Kufa Journal of Engineering
Vol. 17, No. 2, April 2026, P.P. 498-513
Article history: Received 20 April 2025, last revised 14 July 2025, accepted 11 August 2025

MODELING AND SIMULATION OF A T-TYPE FIVE-LEVEL MULTILEVEL INVERTER FOR SOLAR PV SYSTEMS

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https://doi.org/10.30572/2018/KJE/170230

ABSTRACT

The modeling and simulation of single phase five level t-type multilevel is presented in the paper. Solar photovoltaic inverter tailored inverter. The suggested topology is intended to improve. conversion efficiency and power quality and minimized total harmonic distortion. The inverters modeled in grid-connected and islanded operating conditions with PSIM, showing that it is flexible and can perform in different load and environmental conditions. The switching strategy and output waveform shaping is analyzed in detail. emphasizing the benefits of a lower number of switches and a better pulse width. modulation techniques. Sinusoidal output voltage generation is provided by the control system with. strong voltage regulation of both operating modes. The simulation findings support the use of the five-level. T-MLI has a stable operation, good power transfer and low harmonics hence making it. a promising technology to next-generation PV grid integration and standalone energy systems.

KEYWORDS

T-Type Multilevel Inverter, Photovoltaic System, Three Level Inverter, Five Level Inverter, Switching Frequency, Total Harmonic Distortion (THD), Fast Fourier Transform (FFT), Standard Testing Condition (STC).

1. INTRODUCTION

The increasing demand of energy worldwide, and the necessity to have cleaner and more sustainable sources of power, have catalyzed the process of incorporating renewable energy sources into the contemporary power systems. Photovoltaic (PV) energy specifically has become widely used because it is scalable, has low environmental impacts, and its cost of implementation is reducing. An inverter is a critical system in the integration of PV grids and transforms the DC voltage produced by the solar panels into an AC power that is compliant with grid specifications. Even though conventional two-level and multi-stage inverter topology is widely employed, it has several shortcomings: the topology has more switching loss, more components, and is less efficient particularly at high-frequency operation. Such problems also lead to bigger filter requirements and poor quality power.

To deal with these shortcomings, the concept of multilevel inverter (MLI) architectures has surfaced as an effective alternative (Vemuganti et al.,2020), which has the advantage of better output waveform quality, reducing total harmonic distortion (THD), and less voltage stress across switches. The T-type topology is one of the most popular MLIs that offer better harmonic operation using fewer devices, especially with grid connected PV systems. This paper provides a five-level single-phase T-type multi-level inverter (T-MLI) and discusses it as a grid-connected PV inverter N.V. et al. (2023). The suggested topology considerably decreases the amount of active switches relative to the traditional cascaded H-bridge and flying capacitor inverters however, it does not compromise the quality of output and system dependability. The sinusoidal pulse-width modulation (SPWM) is utilized to drive the inverter through optimized carrier configurations to achieve low THD and better voltage use.

Objectives of the research article are:

1. To introduce a five-level single-phase T-MLI that would be applicable to grid-connected photovoltaic systems.
2. In order to study the operational behavior of the proposed inverter topology and establish its capability to produce high-quality output voltage at a lower total harmonic distortion.
3. To develop and test sinusoidal pulse-width modulation schemes, such as phase disposition (PD) and phase opposition disposition (POD), in order to employ sinusoidal phase-based inverter control.
4. To create mathematical models of the inverter and control system to assist with performance validation with simulation models in dynamic solar conditions.

This paper is organized in the following way:

Section 2 includes the design and configuration of the proposed five-level single-phase T-MLI, emphasizing its lower number of switching and its appropriateness to photovoltaic grid integration. Section 3 investigates the working of the converter in detail, with the production 5 voltage. levels by means of sinusoidal pulse-width modulation. Section 4 presents the adaptation of the closed-loop control system, with a proportional-integral (PI) controller -to control the inverter output so that it is synchronized to the grid. Section 5 discusses the modelling of the total PV conversion system comprising of the PV source, DC-DC converter, and control logic and gives the performance analysis of the system in different conditions. solar irradiance and temperature conditions on real-time data.

2. DESIGN AND OPERATION OF A SINGLE-PHASE T-TYPE MLI

Therefore, have a look at Fig.1 -it demonstrates the general block diagram of the system. In essence, we have a DC input source that intercepts on solar energy and executes an MPPT algorithm. After that, we connect that to a boost converter to raise that low voltage and maintain a constant link voltage regardless of the various inverter levels of input (Gudey et al., 2021; Christopher et al., 2013).

The system has a boost converter with MPPT tracking to extract maximum power. The filter is located on the output side of the inverter. The AC load or grid is supplied by an inverter with high-quality power (M.A. et al. 2020).

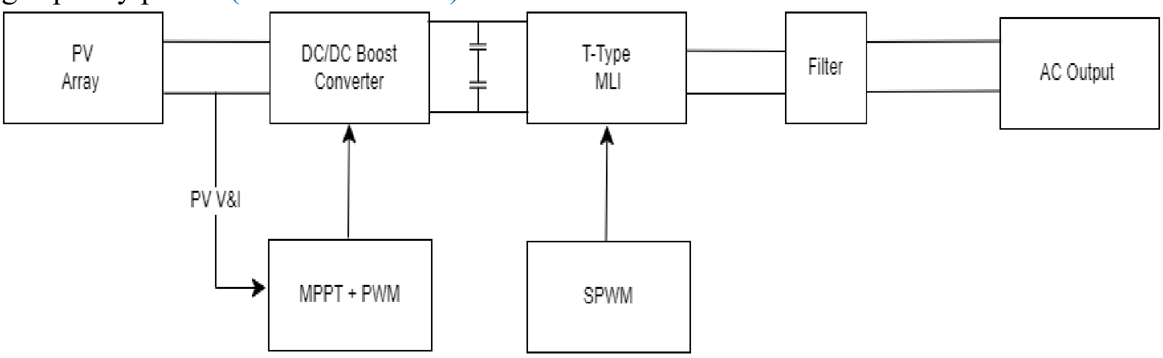


Fig.1 Schematic diagram of proposed system

2.1. Design of boost converter

The generated PV power, which typically has low voltage levels, is increased using a boost converter, as illustrated in Fig. 2. The boost converter parameters (inductor and capacitor) are carefully designed to minimize the ripple in the output voltage and inductor current. The system operates in the continuous conduction mode.

The boost converter is designed based on the following calculations.

The output voltage of boost converter

$$Vout = \frac{Vin}{1-D} \quad (1)$$

The filter inductor

$$Lin = \frac{VinXD}{\Delta I_L X f_s} \quad (2)$$

The output capacitor

$$C_{out} = \frac{I_o XD}{f_s X \Delta V_o} \quad (3)$$

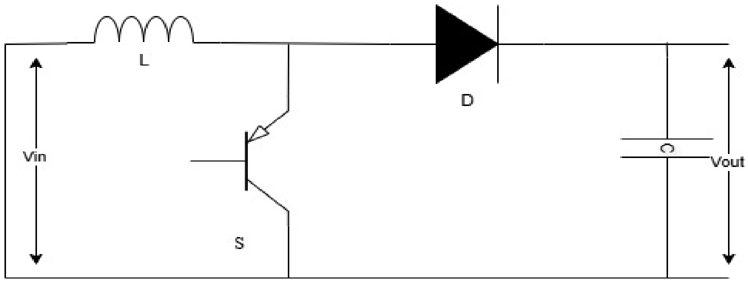


Fig.2 Boost converter

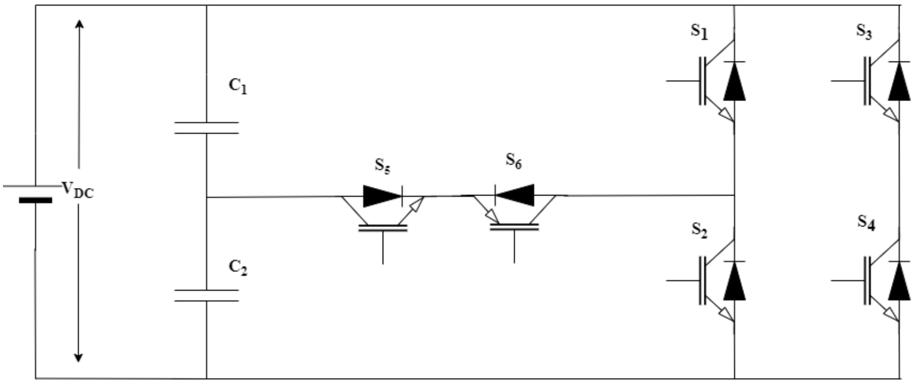
2.2. Design of DC link capacitor

The filter effectively minimizes the current ripple in the inverter output as well as in the DC-link voltage following the boost converter stage. The damping value was selected based on the extent of oscillations present in the system. The inductance and capacitance values were determined using base impedance, which was calculated based on the rated power and voltage parameters of the system. The following formula was used to determine the value of the DC-link capacitor:

$$C_{dc} = \frac{S}{2w_g V_{dc} \overline{V_{dc}}} \quad (4)$$

3. OPERATION OF A SINGLE-PHASE T-TYPE MLI

The device depicted in Fig. 3 and Table.1, referred to as the 5 L T-MLI converter. The converter can generate five distinct output voltage levels. Its bridge configuration consists of a T-type converter leg combined with a half-bridge leg, both connected to a single PV string or array, enabling a single Maximum Power Point Tracking (MPPT) operation. Two redundant switching states are responsible for producing the zero-voltage level, while the recurring states ensure voltage balance across the DC-link capacitors. (Jana et al.,2017, Liu et al.,2016, Ray et al.,2018, H.P. et al. 2021, Aamir et al. 2020). The Table.1 outlines the switching logic of a five-level single-phase T-MLI, where combinations of six switches (S1–S6) and two clamping diodes (D5, D6) generate five discrete output voltage levels: +Vdc, +Vdc/2, 0, -Vdc/2, and -Vdc. For +Vdc, switches S1 and S4 are ON, allowing current to flow from the positive DC bus through the load to the negative DC bus. For +Vdc/2, S4 and S6 are ON while diode D5 conducts, producing a mid-level voltage. The 0V output is achieved by turning ON S1, S3, and S4, effectively creating a shorted path that cancels voltage across the load. For -Vdc/2, switches S2 and S5 are ON, and D6 conducts to clamp the output to a negative mid-level voltage. Finally,



-Vdc is produced when S2 and S3 are ON, allowing full negative voltage across the output (Lin et al.,2023, Ryu et al.,2024, Ryu et al.,2024, Memon et al. 2020, Aamir et al. 2020).

Fig.3 Five level T-MLI

Table.1 Switching stage for five level inverter

Output Voltage	S1	S3	S2	S4	S5	S6	D5	D6
+Vdc	ON	OFF	OFF	ON	OFF	OFF	OFF	OFF
+Vdc/2	OFF	OFF	OFF	ON	OFF	ON	ON	OFF
0	ON	OFF	ON	OFF	OFF	OFF	OFF	OFF
-Vdc/2	OFF	OFF	ON	OFF	ON	OFF	OFF	ON
-Vdc	OFF	ON	ON	OFF	OFF	OFF	OFF	OFF

These switching states enable the inverter to synthesize a stepped AC output waveform suitable for grid integration with reduced harmonic distortion.

4. CLOSED LOOP CONTROL USING DUAL LOOP.

The control configuration for the single-phase system utilizing a DC-DC converter is illustrated in Fig. 4. A widely adopted method for DC-AC grid converters is the current-controlled PWM inverter equipped with low-pass output filters (Sood et al.,2019). The key advantages of this approach are as follows.

- Control of instantaneous current values

- Injection of current in phase with the grid voltage

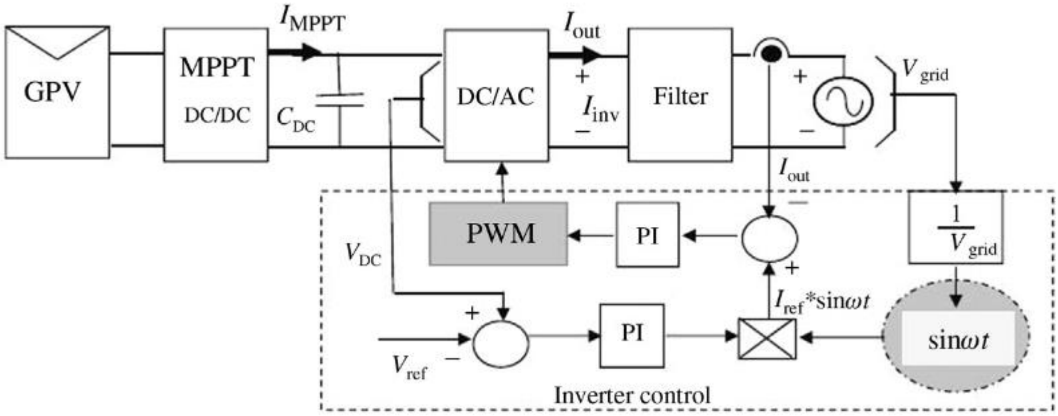


Fig.4 Block diagram for inverter control

A control scheme incorporating a DC-DC converter and an L filter topology is presented. In this method, the reference current is derived from a sinusoidal signal based on a sample of the grid voltage (Hassaine et al.,2019, Hassaine et al.,2020, Sinha et al.,2018, Ciobotaru et al.,2006). The system uses PI controllers to manage performance. To improve the PI controller's effectiveness in this current-control strategy and to reduce voltage fluctuations in the PV generator caused by dynamic changes in irradiance and temperature a faster response from the boost converter, inverter, and DC bus capacitor is essential. Additionally, the grid's main voltage acts as a significant external disturbance at 50 Hz. To address this, a compensation mechanism is applied at the PI controller's output to directly calculate the reference voltage for the inductor. The inverter's output current control loop is depicted in Fig. 4 (Mosa et al.,2013, Boonmee et al.,2013, Barghilatran et al.,2015).

5. RESULTS AND DISCUSSION

This section uses the PSIM software to simulate a multilevel inverter. The input parameters of solar radiation and temperature were determined using the external support tool Excel and a lookup table. Input parameters for one year were inserted using the TBL file. Each simulation had the same input parameters and the load remained constant. Simulation tools modify the PV panel data to reflect a practical 500 W power output. To accurately simulate solar panel performance, it is necessary to collect data on solar radiation measured in watts per square meter which include both daily and seasonal variations. The Fig.9 shows the PV panel data sheet, which exactly matches the practical panel available in the market.

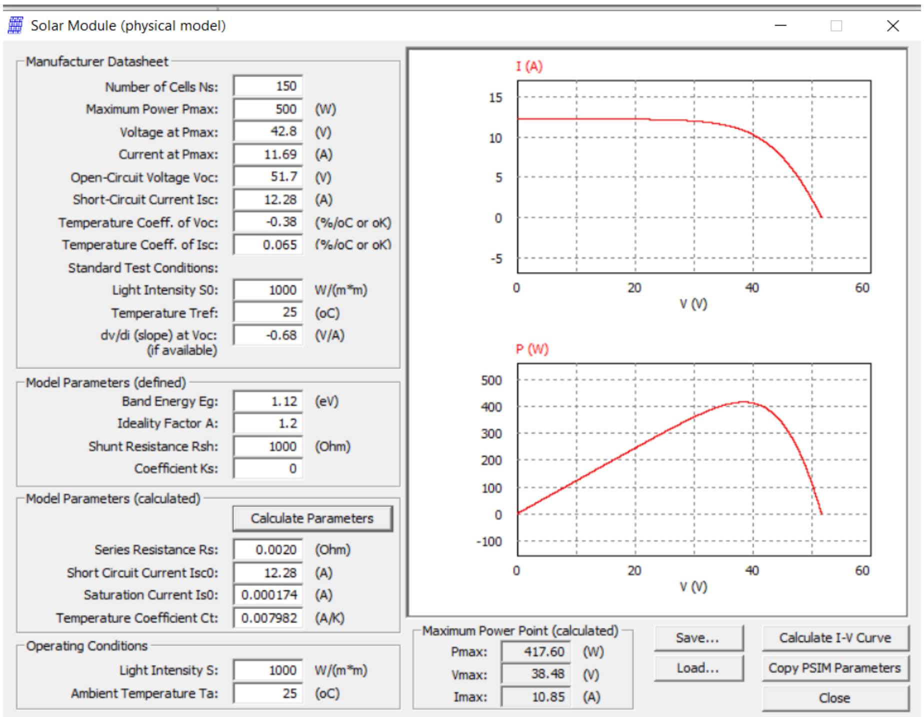


Fig. 5 PV panel detail with parameters

5.1. Islanding Mode of Operation

A load-connected inverter with variable irradiation and temperature is shown in Fig.6. Different loading conditions were considered for the analysis.

The Standard Testing Condition (STC) condition results were considered to be 1000 w/m^2 and 25°C. The PV panel voltage remained constant at 167 V and a boosted voltage of 210 V was available after the boost converter

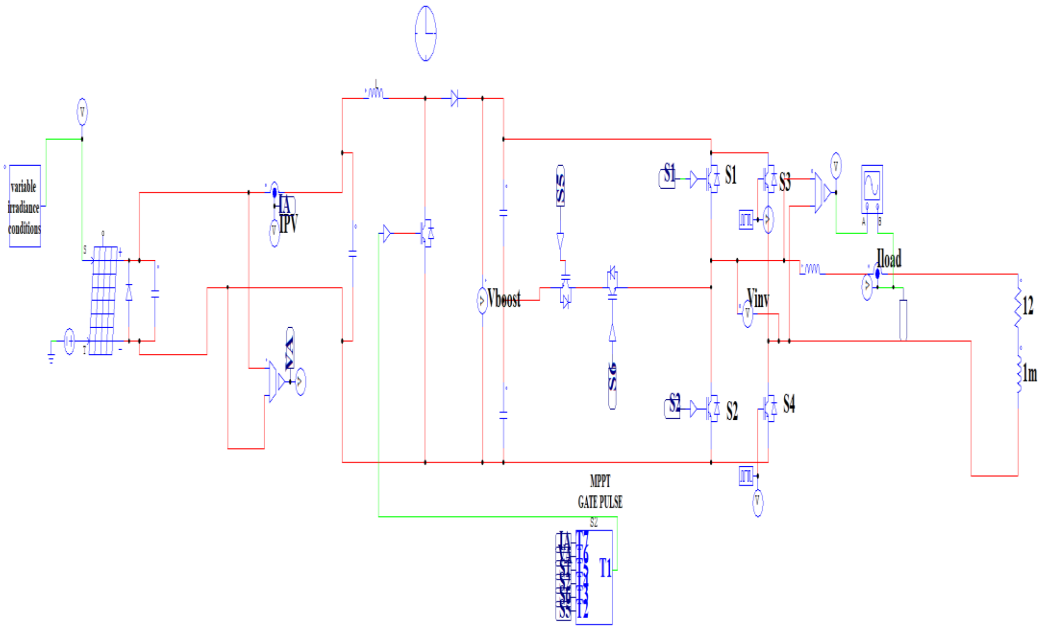
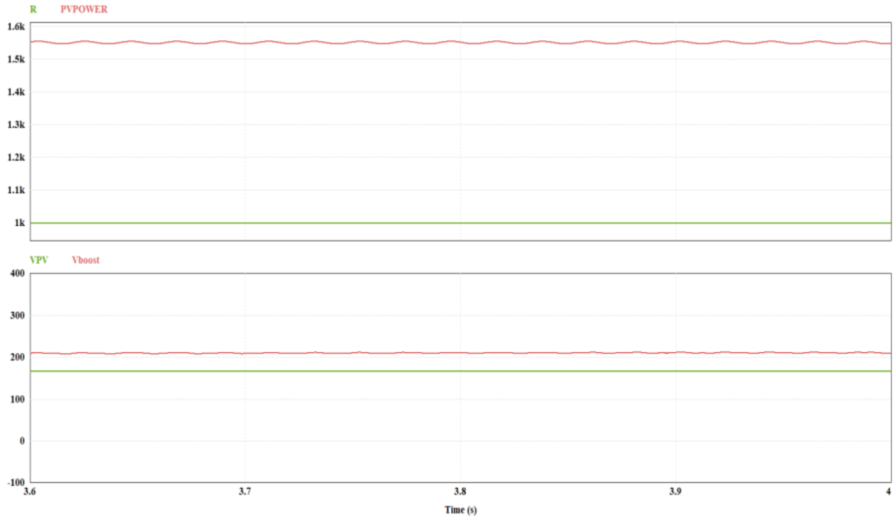


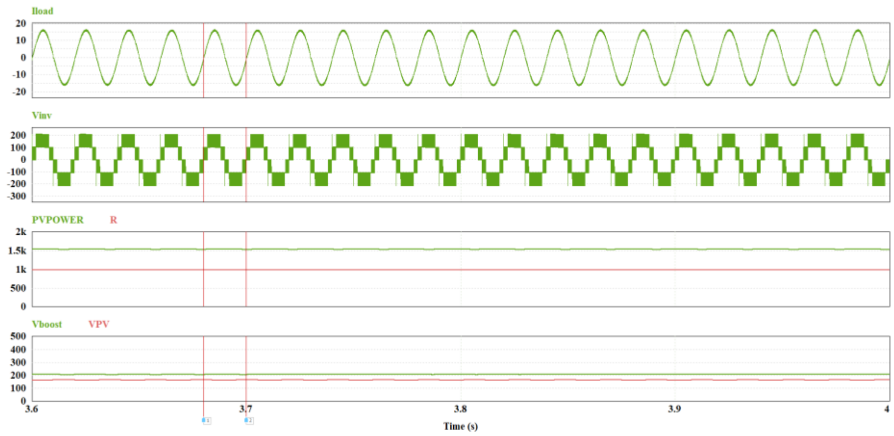
Fig. 6 Five level T-MLI with load

Fig.7 illustrates two key aspects of the PV systems.Standard Test Conditions provide the voltage, current, and power at the max -power point, which is important to test the efficiency of the system. The voltage, load current and tracked power of the inverter demonstrates how it maintains the voltage constant, the load current constant and the power tracked by MPPT. This emphasizes the manner in which the inverter maintains the power delivery constant and extracts the maximum power out of the PV, which also emphasizes the overall performance and efficiency (Majeed et al., 2024; Jaber et al., 2025; Abed et al., 2024).

THD analysis is extremely vital in the measurement of power quality of an electrical system. It simply informs us of the extent of distortion in the voltage or current forms due to the harmonics which are simply multiples of fundamental frequency. THD is used in PV-based inverter systems as it indicates the effectiveness of our filters and control mechanisms in reducing the harmonic content. Reduced THD also implies improved power quality, reduced losses and improved grid compliance.



(a)



(b)

Fig.7 (a) STC condition PV parameters (b) Inverter voltage, load current and tracked power

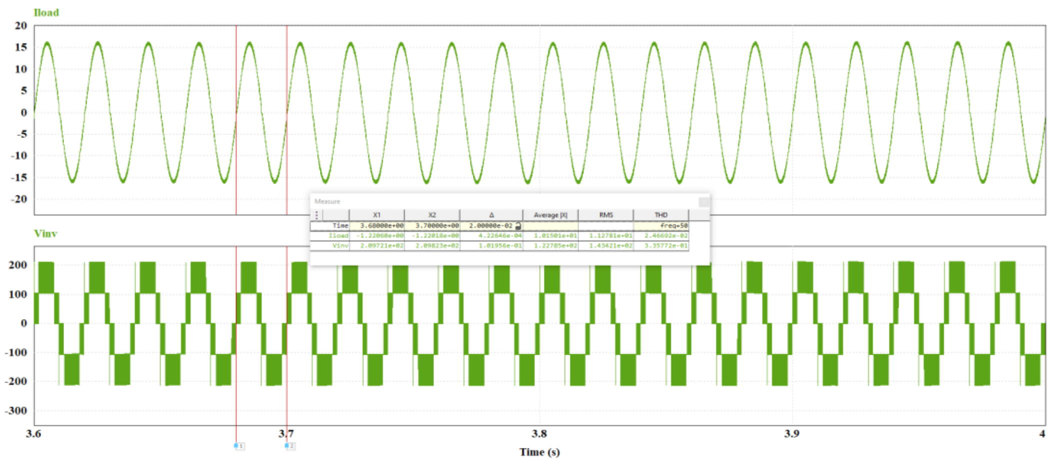


Fig.8 THD analysis of converter

Table.2 Result with STC Condition (25°c & 1000 w/m^2)

Load Type	Panel Power	V_{rms}	I_{rms}	V_{THD}	I_{THD}
R (120 Ω)	1552 W	297 V	2.4 A	32.83 %	3.29 %
R (12 Ω) ,L (1 µH)	1552 W	143 V	11.2 A	33.57 %	2.46 %

Table.3 Result with variable radiation & temp.

Radiation	Load Type	Panel Power	V_{rms}	I_{rms}	V_{THD}	I_{THD}
1000 w/m^2	R (120 Ω)	1551 W	268.39 V	2.17 A	32.91 %	2.06 %
600 w/m^2		856 W	196 V	1.59 A	32.91 %	2.06 %
1000 w/m^2	R (120 Ω),	1556 W	279 V	2.15 A	36.87 %	3.289 %
400 w/m^2	L (1mH)	541 W	107 V	3.8 A	38.87 %	3.289 %

The table presents the performance of a PV based inverter under various sunlight's and loads. At a bright sun (1000 w/m^2), the panel produces approximately 1550 W with a resistive load, and provides moderate voltage THD (32.91) and low current THD (2.06) due to the linearity of the load. In the event that the irradiance is reduced to 600 or 400 w/m^2 power output decreases and voltage falls, inductive loads particularly. The addition of 1mH inductive terminates to both voltage and current THD (up to 38.87 and 3.289) demonstrating that reactive loads and reduced sunlight deteriorate the quality of the waveform and system performance.

5.2. Grid Connected Inverter

The grid-connected fixed-level T-type multilevel inverter enhances the quality of power by reducing THD and providing an approximate sinusoidal output, as indicated in Fig. 9. It also improves the use of the PV by using MPPT to maximize the switching losses and improves efficiency. We require weaker filters with less harmonic content, as it will result in a smaller and cheaper system. Further, this inverter can be bidirectional and thus is applicable in grid tied systems like net metering. In all, it can be said that the five-level T-MLI is highly efficient, stable, and remains within the power quality standards.

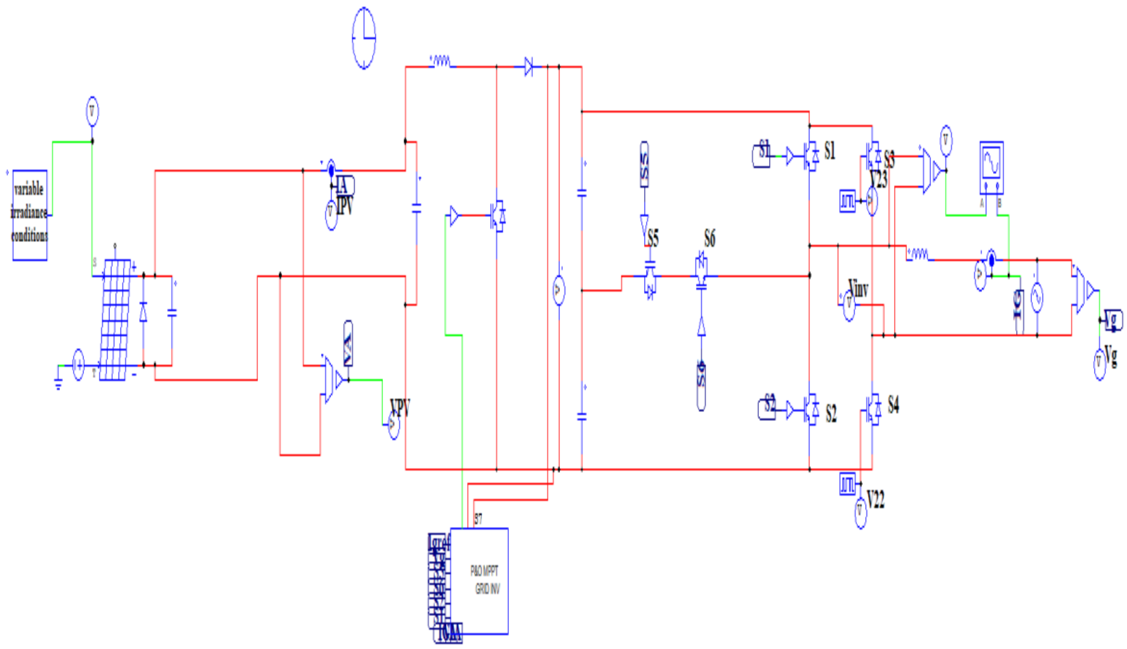


Fig.9 Grid connected mode of inverter

Fig. 10 demonstrates that the inverter dual-loop control is a common technique to increase the performance and stability of a grid-connected inverter. It is composed of an external voltage loop and an internal current loop and they are interrelated to ensure the inverter output is perfect.

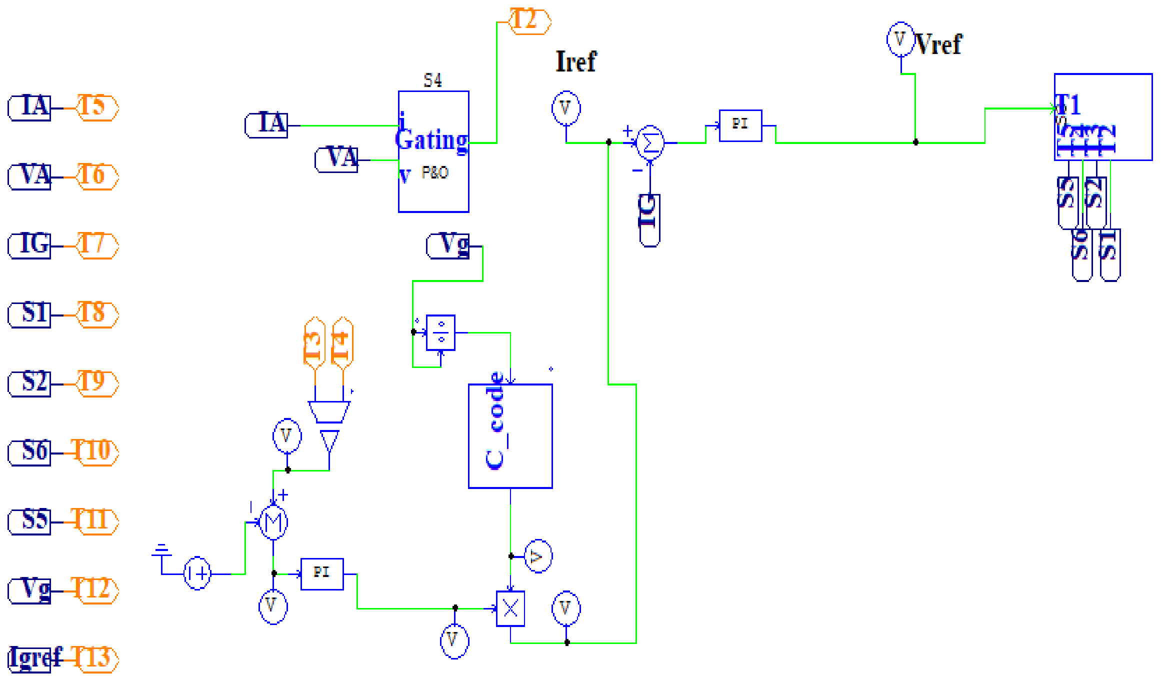


Fig.10 Modelling of inverter control

The simulation results show the performance of the photovoltaic system under various operating conditions, as shown in Fig.10. The tracked MPPT power demonstrates the efficiency of the Maximum Power Point Tracking algorithm in extracting the maximum available power from the PV module.

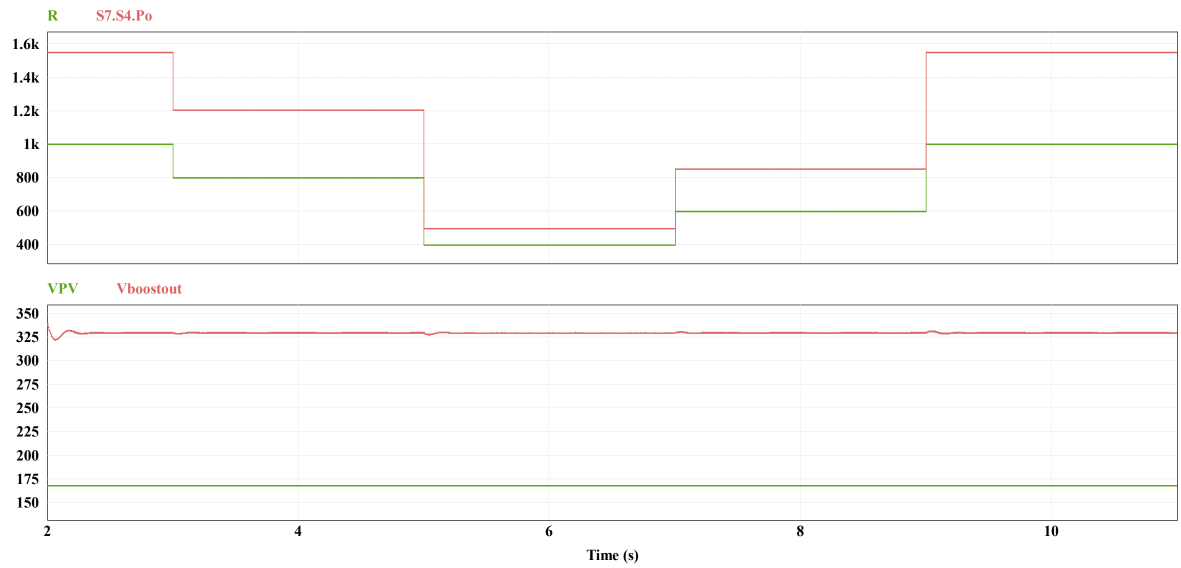


Fig.10 PV voltage, boost voltage, tracked MPPT power and variable irradiation

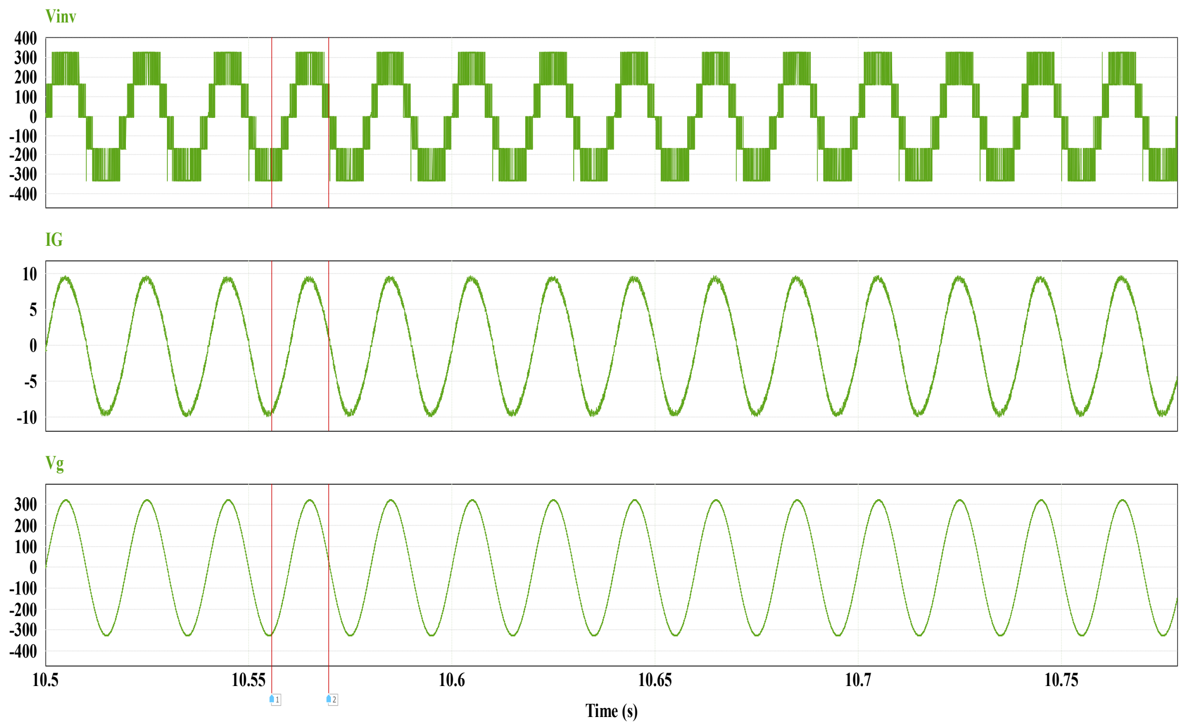


Fig.11 Inverter output voltage, grid current and grid voltage

Fig.12 shows the FFT analysis of the inverter output and grid-side parameters. FFT Analysis of the inverter output voltage, grid current, and grid voltage is essential for evaluating the harmonic performance of grid-connected inverters.

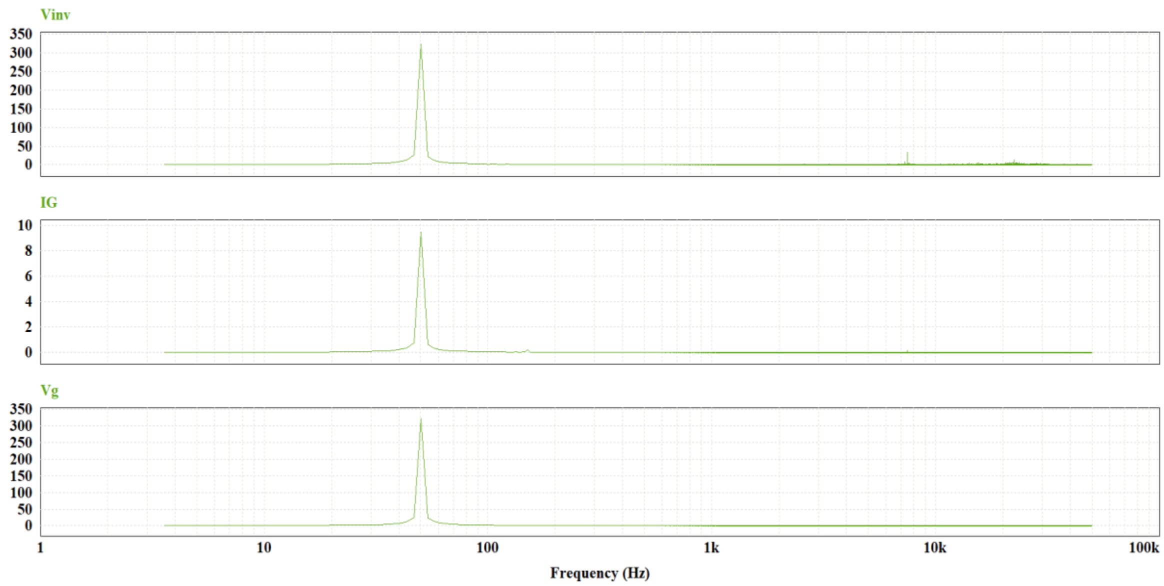


Fig.12 FFT analysis of inverter output voltage, grid current and grid voltage

The graph shows in Fig.13 that as solar radiation increases from 400 to 1000 W/m², panel power rises steadily from about 500 W to 1570 W. However, Vrms peaks at 600 W/m² (240 V) and then decreases slightly to 238 V at 1000 W/m². This suggests that while panel power increases with irradiance, Vrms is regulated by the system, possibly due to inverter control or grid compliance.

The graph shows in Fig.14 the variation of V_{thd} and I_{thd} with respect to solar radiation is shown. As the radiation increases from 400 to 1000 W/m², both V_{thd} and I_{thd} decrease. V_{thd} drops slightly from 0.288% to 0.280%, while I_{thd} shows a more significant drop from 0.050 to 0.042.

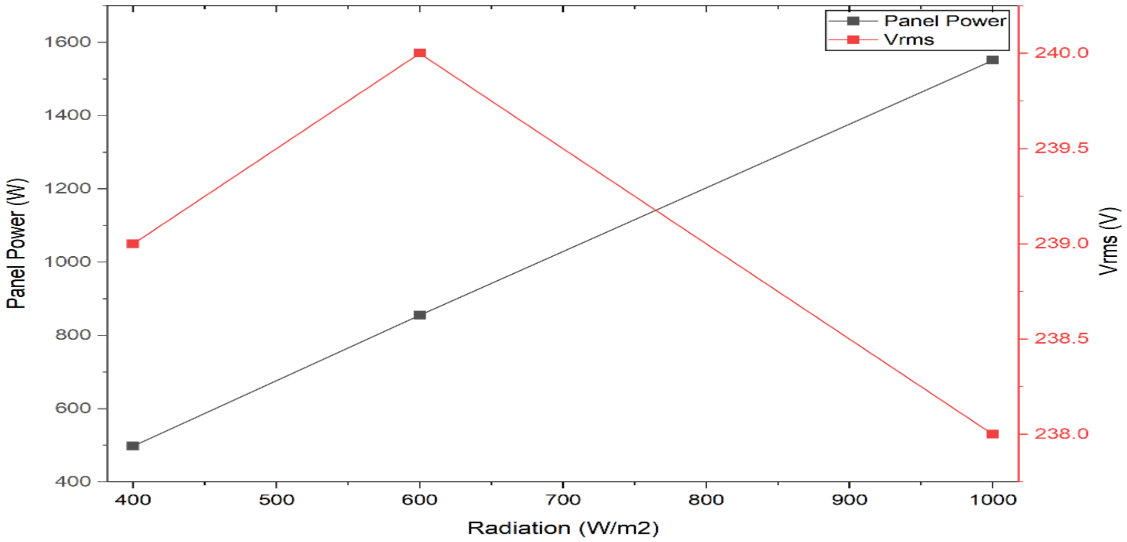


Fig.13 Radiation, Panel Power and Voltage Profile

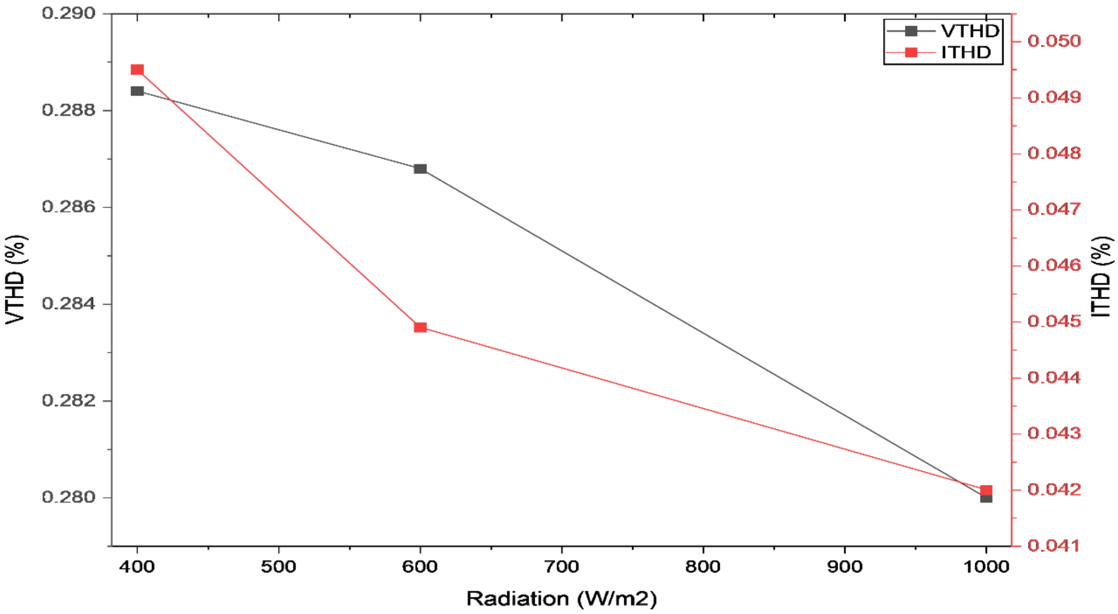


Fig.14 Radiation, Voltage and Current Harmonics

At the process of analysing the different levels of solar irradiance, it can be noted that the panel-side parameters show direct relationship with the irradiance intensity. This is as anticipated because of the basic photoelectric phenomenon, where the voluminous flux of photons causes the creation of more electron holes in the PV cells, which in turn raises the current and power output. Nevertheless, the most important point that can be critically noticed is in the grid-side parameters specifically the voltage, V_{thd}, and I_{thd} that are comparatively constant in all test conditions.

Furthermore, the inverter will probably be powered via a carrier-based PWM that is intended to vary switching states dynamically with reference to the reference signal based on the grid or internal controller. This provides the ability to respond quickly to dynamic changes and the voltage size and frequency in the output will be kept within nominal limits, even in case the DC input varies. Regarding balance of power, surplus or deficit of power is controlled through either the reactive exchange of power with the grid or through the control strategy that adjusts the output current with voltage being held constant. This prevents the grid-tied mode swell or dip in voltages. Thus, the findings prove that the suggested system complies with the grid code, ensuring the voltage stability and harmonic distortion thresholds within dynamic environmental conditions. This shows the strength and flexibility of the modulation strategy of the inverter.

6. CONCLUSIONS

This paper successfully modeled and simulated a single-phase five-level T-type multilevel inverter integrated with a solar photovoltaic system, aiming to boost power quality while cutting harmonic distortion. The T-MLI topology stood out as a practical choice fewer switches than competing multilevel designs meant lower costs and a more compact footprint, ideal for real-world PV setups. Simulation results confirmed stable AC output voltage across both grid-connected and islanded modes. Harmonic distortion stayed well under IEEE 519 limits, ranging from 3.2870% to 3.2890%, and dropped further to 3.2875% with a capacitive filter. Overall, these outcomes highlight the inverter's strong harmonic suppression and voltage regulation capabilities. The T-MLI offers a reliable path to higher efficiency and dependability in solar energy conversion. Looking ahead, exploring advanced control strategies and hardware prototypes could validate these findings under actual operating conditions.

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