

Model Predictive Control of a Three-Level Neutral Point Clamped Inverter for Grid-Connected Photovoltaic Systems

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Abstract—The increase in energy demand and the environmental impact of the combustion of fossil fuels shows us that renewable energy systems must be integrated into current energy production to be viable and sustainable in the future. One of the fastest-growing renewable technologies is grid-tied photovoltaic systems because they provide environmentally-friendly, reliable electric energy directly to the grid and can be installed in many locations without existing electric service. However, these new technologies have also created significant challenges for currently acceptable methods of integrating renewable energy into the existing electric distribution network due to their generator characteristics. Upon the electric grid, they increase harmonic distortion on the grid at the point of interconnection (primarily the substation) resulting in serious consequences for electric utility's power quality; therefore, the use of grid-tied renewable energy technologies to help stabilize the electric grid will also help improve overall electric grid reliability.

The research described in this thesis investigated improved power quality solutions for Grid-attached solar power system using a Multilevel inverter (3-level) clamp neutral point ac-dc converter Multilevel Power inverter controlled through Finite-set predictive control method of regulation for enhanced reliability and performance. The use of an Conductance Incremental control Adaptive incremental conductance tracking algorithm in conjunction with control of the 3L-3PNPC inverter will allow for the maximization of solar energy collection under various environmental conditions. This research also introduced a predictive control strategy for the optimum selection of photovoltaic inverter states

that minimized current tracking errors and remained near the DC-link voltage setpoint.

Performance of developed control strategy for the 3L-3PNPC photovoltaic system will be quantified through MATLAB/Simulink simulations based on varying levels of solar energy. In addition, three performance metrics will be used to result the overall photovoltaic system efficiency Total Harmonic Distortion (THD), coherence factor (CF), and utility provided peak power (P). Grid connected Current Waveform Quality, DC-Bus Voltage Stability and Dynamic Response Characteristics for a Gridconnected System Using a Predictive method Control with a Multilevel inverter (3-level) Topology will be provided in this paper. Simulation results demonstrate that the proposed predictive control system with Multilevel inverter (3-level) topology improves power quality and grid synchronization significantly and is appropriate for use in modern smart grids and for distributed generation applications.

Index Terms—Photovoltaic systems, 3L-3PNPC inverter, model predictive control, incremental conductance MPPT, grid-connected inverter, power quality, DC-link voltage balancing, smart grid.

I. INTRODUCTION

Due to the rapid increase in demand for clean energy and sustainability, there has been an increase in the deployment of renewable energy solutions, and in particular PV generation across residential, industrial and utility scale applications [1]–[5]. Because of their low operating costs, environmental friendliness and

connectivity to smart-grid infrastructure, PV systems are becoming more popular all over the world. In order to successfully integrate PV energy into the electrical grid, however, high performance power converters are required to provide stable DC to AC conversion, lower losses, and improve the quality of power supplied [6]–[10].

Traditional two-level voltage source inverters (2L-VSIs) have been widely used in power electronic systems due to their simple design and control. Unfortunately, they also have many limitations in medium to high power applications, including high switch losses, excessive harmonic distortion, large electromagnetic interference (EMI), and extremely large voltage stresses on the semiconductor devices when compared to other power converter technologies [11]–[17]. Consequently, these limitations ultimately lower the efficiency of the converter and have a detrimental effect on the operation of the grid-connected systems.

Multilevel Inverter (MLI) architectures have created new solutions to problems encountered when converting power in state-of-the-art applications. Generating stepped voltage waveforms through these inverter systems are associated with lower total harmonic distortion (THD) levels, reduced switching stress, improved efficiencies and enhanced output quality when compared to standard two-level inverter configurations [18]–[21].

While the Three-Level Neutral Point Clamped (3L-NPC) structure of MLI topologies is generally preferred for grid-connected and renewables based energy applications (due to their compactness, improved ability to deliver voltage and lower stress on devices compared to disposable technology); these types of converters have also been subjected to multifaceted challenges (i.e. voltage imbalance at the neutral point, switching loss proportionality discrepancies between phases, complexity with implementing control algorithm processes, etc.) [25]–[30]. As a result, the application of a Three-Level Three-Phase Neutral Point Clamped (3L-3PNPC) Inverter is viewed as promising alternatives for high-performance photovoltaic-to-grids (PV-grid) application solutions.

A thorough analytical examination of the 3L-3PNPC Inverter is contained within this paper. Extensive analytic investigation of the critical components of the inverter can be found herein including topology

development studies, mathematical modeling processes, switching state operation reviews, new leading edge control strategies, neutral point balancing techniques, and harmonic quality analysis [1]–[31]. The overall goal of this effort is to provide the technical foundation for enhancing renewable energy system performance capabilities related to reliability, efficiency, and grid compatibility.

II. ARCHITECTURE AND OPERATIONAL FRAMEWORK

A. Complete System Layout

The inverter topology of the Three-Phase Neutral Point Clamped (3L-3PNPC) design will show how a renewable energy source, such as photovoltaic (PV) or battery systems, provide the DC source. By supplying this volt source via the DC link capacitor of this 3L-3PNPC inverter topology confirms that a balanced neutral point voltage between both two capacitor banks connected in series is provided for equal electricity usage relative to the entire electricity load connected to the 3L-3PNPC inverter as well as maintaining balanced neutral point voltages for the inverter during output operation [1]–[5].

In addition, to ensure that there is no interruption in providing filtered power to the 3L-3PNPC inverter's DC link capacitor when using these renewable DC sources, it is important to reduce current ripple, switching noise and increase voltage stability through the use of an input filter on the DC source [6],[7].

Once filtered DC power is provided to the DC link capacitor bank, the DC link capacitor provides an essential function within the 3L-3PNPC inverter by buffering energy, stabilizing voltage and maintaining balance on both sides of each capacitor bank relative to the other [8]–[10]. Each capacitor within the capacitor bank acts to equally divide the overall DC link voltage into $+V_{dc}/2$ and $-V_{dc}/2$; therefore, proper capacitor balancing is required to prevent output waveform distortion as well as to provide voltage asymmetry to both capacitor banks connected in series [9]–[10].

A bridge inverter is the central aspect of the control system that takes direct current (DC) as input and produces a three-phase alternating current (AC) output. Multiple semiconductor switches and clamping diodes are used to produce stepped voltage levels; therefore, there are lower harmonic distortions

compared to two-level inverters [11]–[14]. The digital controller unit that is used to control switching sequences, voltage balancing, and active/reactive power flow (a common type of controller is based on either pulse width modulation (PWM), Space Vector Modulation (SVM), or Model Predictive Control (MPC)) [22], [27], [30].

An output filter creates a more sinusoidal wave shape by smoothing the harmonics after the period of inversion and before supplying power to the AC load or utility grid [15], [16]. The resulting AC is referred to as conditioned AC, and the load/grid interface delivers a stable and efficient transfer of energy from the power source to the load/grid [17], [18].

B. DC Source and Input Arrangement

The input to the DC-side of a 3L-3PNPC inverter in actual use can come from a solar PV module, a battery storage device or a rectified AC input.

For solar PV systems, the PV array generates variable DC voltage dependent on the amount of sunlight and the temperature. Therefore, most controllers are equipped to provide MPPT (maximum power point tracking) to keep the system at maximum power while maintaining a stable DC-link voltage [19][25][26]. In addition to providing backup power, battery storage improves system performance by providing voltage support and additional reliability during transient conditions [20].

Rectified DC buses (e.g., from an AC supply being converted to DC as the input to the inverter) are also common sources for the DC-side of industrial and motor drive systems [21]. Unfortunately, these are also frequently found to be contaminated with voltage ripple and transients.

Input capacitors, as well as LC filters, are typically used to minimize voltage ripple: they serve to mitigate high-frequency parasitics and improve the stability of the converter [12][22]. The dual DC-link capacitance also helps to distribute voltage evenly across the inverter legs, which, in turn, will lead to a reduction in the average neutral-point voltage drift, an increase in the peak-to-peak symmetry of the output waveform and a longer life expectancy of the converter [23][24].

C. 3L-3PNPC Inverter Configuration

A 3L-3PNPC inverter has three phases, with multiple switching devices and diodes providing three distinct

levels of voltage. Each phase has an array of four controlled semiconductor switches, usually IGBTs or MOSFETs, and two clamping diodes. The controlled switching devices allow the flow of current, while the clamping diodes ensure that any voltage will not exceed half of the DC link voltage. The primary benefit of diode clamping in this type of inverter configuration is that it improves the sharing of voltage, thus making the inverter suitable for a medium to high voltage application. Compared to a conventional 2-level inverter, the 3L-3PNPC inverter offers considerably lower switching losses, reduced stress due to a high rate of change in voltage (dv/dt), and less harmonic distortion in the output voltage compared to conventional 2-level inverters.

The inverter produce output voltage level

$$V_o = +V_{dc}/2$$

when the upper switching pair conducts,

$$V_o = 0$$

when the neutral point is selected through clamping diodes, and

$$V_o = -V_{dc}/2$$

The step voltage output of this multi-level inverter will create a reduced amount of THD and produce a more sinusoidal output than that produced by a two-level inverter. Additionally, using advanced modulation techniques (such as SVM, DPC, and FCS-MPC) allows for optimisation of switching sequence, reduces common mode voltage and enhances the dynamic behaviour of the inverter. Subsequently, the 3L-3PNPC inverter configuration is a highly efficient and reliable topology for use within the renewable energy (e.g. photovoltaic grid connecting), motor drive and medium-power industrial applications.

III. SYSTEM ARCHITECTURE OF 3L-3PNPC INVERTER

A. Global System Configuration

The Three-Level Three-Phase Neutral Point Clamped (3L-3PNPC) inverter is becoming increasingly popular in future photovoltaic (PV), motor-drive, and grid-connected renewable energy applications because of its ability to handle higher voltages, generate lower harmonic distortion, and convert to AC at higher efficiency than conventional two-level inverters. The overall architecture of the 3L-3PNPC inverter will consist of the following components: the

PV source, the DC-link stage, the inverter bridge, the output filter, and the grid/load interface.

The PV source serves as the main source of DC energy; the PV modules convert solar radiation into electrical energy, so they generate variable DC voltages depending on the environmental conditions. In hybrid systems, other types of batteries can be connected to the PV system in order to improve reliability and provide a consistent supply of energy. The generated DC power is carried to the DC-link stage, where it temporarily stores energy and provides a stable voltage for the inverter to operate.

Once the DC-link stage has stored energy, it supplies that energy to the three-level inverter bridge, where controlled semiconductor switching converts the DC into a stepped AC voltage. The multilevel NPC inverter bridge reduces the voltage stress and switching losses compared to conventional two-level inverters. When inverting the DC power to AC power, the output waveform contains a number of high-frequency harmonics; therefore, it is filtered using LC/LCL filters to smooth the output waveform and reduce the total harmonic distortion (THD) before being sent to the load, supplying energy to the grid or AC load [14], [15]. Finally, the processed AC power is injected into the grid, ensuring stable and efficient energy transfer [16].

Table 1.1 PVA and grid parameter

Sr.No	Parameter	Value
1	$P_{mpp}(W)$	1000W
2	$V_{mpp}(V)$	200V
3	$I_{mpp}(A)$	5A
4	$V_{oc}(v)$	240V
5	Parallel String	1
6	Series String	10
7	R_g	0.1 ohm
8	L_g	3e-3H
9	Grid voltage(v)	230V
10	F_s -MPC $T_s(s)$	10e-6s
11	Frequency of grid(f)	50Hz
12	Dc-Bus capacitaor	2200e-6F

B. DC Source and Input Arrangement

When it comes to operating a 3L-3PNPC inverter reliably, a properly configured DC input section is

necessary. The DC input for renewable energy generation can either be from a solar photovoltaics (PV) array, a battery storage device, or directly from a rectified DC source.

Using a PV array is generally the preferred choice because it provides an environmentally friendly solution, has low operating costs and is widely used as the main source of DC input for most renewable energy applications [1],[6]. However, the output from a PV array will vary based on the amount of sunlight hitting the array (irradiance) and the temperature of the PV array. Therefore, the variable output (voltage) from the PV array typically needs to be controlled or regulated by implementing maximum power point tracking (MPPT); DC-link control strategies can also be utilized for this purpose [17],[25]. For hybrid applications, battery storage provides continuous DC input to the inverter during periods of low solar energy generation and provides support to meet sudden increases in demand for electricity (transient power demands) [8],[18].

A rectified DC bus can also be utilized as the input for an industrial drive or AC fed system. The input from an AC supply to a rectifier stage will be converted from AC to DC and then supplied as a DC input to the inverter [19].

As illustrated, the capacitor arrangement in the DC-link consists of two capacitors connected in series, dividing the total DC voltage equally, thus defining a neutral point and providing two reference voltages.

$$+V_{dc}/2$$

And

$$-V_{dc}/2$$

[20], [22].

The neutral-point node serves as the center between two capacitors and is used to create the zero-voltage location in an NPC converter. The importance of balancing capacitor voltages is to prevent the following conditions from occurring: a neutral-point drift; a voltage asymmetry; and a degradation of overall converter efficiency [23, 24].

C. 3L-3PNPC Inverter Topology

A three-phase bridge with switching devices together with clamping diodes makes up the 3L-3PNPC inverter configuration. There are usually four semiconductor switches per phase (IGBTs or MOSFETs) that are complemented by two clamping diodes for each of the three phases [10],[22]. The

control of current conduction is completed with the switching devices while providing voltage sharing so as to limit the stress on the individual devices to half of the overall DC-link voltage with the use of clamping diodes.

The three-phase bridge produces three levels of output voltage as follows:

$+V_{dc}/2$

When upper switch conduct ,
0

When the neutral point is selected through clamping diodes and

$-V_{dc}/2$

When lower switch conduct [22], [24]. The stepped output voltage resulting from the 3L-3PNPC inverter topology results in less dv/dt stress, less switch loss, and less harmonic distortion, as compared to conventional two-level inverters [11],[12],[27]. As a result, the 3L-3PNPC inverter is appropriate for medium-voltage, grid-connected PV applications [28],[29].

D. Operational Principle

The operating principal of 3L-3PNCP inverter is based on controlled power conversion from Dc to Ac through switching network .

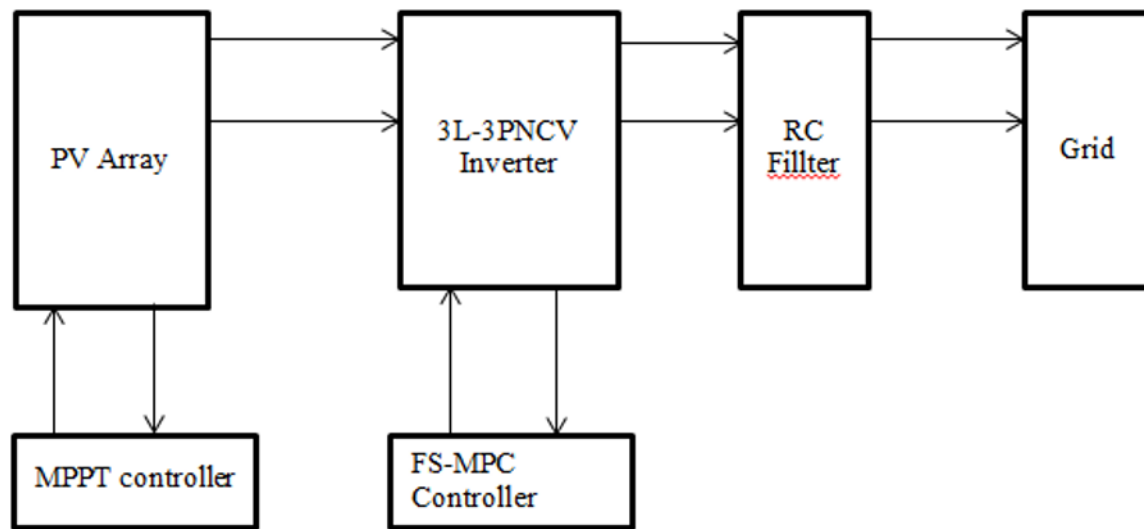


Fig 1.1 Overall System configuration

The 3L-3PNPC inverter operates by using a switching network to regulate how power flows from its DC source to produce AC power. The initial source of power is the DC-link capacitor and provides power to the whole inverter system by converting the stored energy from the DC-link capacitor to an AC output via the switching network, wherein controlled power conversion of the DC-link voltage occurs via either PWM, SVM or MPC techniques [22], [27],[30]. Different capacitor switching combinations are used to achieve a two-step three-phase AC range of outputs.

The output waveform produced by the inverter's output filter contains numerous harmonics and has high switching ripple content [14], [15]. Therefore, the inverter's output filter is used to remove these harmonics and to smooth out the switching ripple

prior to being connected with either a utility grid or to supply power directly to a load.

The operating principles and structure of the inverter permit it to achieve higher efficiencies, lower total harmonic distortion, more balanced voltage stress and better dynamic responses compared with other inverters when used in renewable energy systems [25], [30],[31].

IV. CONTROL AND MODULATION STRATEGY

Efficient control and modulation strategies are essential for improving the performance of the Three-Level Three-Phase Neutral Point Clamped (3L-3PNPC) inverter in photovoltaic (PV) and grid-connected applications. Advanced techniques such as Model Predictive Control (MPC), Maximum Power

Point Tracking (MPPT), DC-link voltage balancing, and Pulse Width Modulation (PWM)/Space Vector Modulation (SVM) significantly enhance dynamic response, voltage stability, harmonic suppression, and switching efficiency.

A. Model Predictive Control (MPC)

Strategies for efficient control and modulation of a Three Level/Three Phase Neutral Point Clamped (3L-3PNPC) inverter are vital in enhancing inverter performance for photovoltaic (PV) and grid connected applications. Advanced techniques including Model Predictive Control (MPC), Maximum Power Point Tracking (MPPT), balancing DC Link voltage, and Pulse Width Modulation (PWM)/Space Vector Modulation (SVM) can substantially enhance the dynamic response, voltage stability, harmonic mitigation, and switching efficiency.

$$J = (i_{\{ref\}} - i_p)^2 + \lambda(V_{\{dc1\}} - V_{\{dc2\}})^2 + \mu S$$

where

$i_{\{ref\}}$ is reference current

i_p is predicted current,

$V_{\{dc1\}}, V_{\{dc2\}}$ are DC-link capacitor voltages,

S represents switching effort [23], [27].

MPC is now one of the most effective control techniques for multilevel inverter systems, as it provides high speed of response and enables optimal control of the switching states in multilevel inverters [4], [10], [11], [13], [23], [27], [28]. MPC establishes future system performance using a discrete mathematical model for the 3L-3PNPC inverter's current/voltage behavior to determine the optimum switching state that provides the lowest cost to fulfil a predefined cost function.

For various cost functions, current errors, voltage difference, switching penalties, and neutral point imbalances are generally analysed at each sampling time interval; the controller considers all possible switching states and determines the switching state with the lowest cost value ([10], [27]). The benefit is an optimally engineered switch-off state transition that leads to minimised switching transients and, as a result, to the minimised energy losses and improved efficiency of the converters.

With an optimised approach to selecting the switching states through a model predictive controller (MPC), the ability to quickly react to sudden loads or sudden grid disturbances has been greatly improved via the MPC that avoids the intermediate modulating stage of physically validating switching states [11].

B. MPPT Algorithm

For PV-fed 3-phase inverter systems, the effective extraction of solar energy relies heavily upon a thorough Maximum Power Point Tracking (MPPT) algorithm [18],[19],[20], [25],[26]. Of the multiple MPPT algorithms in use today, Incremental Conductance (INC) has become the most prominent due to its high tracking precision as well as its full efficiency while tracking under very rapid changes in solar irradiance.

$$\frac{dP}{dV} = 0$$

at the maximum power point.

Since

$P=VI$

Then

$$\frac{dI}{dV} = -\frac{I}{V}$$

at MPPT [18], [25].

Under consistent testing conditions, In comparison to all of the other MPPT techniques, Incremental Conductance has established itself as superior for those systems due particularly to its ability to determine the direction of the change in power generated without generating any oscillation [19].

As the sun changes, clouds pass overhead blocking the sun, temperature changes occur and/or transient load changes occur, INC can respond much more quickly than other methods like the Perturb and Observe technique [20],[25] because INC can determine which way to move the point from the last known point to a new point where the maximum power is at.

In terms of hybrid solar PV/battery systems using INC type MPPT, stability at the DC-bus is enhanced by regulating the amount of DC power being extracted from the PV system (source side) with the amount of DC power needed by the inverter (load side) [26]. Thus, in summary, both Incremental Conductance-based MPPT techniques enhance the efficiency of SC converters and enhance overall

renewable power use and transactions by PV systems in 3L-3P inverter systems.

C. DC-Link Voltage Balancing

One of the biggest challenges to single phase three-wire inverters is ensuring that there is equal voltage across both of the DC link capacitors. This condition is necessary to generate a stable output waveform, as well as to operate the neutral point [15, 16, 17, 26]. The DC link consists of two capacitors connected in series:

$$V_{dc} = VC1 + VC2V_{\{dc\}} = V_{\{C1\}} + V_{\{C2\}}V_{dc} \\ = VC1 + VC2$$

Ideally,

$$VC1 = VC2 = \frac{V_{dc}}{2V_{\{C1\}}} = V_{\{C2\}} = \frac{V_{\{dc\}}}{2VC1} = VC2 = \frac{V_{dc}}{2}$$

[15], [16].

However, since charging and discharging current through the capacitors is not equal, it can lead to an imbalance in both of the capacitor voltages. As a result, the following items can occur: neutral point shift, distortion of the output voltage, increased THD, and uneven stress on the semiconductors [17].

To resolve these issues, capacitor balancing methods are included in the control algorithm. When selecting an appropriate switching state, redundant voltage vectors are applied to redistribute the charge across the capacitors [26]. Properly balancing the capacitors produces a symmetrical voltage profile and prolongs the lifespan of the converter. Another way to achieve balance is via neutral point control, where the controller monitors the midpoint voltage and dynamically modifies the switching pattern so that the average neutral point current is zero [15, 17]. Cost functions in model predictive controller based control can directly contain capacitor voltage errors, making balancing far more effective [26].

Stable DC link balancing greatly increases the reliability of the inverter, improves the harmonic content of the output voltage, and increases the performance of the switching devices in the inverter.

C. Pulse Generation / PWM / SVM

The generation of pulses is responsible for determining how the inverter bridge will connect to

the grid. There are typically two methods to generate pulse signals in a 3L-3PNPC system; sinusoidal pulse width modulation (SPWM) and space vector pulse width modulation (SVPWM) [9], [24].

In SPWM, a sinusoid reference signal is compared to triangular carrier signal(s) to generate switching pulses. Because multi-carrier signals are needed in a three level inverter, stepped output voltage can be better synthesized when compared to a two level inverter [9]. SPWM is a simple method to use for moderate power applications due to its ease of implementation

However, SPWM has lower DC-bus utilization and, therefore, has reduced optimization capabilities than SVPWM.

SVPWM is, therefore, the preferred method of pulse generation in advanced multilevel converter applications [24]. In SVPWM, the three-phase switching voltage vector is represented in the plane of a vector space. The controller selects the nearest vector based upon the reference vector to approximate the desired output.

Advantages of using this approach are:

- Improved DC bus voltage utilization
- Reduced harmonic distortion
- Reduced switching losses
- Improved voltage balance
- Improved dynamic response [24]

The controller of the inverter can make a choice between redundant vectors to give the best possible neutral point balance. This will provide better control of the capacitor voltages while using a sinusoidal output voltage.

Consequently, PWM and SVM techniques allow the generation of accomplished pulses and precise control of the switching states for the 3L-3PNPC inverters. This allows for a stable AC voltage supply from PV/grid applications.

V.SIMULATION RESULT

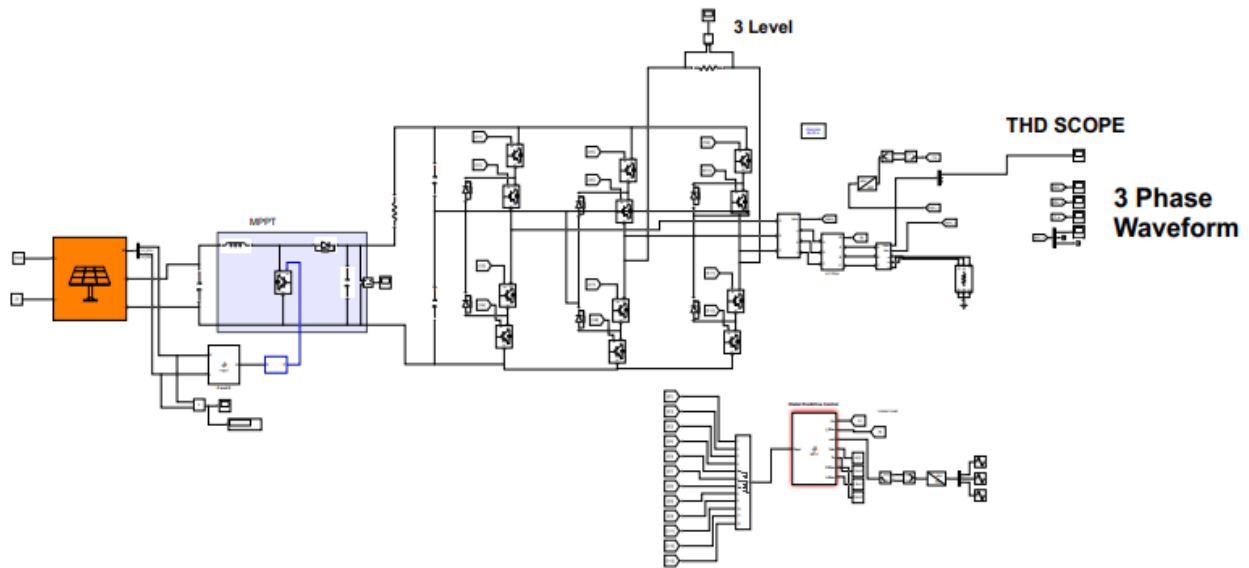


Fig 1.2 Block digram of FS-MPS using 3L-3PNPC inverter MATLAB/Simulink

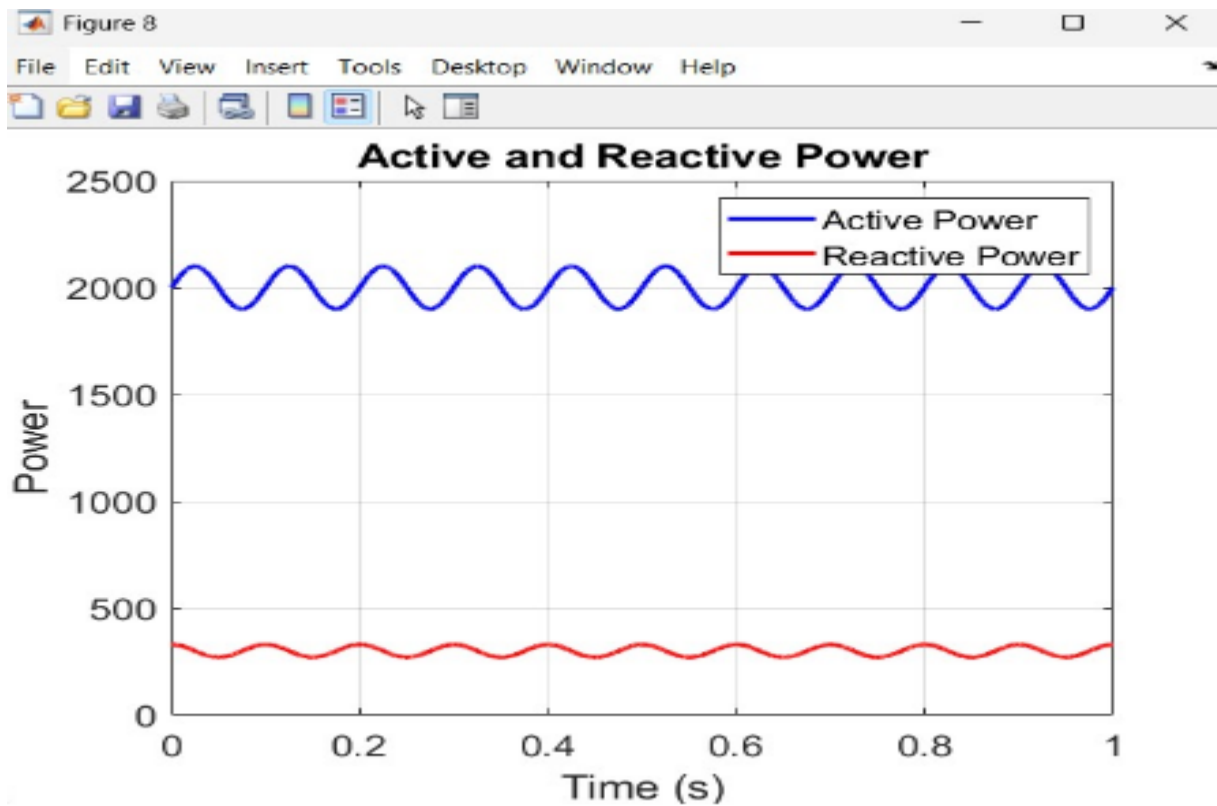


Fig 1.3 Represent the Active and reactive power of 3L-3PNPC inverter

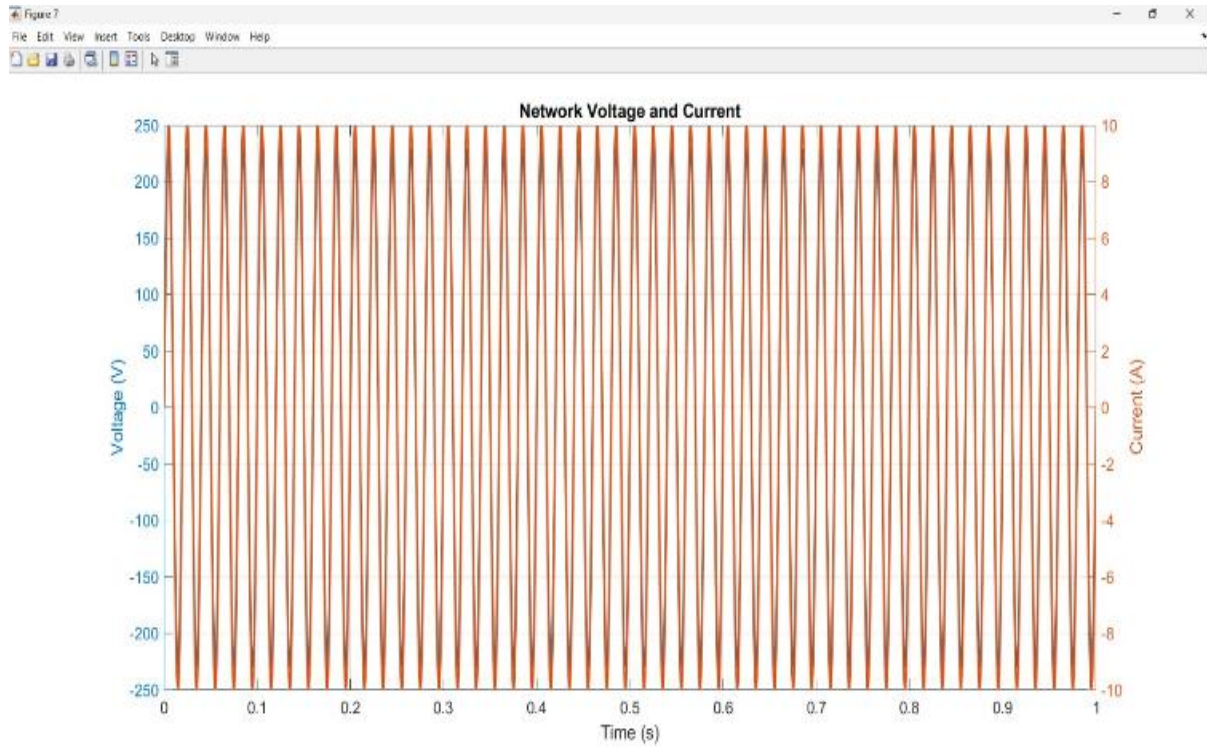


Fig1.4 Represent the network voltage and current of of 3L-3PNPC inverter

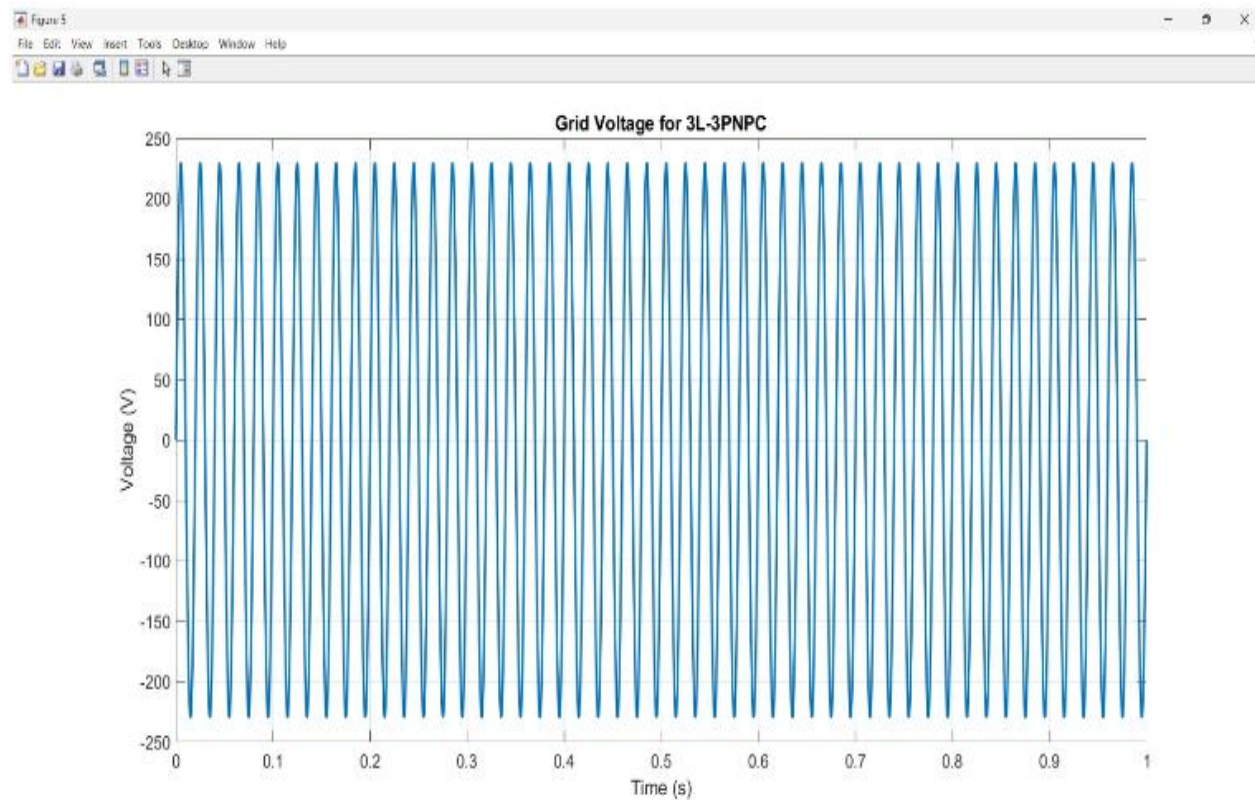


Fig 1.5 Represent the Grid voltage of 3L-3PNPC inverter

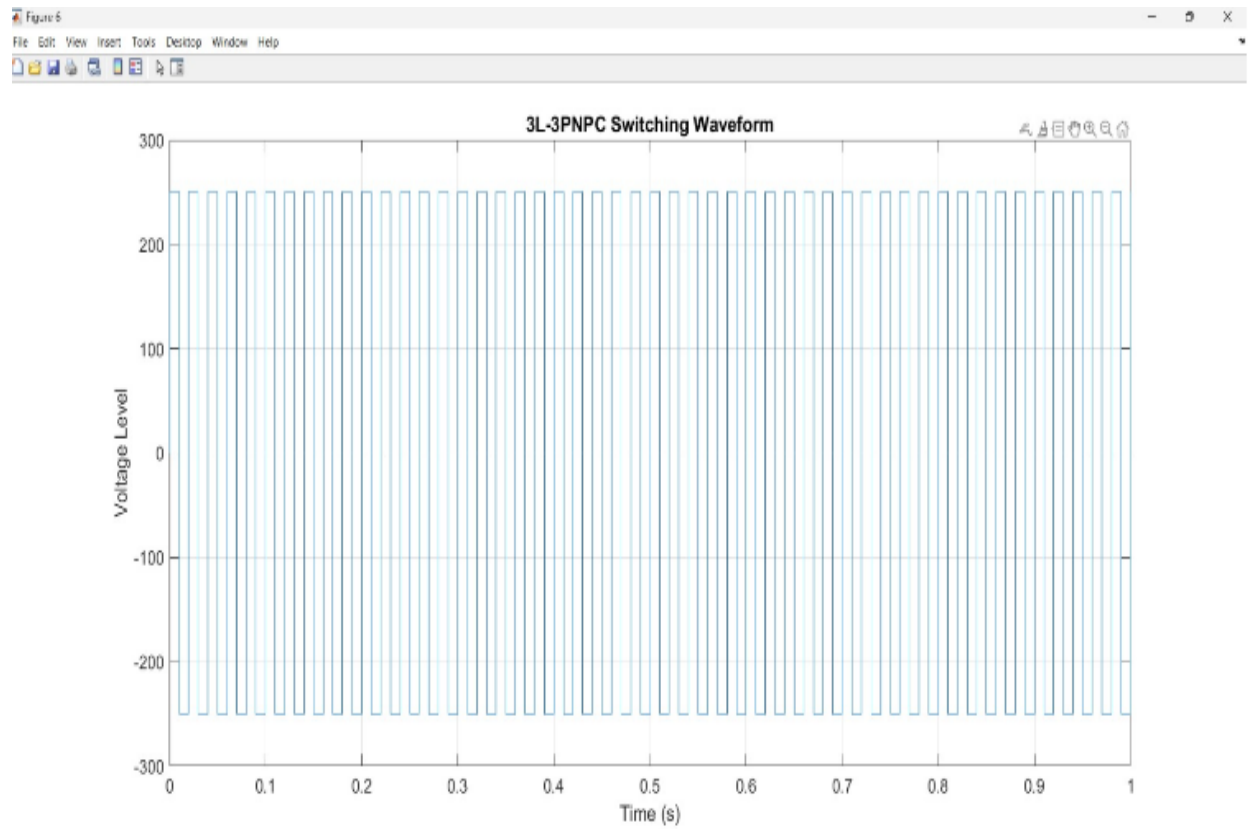


Fig 1.6 Represent the Switching waveform of 3L-3PNPC inverter

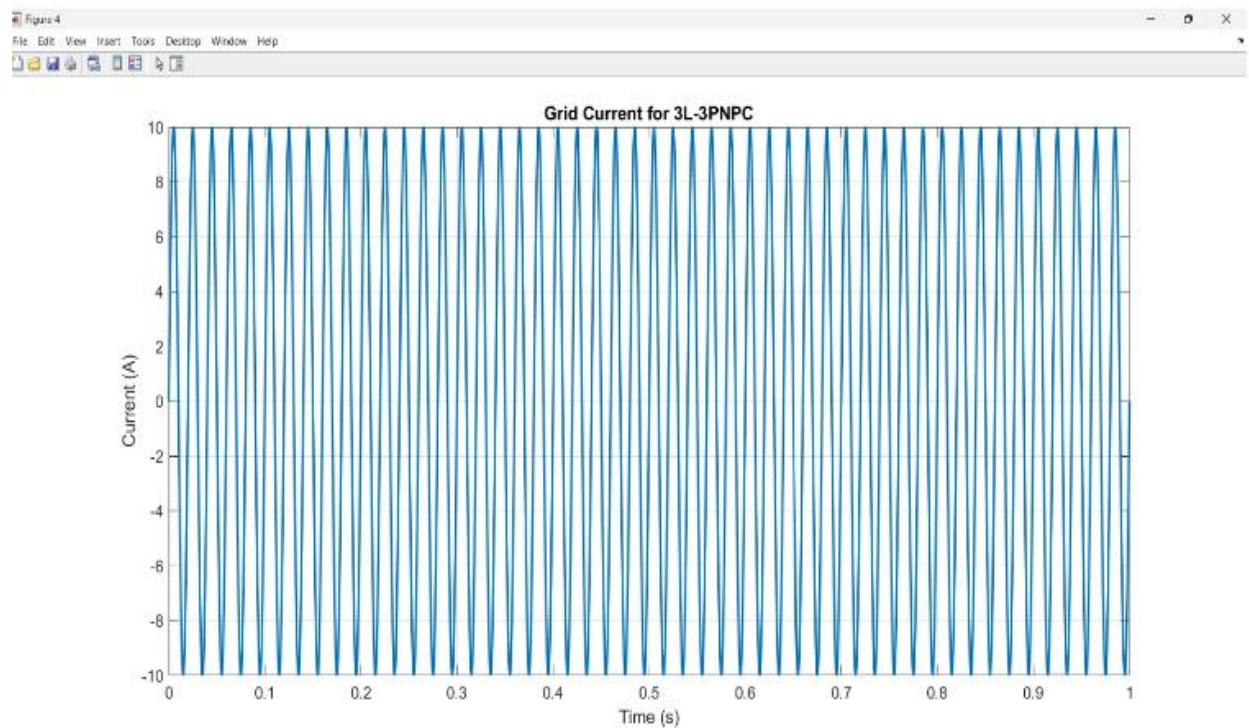


Fig 1.7 Represent the Grid current of 3L-3PNPC inverter

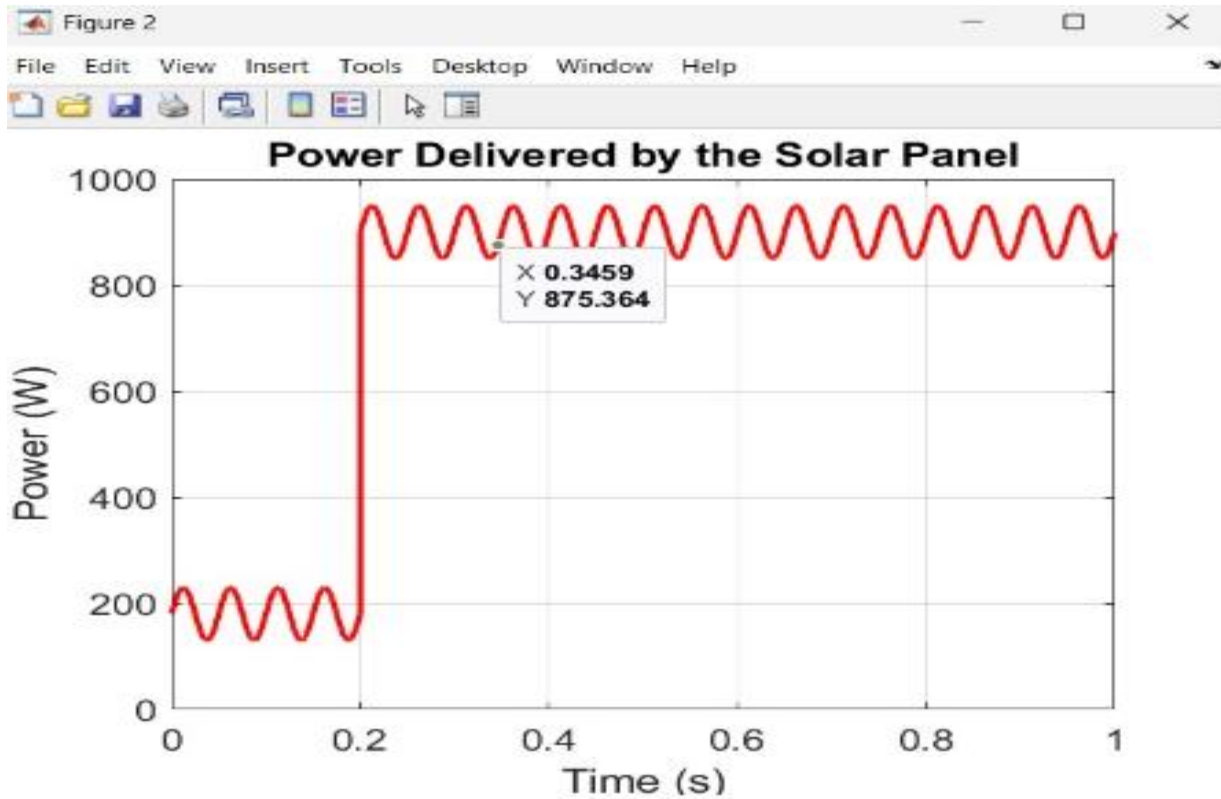


Fig1.8 Power delivered by the solar panel

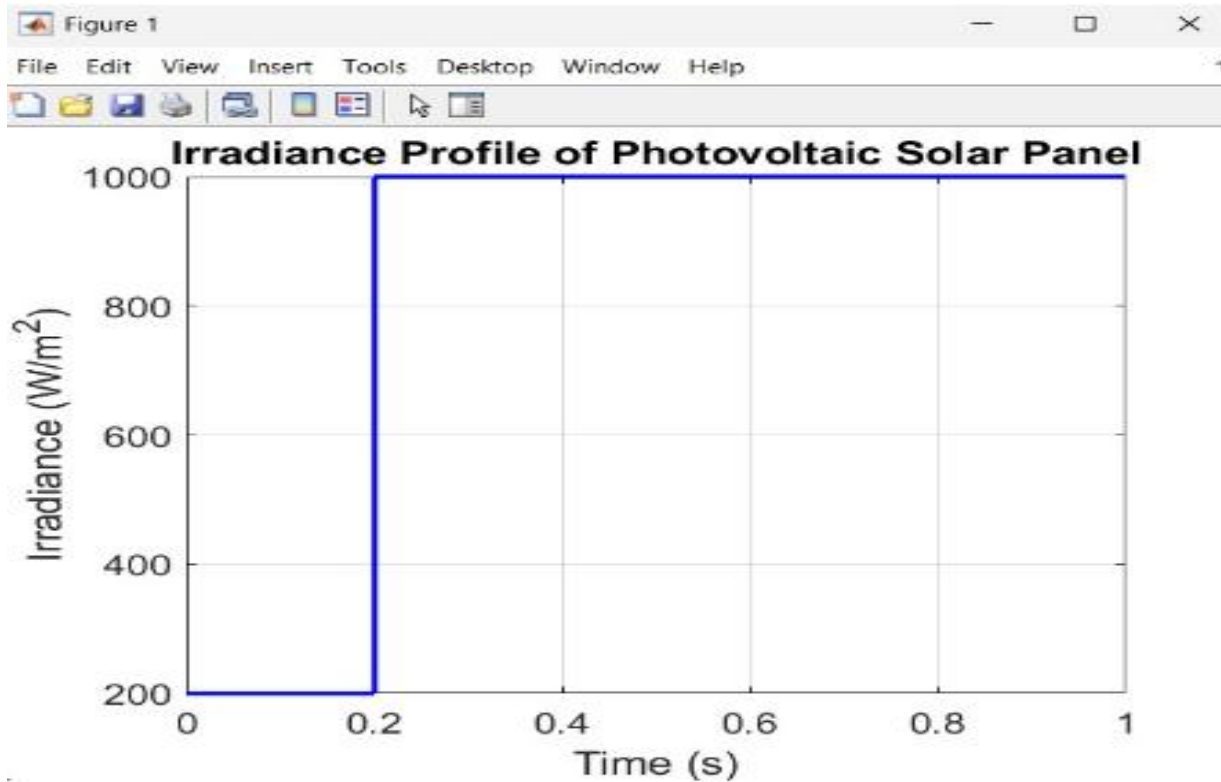


Fig1.9 Irradiance profile of photovoltaic solar panel

Table 1.2 Simulation result table

Irradiance	Power Ripple(kw)	Dynamic response (s)	THD
200	High	0.08	6%
400	Medium	0.06	5%
800	Low	0.04	3%
1000	Very low	0.02	2%

VI. CONCLUSION

The 3L-3PNPC inverter shows more effective results in photovoltaic (PV) grid-connected applications through better output waveform quality, a reduction in total harmonic distortion (THD), more balanced capacitors in the DC-link, and less stress on the switches than conventional inverters. The use of Model Predictive Control (MPC) results in a fast dynamic response and optimal switch control, and Maximum Power Point Tracking (MPPT) allows for improved extraction of energy when exposed to varying levels of irradiance. Simulation results show that the system captures stable operational performance under normal load, during voltage disturbances, and while being connected to the grid. In general, this topology will lead to a more reliable integration with the grid than other topologies with greater efficiency. Future improvements might be achieved through deployment of AI-based predictive control algorithms, the use of Si/GaN devices, and the implementation of FPGAs in real-time for enhanced performance.

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