PLECS-BASED THERMAL MODELLING AND ANALYSIS OF NPC THREE-LEVEL PV GRID-CONNECTED INVERTERS

Lappeenranta–Lahti University of Technology LUT

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ABSTRACT

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PLECS-based thermal modelling and analysis of NPC three-level PV grid-connected inverters

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This study, based on the PLECS simulation platform, investigates the thermal characteristics and power loss mechanisms of a three-level neutral-point-clamped (NPC) photovoltaic grid-connected inverter. A comprehensive simulation model was developed integrating a photovoltaic arrays, an MPPT-controlled boost circuit, and a three-level inverter. Through dynamic environmental simulations (gradual irradiance variations and step changes), the switching losses, conduction losses of power devices, and their impacts on junction temperatures were systematically analysed. The research further proposes system loss optimization through simplified Space Vector Pulse Width Modulation (SVPWM) strategies, adaptive modulation techniques, and novel power devices (SiC MOSFETs), combined with an improved fuzzy incremental conductance MPPT algorithm to enhance dynamic response capabilities. These findings provide a theoretical foundation for thermal design, control strategy optimization, and high-reliability operation of photovoltaic grid-connected inverters, contributing significantly to advancing renewable energy systems toward enhanced efficiency and prolonged operational lifespan.

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SYMBOLS AND ABBREVIATIONS

Roman characters

p	power	W
T	temperature	ºC, K
U	voltage	V
I	current	A
R	resistance	Ω

Abbreviations

PLECS	Piecewise Linear Electrical Circuit Simulation
NPC	Neutral-Point-ClampedPV
PV	Photovoltaic
SVPWM	Space Vector Pulse Width Modulation
MPPT	Maximum Power Point Tracking
SiC	Silicon Carbide
MOSFET	Metal-Oxide-Semiconductor Field-Effect Transistor
IGBT	Insulated Gate Bipolar Transistor
GaN	Gallium Nitride
PWM	Pulse Width Modulation

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1 Introduction

Photovoltaic (PV) power generation system is a very important renewable energy technology, which plays a vital role in the current increasingly serious global energy crisis and environmental problems. The inverter is the core component in a PV system that converts DC power to AC power, and its performance directly affects the efficiency and stability of the PV system. However, some of the devices in the inverter generate a lot of heat due to long-term operation, which leads to problems such as functional failures. This is an important factor that currently restricts the stability of photovoltaic power generation systems. Especially in three-phase three-level midpoint clamp inverters that are widely used in grid-connected PV. The more complex structure and higher power make the inverter face more challenges in controlling the heat. In this context, this thesis focuses on the thermal modelling models of NPC inverter power devices, which provide important support for designing more efficient heat dissipation systems and improving the reliability of inverters. This research topic is important for improving the overall performance of PV systems.

In the past, a lot of analyses have been conducted on this topic, but the studies for the thermal characteristics of inverters are relatively limited. The studies that have been conducted mainly focus on the thermal analysis of single-level inverters, or the thermal modelling of three-level inverters based on simplified models, which is difficult to comprehensively reflect the actual thermal performance under complex operating conditions.

The aim of this study is to build a thermal modelling model for a three-phase, three-level NPC grid-connected inverter using the Plecs simulation tool, and to analyse the thermal characteristics of the power devices under different operating conditions. By constructing a thermal model of the PV system and combining it with simulation analysis, the thermal behaviour of the inverter power devices is investigated to explore their performance changes under complex operating conditions. Thus, it provides an important reference for the thermal management design of PV grid-connected inverters.

2 Method

In this section, I will briefly introduce a photovoltaic power generation system constructed with a three - level neutral - point - clamped inverter. The photovoltaic grid - connection is modeled using PLECS, and then the heat generation of the inverter during operation is simulated.

2.1 Research Summary and Background

This research focuses on the three-level neutral point clamped (NPC) inverter applied in photovoltaic (PV) grid-connected systems, with an emphasis on studying its fundamental working principles and the thermal analysis model of the power devices within the circuit. In such PV grid-connected systems, the three-phase NPC inverter serves as the critical link between the PV panels and the public power grid, functioning as a power conversion unit. It primarily consists of multiple switching devices and a filtering system. In practical applications, since switching devices are not ideal switches, their on-state resistance cannot be neglected, and their switching actions cannot achieve instantaneous turn-on and turn-off. As a result, switching losses and conduction losses become significant sources of power dissipation in the system. These losses are often dissipated in the form of heat. In real-world applications, the heat generated by power devices ultimately leads to an increase in system temperature, affecting the system's efficiency and stability, and in severe cases, compromising the safe operation of the system [Ren, X.M, 2025]. Therefore, conducting thermal analysis research on the power devices in three-level inverters is of great significance for ensuring the safe and stable operation of PV power generation systems.

In the practical operation of a three-level inverter, the heat dissipated by power devices primarily originates from switching losses and conduction losses. Among these, switching losses are caused by the switching devices during turn-on and turn-off processes. Since instantaneous switching is unachievable, the voltage across the switching devices and the current flowing through them cannot change instantaneously, ultimately leading to the generation of switching losses. These losses are related to the number of switching actions, meaning that the higher the switching frequency, the greater the switching losses in the system. To mitigate such losses, it is often possible to optimize the switching sequence or design hardware-based soft-switching circuits [Ma, Q.J., 2014]. On the other hand, conduction losses are associated with the on-state resistance of the switching devices. Due to manufacturing limitations, switching devices inevitably possess on-state resistance, resulting in losses whenever current flows through them. The magnitude of these losses is primarily determined by the current flowing through the system.

To perform thermal modelling and thermal analysis of the power devices in a three-level inverter, it is essential to investigate both switching losses and conduction losses. This paper focuses on the three-level NPC inverter within a photovoltaic (PV) grid-connected system. Firstly, the fundamental working principles of the PV grid-connected system are studied. Subsequently, the switching losses and conduction losses of the power devices in the maximum power point tracking (MPPT) circuit and the inverter circuit are analysed. Using Plecs software, the system is modelled and simulated to evaluate the switching losses and conduction losses of the switching devices under normal operating conditions of the PV grid-connected system.

2.2 Basic Working Principle of Photovoltaic Grid - Connected System

The basic block diagram of the photovoltaic (PV) grid-connected system based on the three-level NPC converter is shown in Figure 1. As illustrated, the entire system consists of the PV power generation system, the maximum power point tracking (MPPT) circuit and control system, the three-level NPC inverter, and the three-phase power grid.

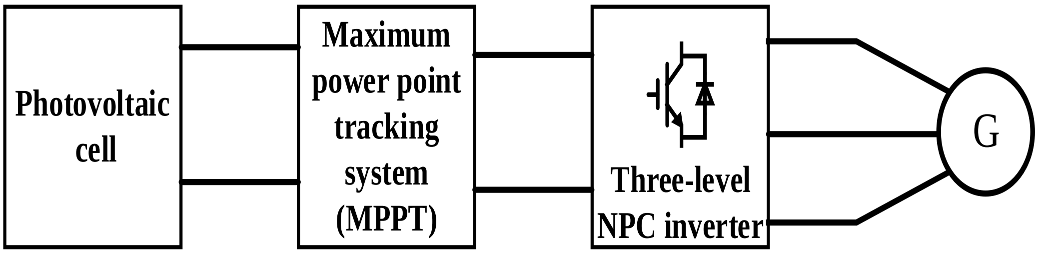


Fig. 1. Schematic Diagram of the Basic Composition of a Three - Level NPC Inverter Photovoltaic Grid - Connected System

2.2.1 Basic Principles of Photovoltaic Power Generation System and Maximum Power Point Tracking

The core principle of photovoltaic (PV) power generation lies in the photovoltaic effect, which directly converts sunlight into electrical energy. This process primarily relies on the properties of semiconductor materials. When photons from sunlight strike the surface of a semiconductor, their energy is absorbed, exciting electrons break free from atoms and generate free electrons and holes. Within a solar cell, a p-type semiconductor (rich in holes) and an n-type semiconductor (rich in electrons) form a p-n junction. Under illumination, an electric field is established at the p-n junction, driving the directional movement of electrons and holes, thereby producing a direct current (DC) voltage and current across the terminals of the cell [Liu, M.Y., 2024].

The solar panel, as the core component of the PV system, consists of multiple solar cells connected in series or parallel and encapsulated into a module. Common materials used include monocrystalline silicon, polycrystalline silicon, and thin-film materials. In practical applications, series connections increase the output voltage, while parallel connections enhance the output current. By designing the series-parallel structure appropriately, the PV system can flexibly adapt to different voltage and current requirements, improving overall power generation efficiency and stability, and making it suitable for various application scenarios.

The DC electricity generated by the solar panel must be converted into alternating current (AC) via an inverter to power household appliances or to be fed into the electrical grid. Based on system design, the converted electricity can be used in either grid-connected or off-grid configurations. Grid-connected systems feed electricity directly into the public grid, exporting excess power when generation exceeds consumption and drawing power from the grid when generation is insufficient. Off-grid systems rely on energy storage devices, such as lithium-ion batteries, to store surplus electricity. These systems are equipped with charge controllers to manage battery charging and discharging, ensuring continuous power supply during periods without sunlight [Ma, M.Y., 2024].

The Maximum Power Point Tracking (MPPT) system in Figure 1 is a key technology in photovoltaic (PV) power generation systems, designed to optimize the output power of solar panels. It primarily consists of a DC-DC converter and the corresponding MPPT algorithm. Since the output power of PV cells is influenced by factors such as light intensity and temperature, their voltage-current (V-I) characteristic curve changes, causing the maximum power point (MPP) to fluctuate. The power-voltage (P-V) and current-voltage (I-V) curves of the PV cell are shown in Figure 2. As illustrated, the relationship between the output power of the PV cell and the output voltage of the panel is not linear but exhibits a maximum power point. When the operating point is at the MPP in Figure 2, the PV panel achieves maximum power output. To the left of the MPP, the output power of the PV cell increases linearly with the increase in the operating voltage; to the right of the MPP, the output power decreases as the operating voltage increases. To ensure that the PV power generation system maintains maximum power output under any external environmental conditions, real-time control of the PV cell's output voltage and current is required.

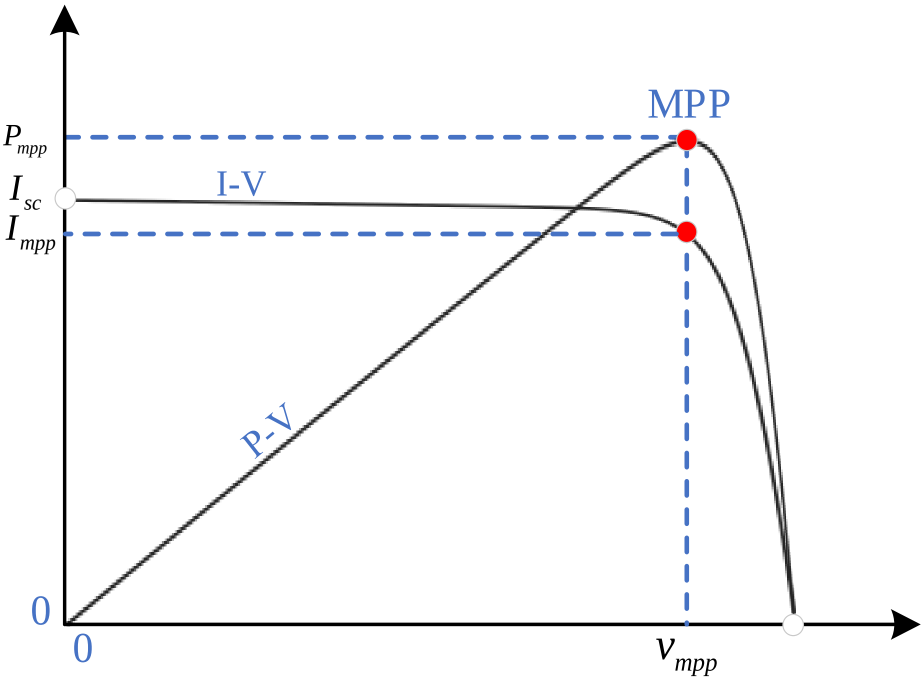


Fig. 2. Schematic Diagrams of P/V Curve and I/V Curve of Photovoltaic Cell

The MPPT algorithm dynamically adjusts the operating point by continuously monitoring the voltage and current of the solar panel, ensuring the system operates near the maximum power point (MPP) and thereby maximizing energy conversion efficiency. Figure 3 illustrates the basic principles of a commonly used MPPT circuit and its closed-loop control system. The MPPT system typically consists of a DC-DC converter, which controls the output voltage and current of the PV cell by regulating the switching devices within the converter. This enables maximum power output under varying external conditions. By employing the MPPT algorithm, the system generates the PWM signals required to control the switching devices. Currently, the most widely used MPPT algorithms include the Perturb and Observe (P&O) method and the Incremental Conductance (INC) method [Zheng, Z., 2025]. The output of the maximum power point tracking system is usually connected to a DC bus, which links to the three-phase grid-connected inverter.

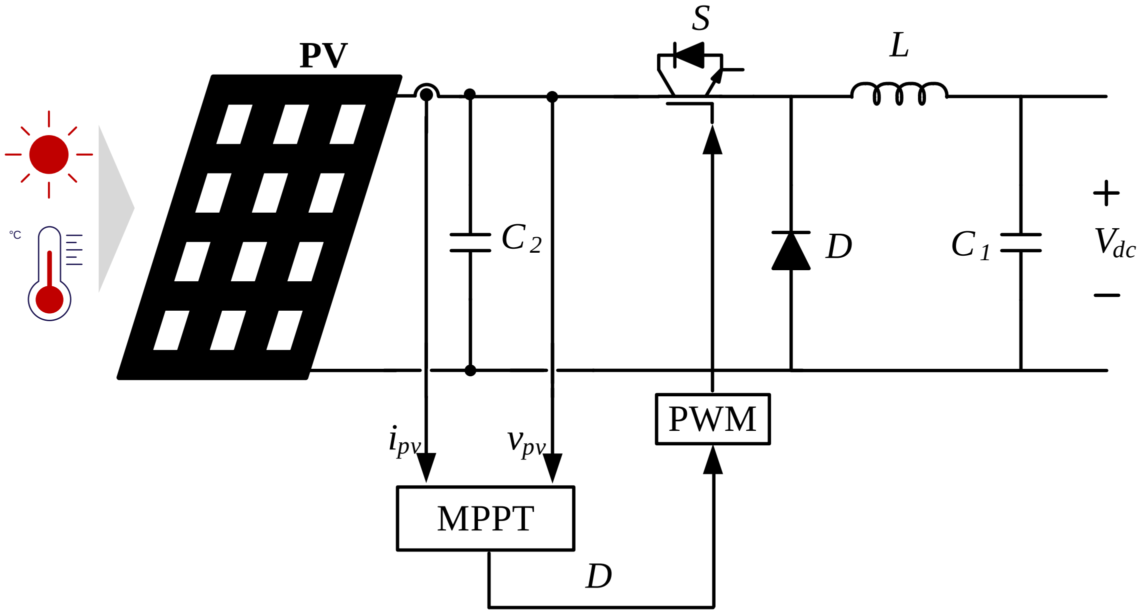


Fig. 3 Schematic Diagram of MPPT Circuit and Control System

2.2.2 Basic Working Principle of Three-Level NPC Inverter

In Figure 1, the three-level NPC inverter connects the DC bus and the three-phase power grid. Since the electricity generated by the PV system is direct current (DC), while most household and industrial devices operate on alternating current (AC), the inverter is required to convert the DC power from the PV system into AC power for delivery to the grid. Figure 4 illustrates the topology of the three-level NPC inverter. As shown, the three-level NPC inverter primarily consists of three bridge legs (A, B, and C) and two DC-side stabilizing capacitors (C1 and C2). The capacitors C1 and C2 are responsible for maintaining the stability of the bus voltage, and since their capacitances are equal, the bus voltage is divided into two parts, Vc1 and Vc2, satisfying Vc1 = Vc2 = Vdc/2, where Vdc is the bus voltage. The connection point of the two capacitors is referred to as the neutral point, and the voltage at this node can be considered as 0. Each of the three bridge legs (A, B, and C) is composed of four switching devices and two diodes. The output voltage of each bridge leg has three states: -Vdc/2, 0, and Vdc/2, resulting in a total of 27 different operating states for the three bridge legs. Taking the A-phase bridge leg as an example, the output voltage state is determined by the switching states of the four switches Sa1, Sa2, Sa3, and Sa4. The states of the switches are represented by 0 and 1, where 1 denotes "on" and 0 denotes "off." When the states of the four switches are 0, 1, 1, 0, node A is directly connected to the neutral point O, meaning the output voltage of the A-phase bridge leg is 0. When the states are 1, 1, 0, 0, Sa1 and Sa2 are turned on, and node A is directly connected to the positive bus, resulting in an output voltage of Vdc/2. Similarly, when the states are 0, 0, 1, 1, the output voltage is -Vdc/2 [Jiang, Y.Z., 2017].

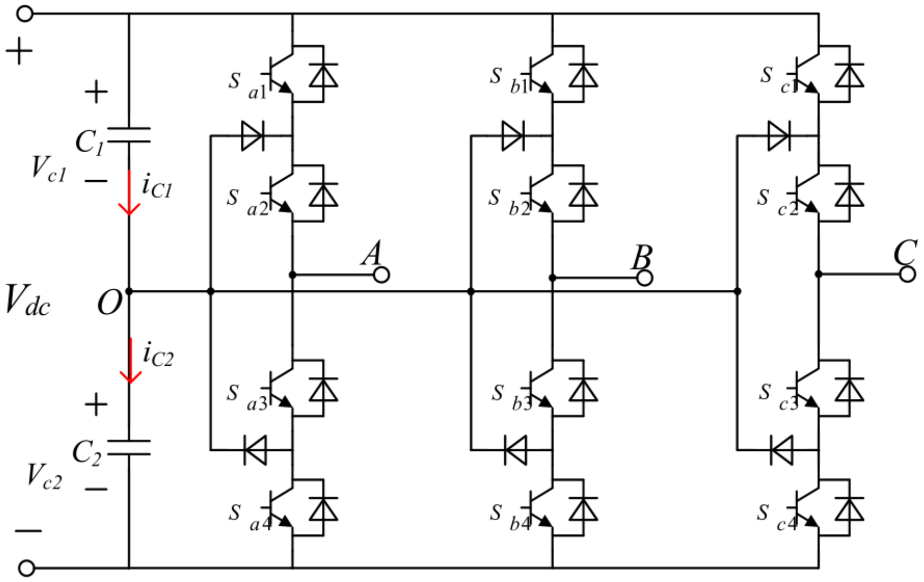
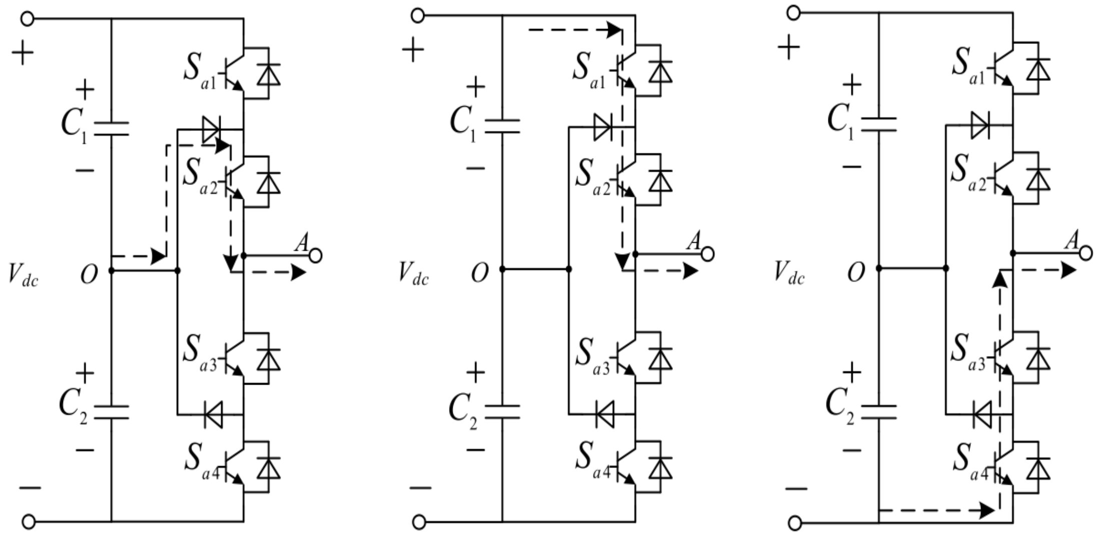


Fig. 4 Schematic Diagram of the Topological Structure of Three - Level NPC Inverter

Taking the case where the A-phase current ia > 0 (i.e., ia flows toward the grid) as an example, the circuit states of the A-phase bridge leg under the three different conditions are shown in Figures 5(a), (b), and (c), respectively.



(a) Va = 0 **(b) Va = Vdc/2** **(c) Va = -Vdc/2**

Fig. 5 Schematic Diagram of Current Flow Path of Phase A Bridge Arm under Different Working States

By controlling the switching states of the three bridge legs, the three-level NPC inverter converts DC power into three-phase AC power. Compared to a two-level inverter, this converter offers several significant advantages. For instance, the three-level NPC inverter produces more output voltage levels, significantly reducing harmonic content and thereby decreasing the size and cost of the filtering circuit. Additionally, since each bridge leg consists of four switching devices connected in series, each power device only bears half of the DC bus voltage, allowing the use of lower-voltage-rated devices, which reduces losses and enhances system reliability. By employing optimized modulation strategies such as Space Vector Pulse Width Modulation (SVPWM), switching losses can be effectively reduced compared to traditional topologies, significantly improving system efficiency [Luo, Z.P., 2021]. Despite these advantages, the three-level NPC inverter also faces challenges, including increased complexity in modulation and higher costs due to the larger number of switching devices. Moreover, the doubling of switching devices necessitates careful consideration of their thermal effects to mitigate risks associated with switching losses and conduction losses, ensuring system safety and stability

2.3 Building of the Simulation Model for Three - level NPC Photovoltaic Inverter

Building a simulation model of a three-level Neutral-Point Clamped (NPC) photovoltaic inverter plays a crucial role in the design and optimization of PV power generation systems. Its primary function is to enable in-depth analysis of inverter performance under complex operating conditions through digital simulation, thereby providing theoretical support and technical validation for practical system development. For example, simulations allow for flexible testing of various modulation strategies—such as Space Vector Pulse Width Modulation (SVPWM)to assess their impact on output waveform quality, quantitatively evaluate harmonic distortion against grid-connection standards, and optimize key parameters such as switching frequency and dead time, thereby enhancing inverter efficiency and reliability .

The simulation model can also replicate the dynamic response characteristics of the PV system under varying environmental conditions, such as sudden changes in solar irradiance, grid voltage fluctuations, or load variations. This includes evaluating the real-time performance of Maximum Power Point Tracking (MPPT) algorithms and the stability of the neutral-point voltage. Through parametric analysis (such as adjusting the DC bus capacitor size, filter inductor values, or IGBT device types) the model enables rapid identification of optimal component configurations, significantly reducing the cost of hardware trial and error. Moreover, the simulation model supports preliminary thermal management design. By simulating switching and conduction losses of power devices, it can predict temperature rise trends and aid in the optimization of heat dissipation structures, thereby prolonging the operational lifespan of the equipment.

2.3.1 Construction of the simulation model

The overall simulation model of the three-level NPC photovoltaic (PV) inverter constructed in this study is shown in Figure 6. As illustrated, the hardware circuit of the simulation model consists of three main parts: the PV cells, the maximum power point tracking (MPPT) circuit composed of a Boost converter, and the three-level inverter connecting the DC bus to the three-phase grid. This setup achieves a three-phase, two-stage power conversion process, enabling the transformation of the electricity generated by the PV system into three-phase AC power with optimal efficiency for delivery to the grid.

To simulate the series-parallel configuration of the PV cells, the PV cell model in this simulation is constructed using 40 individual cells grouped into a module. Specifically, each module is arranged in a 20-series * 2-parallel configuration. A total of four such modules are used, connected in a 2-parallel * 2-series arrangement to form the PV cell array in the simulation. The specific connection scheme of the four modules is shown in Figure 6. Ultimately, the constructed PV cell array has a rated output voltage of 400V.

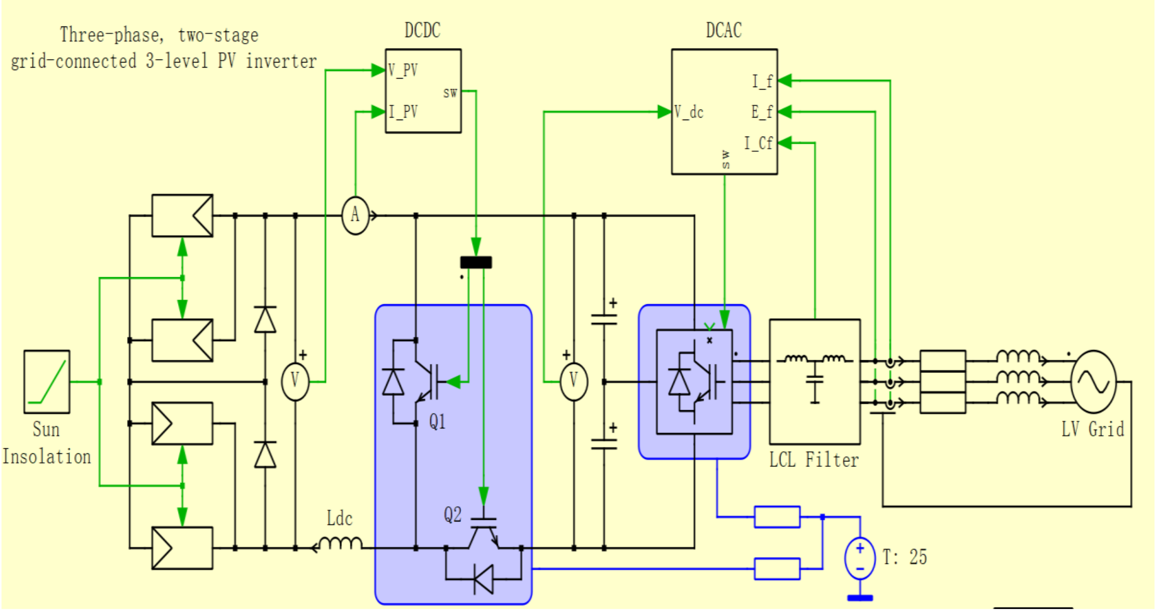


Fig. 6 Overall structural diagram of the simulation model for the three-level NPC photovoltaic inverter

The Boost converter is used to achieve maximum power point tracking (MPPT) control for the PV cells, ensuring that the system can track the maximum power point under varying external conditions. The closed-loop control section of the MPPT system is shown in Figure

7. This section employs the Incremental Conductance MPPT algorithm combined with a dual-loop control strategy for PV cell voltage and current, ultimately enabling control of the switching devices in the Boost converter.

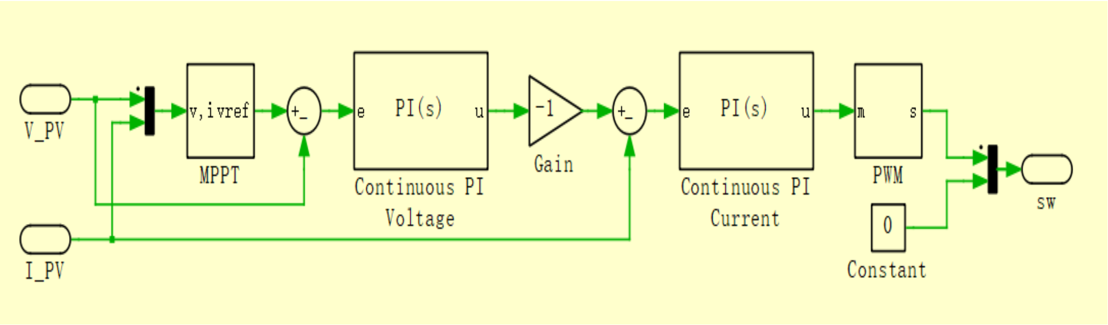


Fig. 7 Schematic diagram of the implementation of the maximum power point tracking (MPPT) control system

At any given moment, the output power of the PV cell satisfies the relationship $P = V * I$, where P is the power, V is the voltage, and I is the current. By differentiating both sides of this equation with respect to voltage, we obtain Equation.

$$\frac{dP}{dV} = \frac{d(V^* I)}{dV} = I + V^* \frac{dI}{dV} = 0 \qquad (1)$$

where *P* is power (W), *V* is voltage (V), and *I* is the current (A).

As can be seen from the P/V curve in Figure 2, when the derivative of power with respect to voltage is 0, that is, at the maximum point of the P/V curve, the maximum power output can be achieved. Further simplifying the above equation, we can obtain:

$$\frac{dI}{dV} = -\frac{I}{V} \qquad (2)$$

When this condition is satisfied, the PV cell achieves maximum power output. The simulation implementation of the maximum power point tracking (MPPT) algorithm designed based on the above equation is shown in Figure 8.

Through the MPPT algorithm, the reference value for the output voltage of the PV cell is ultimately obtained. By comparing this reference value with the actual voltage of the cell, the current voltage error is determined. This error signal is then fed into the voltage outer-loop PI controller, whose output serves as the reference for the current inner loop. Similarly, the current inner loop controls the output current of the PV cell. Ultimately, the PI controller outputs a duty cycle signal, which is used to generate the PWM required for the Boost converter.

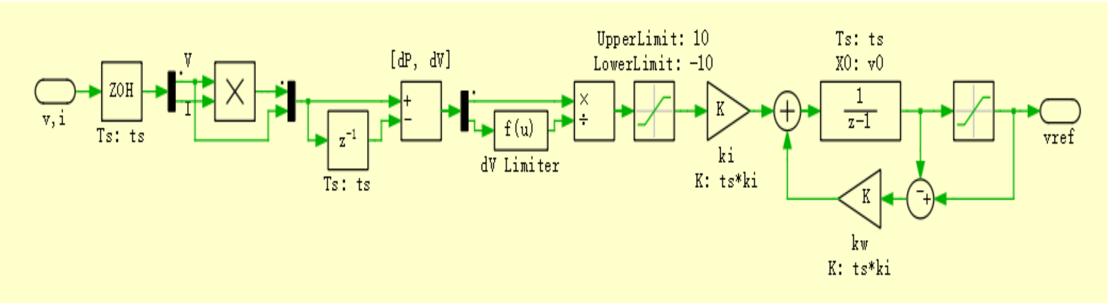


Fig. 8 Building of the simulation model for the incremental conductance MPPT algorithm

Fig. 9 demonstrates the specific implementation schematic of the closed-loop control strategy of the three-level inverter in this simulation. Since the three-level inverter is connected to the DC bus at one end and linked to the three-phase grid at the other end, it has to ensure the stability of the DC bus voltage on one hand, and on the other hand, it has to achieve reliable grid connection on the AC side, such as sinusoidalizing of the grid current and unit power factor [Gui, H.Y., 2005].

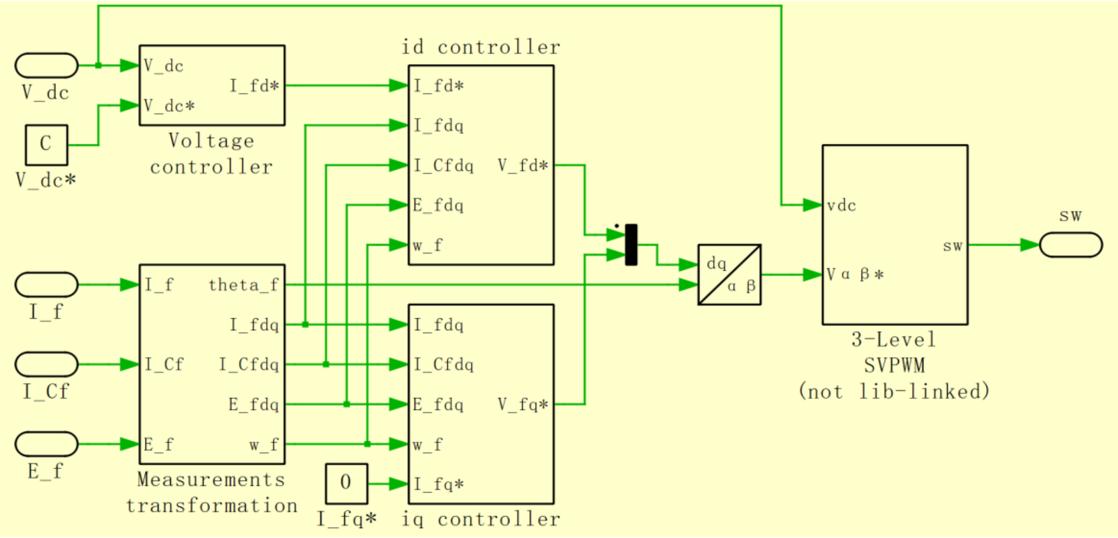


Fig. 9 Schematic diagram of double closed-loop control strategy for three-level inverter

Based on the above control requirements, the three-level inverter designed in this project adopts the double closed-loop control strategy of voltage outer loop + current inner loop. Among them, the voltage outer loop controls the DC bus, and the actual error of the current bus voltage is obtained by performing an error operation between the actual bus voltage and the reference value, and is used as the input of the voltage outer loop PI controller, and the output of the PI controller is used as the reference value of the active component of the current inner loop; The current inner loop is divided into two parts, one for the active component controller and the other for the reactive component controller. Since the system losses are not considered when the three-phase inverter is operating, i.e., there is only active component on the AC side, and the power at the DC side and the AC side of the inverter can be considered equal, the output of the voltage outer loop can be used as a given value for the active component of the current inner loop, and the reference value for the reactive component can be set to zero; The active and reactive components of the AC side current are sent to the corresponding PI controllers after the error is obtained from their reference values to obtain the grid-side reference voltage vector; the SVPWM modulation module finally obtains the PWM signals used to drive the switching devices in the three-level inverter according to this reference vector.

3 Analysis

In this section, I will run the simulation model that has been built. By inputting appropriate parameters to make it as realistic as possible and analysing the simulation results obtained, it will provide an important reference for the heat control of the inverter.

3.1 Results of simulation runs

I set the number of each PV module to 40 and then set the light intensity to be 0.5 at the beginning, and after three seconds, it starts to increase at a fixed rate until it increases to 1. Fig. 10 shows the simulated waveforms of the light intensity, output voltage, and output current of the PV cell, respectively. When the light intensity is stable, the output voltage and output current of the PV cell are able to output stably. At t = 3s, the light intensity begins to ramp up, the PV cell sends out an increase in electrical energy, under the control of the MPPT algorithm, the output current of the PV cell increases slowly, i.e., it always follows the external environmental changes to adjust the PV cell power output.

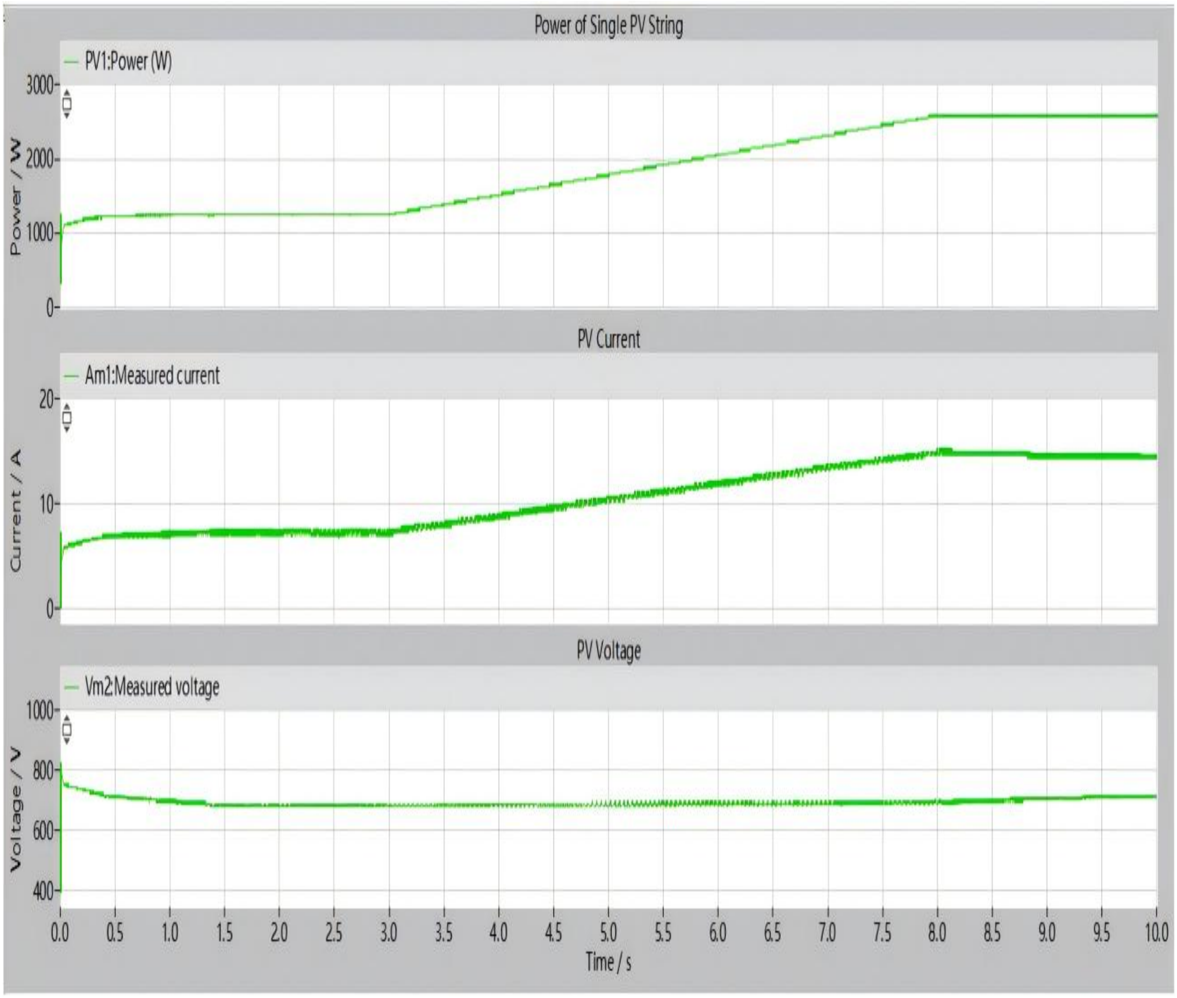


Fig. 10 Simulated waveforms of photovoltaic cell light intensity, output voltage and output current

Figure 11 shows the PV tracking curves of PV panel output power and output voltage plotted by the system in real time. The bolded part in the simulation graph is the power output from the PV cells under the MPPT control algorithm when the external environment changes. As can be seen from the simulated waveforms, the output voltage of the PV panel gradually increases when the work starts. When the MPPT system detects that the derivative of output power and output voltage is less than zero, it reduces the output voltage. And when it detects that the derivative is greater than zero, it increases the output voltage. According to the formula mentioned in Part II we know that the output power of the solar PV panel reaches its maximum when the derivative of both is zero. Thus, we can see that the operating point of the PV panel always runs back and forth near the maximum point of the PV curve and gradually increases with the increase in light intensity.

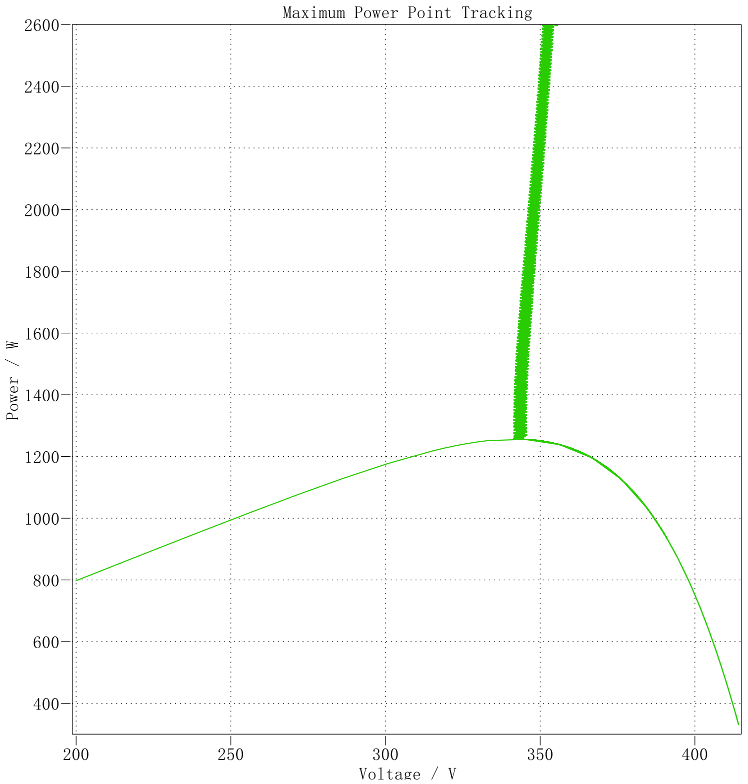


Fig. 11 Simulation of PV tracking curve

As illustrated in Figure 12, with the bus voltage reference set at 800V, the system's feedback control enables the bus voltage to rapidly converge and stabilize around the target value after a brief startup period. This outcome not only validates the effectiveness of the designed voltage closed-loop PI controller but also demonstrates the system's robust regulation capability against DC-side disturbances, such as solar irradiance fluctuations.

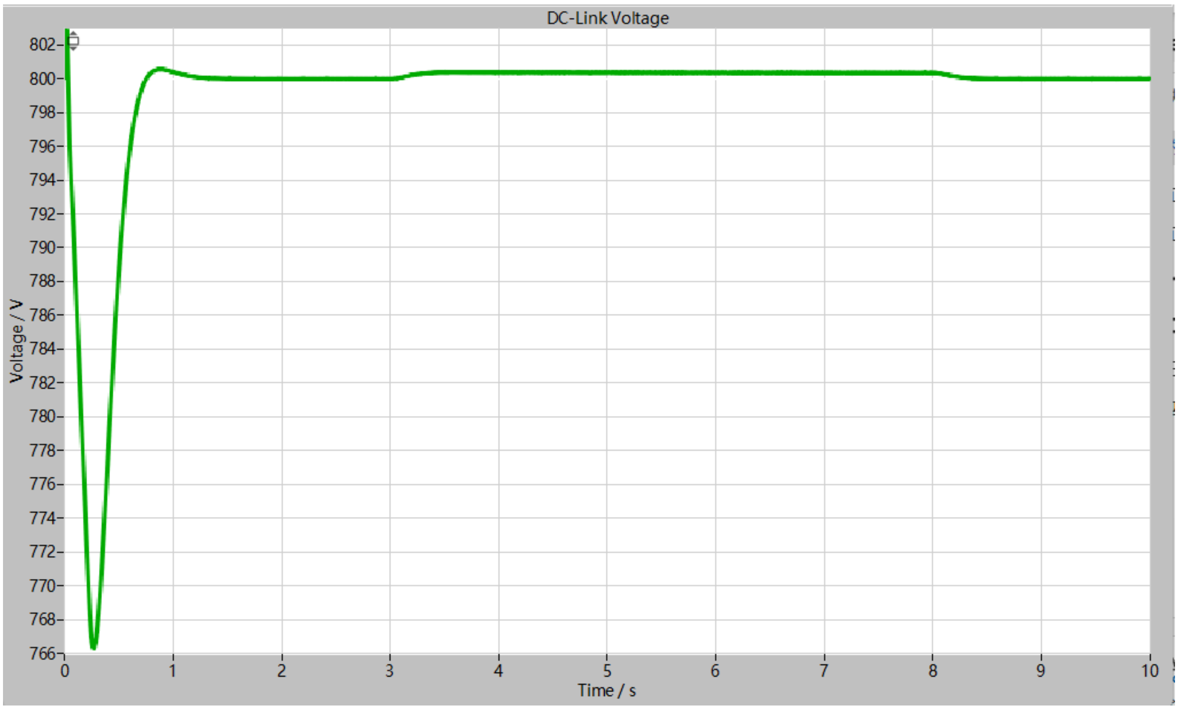


Fig. 12 Simulated waveform of DC bus voltage

The three-phase voltage and current waveforms presented in Figure 13 exhibit excellent sinusoidal characteristics with synchronized voltage-current phases, achieving unity power factor. These results indicate that the dual-loop control strategy (comprising an outer voltage loop and an inner current loop) plays a pivotal role in harmonic suppression and synchronized output, ensuring the inverter's compliance with grid-connection standards and facilitating efficient, stable power delivery to the utility grid.

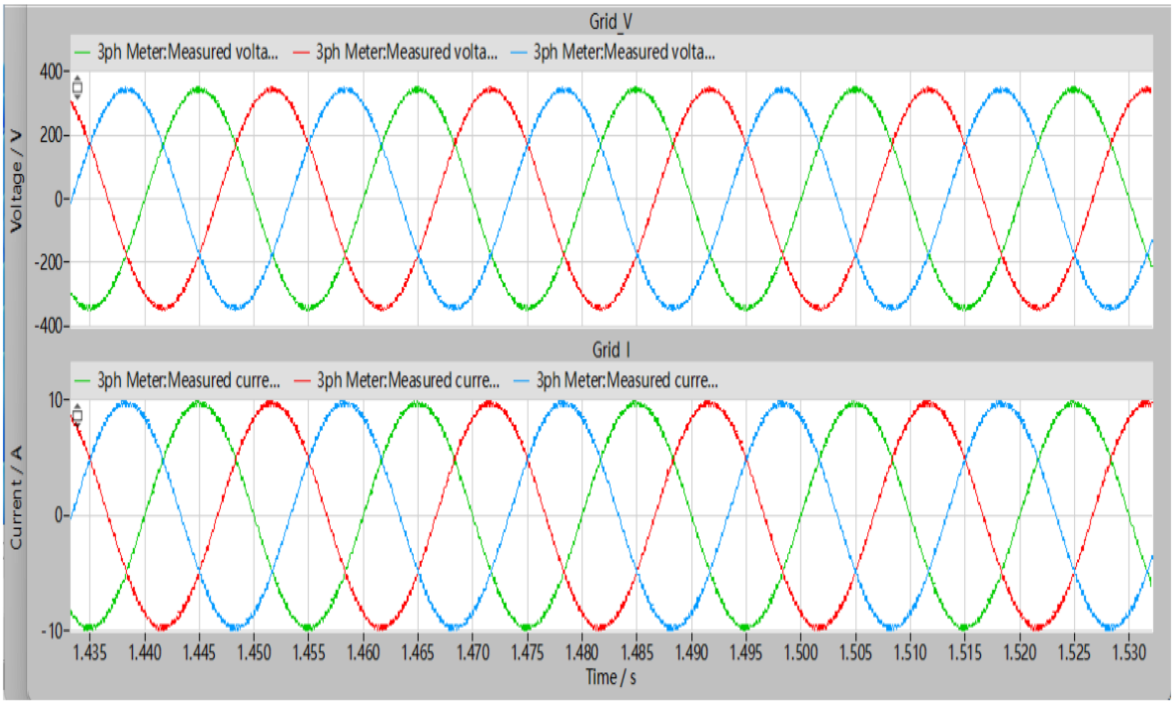


Fig. 13 Simulated waveforms of voltage and current at the grid end

These simulation results above show that the three-level NPC PV grid-connected inverter built in this paper has excellent control performance in MPPT control, three-phase inverter control, etc., and effectively achieves the control objectives of each part of the circuit. It can effectively transform the DC power generated by the PV panels into the AC power required in the grid with maximum power and ensure the stability of the output voltage and current.

3.2 Thermal simulation and power loss of power devices in three-level NPC photovoltaic inverters

In this section, the DC-DC converter and three-phase inverter in the three-level NPC PV grid-connected inverter will be analysed by thermal simulation using the thermal simulation analysis function of Plecs software. The junction temperature and losses of the power devices are calculated under normal system operation.

Figure 14 shows the simulated waveforms of the losses of the power devices in the DC-DC and its controlled boost circuit part and the DC-AC and its controlled three-phase inverter part, respectively, during the thermal simulation operation. From the figure, it can be seen that the loss power of the switching tubes in the DC-DC converter is about 45 W when it is stable. The power losses in this system are primarily attributed to the combined effects of switching losses and conduction losses. The quantified values reflect the relatively low switching frequency employed and the comparatively small current load in this section. By comparison, the inverter section exhibits higher power losses (approximately 100 W) due to the increased number of switching devices and more frequent switching operations. This result highlights the critical influence of switching device selection and driving methods on overall system losses, particularly in high-frequency, high-power applications. By adjusting the parameters of the different parts of the simulation model, it is possible to simulate the loss size of the system under this control strategy under different conditions. It is an important reference for the heat sink design of the system and the power consumption design of the system.

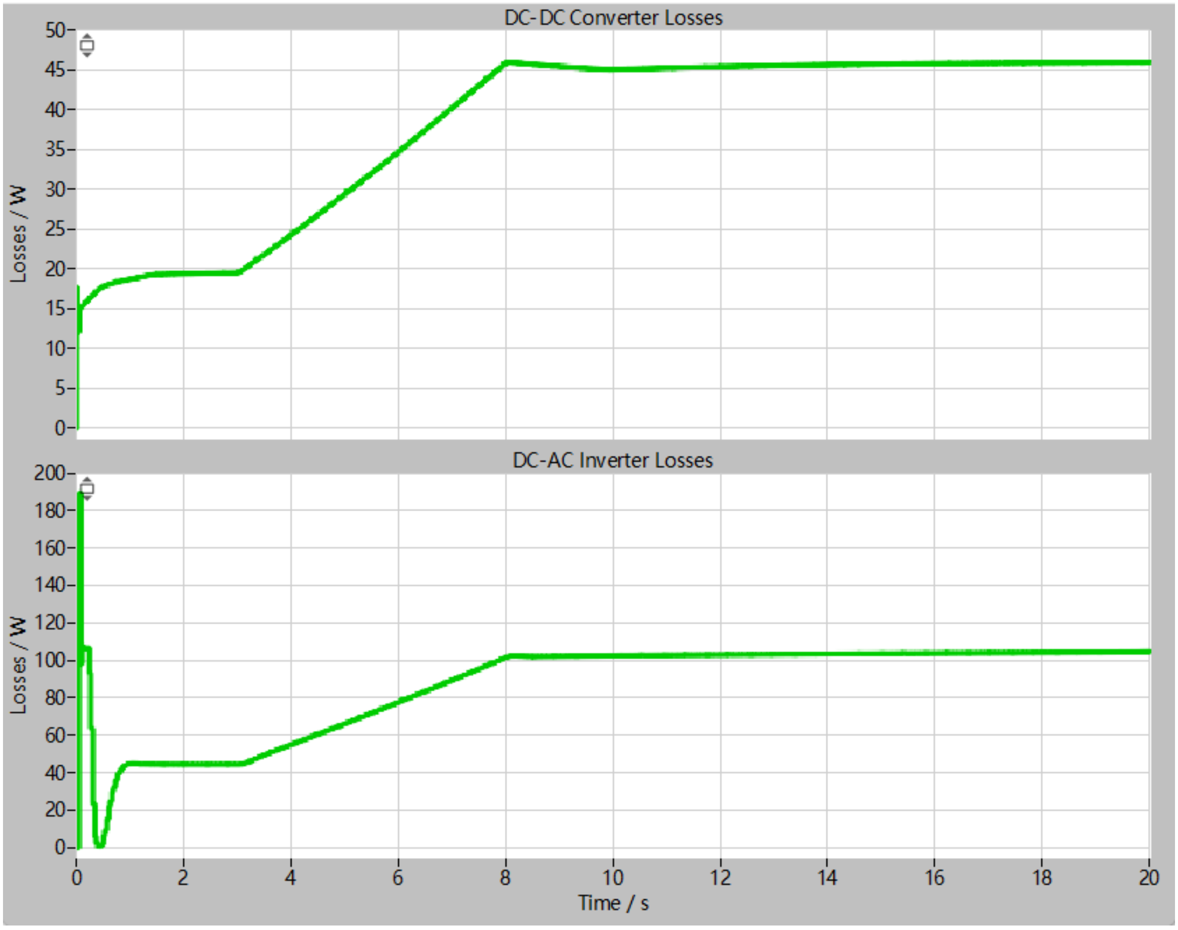


Fig. 14 Simulated waveforms of the loss of each part of the power device

Figure 15 demonstrates the simulated waveforms of this simulation for the switching tube junction temperature in the DC-DC-controlled switching tube and the DC-AC-controlled three-phase inverter. We set the running time of the system to 60s and the outside temperature to 25°C and then simulate the simulation. For the DC-DC converter section, despite continuous switching operations, the devices exhibit small temperature fluctuations and eventually stabilize at approximately 105°C. This thermal behavior confirms that the thermal management system effectively maintains heat balance under normal operating conditions in the DC-DC stage.

In contrast, the three-phase three-level inverter, subjected to higher power loads and more frequent switching actions, demonstrates significantly different thermal characteristics. The junction temperature of its switching devices reaches approximately 140°C with pronounced thermal oscillations. Although this temperature remains within the allowable operating range of the IGBT modules, it approaches the upper thermal limit of the devices. Prolonged operation under such elevated temperatures may accelerate device aging and potentially compromise system reliability.

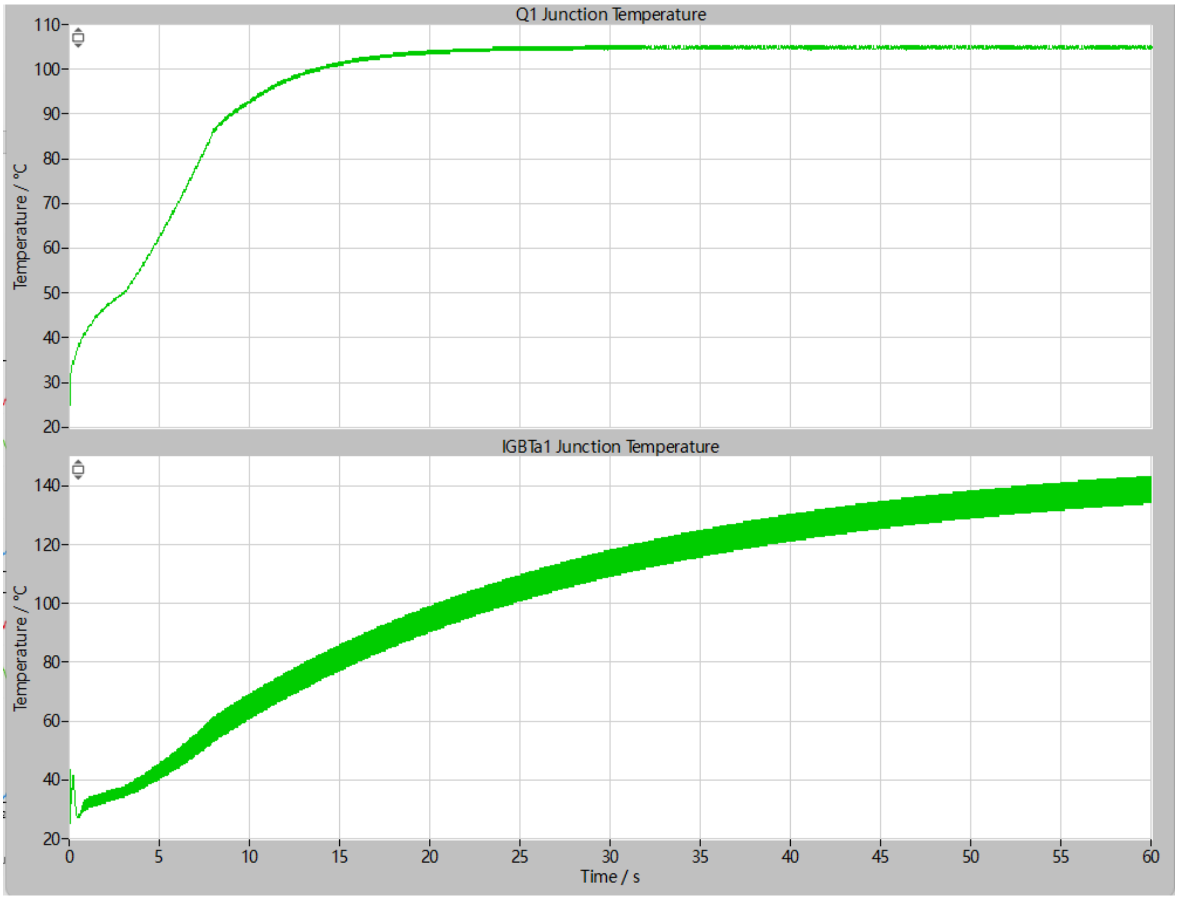


Fig. 15 Simulated waveforms of junction temperature of power devices of the converter

The operating temperature range of IGBTs (Insulated Gate Bipolar Transistors) is usually -40°C to 150°C. The maximum temperature at which different models can be operated varies from model to model, and generally does not exceed 180°C. The maximum temperature of IGBTs is -40°C to 150°C [Yang, X., 2023]. Therefore, through the thermal simulation of the simulation model, we can choose different types of switching tubes according to the actual situation. It is also possible to add heat sinks at locations where additional heat dissipation is required, thus ensuring proper operation of the switching tubes. Using the three-level NPC photovoltaic inverter system model and thermal simulation model constructed in this project, it can be seen that this simulation can effectively calculate and simulate the loss and junction temperature of the system switching devices, which can provide reliable guidance for the design of the hardware and the design of the heat sink.

3.3 Improvement Suggestions and Optimization Strategies

In three-level NPC inverters, the PWM modulation strategy directly affects the switching losses of power devices and the quality of output waveforms. Although the currently employed SVPWM method can effectively reduce harmonic content, its implementation process is relatively complex and requires substantial computational resources. To address this issue, simplified SVPWM algorithms can be adopted.

For instance, by dividing each major sector of the space vector plane into two right-angled triangular sub-regions, the reference vector can be synthesized using the nearest basic vectors corresponding to its residing sub-region [Yang, Z, 2020]. This approach not only substantially decreases computational burden but also eliminates the need for midpoint voltage balancing control in NPC three-level inverters, thereby reducing overall control complexity.

Additionally, an adaptive modulation strategy can be implemented to dynamically adjust the modulation index and switching frequency in real-time based on variations in load, ambient temperature, and operating conditions. Specifically, under low switching frequencies, a fixed modulation scheme is adopted to reduce the core device temperature. At high switching frequencies, a hybrid modulation strategy incorporating different loss distribution methods is implemented. By integrating real-time extracted junction temperature data and dynamically adjusting the hybrid ratio through a tuning function, the system achieves balanced loss distribution and thermal equilibrium control [Feng, Z.J., 2025]. This approach significantly reduces overall power losses and mitigates localized thermal imbalance issues.

Furthermore, power losses can be reduced through improvements in MPPT algorithms. The conventional incremental conductance method can be enhanced by incorporating fuzzy logic and adaptive control techniques to enable online parameter adjustment. The improved algorithm demonstrates superior tracking performance under rapidly varying conditions of irradiance, temperature and load, effectively minimizing oscillation during the tracking process and thereby increasing the overall energy efficiency of photovoltaic systems [He, W.J., 2023].

Finally, system optimization can also be approached from the inverter design itself. For instance, SiC MOSFETs or GaN devices can replace conventional IGBTs in high-temperature and high-load sections, leveraging their lower conduction and switching losses as well as wider operating temperature range to reduce system energy consumption and thermal load. The inverter topology can also be optimized by adjusting the bridge-arm structure and switching device configuration through modular design to improve current and thermal distribution uniformity. In terms of drive circuit design, soft-switching techniques (zero-voltage or zero-current switching) can be adopted along with optimized drive parameters to minimize transient losses during switching transitions [He, X.K., 2023].

Conclusions

This study is based on the PLECS simulation platform and focuses on the thermal characteristics and power loss issues of a three-level NPC photovoltaic grid-connected inverter. A complete simulation model encompassing photovoltaic arrays, an MPPT-controlled Boost circuit, and a three-level inverter was constructed to systematically analyse the thermal behaviour of power devices and system performance under various operating conditions. The simulation results demonstrate that the system effectively tracks the maximum power point while maintaining stable DC bus voltage and achieving high-quality three-phase grid connection, thereby verifying the feasibility of the control strategy. Thermal simulations reveal that the junction temperatures of the inverter power devices approach the upper allowable limits under full-load conditions, whereas the temperature rise in DC-DC components remains relatively low. This indicates that thermal management of the inverter constitutes a critical challenge for system reliability.

The research further proposes reducing switching losses through optimized modulation strategies (simplified SVPWM algorithms) and adopting novel power devices (SiC MOSFETs), while enhancing dynamic response capabilities with improved MPPT algorithms. By simulating dynamic environmental scenarios (e.g., step changes in irradiance), the study more realistically reflects temperature variations and power device losses during operation. These findings provide valuable references for the thermal design and control optimization of practical systems.

However, the study still has certain limitations. The simulation model does not account for practical factors such as device aging, detailed design of circuits and heat sinks, nor does it validate the thermal behaviour under prolonged operation. Future work should involve validating the simulation results through hardware experiments and constructing physical prototypes to comprehensively evaluate system reliability. Additionally, further exploration is required into driver optimization and cost-effectiveness analysis of novel power devices, along with the development of more robust thermal management strategies tailored for extreme environments.

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