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Photovoltaic-Based Eleven-Level Cascaded H-Bridge Inverter with Bidirectional Switches to Minimum Harmonic Distortion

C Dinakaran[1*], and Dr.T Padmavathi[2]

[1]*Electrical and Electronics Engineering, GITAM School of Core Engineering, GITAM (Deemed to be University), Visakhapatnam, Andhra Pradesh, India; Email: dina4karan@gmail.com*
[2]*Electrical, Electronics and Communication Engineering, GITAM School of Core Engineering, GITAM (Deemed to be University), Visakhapatnam, Andhra Pradesh, India; Email: ptadi@gitam.edu*

***Correspondence:** *C Dinakaran, dina4karan@gmail.com*

ABSTRACT- In this article, a single-phase modified cascaded H-Bridge eleven-level inverter that produces a precise sinusoidal output voltage while significantly reducing THD. The proposed topology enables a reduction in the number of switches relative to the traditional cascaded H-bridge inverters but with a THD of about 3. The designed inverter construction consists of four bidirectional switches, including a conservative H-Bridge that allows adequate voltage control and enhances overall structure performance. The primary goal of this effort is to decrease the number of devices without sacrificing power quality and to provide an affordable solution that is suitably tailored for various applications that demand high-quality AC voltage. By minimizing harmonics and guaranteeing that the production voltage waveform intentionally closes a sinusoidal waveform, a suitable switching policy contributes to the development of the system's performance. The integrity of the system's design produces flexibility, making it efficiently extendable to deliver higher output voltage levels should ultimate demands desire it. The designed system is modeled and simulated using the MATLAB/SIMULINK and PROTEUS domains to demonstrate its feasibility. The findings of the experiment indicate that they are very close to simulation, confirming the pragmatic practicability of the system. Moreover, experimental outcomes further validate the successful process of the inverter, demonstrating valuable performance in terms of output quality and system performance.

Keywords: Multilevel Inverter, Modern H-Bridge Inverter, Photovoltaic System, Fuzzy Controller, Maximum Power Point Tracking (MPPT), Total Harmonic Distortion (THD).

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1. INTRODUCTION

An essential component of industrial, social, and economic development is energy [1]. A nation's level of civilization and development is determined by how well its citizens use energy to meet their daily needs. As fossil fuel supplies run out in a few years, energy consumption is rising quickly [2]. As the rate of energy use rises, the supply is exhausted, leading to inflation and a shortage of energy [3].

In order to meet future energy demands, alternative or renewable energy sources must be developed [4]. Photovoltaic (PV) systems have gained significant attention due to the global push for clean and renewable energy. However, integrating PV systems with the grid or loads requires efficient and reliable power electronic converters. Multilevel inverters (MLIs), especially cascaded H-bridge inverters (CHBIs), are favored for their capability to handle high voltages with lower total harmonic distortion (THD) and reduced electromagnetic interference (EMI) compared to conventional two-level inverters. A CHBI uses multiple H-bridge cells connected in series, each powered by independent DC sources (like PV arrays), to generate stepped output voltages. This configuration minimizes voltage stress on individual components and enhances waveform quality. Energy can be derived from a variety of sources, including thermal energy, kinetic energy, and bioenergy. Due to the employment of sophisticated power electronic components, solar and wind power plants are highly well-known among the many nonconventional energy sources [5]. Solar energy is inexpensive and pollution-free, and the planet receives it from the sun in the form of electromagnetic radiation [6]. Residential, commercial, and rural lighting applications employ the energy that solar collectors in solar photovoltaic systems collect [7]. These PV systems are linked to the electric grid and are reasonably priced [8].

Due to their numerous benefits over traditional inverters, multilevel inverters are currently receiving a lot of interest for high power medium voltage applications [9]– [10]. Their capacity to function at low switching frequencies, reduced voltage distortion, and less common mode noise generation are their main advantages [11]– [12]. Creating multiple DC voltage levels from a sinusoidal output voltage is the primary goal of multilevel converters [13]. The overall harmonic distortion decreases as the number of levels rises [14]. However, a multilayer inverter's control algorithm will need to become increasingly sophisticated as voltage levels rise [15]. Flying capacitors, diode clamped, and cascaded inverters are the most well-known and universal multilevel inverter architectures [16]. Because energy demands are increasing daily, certain newly built devices have also been created in recent years to reduce the number of power switching devices [17]. Therefore, a redesigned inverter uses less power without causing any loss [18].

Despite the fact that the current multilevel inverter topologies enhance the quality of the output waveforms, they can be characterized by the necessity to use a lot of switches, DC sources, and complicated control schemes. This adds cost and low efficiency to the system. To overcome these setbacks, the following paper suggests a modified eleven-layer cascaded H-bridge inverter based on the bidirectional switches. The main achievements of this work are:
(i) Fewer switches than conventional CHB inverters.
(ii) Reduced overall harmonic distortion (THD).
(iii) MPPT combined with the control of fuzzy logic.
(iv) Better efficiency and voltage quality.

It also compares its features with the current inverter topologies to bring out the benefits of the proposed system.

2. PROPOSED TOPOLOGY

This research suggests a redesigned single-phase, eleven-level grid-connected inverter for photovoltaic systems that uses fewer switches and conserves power [19]. The most significant use of photovoltaic solar systems nowadays is grid integration of renewable energy sources, which is based on photovoltaic solar energy conversion systems and is attracting more attention than conventional standalone systems [20].

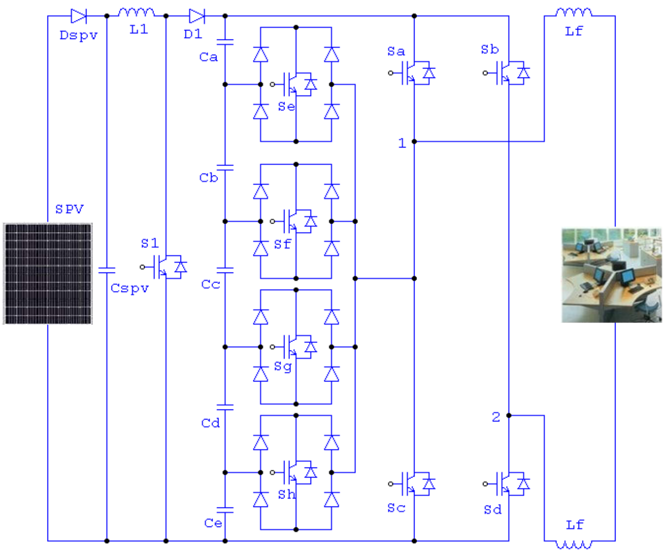

Figure 1. Proposed single phase eleven level grid-connected inverter for photovoltaic system

Due to the additional advantages of using unconventional energy sources in distributed generating power systems, the current trend is growing [21]. For this reason, the paradigm grid system places new demands on dispersed generation, including high-quality electricity, flexibility, and dependability. In this situation, power electronic technology is crucial to renewable energy sources. Photovoltaic systems can more efficiently capture power and meet power demands thanks to the usage of power electronic converters. A boost converter is used to connect the solar panel to the grid. By using a modified multilevel inverter, the boost converter allows the voltages to be increased without the need for additional components.

The proposed system consists of single-phase conventional H – Bridge along with four bidirectional and capacitor voltage divider formed by C_a, C_b, C_c, C_d and C_e as shown in *fig. 1*. The advantages of the modified H-bridge architecture over other multilevel inverter types are fewer switches, capacitors, and power diodes. This system lowers overall harmonic distortion by increasing the number of levels by eleven to produce output waveforms that are almost sinusoidal. Eleven output voltage levels can be produced by an inverter with the correct switching.

$(V_{dc}, 4V_{dc}/5, 3V_{dc}/5, 2V_{dc}/5, V_{dc}/5, 0, -V_{dc}/5, -2V_{dc}/5, -3V_{dc}/5, -4V_{dc}/5, -V_{dc})$

3. MATHEMATICAL MODELING

3.1. Output Voltage Equation

The proposed inverter has eleven levels of output voltage generated with the help of a capacitor voltage divider and switching combinations. The output voltage

$$V_0(t) = S(t).V_{dc}$$

Where S(t) is the switching function that is given as,

$$S(t) \in \left\{1, \frac{4}{5}, \frac{3}{5}, \frac{2}{5}, \frac{1}{5}, 0, -\frac{1}{5}, -\frac{2}{5}, -\frac{3}{5}, -\frac{4}{5}, -1\right\}$$

3.2. Switching Function

There are binary variables that can be used to describe each state of the switch

$$S_a, S_b, S_c, S_d, S_e, S_f, S_g, S_h \in \{0,1\}$$

The expression of the generalized output voltage,

$$V_0 = V_{dc}(S_a - S_b) + \frac{V_{dc}}{5}(S_e + S_f + S_g + S_h)$$

This equation is a representation of the various combinations of switching to generate various levels of voltage.

3.3. Harmonic Analysis

Fourier series can be used to express the output voltage waveform:

$$V_0(t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_{dc}}{n\pi} \sin(n\omega t)$$

Where, n is harmonic order;
ω is angular frequency

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3.4. Total Harmonic Distortion

The total harmonic distortion (THD) is an attribute of an electrical signal expressed in percentage units.

$$THD = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2}}{V_1}$$

Where V_1 is fundamental component, and V_n is n^{th} harmonic component.

4. MODES OF OPERATION

Switching functions are also a mathematical representation of the switching states which characterize the dependence between the switching operation and the levels of output voltage. Compared to alternative inverter topologies, the suggested topology uses a lot less electricity. Eleven output voltage levels can be produced by the inverter with the correct switching pattern. $(V_{dc}, 4V_{dc}/5, 3V_{dc}/5, 2V_{dc}/5, V_{dc}/5, 0, -V_{dc}/5, -2V_{dc}/5, -3V_{dc}/5, -4V_{dc}/5, -V_{dc})$ from Input photovoltaic supply as shown in Table 1. As illustrated in *fig. 2*, the eleven level inverter operations can be separated into eleven switching states. The following is the generation of the essential output voltages for the eleven levels as illustrated in *fig. 3*.

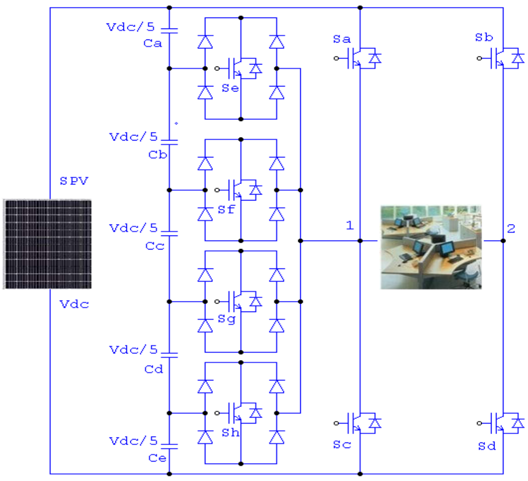
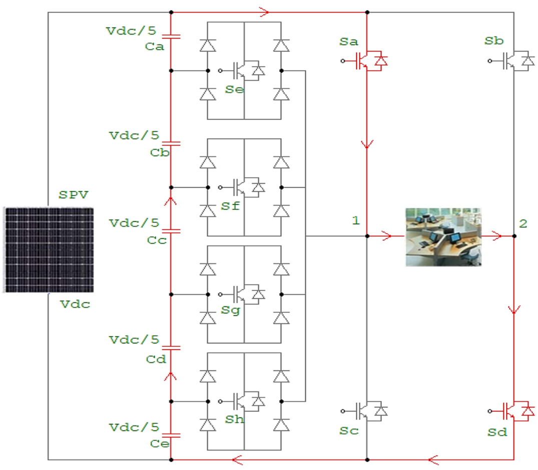
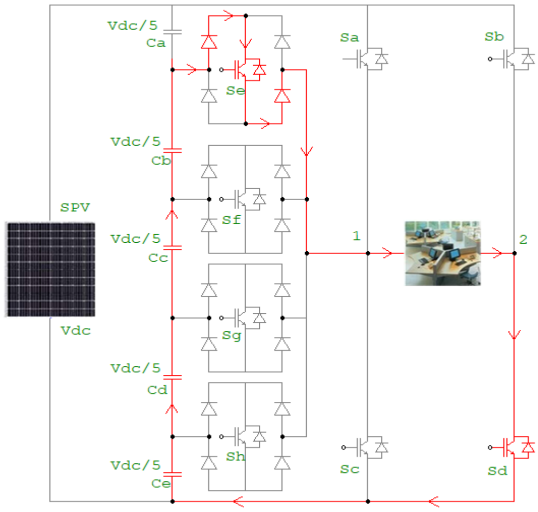


Figure 2. Eleven Level Inverter for Switching Operation



(a)



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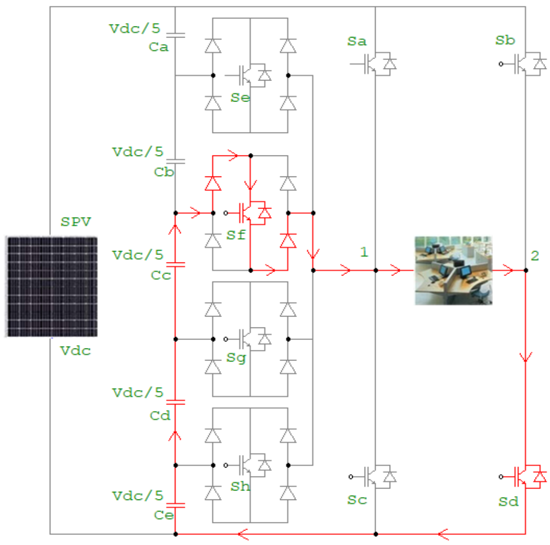

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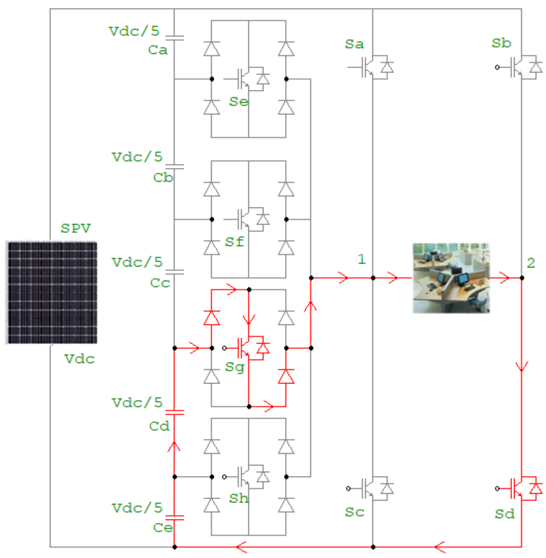

(d)

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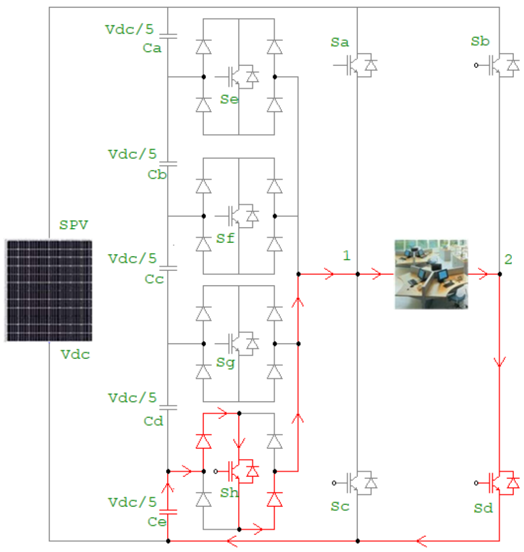

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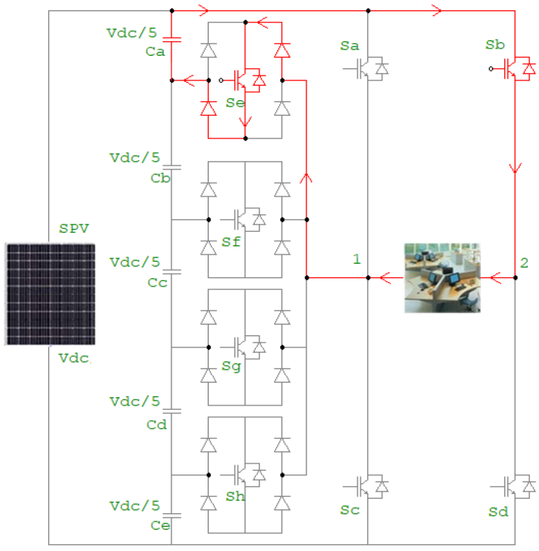

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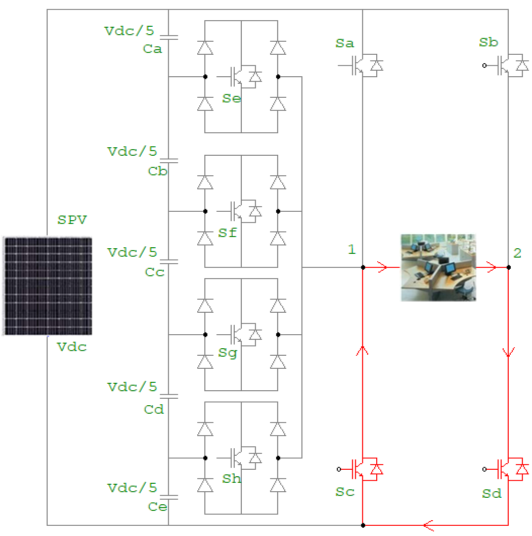

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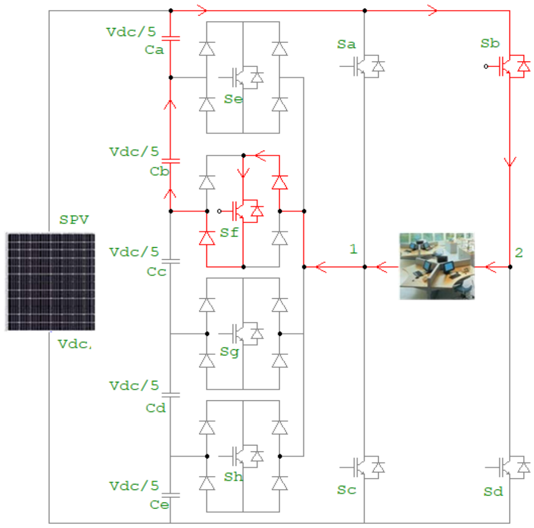
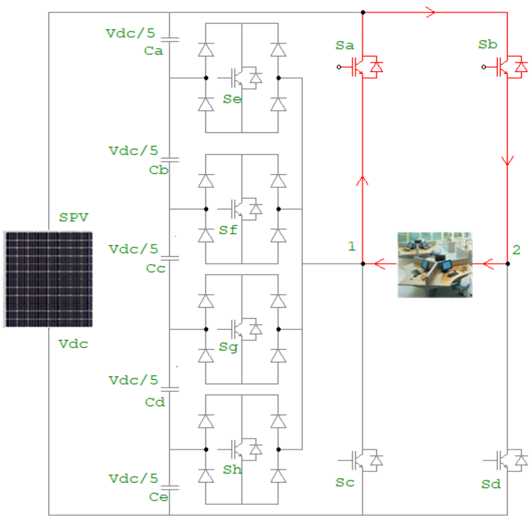


(i)



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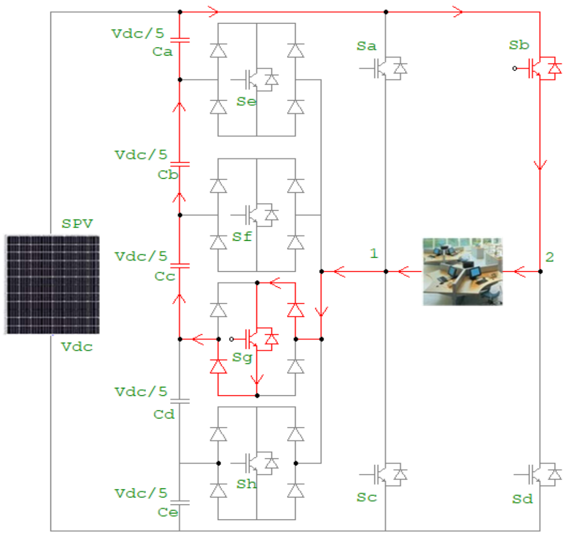

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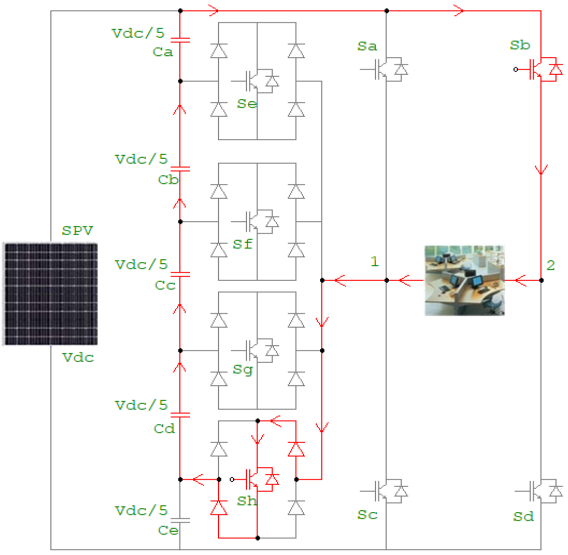

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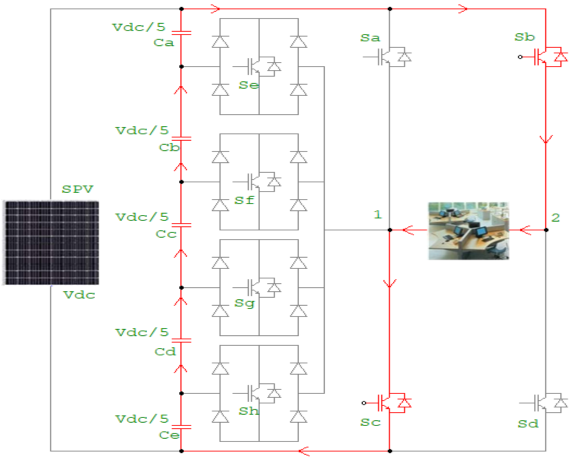

(l)

Figure 3. Switch Combination required to generate the output voltage (V_{ab}), (a) $V_{ab} = V_{dc}$, (b) $V_{ab} = 4V_{dc}/5$, (c) $V_{ab} = 3V_{dc}/5$, (d) $V_{ab} = 2V_{dc}/5$, (e) $V_{ab} = V_{dc}/5$, (f) $V_{ab} = 0$, (g) $V_{ab} = 0^*$, (h) $V_{ab} = -V_{dc}/5$, (i) $V_{ab} = -2V_{dc}/5$, (j) $V_{ab} = -3V_{dc}/5$, (k) $V_{ab} = -4V_{dc}/5$, (l) $V_{ab} = -V_{dc}$

Table 1. Switching states and corresponding output voltages for 11 inverters

Output Voltage	Switch Connecting Load Positive to Vdc	Switch Connecting Load Negative to Ground	Other Switches	Figure Reference	Remarks
+Vdc+V_{dc}	Sa	Sd	All others OFF	Fig. 3(a)	Maximum positive output voltage
4Vdc5\frac{4V_{dc}}{5}	Se	Sd	All others OFF	Fig. 3(b)	Four-fifth positive voltage
3Vdc5\frac{3V_{dc}}{5}	Sf	Sd	All others OFF	Fig. 3(c)	Three-fifth positive voltage
2Vdc5\frac{2V_{dc}}{5}	Sg	Sd	All others OFF	Fig. 3(d)	Two-fifth positive voltage
Vdc5\frac{V_{dc}}{5}	Sh	Sd	All others OFF	Fig. 3(e)	One-fifth positive voltage
00 or 0*0^*	Sc&Sdor Sa &Sb	Same as left	All others OFF	Fig. 3(f), 3(g)	Zero voltage; line short-circuited
−Vdc5-\frac{V_{dc}}{5}	Se	Sb	All others OFF	Fig. 3(h)	One-fifth negative voltage
−2Vdc5-\frac{2V_{dc}}{5}	Sf	Sb	All others OFF	Fig. 3(i)	Two-fifth negative voltage
−3Vdc5-\frac{3V_{dc}}{5}	Sg	Sb	All others OFF	Fig. 3(j)	Three-fifth negative voltage
−4Vdc5-\frac{4V_{dc}}{5}	Sh	Sb	All others OFF	Fig. 3(k)	Four-fifth negative voltage
−Vdc-V_{dc}	Sc	Sb	All others OFF	Fig. 3(l)	Maximum negative output voltage

Table 2. Output Voltage according to the switches ON – OFF Condition

V_0	S_a	S_b	S_c	S_d	S_e	S_f	S_g	S_h
V_{dc}	1	0	0	1	0	0	0	0
$4V_{dc}/5$	0	0	0	1	1	0	0	0
$3V_{dc}/5$	0	0	0	1	0	1	0	0
$2V_{dc}/5$	0	0	0	1	0	0	1	0
$V_{dc}/5$	0	0	0	1	0	0	0	1
0	0	0	1	1	0	0	0	0
0^*	1	1	0	0	0	0	0	0
$-V_{dc}/5$	0	1	0	0	1	0	0	0
$-2V_{dc}/5$	0	1	0	0	0	1	0	0
$-3V_{dc}/5$	0	1	0	0	0	0	1	0
$-4V_{dc}/5$	0	1	0	0	0	0	0	1
$-V_{dc}$	0	1	1	0	0	0	0	0

Table 2 shows the switching combinations that generated the eleven output voltage levels.

$(V_{dc}, 4V_{dc}/5, 3V_{dc}/5, 2V_{dc}/5, V_{dc}/5, 0, -V_{dc}/5, -2V_{dc}/5, -3V_{dc}/5, -4V_{dc}/5, -V_{dc})$

5. CLOSED LOOP CONTROL STRATEGY

This system consists of Maximum Power Point Tracker, conventional H – Bridge, PV panel, four bidirectional switches and fuzzy controller as shown in *fig. 4*. Need have closed loop system to increase the system efficiency and control the power from PV panel. MPPT is interconnection between photovoltaic system and grid. The function of MPPT is collecting the maximum amount of voltage form photovoltaic panel. In the control system is having actual voltage and reference voltage (V_{dc}&V_{dc}^*). The actual and reference voltage compares with the help of fuzzy controller. V_{dc} & V_{dc}^* get the same voltage levels then gives to grid through filter. Otherwise check the values of V_{dc} & V_{dcref} using trial and error method. The gating pulse gives to the switches (S_a to S_h) in inverter.

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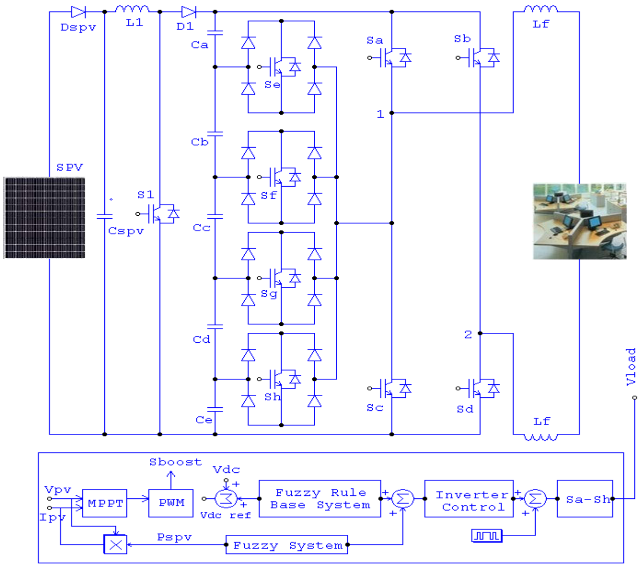

Figure 4. Eleven Level Inverter with closed-loop control algorithm

5.1. MPPT Algorithm

The power of a photovoltaic (PV) system is continuously dependent on the values of solar irradiance, temperature, and load. At a specific irradiance and temperature, the PV array reaches a specific operating point that is referred to as the Maximum Power Point (MPP) whereby the product of voltage and current is maximized. When the PV system is run out of this point, it results in a high-power loss.

A Maximum Power Point Tracking (MPPT) algorithm is used to make sure that the PV system will always be working at the maximum power point with different environmental conditions as shown in *fig. 5*. MPPT techniques are dynamic in that they regulate operating voltage or duty cycle of the power converter to which the PV array is attached so as to get the highest available power.

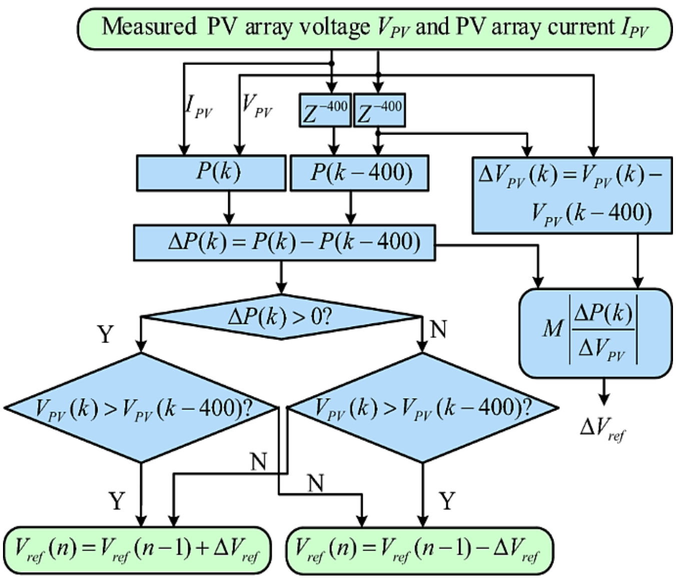

Figure 5. Flow Chart of MPPT Algorithm

5.2. Fuzzy Logic Controller

In order to eliminate the shortcomings of traditional MPPT algorithms, the MPPT is used with a fuzzy logic controller (FLC). The rule base is usually represented by some linguistic variables namely: NB, NS, ZE, PS, PB as illustrated in *table 3*.

Table 3. A Typical fuzzy rule base table

E / ΔE	NB	NS	ZE	PS	PB
NB	NB	NB	NS	ZE	PS
NS	NB	NS	ZE	PS	PM
ZE	NS	ZE	ZE	PS	PM
PS	ZE	PS	PM	PB	PB
PB	PS	PM	PB	PB	PB

6. RESULTS & DISCUSSION

6.1 Simulation Result

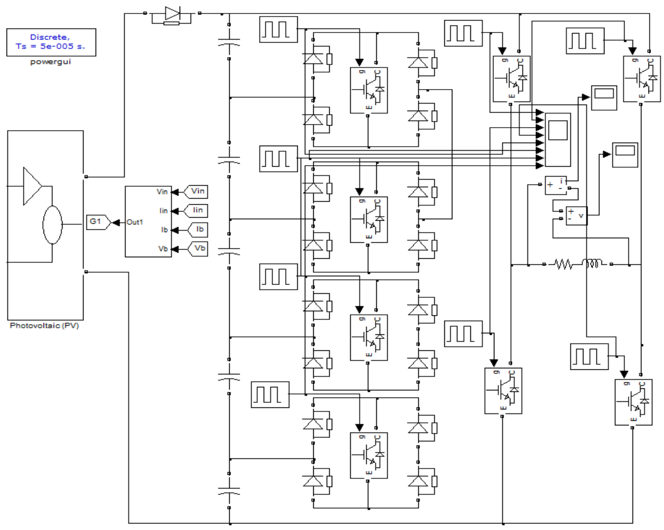

Figure 6. Simulation circuit for Modified Eleven Level Inverter

Test results for the suggested approach are displayed in *fig. 6*. The MATLAB/SIMULINK environment with SIMPOWER system toolbox was used to develop this model, and *figures 7* through 11 show the output waveforms.

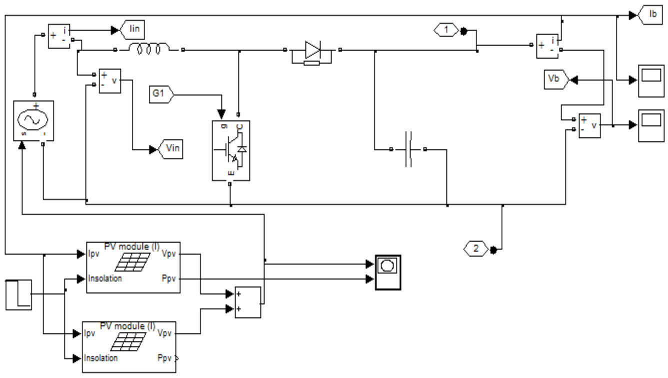

Figure 7. Sub Circuit for MPPT Boost Controller

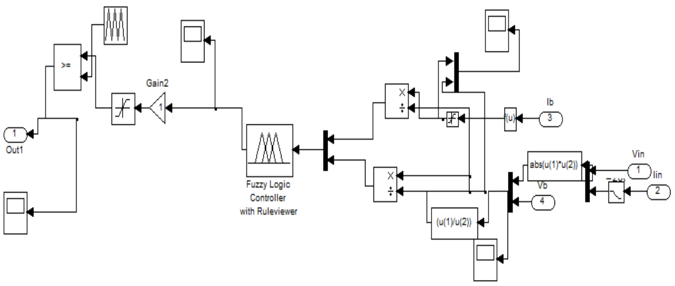

Figure 8. Sub Circuit for fuzzy rule base system

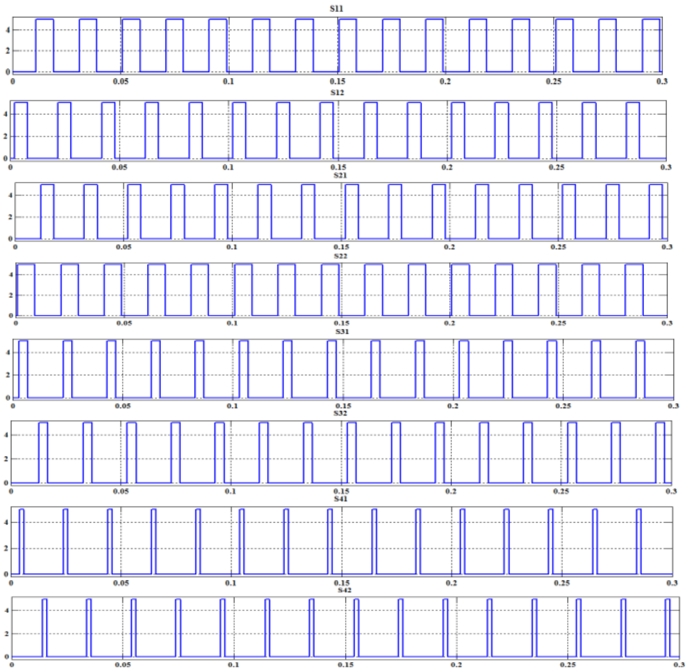

Figure 9. PWM Signal for Eleven Level Inverter

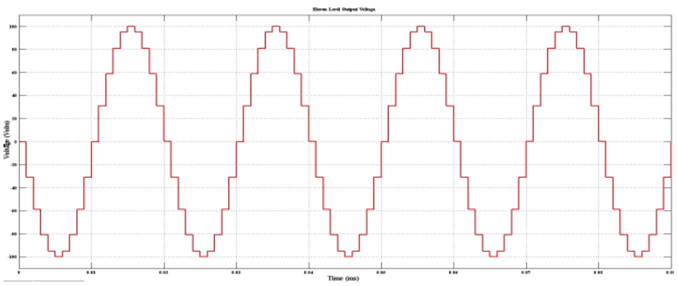

Figure 10. Output Voltage for Modified Eleven Level Inverter

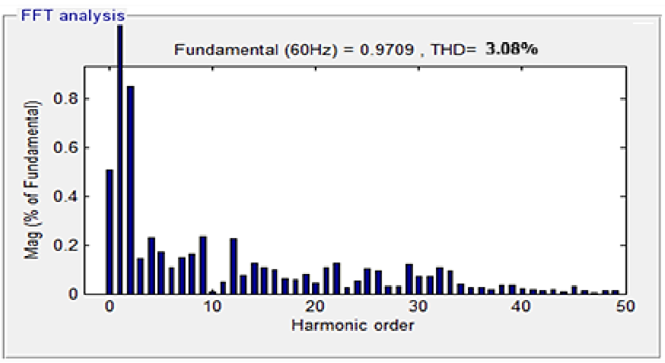

Figure 11. THD for Modified Eleven Level Inverter

The achieved value of THD of the proposed inverter is greatly lower than typical inverter topology confirming better harmonic performance.

6.2. PROTEUS Model

The most widely used simulator is Proteus. Almost any circuit involving the design of electric fields can be simulated using it. With a Graphical User Interface (GUI) that closely resembles the actual prototype model, it is simple to use. Additionally, it may be used to construct printed circuit boards (PCBs), as illustrated in *figure 12*, and *figures 13* to *14* display the output waveforms. The amount of voltage blocked by power switches is lower than that of the majority of the topologies that were given, including cascaded inverters, diode clamped inverters, and flying capacitors. These findings come from contrasting the suggested inverter with the topological inverters that were provided, as seen in *table 4*. The comparative analysis is illustrated in *table 5*.

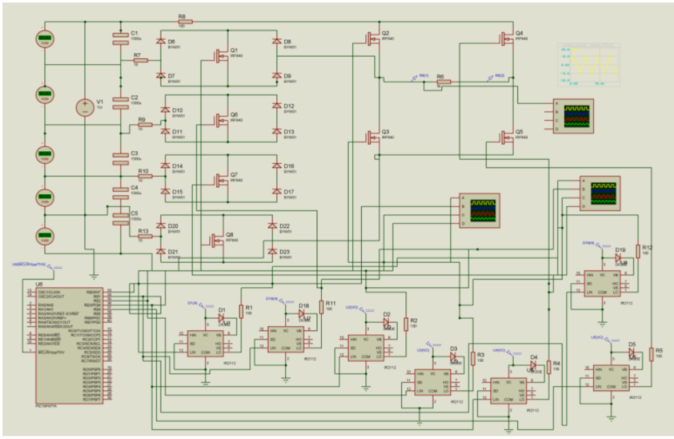

Figure 12. Development of Eleven Level Inverter in PROTEUS Software

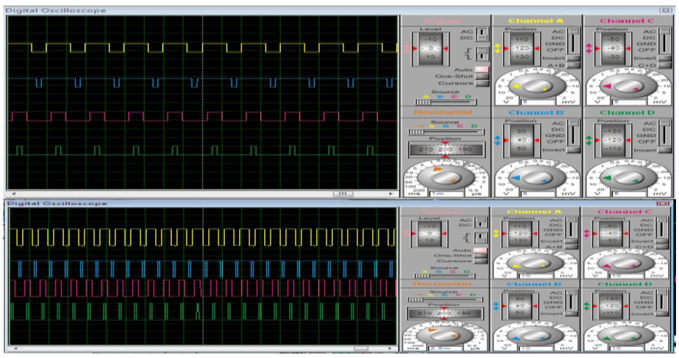

Figure 13. Output Pulse for Modified Eleven Level Inverter

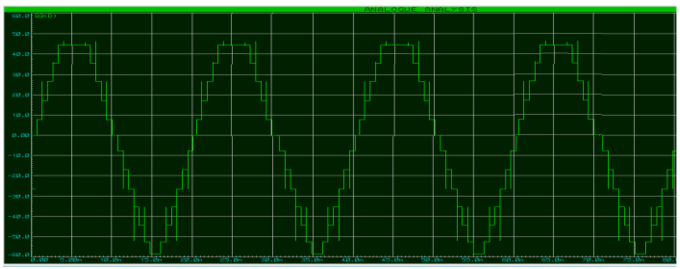

Figure 14. Output Voltage for Modified Eleven Level Inverter

Table 4. Comparison between parameters for various levels of Multilevel Inverters

Voltage Levels	No. of Capacitor	No. of Diodes	No. of Bidirectional Switches	No. of Switches	% THD	No. of Phases
5	2	4	1	4	11.79	1
7	3	8	2	4	7.36	1
9	4	12	3	4	5.15	1
11	5	16	4	4	3.08	1

6.3. Hardware Results

Hardware Components

- PV Panel: 12V / 24V DC source
- DC-DC Boost Converter
- Power Switches: IGBTs
- Driver Circuit: opto-isolated drivers, IR2110.
- Microcontroller: PIC.
- Capacitors: Network voltage divider.
- Load: Resistive / RL load

Measurement Setup

- Waveform captures Digital Storage Oscilloscope (DSO).
- THD measuring power analyser.
- Voltage and current sensors

Experimental Observations

- Output voltage waveform is similar to that of simulation.
- THD is recorded at about ~3%
- Constant load operation under different conditions.

Efficiency and Loss Analysis

Efficiency Calculation, $\eta = \frac{P_{out}}{P_{in}} x100$

Switching Loss, $P_{sw} = \frac{1}{2} VI(t_{on} + t_{off})f$

Conduction Loss, $P_{cond} = I^2 R_{on}$

Table 5. Comparative Analysis

Topology	Switch Count	DC Sources	THD (%)	Efficiency (%)
Conventional CHB	High	Multiple	5–8%	85–90
Diode Clamped	High	Single	4–6%	88–92
Flying Capacitor	Very High	Single	3–5%	87–91
Proposed Method	**Low**	**Single PV**	**~3%**	**>92%**

7. KEY OBSERVATIONS & ANALYSIS

THD Decreases with Voltage Levels:

- As the number of voltage levels increases, the Total Harmonic Distortion (THD) significantly reduces—from 11.79% at 5 levels to just 1.08% at 11 levels.
- This confirms a well-known benefit of multilevel inverters: higher levels yield better waveform quality.

Capacitor, Diode, and Bidirectional Switch Count Increases:

- Each added level increases the number of passive and active components needed:
- Diodes grow linearly (4 per level increment),
- Capacitors and bidirectional switches also increase accordingly.
- This impacts cost, size, and control complexity.

Constant Number of Switches:

- Interestingly, the number of regular switches remains constant at 4 across all configurations.
- This suggests a specific topology (likely a modified H-bridge with auxiliary components) is being used that maintains switch count.

Single-Phase Operation:

- All configurations are single-phase, indicating these results are likely for residential or standalone PV systems, or for modular use in multi-phase configurations.

Implication for 11-Level Inverter Design Choosing an 11-level inverter:

- Greatly improves output quality and ensures compliance with grid standards (e.g., IEEE 519).
- Comes at the cost of increased component count and complexity, especially due to bidirectional switches and capacitors.
- It is most suitable for high-performance PV systems where efficiency and waveform quality are critical.

8. CONCLUSION

This paper provided a modified photovoltaic eleven-level cascaded H-bridge inverter using bidirectional switches to provide better power quality at lower number of components. The suggested topology is effective in reducing the switching quantity, diodes, and DC sources than those of multilevel inverter structures and still performs well. An appropriate switching strategy and closed-loop control system, which is a combination of MPPT, and fuzzy logic control guarantees the efficient extraction of power and stable functioning. The inverter can produce a near-sinusoidal output voltage with large amounts of Total Harmonic Distortion (THD) reduced. The results of simulations in MATLAB/SIMULINK and Proteus were performed under an experimental implementation, which demonstrated a great affinity between theoretical and practical results. The findings affirm that the suggested inverter has Reduced THD, Improved efficiency, Lower switching stress, improved quality of the output voltage. Compared to conventional cascaded H-bridge inverters, it is revealed that the proposed topology is also better in terms of components minimization and harmonic performance. Future research will involve integration of real-time grid, optimization of control measures and topology expansion to three-phase to enable large-scale application of renewable energy.

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