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# MULTIPLE ORDER HARMONIC ELIMINATION IN PHOTO VOLTAIC SYSTEM USING SPWM BASED ELEVEN LEVEL CASCADED H-BRIDGE MULTILEVEL INVERTER

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## Abstract

*The detailed examination of utilizing renewable energy sources, particularly integrating Photovoltaic (PV) arrays and Multilevel Inverters (MLI), is thorough and underscores the importance of addressing environmental issues linked to fossil fuels. The selection of Sinusoidal Pulse Width Modulation (SPWM) and its benefits, such as low switching losses and high efficiency, are well-articulated. The simulation results showing sinusoidal waveforms for resistive loads and the focus on reducing Total Harmonic Distortion (THD) using an LC filter further highlight the commitment to achieving high-quality power output. THD reduction is crucial for maintaining the stability and reliability of power systems. The incorporation of a seven-level MLI adds complexity and sophistication to the system, potentially allowing for more precise control over the output waveform and enhancing the overall performance of the* *renewable energy system. The consideration of factors like efficiency, reliability, and grid compatibility aligns with best practices in the design and implementation of renewable energy systems. Your approach clearly aligns with the broader industry trend towards cleaner and more sustainable energy solutions. Overall, the strategic and effective use of renewable energy, SPWM for control, addressing THD through an LC filter, and incorporating an eleven-level MLI showcases multi-order harmonic elimination for maximum power generation as presented in this paper.*

**Keywords :** Multilevel inverter (MLI), photovoltaic (PV), total harmonic distortion (THD), solar, sinusoidal pulse width modulation (SPWM).

## I. Introduction

This paper provides a concise overview of the challenges faced by the electrical power system, emphasizing the shortage of fossil fuel-based energy sources and the increasing focus on renewable energy alternatives [I]. Here in this paper novelties are correctly pointed out and the key renewable sources such as solar energy, wind energy, and nuclear energy, highlight their potential role in overcoming issues related to fossil fuel scarcity and environmental concerns. The mention of the rising daily demand for energy is crucial, as it reflects the growing challenges in meeting the energy needs of modern society [II]. Integrating renewable energy sources with traditional energy systems is indeed a strategy that has gained prominence to address this demand. The decline in fossil fuel consumption due to the increased use of renewable energy sources is a positive development, contributing to a reduction in greenhouse gas emissions and the mitigation of global warming [III]. It's important to acknowledge the environmental impact of energy choices and the role renewable sources play in creating a more sustainable energy landscape. Overall, the statement effectively communicates the current challenges and trends in the power sector, emphasizing the need for a transition to more sustainable and environmentally friendly energy sources [IV]. This research provides a clear insight into the advantages and challenges associated with solar energy utilization. The mention of solar energy's availability and its potential for operating as an independent generating unit or connecting to a grid aligns with its versatility and adaptability to different applications [V]. The emphasis on using solar energy to power remote areas where traditional electrical power is unavailable or costly highlights one of the key benefits of this renewable source. The reference to multi-input converters and power electronics devices reflects the technological advancements aimed at optimizing power generation, reducing voltage fluctuations, and mitigating harmonics in the system [VI]. Acknowledging the challenges, such as the cost and efficiency issues, is important. While solar energy systems have made significant progress, the mention of their current limitations in terms of cost and efficiency adds a realistic perspective to the renewable energy system [VII]. It's crucial to address these challenges to make solar energy more competitive in the power generation market [VIII]. The idea of using several converter types to integrate micro-sources, energy storage devices (ESD), and various forms of load into a single DC bus is interesting [IX]. This approach can enhance system efficiency and flexibility, providing a potential solution to some of the challenges associated with solar energy systems [X]. The detailed description provides a well-rounded overview of the opportunities and challenges in the use of solar energy, showcasing its potential in powering remote areas and the ongoing efforts to improve efficiency and cost-effectiveness [XI].

## II. Solar Cell Modelling

The paper presents a clear and precise overview of the basic structure and operation of a solar cell, a key component in solar panels [XII]. It describes the solar cell as a p-n junction diode, where the N region is thin and lightly doped to allow light to pass through easily. This structure is essential for absorbing photons and generating electron-hole pairs. The depletion region is primarily on the P side, with the P region being less doped. This arrangement creates an electric field and built-in voltage, aiding in the separation and movement of electron-hole pairs. Solar panels consist of multiple solar cells connected together [XIII]. The discussion of parallel and series connections of cells reflects the typical design of photovoltaic modules for efficient energy production. Electron-hole pairs (EHPs) are mainly generated in the depletion layer when sunlight photons strike the solar cell [XIV]. This process is fundamental for converting light energy into electrical energy. The description accurately explains that due to the electric field and built-in voltage, electrons move toward the N region while holes move toward the P region [XV]. When a load is connected, electrons flow through the load, creating an electric current, and recombine with holes in the P region, completing the electrical circuit. This explanation provides a solid foundation for understanding how a solar cell converts sunlight into electrical energy. It is a concise and accurate description of the fundamental principles involved in solar energy conversion [XVI].

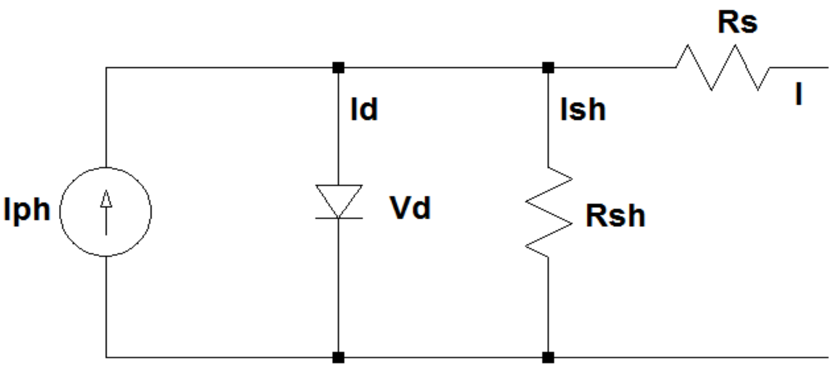



**Fig 1.** Single solar diode model

The single solar cell model will be built using a diode, two resistors, and a single current source. This model is referred to as a single-diode model. The characteristic equation of the PV cell is provided below:

$$\mathrm{I} = \mathrm{I_{lg}} - \mathrm{Ios}\left[\exp\left\{\mathrm{q} \times \frac{\mathrm{V+I\times Rs}}{\mathrm{A\times K\times T}}\right\} - 1\right] - \frac{\mathrm{V+I\times Rs}}{\mathrm{Rsh}} \tag{1}$$

Where,

$$\mathrm{Ios} = \mathrm{Ior} \times \left(\frac{\mathrm{T}}{\mathrm{Tr}}\right)^3 \times \left[\exp\left\{\mathrm{q} \times \mathrm{Ego} \times \frac{\frac{1}{\mathrm{Tr}}-\frac{1}{\mathrm{T}}}{\mathrm{A\times K}}\right\}\right] \tag{2}$$

$$I_{lg} = \{I_{scr} + K_i \times (T-25)\} \times \text{lambda} \quad (3)$$

The characteristic equation of the solar module is influenced by its connections, which indicate the number of cells connected in parallel and series. Shunt resistance primarily reduces current fluctuation in the solar module, whereas series resistance has a greater impact on this fluctuation [XVII].

$$I = Np + Ilg \times Ios \times \left[ \exp\left\{ q \times \frac{\frac{V}{Ns} + I \times \frac{Rs}{Np}}{A \times K \times T} \right\} - 1 \right] - \frac{V \times \frac{Np}{Ns} + I \times Rs}{Rsh} \quad (4)$$

The figure 2 shown below displays the I-V and P-V curves. It was observed that at low operating voltages, the cell behaves as a constant $C_s$. Additionally, at low operating currents, it acts as a constant $V_s$.

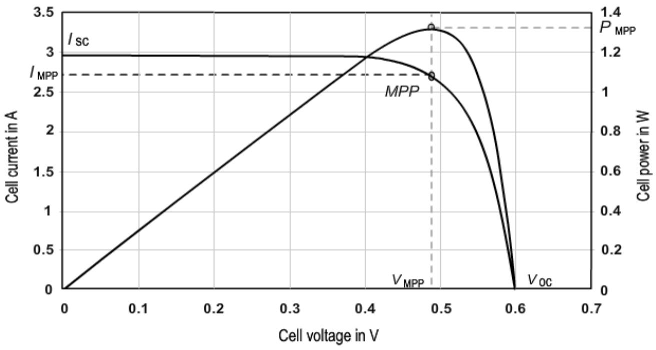



**Fig 2.** P-V and I-V curve

When a photon of light strikes the upper layer of a solar cell, it liberates free electrons, a fundamental process for generating electrical energy in photovoltaic systems. The efficiency of this process depends on the intensity of the incident light. To determine the appropriate light intensity required for optimal performance, the threshold energy formula can be employed. This formula provides a means to calculate the minimum energy necessary for electron excitation, thereby influencing the efficiency of solar energy conversion. Understanding and applying this threshold energy is crucial for optimizing solar cell performance and enhancing the overall effectiveness of photovoltaic technology [XVIII].

## III. Eleven-Level Multilevel Inverter

An eleven-level multilevel inverter (MLI) is a type of power electronic converter that provides eleven distinct voltage levels at its output. These inverters are used to improve the quality of the output waveform, reduce harmonic distortion, and increase power conversion efficiency. By switching its semiconductor devices, the eleven-level MLI generates a staircase-like voltage waveform. A control strategy is implemented to select the correct switching states based on the reference signal or desired output [XIX]. Such inverters are frequently used in renewable energy systems, motor drives, and other applications where high-quality output is necessary. One major advantage of multilevel inverters, like the eleven-level MLI, is their ability to minimize harmonic distortion, resulting in waveforms that more closely resemble a sine wave.

The design of an eleven-level MLI is determined by the arrangement of its semiconductor switches and capacitors, with common configurations being cascaded H-bridge and flying capacitor topologies [XX].

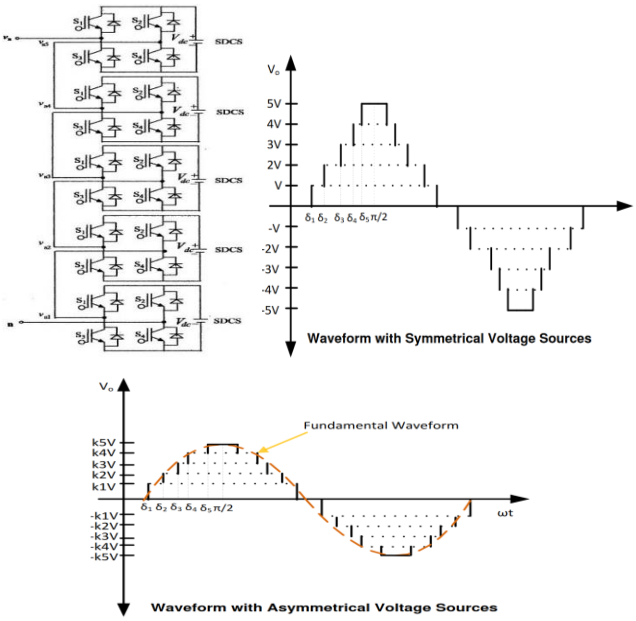



**Fig 3.** 7 Level MLI

Simulating an eleven-level multilevel inverter (MLI) involves creating a model with simulation tools like MATLAB/Simulink, where both the control strategy and circuit elements are incorporated. This process usually includes assessing the output waveform, harmonic distortion, and overall efficiency [XXI]. For seven-level inverters, control methods such as Sinusoidal Pulse Width Modulation (SPWM) or space vector modulation are employed to determine the switching states of the semiconductor devices [XXII]. The implementation of multilevel inverters can be more intricate than traditional inverters due to the necessity for multiple voltage sources or capacitor voltage balancing in cascaded setups, adding to the system's complexity. The use of seven-level multilevel inverters reflects ongoing progress in power electronics, focused on improving system performance by reducing harmonic distortions, increasing efficiency, and enhancing the overall reliability of the power conversion process [XXIII].

## IV. Sinusoidal Pwm (Spwm) Technique

Sinusoidal Pulse Width Modulation (SPWM) is a widely utilized technique in power electronics for controlling inverter output voltage waveforms, particularly in applications such as motor drives and power converters. This technique is recognized for its ability to generate a nearly sinusoidal output with minimal harmonic distortion. SPWM works by varying the pulse width in a pulse train to approximate a sinusoidal waveform. It involves comparing a reference sinusoidal waveform, which represents the desired output voltage, with a triangular carrier waveform, with the comparison determining the pulse width of the inverter's output. SPWM effectively reduces harmonic distortion, resulting in a cleaner sinusoidal waveform [XIV]. It is easily implemented with microcontrollers or digital signal processors (DSPs) and is commonly used in applications that require high-quality, low-distortion sinusoidal outputs, including motor drives, uninterruptible power supplies (UPS), and grid-tied inverters for renewable energy systems [XXV]. The technique's efficiency lies in its ability to minimize harmonic content and improve power delivery. Additionally, SPWM allows for adjustments in the modulation index and output voltage amplitude and can be applied using both analog circuits and digital signal processing methods [XXVI].

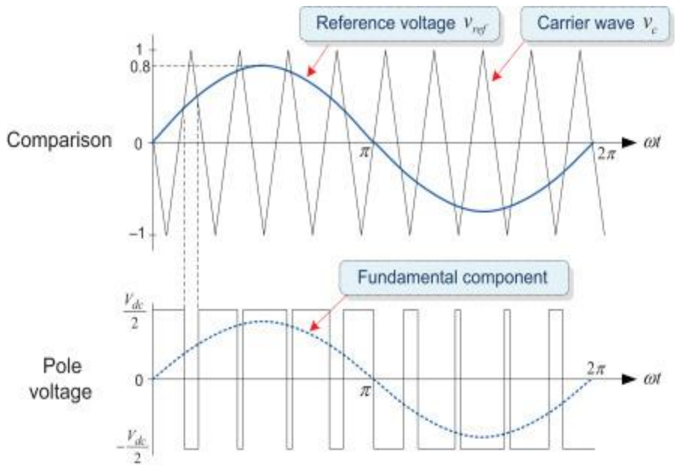



**Fig 4.** SPWM waveform

The LC filter, which combines an inductor and a capacitor filter, is used to remove AC components. In an inductor filter, RF changes directly with the load, whereas in a capacitor filter, RF changes inversely with the load. Consequently, when these filters are used together, RF becomes independent of the load. The choke increases the resistance to AC components and is suitable for DC components [XXVII].

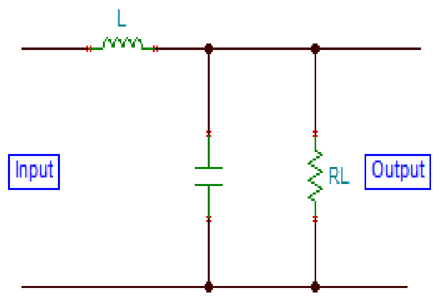



**Fig 5.** Design of LC Filter

It is arranged in series with the load, while the capacitor is connected in parallel to filter out the AC component. This setup removes ripples and results in a smooth DC output [XXVIII].

## V. Matlab Simulation and Results

The eleven-level MLI simulation is carried out using MATLAB/SIMULINK, illustrated in Figure 6. The model incorporates an MLI with sinusoidal PWM (SPWM) and operates across three phases. Figure 6 indicates that the model does not include any filters. A resistive load is connected to the MLI, with a solar PV array acting as the power source.

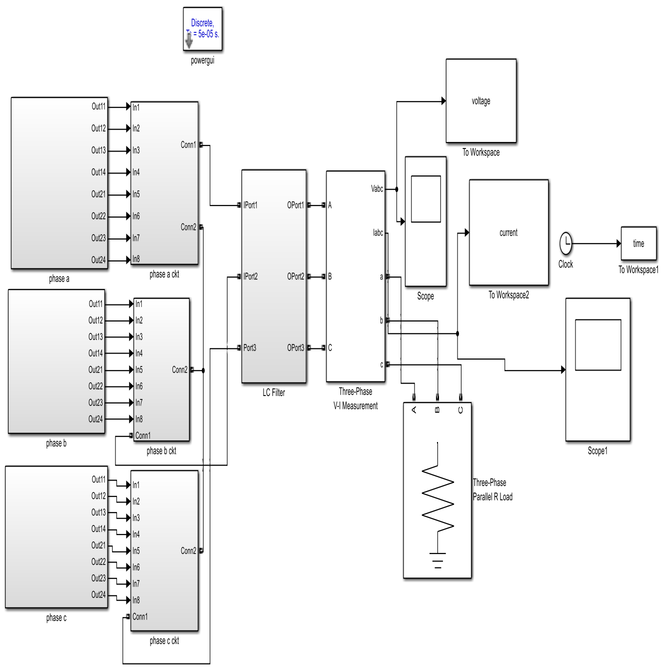
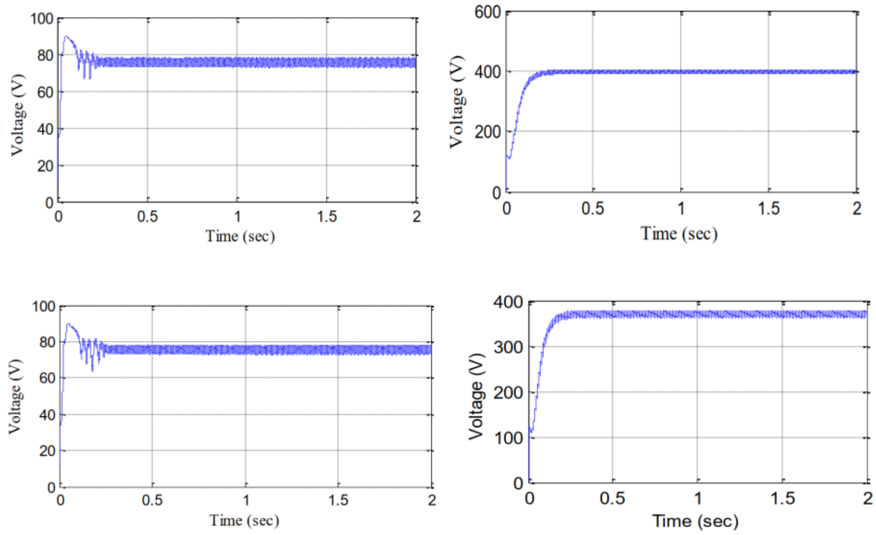


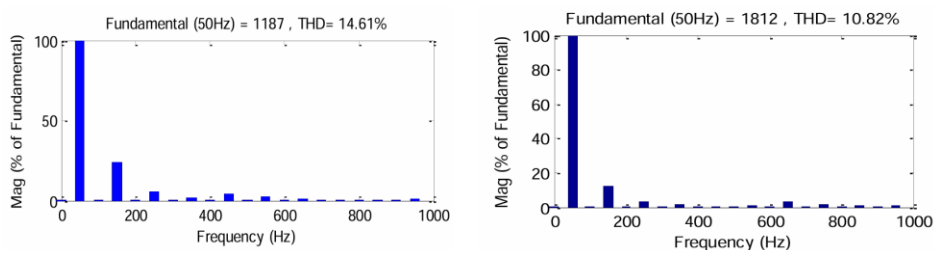

**Fig 6.** 11 Level MLI with LC filter

Figure 7(a) shows the line voltage for an 11-level MLI with an LC filter, while Figure 7(b) depicts the line voltage for an 11-level MLI using SPWM with an LC filter. The inclusion of the LC filter results in a reduction in Total Harmonic Distortion (THD) to a lower value. Figure 8(a) presents the FFT analysis of the line voltage for an 11-level MLI without an LC filter, and Figure 8(b) provides the FFT analysis of the line voltage for an 11-level MLI using SPWM without an LC filter. Lastly, Figure 9(a) displays the FFT analysis of the line voltage for an 11-level MLI with an LC filter, while Figure 9(b) shows the FFT analysis of the line voltage for an 11-level MLI using SPWM with an LC filter.



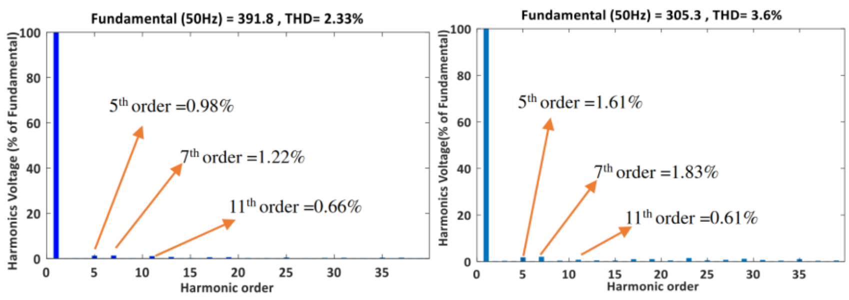

(a) (b)

**Fig 7.** (a) Line voltage using 11 level MLI with LC filter (b) Line voltage using 11 level MLI and SPWM with LC filter




(a) (b)

**Fig 8.** (a) FFT analysis of line voltage using 11 level MLI without LC filter (b) FFT analysis of line voltage using 11 level MLI and SPWM without LC filter




(a) (b)

**Fig 9.** (a) FFT analysis of line voltage using 11-level MLI with LC filter (b) FFT analysis of line voltage using 11-level MLI and SPWM with LC filter

The eleven-level MLI, which is connected to a PV model with both MPPT and SPWM controllers, is simulated using MATLAB/SIMULINK as depicted in Figure 10. This model uses sinusoidal PWM (SPWM) to minimize total harmonics in the switching process and operates in three phases. As shown in Figure 11, the model includes LC filters. The MLI is connected to a resistive load to measure voltage, current, and power using this approach.

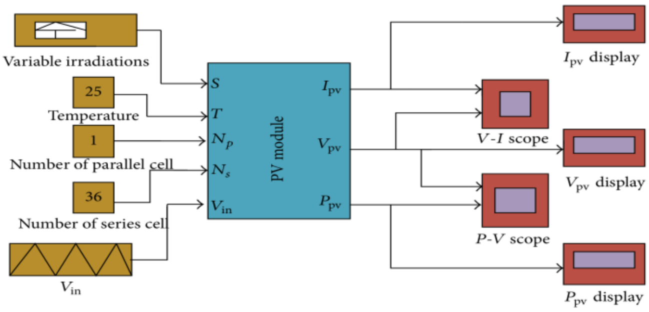



**Fig 10.** Photovoltaic model

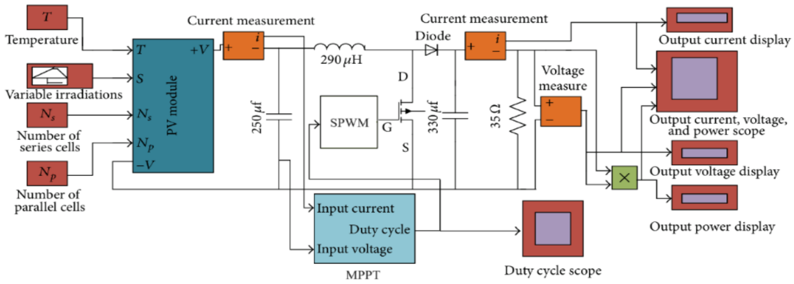



**Fig 11.** Photovoltaic model with 11 level MLI and SPWM with LC Filter

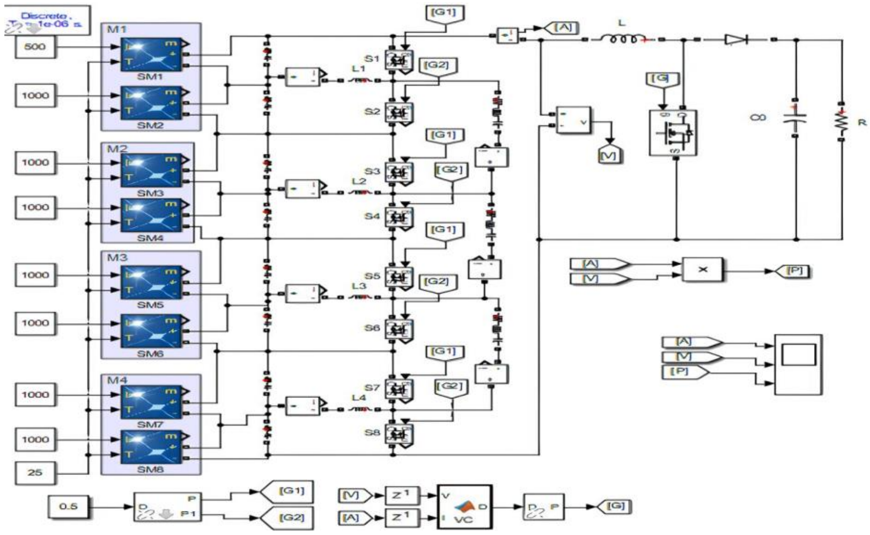



**Fig 12.** Photovoltaic model with 11 level MLI and SPWM with LC Filter

**Fig 13.** Hardware implementation Photovoltaic model with 11 level MLI and SPWM with LC Filter

Setting up a photovoltaic (PV) system with an 11-level multilevel inverter (MLI), sinusoidal pulse width modulation (SPWM) control, and an LC filter involves several stages and considerations. The implementation and results are demonstrated through laboratory experiments as shown in Figures 12 and 13. Overall, integrating a PV system with an 11-level MLI and SPWM control along with an LC filter requires meticulous planning, design, and testing to ensure optimal performance and reliability. Collaborating with specialists in power electronics, control systems, and photovoltaic technology can be advantageous throughout the implementation process. Figure 14 illustrates the I-V and P-V characteristics of the PV model using the proposed control technique.

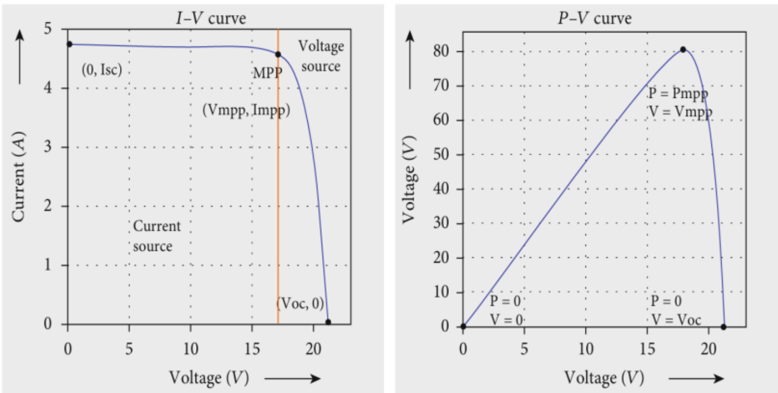



**Fig 14.** IV and PV Characteristics of the Photovoltaic Model

The figure no. 15 shown below depicts the PV generated power, PV output voltage, and PV output current for the PV model using the proposed control technique.

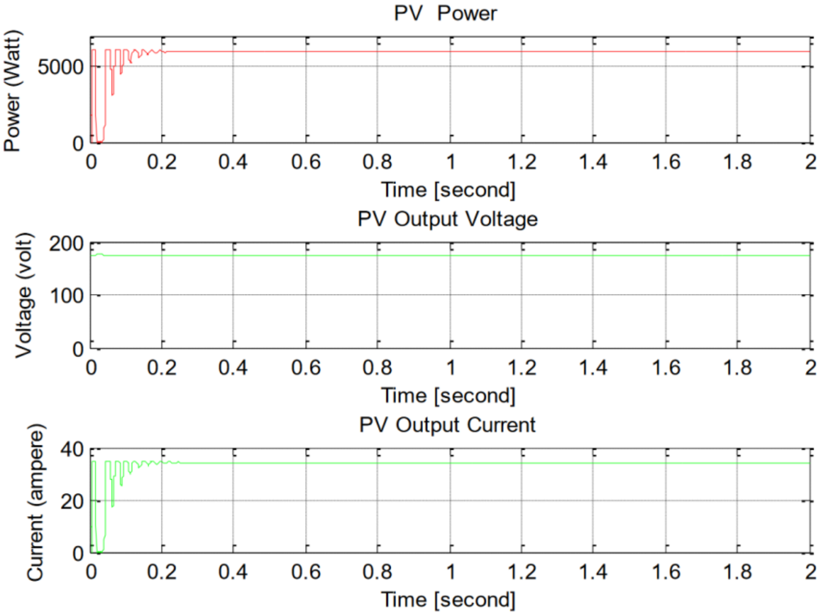



**Fig 15.** PV output power, voltage, current waveform of Photovoltaic model

**Table 1 : Total Harmonic Distortion Comparison using proposed controller**

| Workspace | 3rd Harmonic THD | 5th Harmonic THD | 7th Harmonic THD | 11th Harmonic THD |
|---|---|---|---|---|
| **11 level MLI without LC filter** | 14.61% | 15.24% | 18.65% | 21.42% |
| **11 level MLI and SPWM without LC filter** | 10.82% | 11.24% | 13.45% | 15.66% |
| **11 level MLI with LC filter** | 2.33% | 0.98% | 1.22% | 0.66% |
| **11 level MLI and SPWM with LC filter** | 3.66% | 1.61% | 1.83% | 0.61% |

Based on the results in Table 1, it can be observed that an 11-level MLI without an LC filter results in a Total Harmonic Distortion (THD) of 14.62% in the FFT analysis of the line voltage. When using an 11-level MLI with SPWM but without an LC filter, the THD is reduced to 10.82%. The incorporation of SPWM and an LC filter mitigates the transient effects of power electronics switches. In a subsequent case study, an 11-level MLI with an LC filter achieves a THD of 2.33% at the fundamental frequency, while the combination of SPWM and an LC filter results in a THD of 3.6%, which is below the critical threshold of 5% as per electricity regulations. These results confirm the effectiveness of using SPWM and an LC filter with an 11-level MLI.

**Table 2 : PV output voltage, current and power comparison using proposed controller for 25$^0$C and 1000 W/m$^2$**

| Workspace | Voltage (Max) (in Volts) | Current (Max) (in Amp) | Power (Max) (in kW) |
|---|---|---|---|
| **11-level MLI without LC filter** | 138 | 26.2 | 3.615 |
| **11-level MLI and SPWM without LC filter** | 142 | 28.6 | 4.061 |
| **11-level MLI with LC filter** | 168 | 34 | 5.712 |
| **11-level MLI and SPWM with LC filter** | 175 | 38 | 6.650 |

From the results in Table 2, it is evident that an 11-level MLI without an LC filter generates an output voltage of 138 volts and an output current of 26.2 amps, resulting in a total power of 3.615 kW. When using an 11-level MLI with SPWM but without an LC filter, the output voltage increases to 142 volts and the current rises to 28.6 amps, yielding a total power of 4.061 kW. The application of SPWM and an LC filter helps mitigate the transient effects of power electronics switches. In a subsequent case study, an 11-level MLI with an LC filter achieves a THD of 2.33% at the fundamental frequency, with an output voltage of 168 volts and a current of 34 amps, delivering a total power of 5.712 kW. When SPWM is used with an LC filter, the THD is 3.6%, which is below the critical threshold of 5% set by electricity regulations. This technique results in an output of 175 volts and 38 amps from the PV model, with a total power output of 6.650 kW. These findings validate the effectiveness of using SPWM and an LC filter with an 11-level MLI.

## VI. Conclusion

This research presents a Multilevel Inverter (MLI) that employs Sinusoidal Pulse Width Modulation (PWM) with a Photovoltaic (PV) array as the input source to reduce switching distortion, aided by an LC filter. The 11-level MLI operates using Sinusoidal PWM, a simpler method compared to other PWM techniques, achieving approximately 2.33% THD with the LC filter. When using an 11-level MLI with SPWM and an LC filter, the THD increases to 3.6% due to switching losses. Initially, without the LC filter, the Total Harmonic Distortion (THD) of the output voltage waveform is 14.61%, which improves to 10.82% with SPWM alone. Introducing the LC filter further reduces the THD to 3.6%. The proposed technique generates an output voltage of 175 volts and an output current of 38 amperes, resulting in a total PV output power of 6.650 kW. The waveforms produced are close to sinusoidal, and the proposed method enhances the waveform quality. The reduction in THD after adding the LC filter improves the output waveform quality in power electronic systems, indicating that the LC filter effectively smooths the waveform and reduces harmonic distortion.

### Conflict of Interest:

The authors declare no conflicts of interest.

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