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Control Strategies for 3-Level NPC Inverter-Based PV Systems: A Comparative Analysis of PI and PID Controllers in Boost and Direct Configuration

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***Abstract*—This paper presents tow design and control architecture of an efficient solar power generation system for grid connection, aimed at optimizing energy production while ensuring seamless integration with the utility of grid. The first proposed system utilizes advanced power electronics includes a PV array connected to multiple parallel DC-DC converters, NPC 3-level inverter, grid, and a filter, with the inverter control implemented using a proportional-integral (PI) controller ensuring high efficiency and enhanced reliability. The second system, in contrast, excludes the boost converter, using the same NPC 3-level inverter with proportional-integral-derivative (PID) control for inverter operation. A multilevel inverter is employed for high-quality AC power conversion to minimizing harmonic distortion and reducing the impact of switching losses. The control strategy is based on a hybrid approach combining Maximum Power Point Tracking (MPPT) to optimize energy harvest from the PV system. Results suggest that while the boost converter with a PI-controlled inverter provides better efficiency and voltage regulation, the system without the boost converter, using PID control, offers a simpler and more cost-effective solution.**

***Keywords*—Solar Power Generation, DC-DC Boost Converters, Multilevel Inverter, Maximum Power Point Tracking (MPPT), PID Control, Renewable Energy Systems**

I. Introduction

With the increasing demand for renewable energy solutions, photovoltaic (PV) systems are emerging as a significant source of clean electricity. Grid-connected PV systems are crucial for facilitating the integration of solar energy into the electrical grid. They rely on inverters to convert the direct cur-rent (DC) output from the PV array into alternating current (AC) compatible with the grid.

In large-scale PV systems, such as a 500 kW PV system with a 1000 V DC output, the performance of the inverter and its control strategy significantly affect system efficiency, stability, and power quality. This study evaluates two grid-connected PV system configurations that utilize NPC 3-level inverters, focusing on the impact of a boost converter and the choice between PI and PID controllers.

In the first configuration, the boost converter is used to step up the voltage to 1000V from the PV array. The DC voltage is then fed into the NPC 3-level inverter, which outputs 20 kV to the grid. The inclusion of the boost converter improves voltage regulation and ensures stable operation under varying sunlight conditions.

In contrast, the second configuration omits the boost converter. The PV array directly provides 1000V DC to the NPC 3-level inverter, which is controlled using a PID controller. This configuration does not have the voltage regulation benefits of the boost converter but uses the PID controller for better dynamic control and faster response to transient conditions.

This paper aims to investigate and compare the performance of these two configurations. We focus on key metrics such as energy conversion efficiency, voltage regulation, transient response, and harmonic distortion under varying load and irradiance conditions. Through simulation results, this study will provide insights into the advantages and limitations of each configuration.

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The global shift toward renewable energy has positioned photovoltaic (PV) systems as a key player in sustainable electricity generation. Grid-connected PV systems are essential for converting solar energy into usable AC power, enabling seamless integration into the electrical grid. The inverter, a critical component of these systems, plays a pivotal role in determining overall performance, including efficiency, stability, and power quality. This study focuses on two configurations of a 500 kW grid-connected PV system using NPC 3-level inverters, examining the impact of a boost converter and the choice of control strategy (PI or PID) on system performance [1], [2],[7].

II. System Description

Figure 1 illustrates the proposed electrical architecture of PV solar power generation provides an output of 400 V DC which is stepped up to 1000 V DC using a multiple parallel boost converter to increase reliability and facilitate maintenance and their parallel configuration ensures that if one converter fails, the others continue to operate, minimizing system downtime. The DC outputs from the converters are then linked to the NPC 3-level inverter which efficiently converts the DC power into a high-quality AC signal for grid integration. This setup improves the system's overall efficiency, reduces harmonic distortion, and allows for easy maintenance and scalability, making it a robust solution for reliable, large-scale solar power generation connected to the grid.

In Configuration 1 Figure 1, the 500 kW PV array provides an output of 400 V DC, which is stepped up to 1000 V DC using a boost DC-DC converter. This converter ensures that the inverter receives a stable DC voltage, even as the output from the PV array fluctuates with changes in solar irradiance. The NPC 3-level inverter is then responsible for converting the boosted DC voltage into AC power, which is fed into the grid of 20 kV.

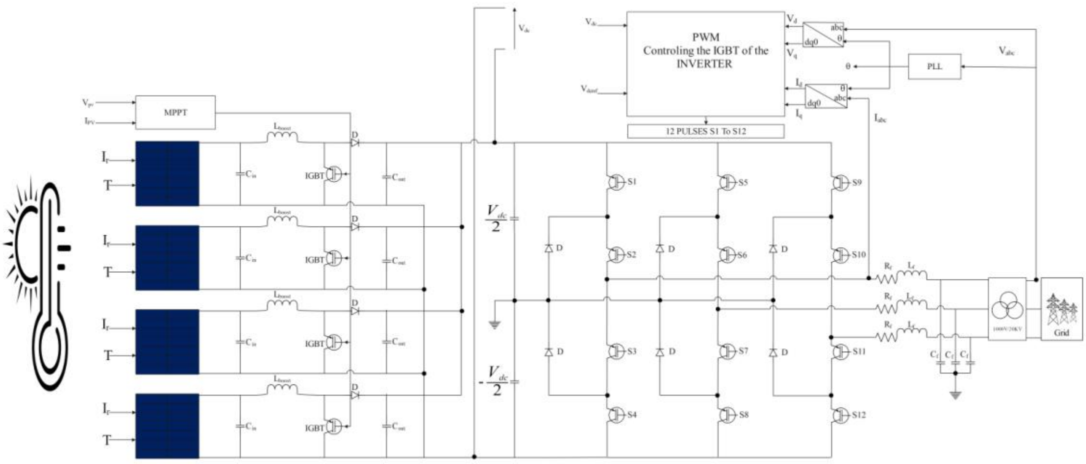

Figure 1 Schematic of a Grid-Connected Photovoltaic System with MPPT, Boost Converters, and PWM-Controlled Inverter for Optimal Power Conversion

on the other hand, Figure 2, omits the boost converter. Instead, the PV array directly provides 1000V DC to the NPC 3-level inverter. The inverter in this system is controlled by a PID controller, which helps improve the system's transient response by adjusting the inverter output based on changes in voltage and the rate of change of the error signal

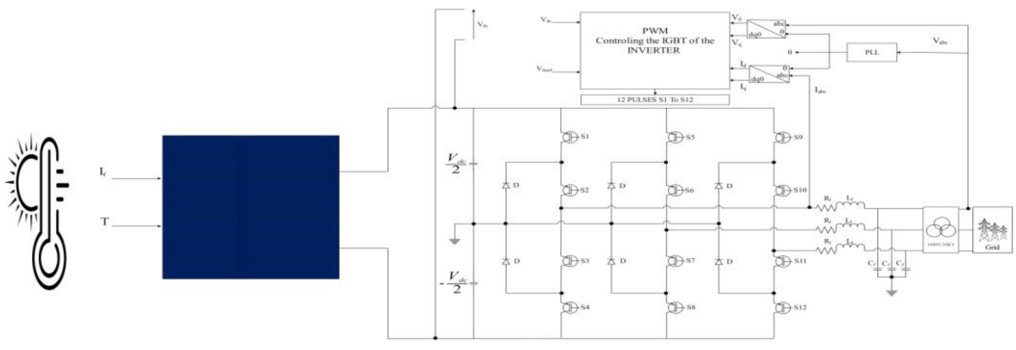

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Figure 2 Schematic of a Grid-Connected Photovoltaic System PWM-Controlled NPC Inverter, and Without Boost Converter

The system architecture (a) is divided into several main components: the solar photovoltaic array, multiple DC-DC boost converters, a multilevel inverter, and the control system.

- Solar Photovoltaic Array: The system consists of an array of solar panels that convert sunlight into DC electricity. The output voltage of the PV array depends on environmental factors such as irradiance and temperature Figure (3,4,5,6).

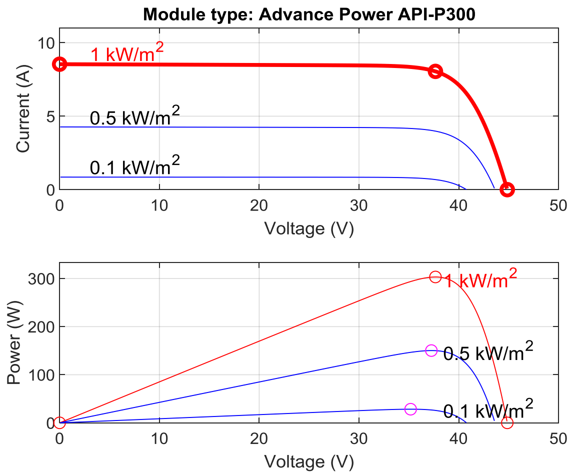

Figure 3 I-V and P-V Characteristics of a Photovoltaic Module under Different Irradiance Levels

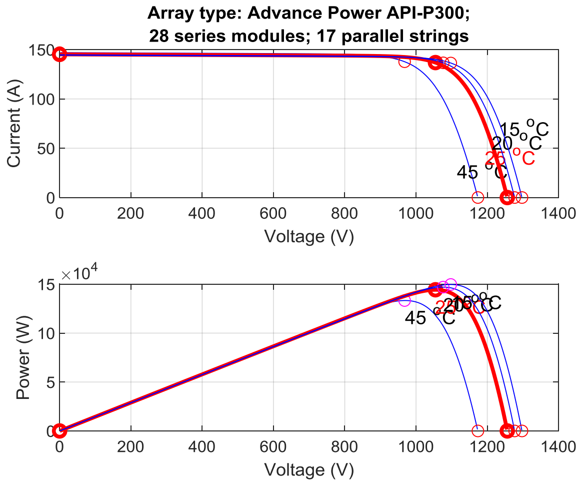

Figure 4 I-V and P-V Characteristics of Photovoltaic Array under Various Temperatures

TABLE 1
PARAMETERS OF PV PANEL FOR CONFIGURATION ONE

Parameters	Rated value
Maximum power(w)	303.163
Open circuit voltage	44.86
Short-circuit current (A)	8.54
Voltage Maximum power point (V)	37.66
Current at Maximum power point (A)	8.05
N_s	28
N_p	17

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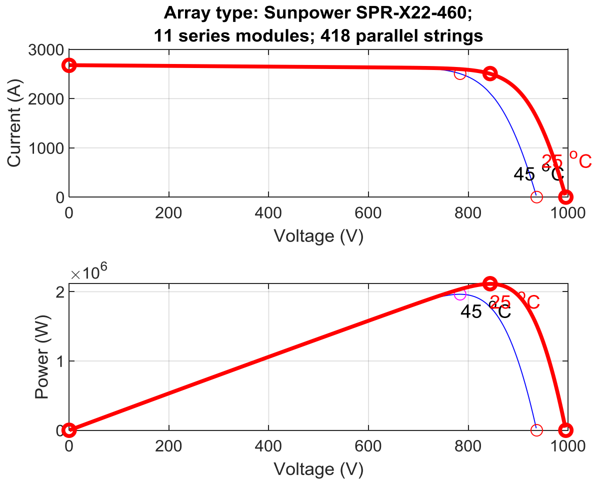

Figure 5 I-V and P-V Characteristics of a Photovoltaic Module under Different Irradiance Levels

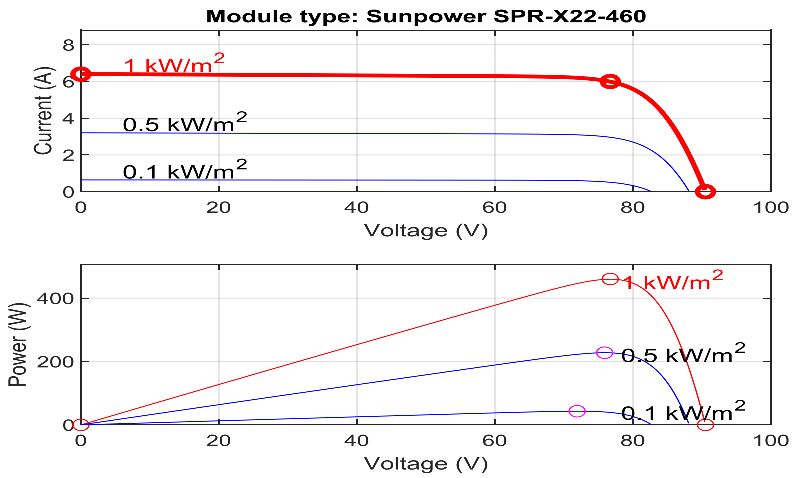

Figure 6 I-V and P-V Characteristics of Photovoltaic Array under Various Temperature

TABLE 2
PARAMETERS OF PV PANEL FOR CONFIGURATION TOW

Parametre	Rated value
Maximum power(w)	460.2
Open circuit voltage (V)	90.5
Short-circuit current (A)	6.4
Voltage Maximum power point (V)	76.7
Current at Maximum power point (A)	6
N_s	11
N_p	418

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- *Multiple Parallel Boost Converters:* The output from the PV array is fed into multiple parallel DC-DC boost converters. These converters step up the DC voltage to a higher level required for grid connection. The parallel configuration ensures redundancy and increases the reliability of the system. Each boost converter operates independently, allowing for easy maintenance and ensuring that the failure of one converter does not affect the entire system.
- *Multilevel Inverter:* The high-voltage DC output from the parallel boost converters is then fed into a multilevel inverter. The inverter is responsible for converting the DC voltage into AC power that can be fed into the grid. The use of a multilevel inverter helps minimize harmonic distortion and switching losses, resulting in high-quality AC power suitable for grid integration.
- *Control System:* The control system consists of two main strategies:
    1. *Maximum Power Point Tracking (MPPT):* This control method ensures that the PV array operates at its maximum power point, optimizing energy extraction under varying environmental conditions.
    2. *PID Control:* A Proportional-Integral-Derivative (PID) controller is used to regulate the output voltage and current to ensure stable operation and smooth grid integration.

III. Mathematical Modelling

The mathematical modelling of the system is divided into the following components:

A. *Photovoltaic Array Model*

The PV array is modelled using the single-diode model, which takes into account the current-voltage (I-V) characteristics of the panels. The output current and voltage of the array are dependent on solar irradiance, temperature, and the load conditions.

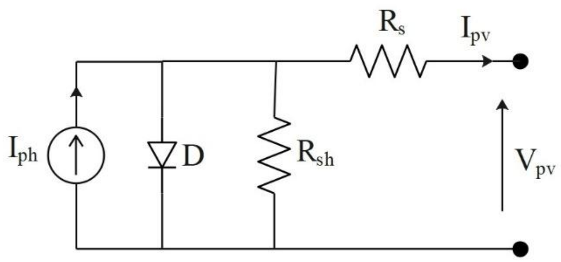

Figure 7 Equivalent Circuit Model of a Photovoltaic Cell

Photocurrent I_{ph} is the current generated by the PV array due to solar irradiation, and it's a key component of the model. It depends on irradiance G and temperature T

$$I_{ph} = \left(I_{ph,STC} + K_I \Delta T\right) . \frac{G}{G_{STC}} \quad (1)$$

The diode saturation current I_0 represents leakage current through the diode at a given temperature. It is critical to account for how the saturation current changes with temperature.

$$I_0 = I_{0,STC} \left(\frac{T}{T_{STC}}\right)^3 \exp\left(\frac{E_g}{nk}\left(\frac{1}{T_{STC}} - \frac{1}{T}\right)\right) \quad (2)$$

E_g is the bandgap energy of the semiconductor material.

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n is the ideality factor of the diode

k is the Boltzmann constant

The current-voltage relationship of the PV module array is given by

$$I_{pv} = I_{ph} - I_0\left(\exp\left(\frac{V_{pv} + I_{pv}R_s}{nV_t}\right) - 1\right) - \frac{V_{pv} + I_{pv}R_s}{R_{sh}} \quad (3)$$

The maximum power point is essential for modelling the efficiency of the PV system. It is typically defined as:

$$P_{\max} = V_{mp}.I_{mp} \quad (4)$$

For a PV array, you need to account for the number of series-connected modules Ns and parallel strings Np which influence the total voltage and current of the array.

$$V_{array} = N_s V_{module} \quad (5)$$

$$I_{array} = N_p I_{module} \quad (6)$$

IV. DC-DC Boost Converter Model

Each boost converter is modelled based on the standard equations for DC-DC conversion. The converter's duty cycle and efficiency are also included in the model to predict the power conversion efficiency and voltage regulation performance.

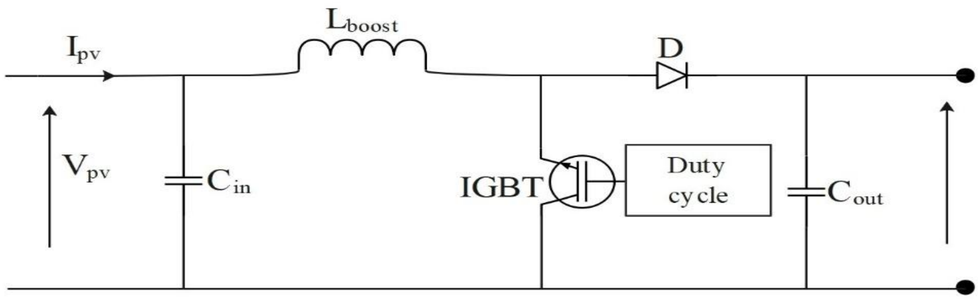

Figure 8 Boost converter

$$V_{out} = \frac{V_{in}}{1-D} \quad (7)$$

V_{out} is the output voltage of the boost converter

V_{in} is the input voltage from the PV array

$$P_{in} = P_{out} \quad (8)$$

$$V_{in}.I_{in} = V_{out}.I_{out} \quad (9)$$

$$L_{boost} = \frac{V_{in}D}{\Delta I_L f_s} \quad (10)$$

f_s is the switching frequency

Δ_{IL} is the inductor current ripple

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$$C_{out} = \frac{I_{out} D}{\Delta V_{out} f_s} \quad (11)$$

ΔV_{OUT} is the output voltage ripple

V. MULTILEVEL INVERTER MODEL

The multilevel inverter is modelled as a combination of several switching devices arranged to produce a stepped output waveform. The switching strategy is implemented based on modulation techniques to achieve the desired output voltage and minimize harmonic distortion.

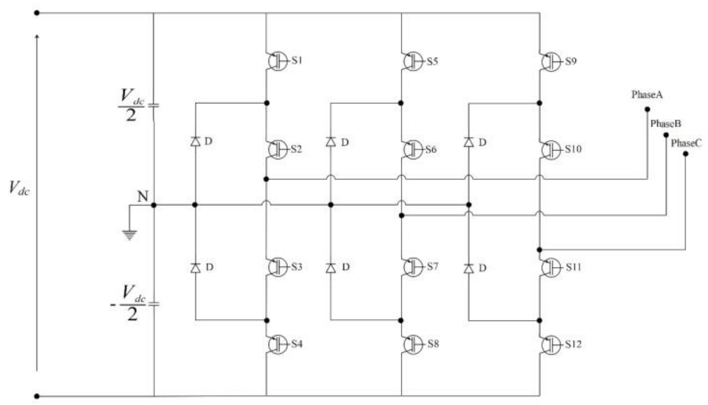

Figure 9 three phases NPC inverter 3 level

VI. CONTROL SYSTEM

B. The MPPT control

The MPPT algorithm (such as Perturb and Observe) is implemented to track the maximum power point of the PV array Figure 10.

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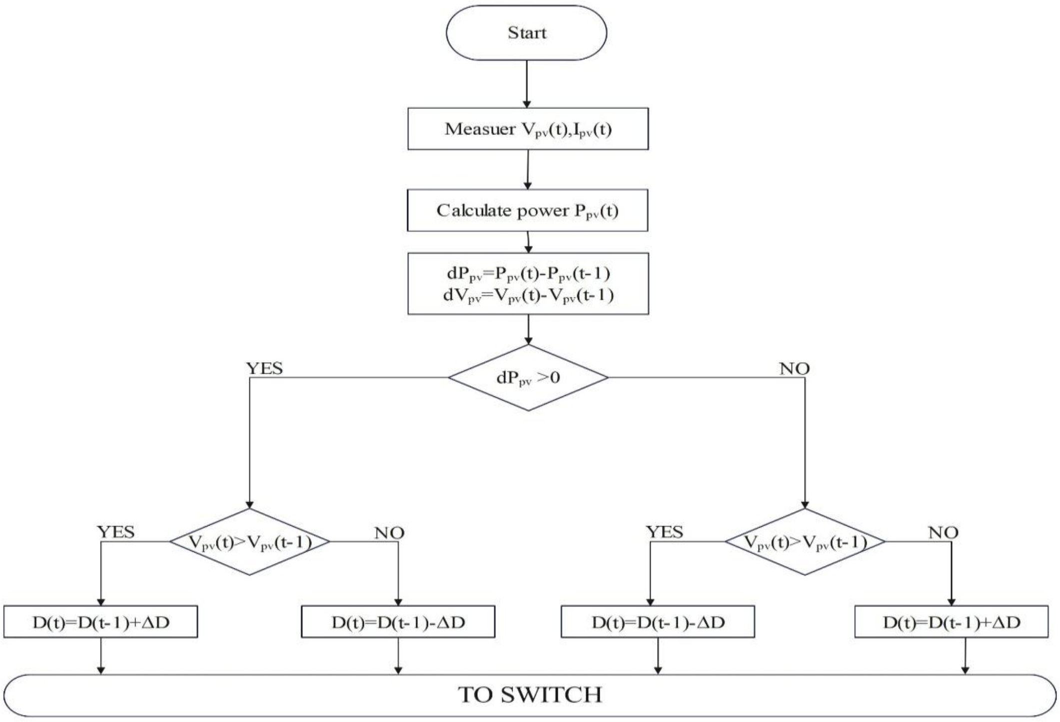

Figure 10 MPPT ALGORITHEM

C. Strategy of controlling the inverter NPC 3 level

The PID and PI controllers are modelled to regulate the output voltage and current by adjusting the controller gains to ensure smooth operation and grid stability.

D. DC bus control

Controlling the DC bus of the inverter with PI controller starting measuring the DC bus voltage value and compare it with reference figure show the diagram bloc used to calculate the parameters of the PI controller

$$F(p)_{PI} = K_{pdc} + \frac{K_{idc}}{p} \quad (12)$$

$$F(p)_{dc} = \frac{1}{pC_{eq}} \quad (13)$$

C_{eq} is the sum of the input capacitor of the inverter

$$F(p)_{CL} = \frac{F(p)_{PI}.F(p)_{dc}}{1+F(p)_{PI}.F(p)_{dc}} \quad (14)$$

We compare F(p)CL with Canonical Closed-Loop Transfer Function equation 15

$$F(p)_{CCL} = \frac{\omega_n^{\ 2}}{s^2 + 2\xi\omega_n s + \omega_n^{\ 2}} \quad (15)$$

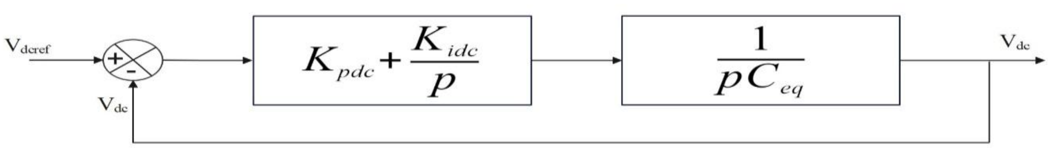

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Figure 11 DC Voltage Regulation with PI Control Loop

E. Current control

A PI or PID controller is used to regulate the inverter's output, ensuring steady voltage and current supply to the grid. The PI controller eliminates steady-state errors and optimizes system efficiency. A PID controller (Proportional-Integral-Derivative) is an extension of the PI controller, adding a derivative term to improve system performance.

The same step used to calculate the parameters of the DC bus controller her we do the modeling of the filter Lf Rf

$$F(p)_{RL} = \frac{1}{pL_f + R_f} \quad (16)$$

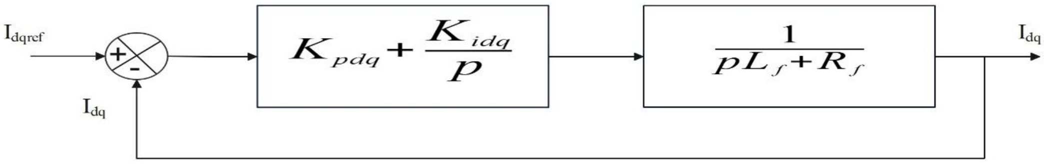

Figure 12 Current Regulation Using PI Control in dq Frame

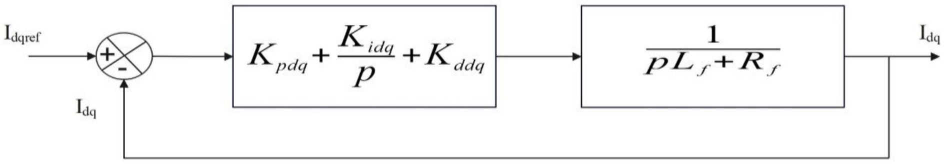

Figure 13 Current Regulation Using PID Control in dq Frame

measuring the three-phase source voltages V_{abc} and using a Phase-Locked Loop (PLL) to extract the phase angle θ of the voltage then transform the V_{abc} and the I_{abc} to the dq frame

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = \frac{2}{3} . \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} . \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} (17)$$

$$\begin{bmatrix} I_d \\ I_q \end{bmatrix} = \frac{2}{3} . \begin{bmatrix} \cos(\theta) & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin(\theta) & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix} . \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \quad (18)$$

Figure 14 and 15 show the step of the control of the inverter NPC 3 level

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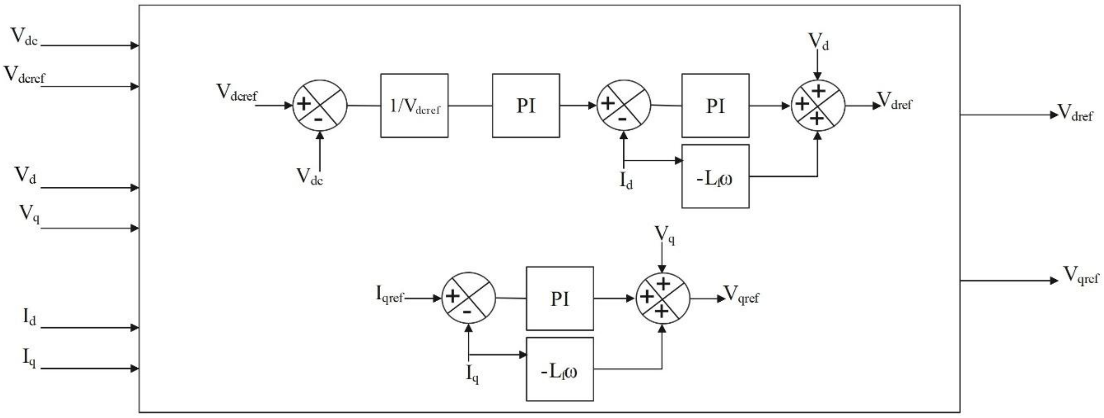

Figure 14 Control System for DC Voltage and dq Current Regulation for the Inverter NPC using PI controller

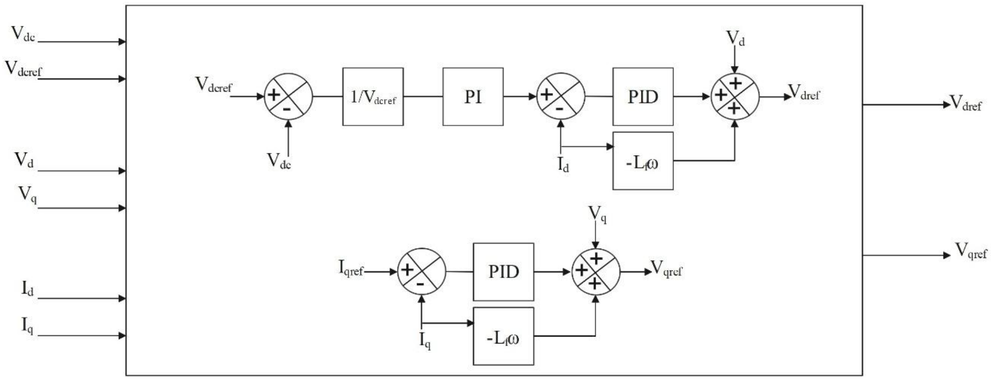

Figure 15 Control System for DC Voltage and dq Current Regulation for the Inverter NPC using PID controller

Equations demonstrate the steps of controlling the inverter NPC 3 level 19 until 21

$$\begin{cases} V_{dref} = D_{nd} - V_d + L_f \omega I_q \\ V_{qref} = D_{nq} - V_q - L_f \omega I_d \end{cases} \quad (19)$$

$$D_{ndq} = PI(I_{dqref} - I_{dq}) \quad (20)$$

$$D_{ndq} = PID(I_{dqref} - I_{dq}) \quad (21)$$

VII. RESULTS AND DISCUSSION

Simulation of the entire system was performed using MATLAB/Simulink to validate the performance of the proposed architecture under different conditions:
For first configuration:

4 PV arrays with 4 Boost converters in parallel, connected to an NPC (Neutral Point Clamped) inverter and then to the grid

Result of Controlling the input voltage inverter NPC 3level figure 16

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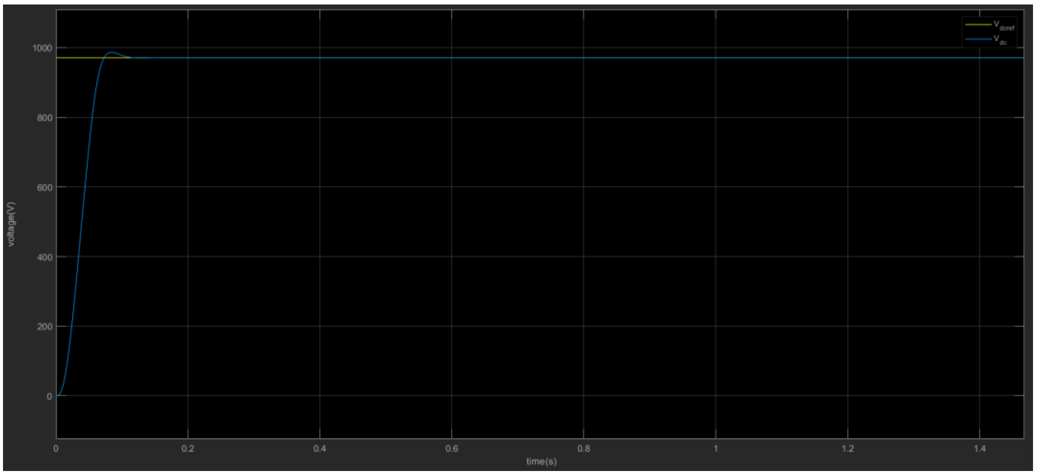

Figure 16 control of input inverter voltage V_{dc}

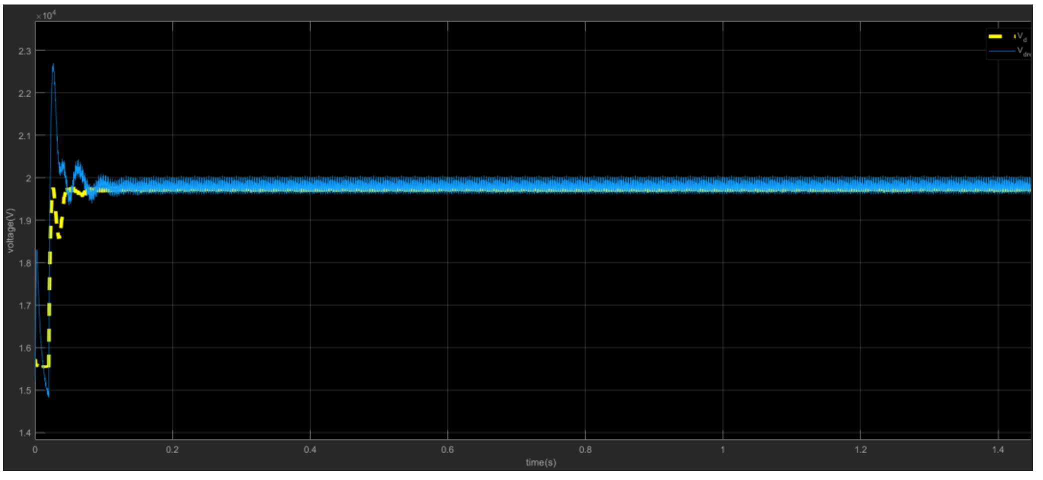

Figure 17 control of the output voltage in frame d V_d and V_{dref}

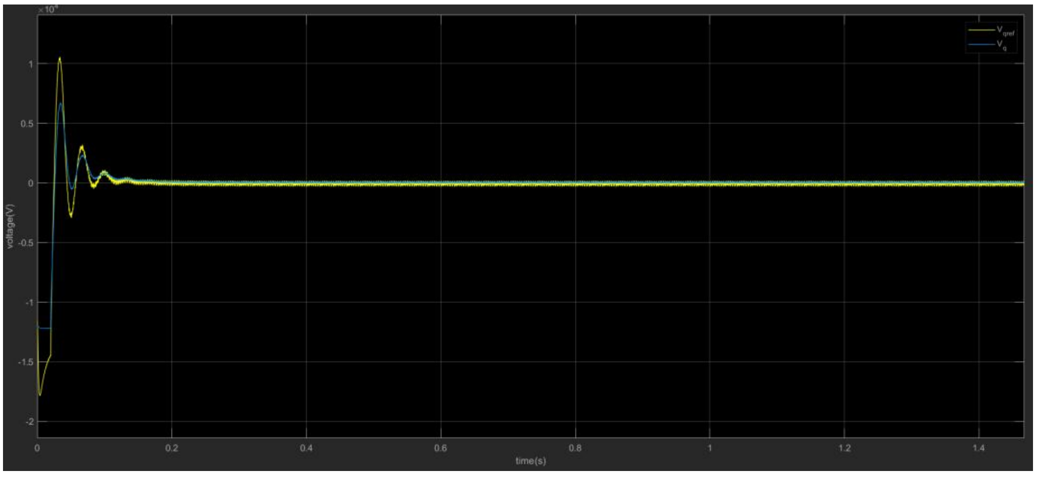

Figure 18 control of the output voltage in frame q V_q and V_{qref}

Figure 19 show the three phase current grid, figure 20 illustrate the inverter voltage

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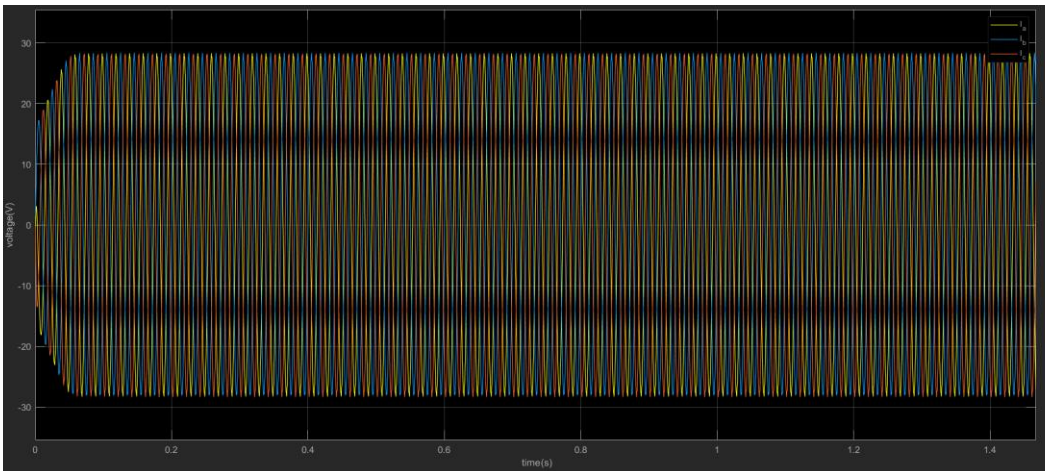

Figure 19 three phase current grid I_{abc}

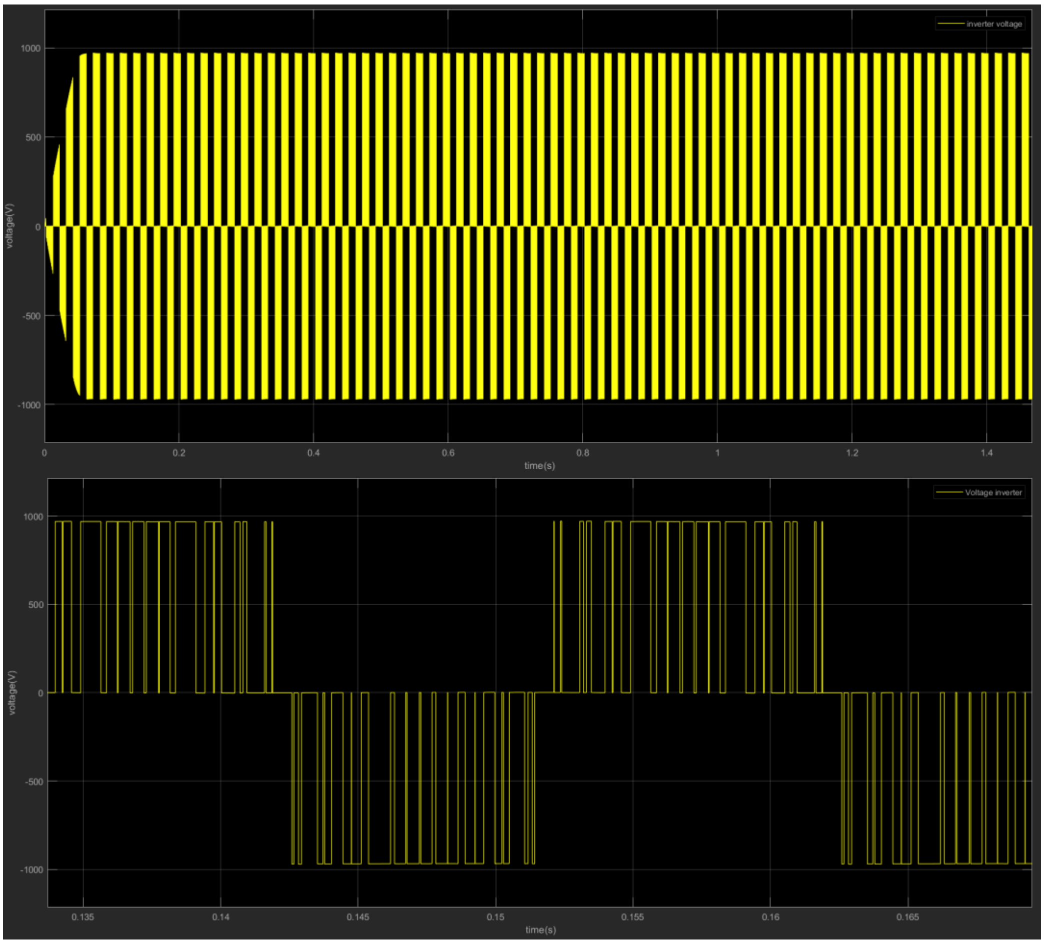

Figure 20 inverter voltage NPC 3level

The Boost converters enable individual MPPT for each PV array, which is particularly useful if the panels experience different sunlight conditions or orientations.

However, each Boost converter introduces conversion losses, which can reduce the overall system efficiency

For configuration 2: PV array (with the same total capacity as the 4 PV arrays in Configuration 1), connected directly to an inverter (without a Boost converter) and then to the grid.

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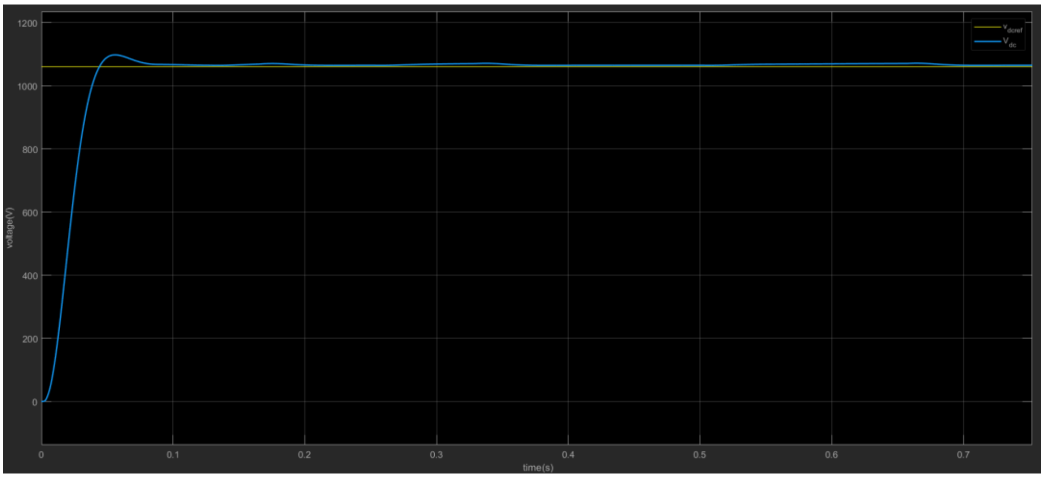

Figure 21 control of input inverter voltage V_{dc}

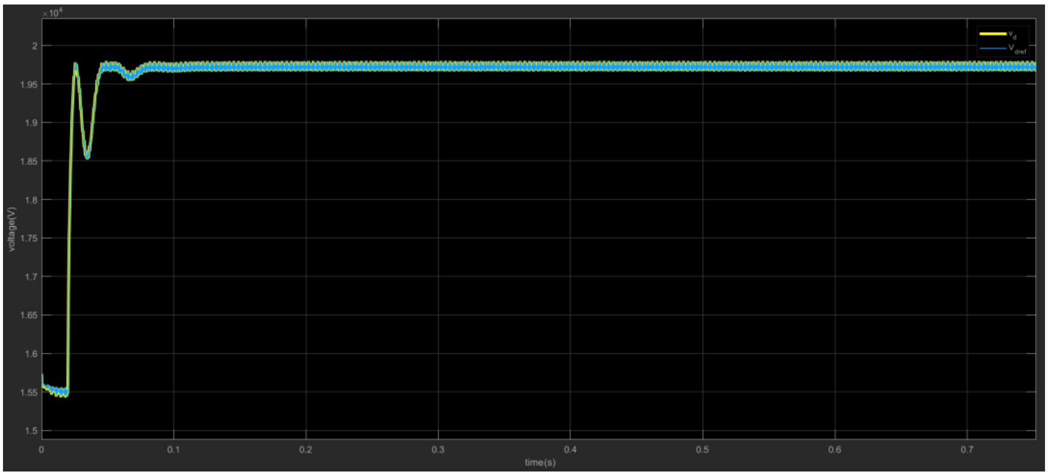

Figure 22 control of the output voltage in frame d V_d and V_{dref}

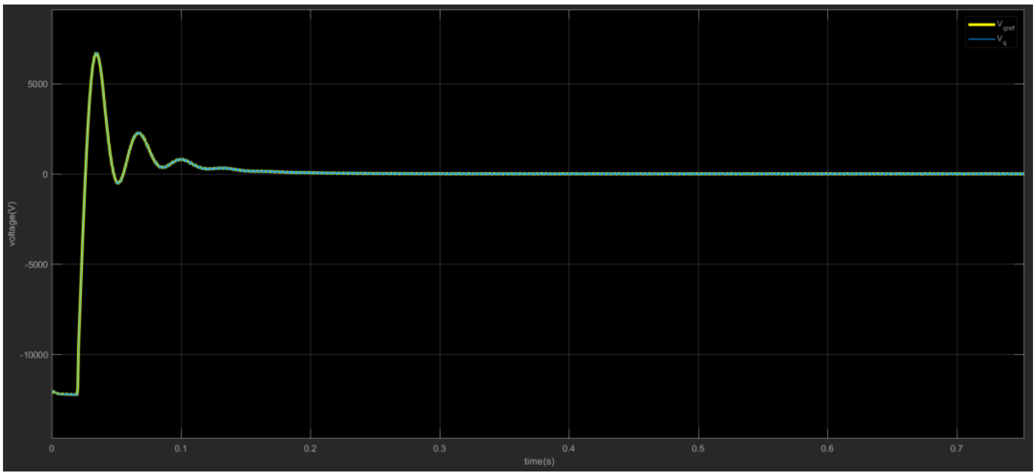

Figure 23 control of the output voltage in frame q V_q and V_{qref}

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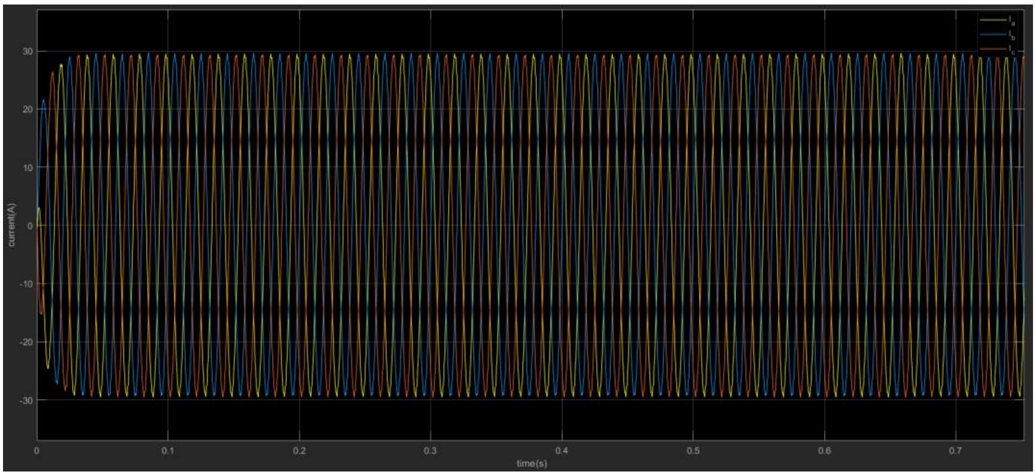

Figure 24 three phase current grid I_{abc}

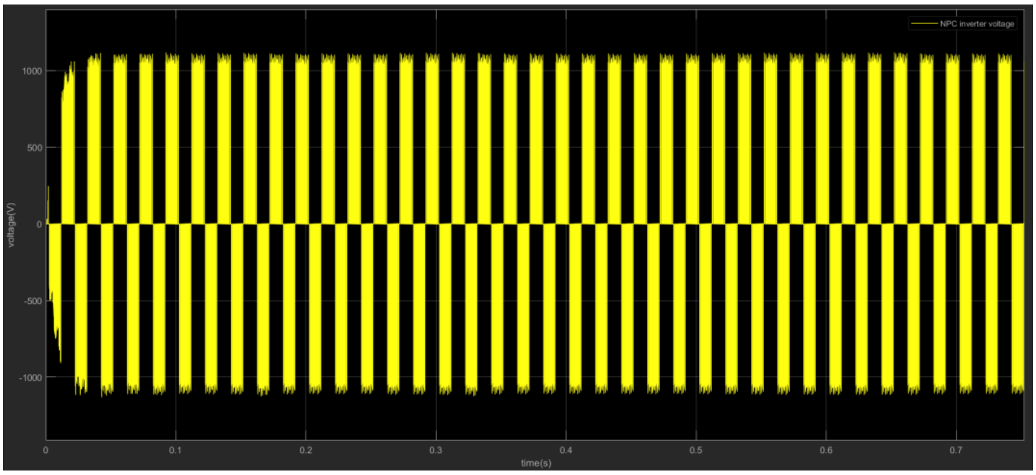

Figure 25 inverter voltage NPC 3level

Without Boost converters, there are no additional DC-DC conversion losses.
However, the lack of individual MPPT can lead to underutilization of available power if sunlight conditions are non-uniform.

VIII. CONCLUSION

This paper presents a robust and efficient architecture for grid-connected solar power generation. The use of multiple parallel boost converters improves system reliability and allows for easier maintenance, while the multilevel inverter ensures high-quality AC power output. The combination of MPPT and PID control strategies optimizes energy extraction and regulation, making the system adaptable to varying environmental conditions. Simulation results validate the effectiveness of the system, demonstrating high efficiency, stable operation, and reliable grid integration. This approach offers a scalable solution for large-scale solar power installations and provides a solid foundation for further research in renewable energy systems.
In summary, Configuration 1 generally offers better performance and flexibility but is more complex and expensive. Configuration 2 is simpler and less expensive but may underperform under non-optimal conditions. The PID controller more complex but provides better performance in systems with fast dynamics, The PI is simpler and easier to tune. [4],[3].

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