phase Opposition Disposition (POD), and Alternate Phase Opposition Disposition (APOD) are three variations of LS-PWM. The general control structure of the PWM technique used is shown in Fig. 4.

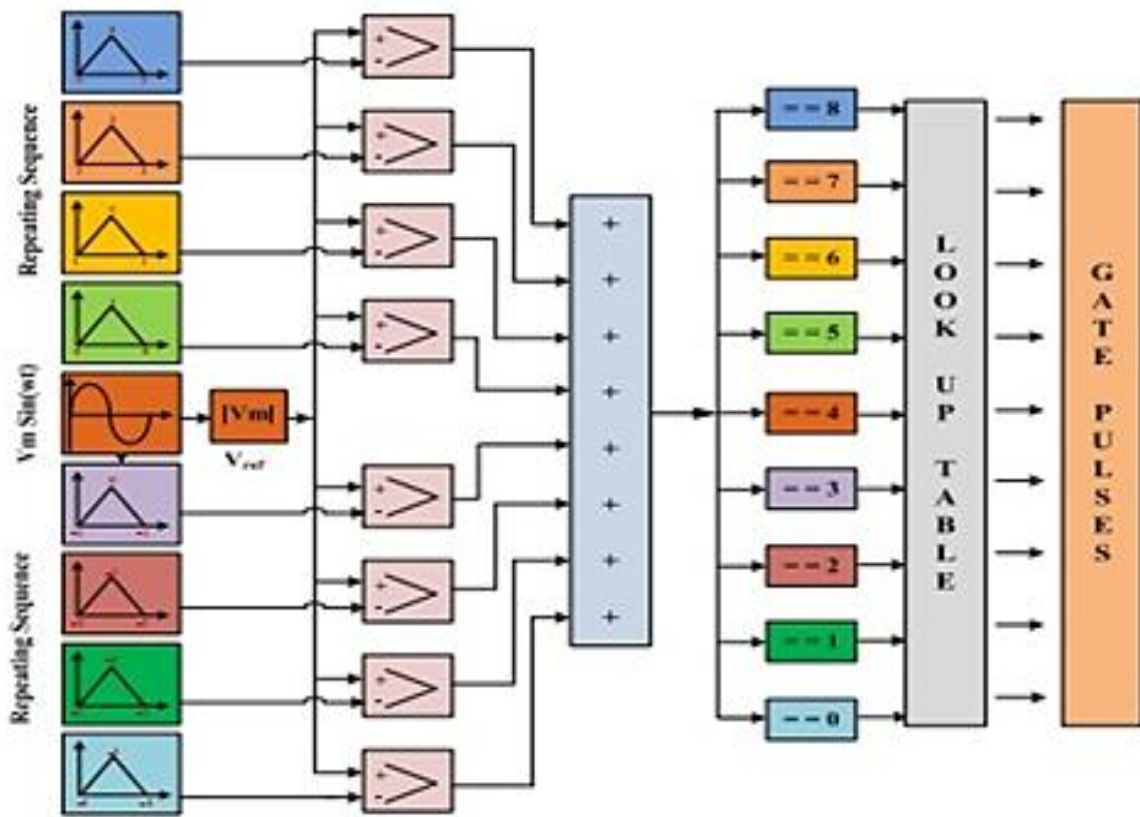


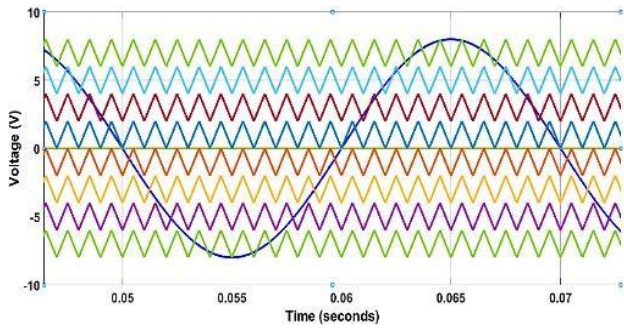
Fig. 4. Control Logic for PWM

2.3.1 Phase Disposition PWM (PD-PWM)

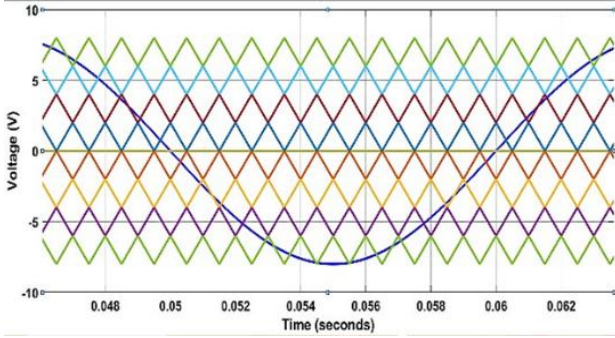
In the PD-PWM method, there is a vertical stack of all the carrier signals without any phase shift in between, and they are aligned in phase, as they have the same phase angle. All the carriers are simultaneously as related to the reference. Fig. 5 (a) shows that this technique produces switching pulses that are synced in phase, which often reduces the harmonic distortion in the output voltage.

2.3.2 Phase Opposition Disposition PWM (PD-PWM)

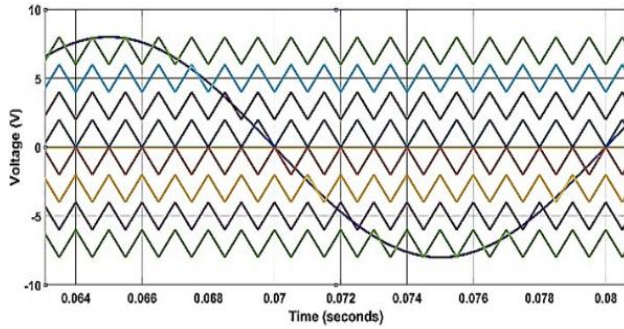
There are two groups of carrier signals in this method. The carriers in the lower half are 180 degrees out of phase with reference to the upper group of carriers, but the carriers in the upper phase are in phase with one another as shown in Fig. 5 (b). This opposing phase arrangement aids in the cancellation of some harmonic components and enhances the output waveform quality.



(a). Phase Disposition



(b). Phase Opposition Disposition



(c). Alternative Phase Opposition Disposition

Fig. 5. PWM techniques

2.3.3 Alternative Phase Opposition Disposition PWM (APOD-PWM)

In this type, there are two groups of carrier signals. The carriers in the lower half are 180 degrees out of phase with reference to the upper group of carriers, but the carriers in the upper phase are in phase with one another as shown in Fig. 5 (c). This opposing phase arrangement aids in the cancellation of some harmonic components and enhances the output waveform quality.

2.4 Perturb and Observe (P&O) Algorithm

P&O is one of the ancient, classical and a very famous MPPT technique because of it is simple in design and practical easier to implement algorithm, as seen in the flowchart in Fig. 6 This algorithm works by regularly varying the PV Systems operating voltage and current are first measured by the algorithm, which then computes the instantaneous power and compares it to the power that was previously measured. The method keeps perturbations in the direction in which power increases; if the power falls, the opposite is done. The system converges closer to the Maximum Power Point (MPP) because of this iterative process. P&O may swing around the MPP and react slowly to the quickly changing irradiance, despite its efficiency in steady state environmental conditions. However, with the little computational work, the flowchart logic guarantees that the PV system continues to operate around it optimal maximum point [12-13].

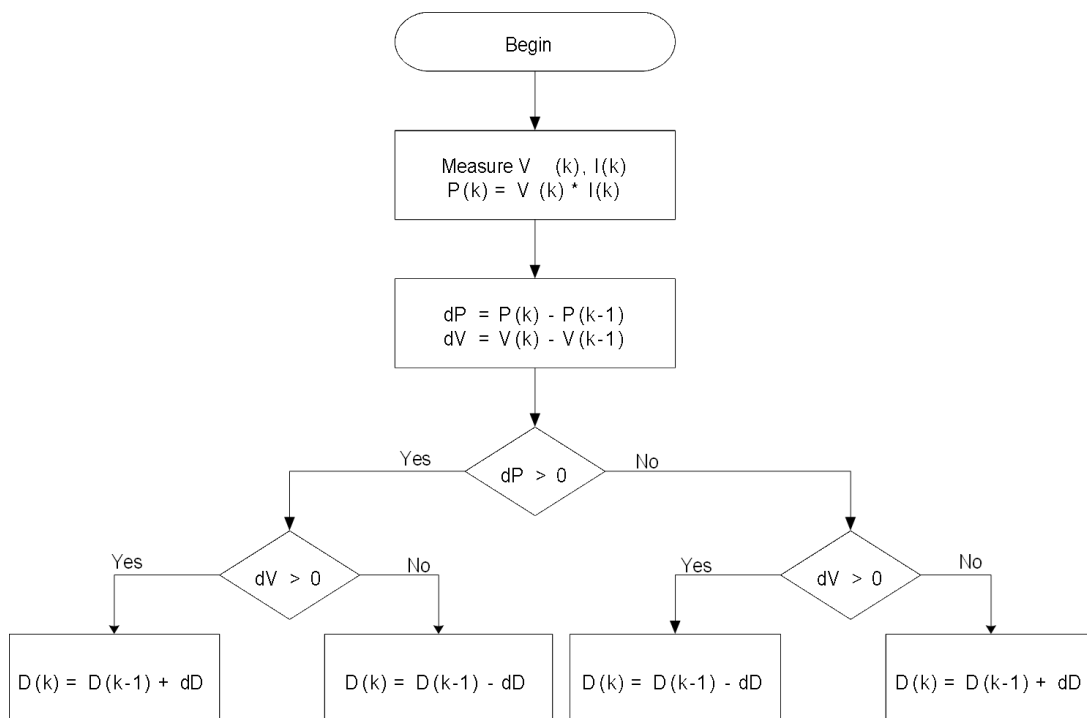


Fig. 6. Perturb and Observe Algorithm

2.5 Simulation Model of PV System With P&O Algorithm

The Simulink feature of MATLAB and the model of the PV energy conversion system integrated by an MPPT controller followed by a boost DC-DC converter is designed in the Simulink feature of MATLAB as represented in Fig. 7 [14-16]. In order to apply the environmental parameters, the PV panel block is fed temperature (C0 and sun irradiance (W/m^2). A P&O MPPT algorithm is fed the PV panels' output voltage (V_{pv}) and current (I_{pv}).

This algorithm dynamically modifies the duty cycle to make the panel run at the maximum point. The

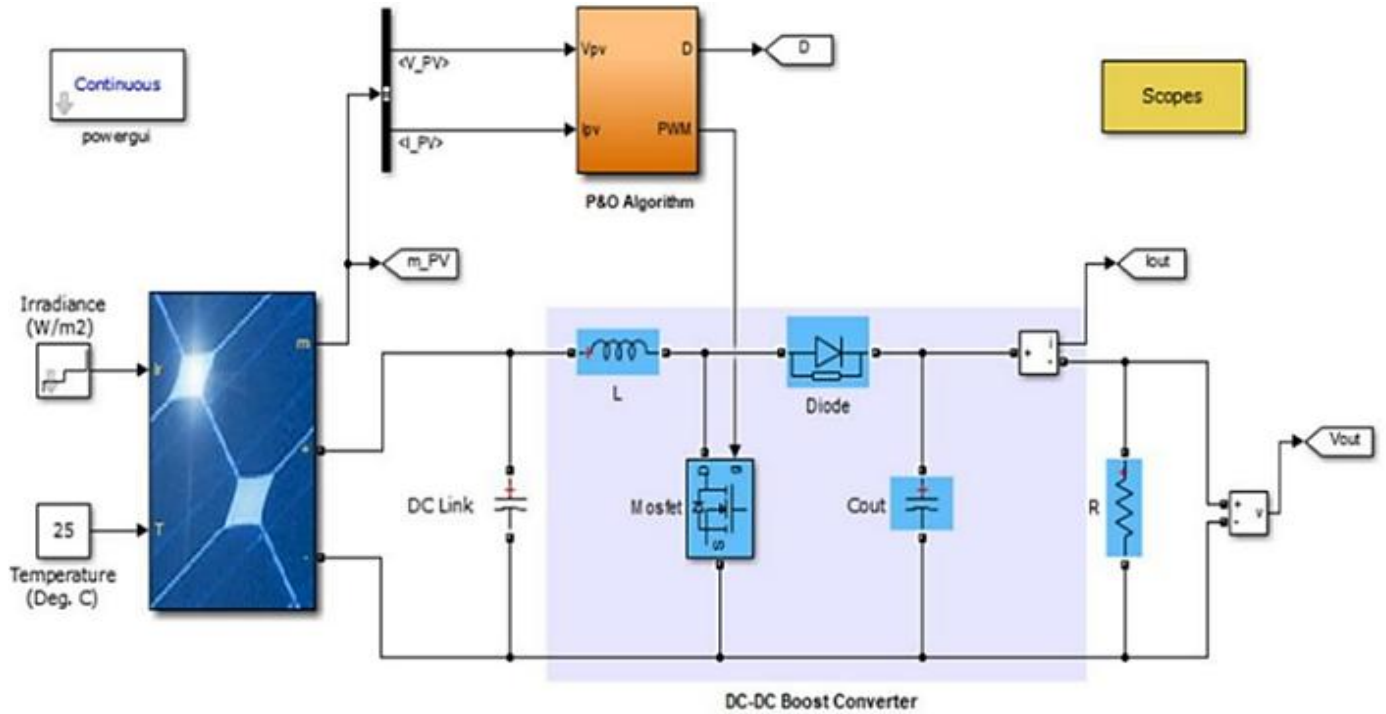


Fig. 7. MATLAB-Simulink Boost DC-DC Converter model with PV

The standard electrical parameters used in the simulation model are shown in Table 2.

Table 2

Electrical Parameters for Simulation Model

S.NO	Electrical Parameters	Values
1	Number of DC Sources	4
2	Rating of DC Sources	$V_1=40\text{V}$, $V_2=80\text{V}$, $V_3=120\text{V}$, $V_4=240\text{V}$
3	Number of switches	8 IGBTs
4	Number of Levels	13-levels
5	Resistance	24ohms
6	Inductance	20mH

MOSFET in the boost converter is switched by the pulse width modulation (PWM) signal that is controlled by the produced duty cycle.

To filter the fluctuation in the voltage, a DC link capacitor is positioned between the PV Panel and the converter. In order to monitor the output, the system has measurement blocks for the voltage and current that are connected to scope blocks.

This simulation shows efficient voltage management using the boost converter model and accurate power optimization from the PV panel under the various environmental conditions using MPPT.

2.6 Simulation Model of the Cascaded Half-Bridge

To observe the functionality of the proposed multilevel inverter design under various environmental conditions, the simulation model has been developed as shown in Fig. 8. The inverter's switch signals are regulated by multicarrier PWM control, which guarantees the multilevel output voltage levels' waveform. Additionally, the simulation accounts for the variations in load and assesses how the system is reacting to the temperature and irradiance changes. All things considered, this model offers a thorough framework for verifying the control approach and evaluating the efficiency of the proposed system prior to the actual application.

2.7 Simulation Model of Cascaded Half Bridge with P&O Algorithm for PV System

The following Photovoltaic (PV) based cascaded half-bridge multilevel inverter (CHB-MLI) systems simulation model is displayed in Fig. 9. To simulate nonlinear, I-V and PV behavior under variable

irradiance and temperature, the model consists of four independent PV subsystems, each subsystem is represented by a single diode equivalent circuit. To maximize the power extraction from each PV source, a Perturb and Observe (P&O) MPPT controller controls the duty cycle of a DC-DC converter. Four cascaded half-bridge inverter cells, each consisting of two IGBT switches (S_1 - S_8), are fed by the regulated DC outputs. An output waveform of 13 levels is generated by connecting these cells in series. The

Phase Disposition (PD) multicarrier pulse width modulation (PWM) technique is used which arranges carrier signals in phase and compares them with a sinusoidal reference to control inverter operation to generate the switching signals. System performance is assessed by applying the inverter output to the load and measuring output voltage, current, and THD. The integrated model exhibits balanced inverter operation, effective MPPT performance, and quality output waveform.

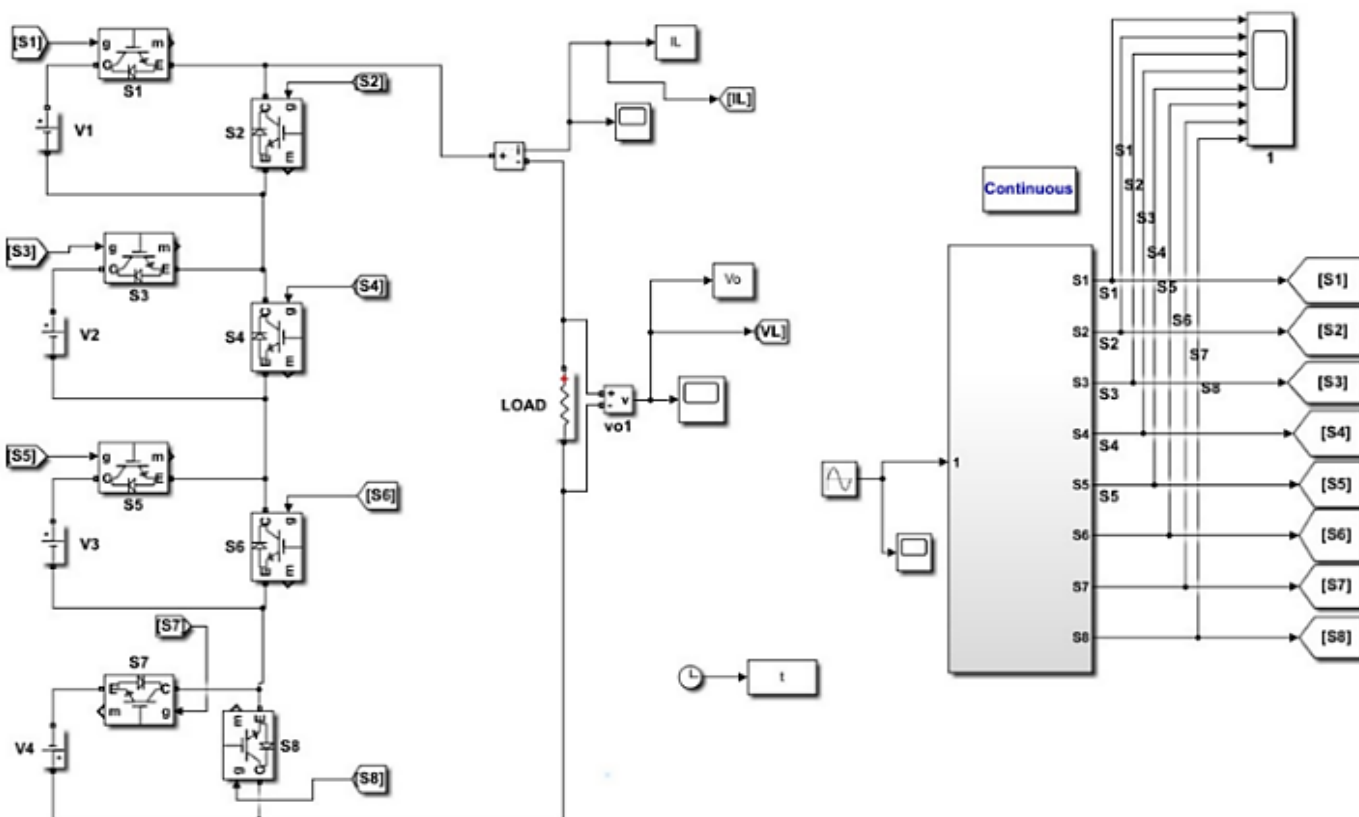


Fig. 8. Simulation Model of Cascaded Half-Bridge

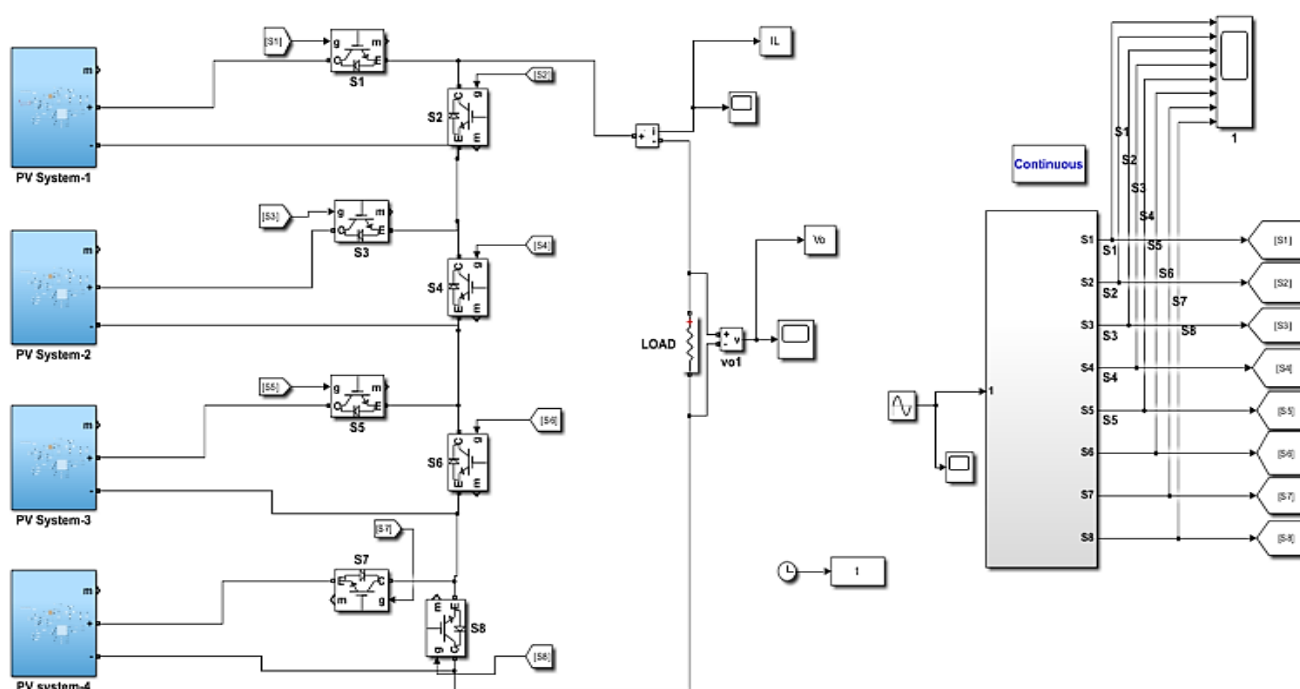


Fig. 9. MATLAB-Simulink Boost DC-DC Converter model with PV

3. Results and Discussions

3.1 Simulation Results of PV System with DC-DC Boost Converter

The simulation model of the photovoltaic (PV) system using the Perturb and Observe (P&O) MPPT algorithm is comprised of a PV Array, a DC-DC boost converter, a P&O-based MPPT controller, and a load. The output voltage and current of the PV Array, which transforms solar energy into DC electricity, change in response to temperature and solar irradiation. The MPPT algorithm controls the duty of a boost converter, which is used to regulate and step up the voltage to fit the load's needs. The P&O algorithm works by regularly altering the PV Voltage and tracking the change in power of those results; if power rises, the perturbation keeps going in the same direction; if, not it reverses. The system can monitor and sustain operation at the maximum power point (MPP) due to this iterative approach. The duty cycle signal produced by the MPPT controller is transformed into a PWM signal to regulate the boost converter switching. In order to show how the system adapts to the dynamical variations in irradiance or temperature, optimal power extraction from the PV array. To attain a constant voltage of 40V, the irradiance level was purposefully set to 400 W/m². In the simulation result of the PV system model including the Perturb and Observe algorithm, as shown in Fig. 10. Fig. 10. (a) shows the voltage generated and Fig. 10. (b) shows the power generated at the given value of irradiance 400 W/m².

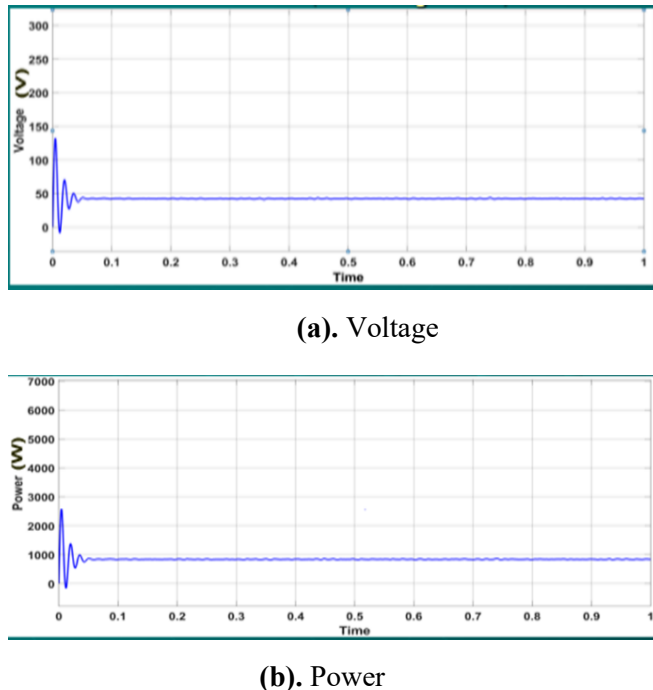


Fig. 10. P&O Algorithm Results (a) Voltage (b) Power at 400W/m²

The P&O controller continuously alters the voltage during the simulation and tracks the resulting

variations in the power. The DC-DC boost converter duty cycle was successfully changed until the operating point converged MPP, or reached 40V. The algorithm continued to operate steadily with little oscillations in spite of the low irradiance, which lowers the current and power output. The P&O algorithm's ability to dynamically adjust to environmental variations while achieving the desired voltage level even in partially shaded or low irradiance environments.

Similarly, to get the higher output voltage of 80V and power level, the value of irradiance increased to 800 W/m² in the simulation model of the system using the P&O MPPT method algorithm, as shown in Fig. 10. By continuously modifying the boost converter's duty cycle, the P&O controller allowed the system to attain the maximum power point that matched the irradiance value. The output voltage stabilizes at a higher value, and the power output is rising correspondingly. The program demonstrated its capacity to effectively track the maximum power point and maximize the energy extraction under high irradiance.

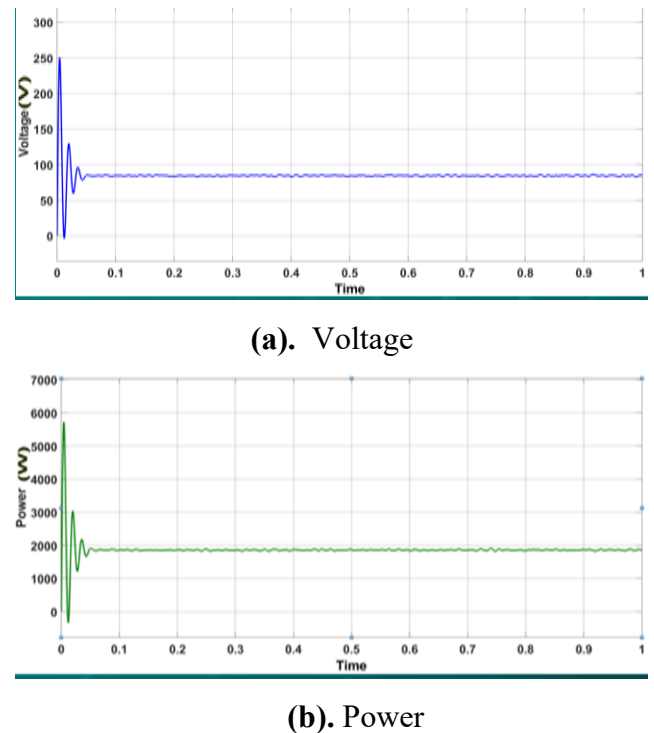


Fig. 11. P&O Algorithm Results (a) Voltage (b) Power at 800W/m²

2.3 Simulation Results of Cascaded Half Bridge with PV System.

The operation of the inverter and phase disposition strategy is confirmed by the switching signals shown in Fig. 12. The gate pulses of the eight switches (S₁ to S₈) were created exactly in accordance with the triangle carrier signals and the reference sinusoidal modulation. In order to prevent the overlap situation or shoot-through situations, each H-bridge functions in the proper order, with the gate signals displaying the

various and steady alternation between complementary switches. The expected logic produced from the PD-PWM approach is matched by the timing of the ON and OFF transitions. The

successful application of the PWM control technique and the proper operation of the inverter system are confirmed by the figure shown, which clearly shows how each switch reacts to the modulation pattern.

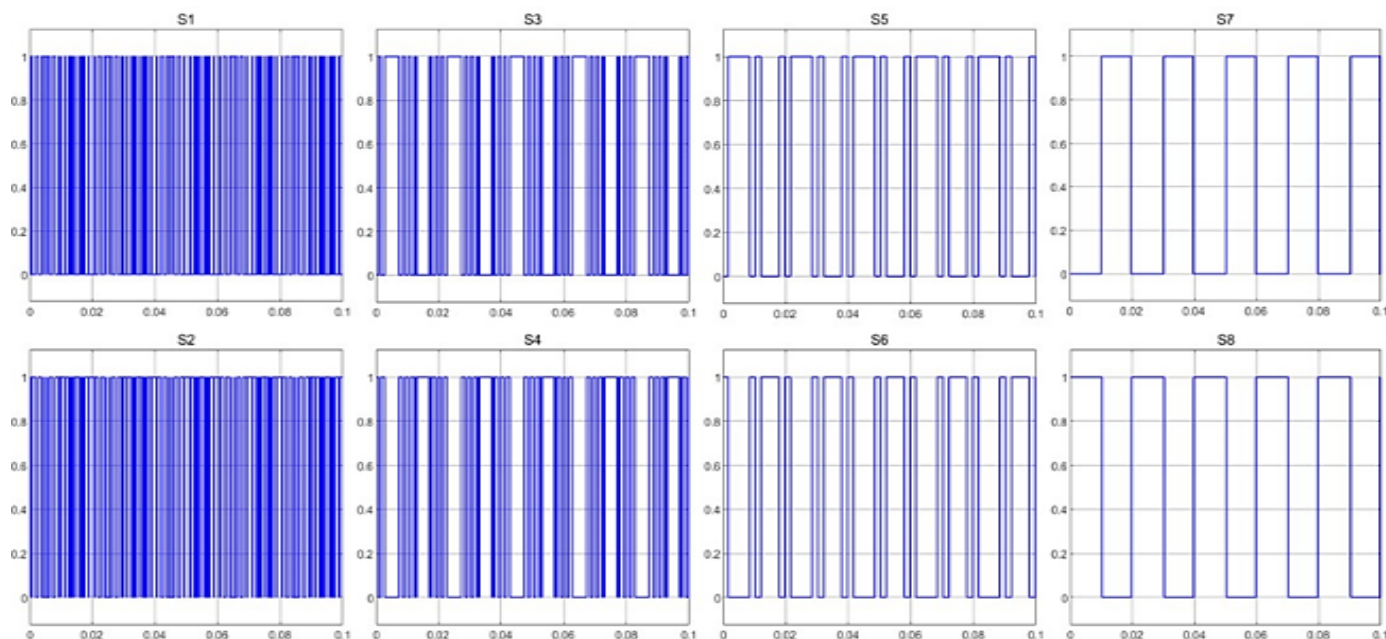


Fig. 12. Switching Pattern of cascaded Half Bridge MLI

The inverter generates the 13-level stepped output voltage waveform as shown in Fig. 13. The waveform clearly shows 13 different levels on each cycle, approximately a sine wave in the shape of a staircase. The output voltage of various cascaded H-bridge switches, each of which adds gradually to the total output, is combined to create the output waveform. Each step corresponds to a precise voltage increment, and the levels are uniformly divided over the positive

and negative half cycles, ranging from -6Vdc to +6Vdc.

Fig. 14. shows the Fast Fourier Transform (FFT) study; the inverter output waveform's total harmonic distortion (THD) is 10.93%. Because the output waveform is 13-level stepped, this THD number indicates the existence of harmonic components in the output voltage.

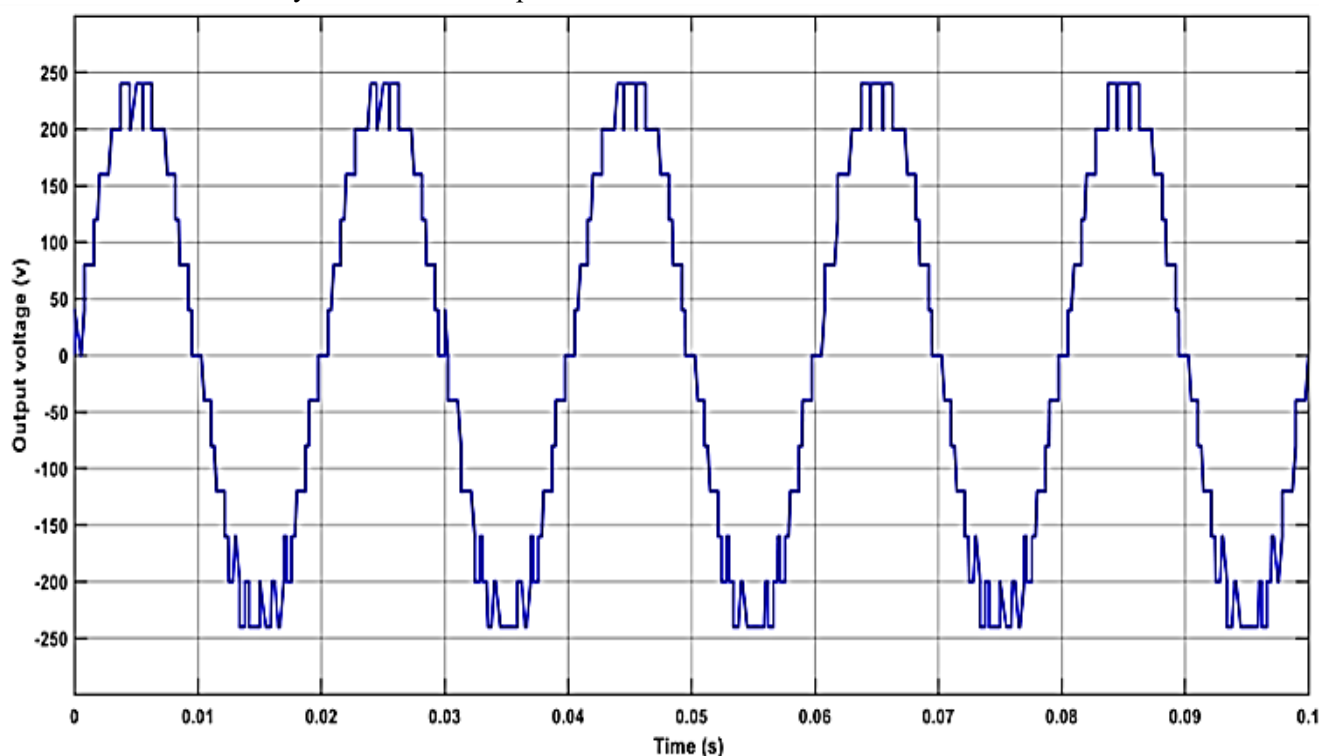


Fig. 13. Output Voltage waveform of the cascaded Half Bridge MLI with P&O Algorithm

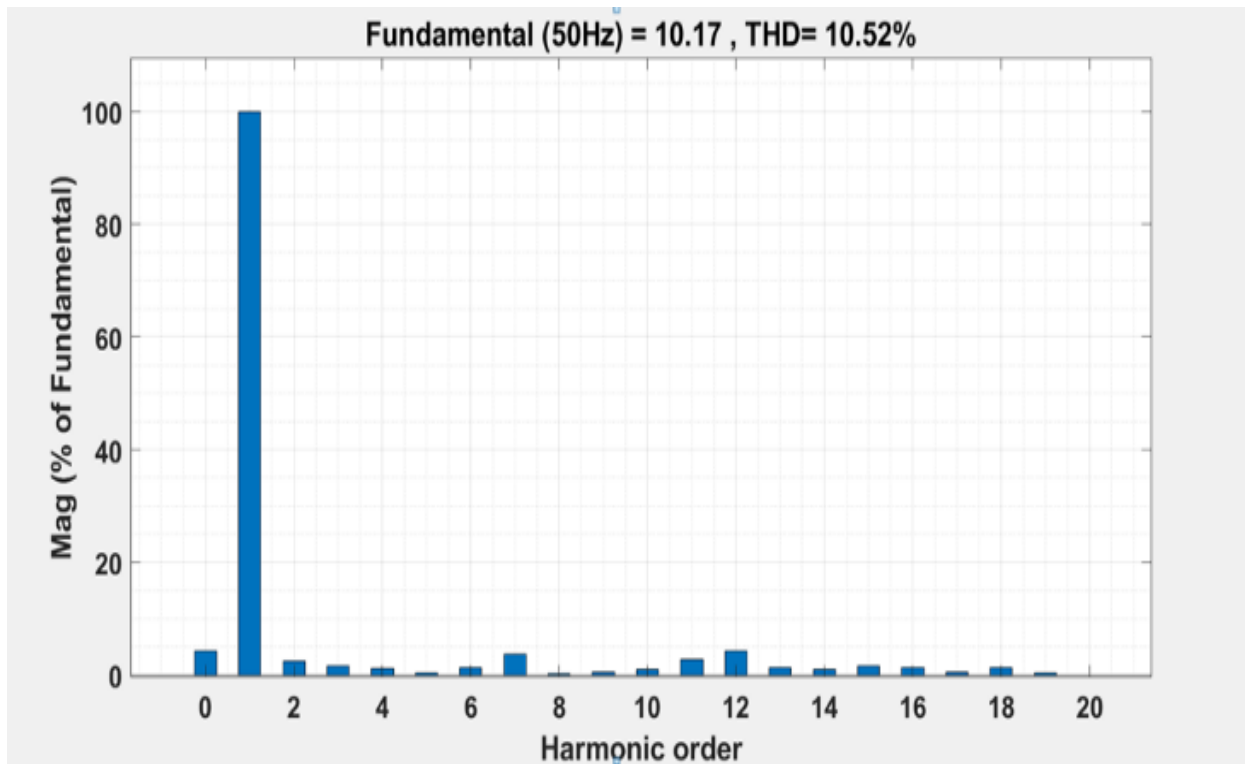


Fig. 14. THD% result of Cascaded Half Bridge MLI with PV System

When validated with literature, as shown in Table 3, the proposed model is found to be efficient than those suggested in studies [17-18]. Based on sufficiently reduced number of switches and DC sources, the proposed MLI topology attains same 13 level output as compared to the results of [17-18]. Thus, efficiency of the proposed topology is significantly improved as compared to the discussed existing topologies.

Table 3.

Comparison of proposed and conventional topologies

Reference number	No of Levels	No of Switches	No of DC sources
[17]	13	12	4
[18]	13	24	6
Proposed	13	8	4

The proposed CHB MLI intrinsically is flexible with scalability to higher voltage levels; however, in general, due consideration is needed for the modular design operation. Since, in the proposed CHB MLI, which uses an efficient modulation process and the system design is asymmetric, most of the usual problems have been avoided, like: modularity, voltage stress, output quality compromise and fault intolerance. On the other hand, prototype development, control complexity, and maintenance can be the obvious considerations in the practical implementation of the proposed system.

4. Conclusion

This research study was conducted to design an MLI with reduced count switches and an increased number of levels. The analysis and modeling of the proposed 13-level cascaded half-bridge multilevel inverter with PV system to improve the overall

efficiency and the performance of the PV system was done in MATLAB Simulink. The Phase Disposition (PD) multicarrier PWM technique was used for generating the switching signals. The Simulation results obtained using MATLAB show the total harmonic distortion (THD) of 10.52%, showing the effectiveness of the proposed inverter design as it produces a stable output compared to the conventional topologies. The proposed system and the suggested topology can be used in the future in off-grid systems. Design of more efficient algorithms and hybrid strategies to tackle MPPT in solar PV systems can be proposed. In the future, the prototype can be developed for the successful implementation of this system.

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