Grid-connected PV system modelling based on grid-forming inverters

Lappeenranta–Lahti University of Technology LUT

Bachelor’s Programme in Electrical Engineering, Bachelor’s thesis

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Examiner(s): Professor Shengxue Tang, D.Sc. (Tech) Hafiz Majid Hussain.

ABSTRACT

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Keywords: Grid-connected inverters, Design optimization, Control strategies, Grid interaction, Stability.

This study investigates the design optimization and control strategies of grid-connected inverters, along with their interactions with the electrical grid. It establishes that the stability of grid-connected inverters is intricately linked to their performance, emphasizing that enhancements in overload capacity and protective mechanisms through hardware design are vital to ensure robustness. The thesis contends that inverters must demonstrate considerable robustness and adaptability to effectively manage varying grid and load conditions. To enhance response times and tracking capabilities, this thesis harnesses sophisticated control theories like Model Predictive Control (MPC), adaptive control, and fuzzy control. The design optimization process encompasses adjustments in circuit layout, thermal management, component selection, and the flexibility of control strategies. Furthermore, the study underscores the importance of inverters' capabilities for frequency regulation, phase synchronization, and voltage control in maintaining grid stability and operational efficiency. It also addresses the opportunities and challenges presented by high-capacity inverters in optimizing energy utilization, underscoring the necessity of judicious capacity selection to achieve a balance between efficiency, start-up latency, and component longevity. Ultimately, this thesis concludes that fine-tuning the design and control strategies for grid-connected inverters is paramount to heighten the utilization efficiency of renewable energy, fortify grid stability, and promote environmental sustainability.

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Abstract

1 Introduction

In the context of the increasingly severe global energy shortage, new energy has begun to receive wide attention, and a large amount of new energy has been applied in the industrial field. Clean energy needs to be applied to GCI when connecting to the power grid, and the performance of such devices will have a significant impact on the operational efficiency of the power grid. In this context, this article conducts simulation and design research on it, and optimizes its control mode to provide support for improving the performance of the power grid. At present, the performance of GCI is continuously improving, the application scope is significantly expanding, and the complexity is significantly increasing. High performance GCI is of great significance for clean energy power plants and charging stations [1]. However, with the expansion of application scope and the increasing complexity of operating conditions, the demand for designing and optimizing inverters is also increasing. Therefore, it is necessary to conduct in-depth research on these issues.

GCI is of great significance to the new energy power system. Based on extensive experience, it is known that the performance of this device is closely related to the safety of the power grid, and also directly determines the quality of power supply. Therefore, it is necessary to conduct in-depth research on its structural composition, simulation, and parameter design, in order to provide support for improving the performance of the power grid[2]. In the field of new energy, research on GCI is constantly increasing and has achieved a series of important results. The relevant research focuses on the principle, circuit design, and control mode of this device, as well as its impact on the power grid. Numerous pieces of evidence indicate that parameter design results significantly affect the performance of such devices, and selecting scientifically reasonable control strategies can significantly improve the reliability of the power grid. Some scholars have also discussed the problem of fault detection in inverters and proposed corresponding detection models, which have shown high reference value. Currently, many scholars have studied the design and control mode related issues of GCI from different perspectives. Existing research has shown that design parameters directly affect the performance and efficiency of such devices, and scientific and efficient control strategies are beneficial for improving their operational stability. For example, simulation analysis by MIT scholars shows that after optimizing the design parameters, the performance of GCI is significantly improved, and it can operate efficiently and smoothly in complex power grids. Researchers from Beijing Institute of Technology discussed the changes in inverter performance under extreme temperature and humidity conditions, and then proposed some targeted prevention strategies. Some scholars have discussed the fault diagnosis and protection strategies of GCI, and discussed its impact on the reliability of the power grid. The University of California conducted a study analyzing the performance changes of GCI in different working environments, and found that in high-altitude and high humidity environments, the insulation of GCI significantly decreases, thereby affecting its reliability. Then, based on the research results, corresponding protection modes were proposed to provide support for its reliable operation under high cold and humid conditions.

Although the performance level of GCI continues to improve and its application areas have significantly expanded, there are still some key issues that need to be addressed. Some theoretical models related to GCI have been established, but corresponding empirical verification is still lacking, so the application value of these models in complex working conditions is not very clear. Related experimental studies have shown significant effectiveness in validating these models, and the results obtained can provide support for their practical applications. Some scholars have discussed the design and control mode of GCI, but did not consider the limitations of complex environments and conditions during the research, resulting in weak reference value of the obtained results. For example, in high altitude or low temperature environments, the performance of GCI will significantly decrease. When designing, it is also necessary to consider factors related to power grid configuration and energy characteristics, in order to carry out targeted optimization design. In addition, there have been many studies on the fault diagnosis and protection of inverters, but the practicality of the research results has not been fully tested [3]. The relevant empirical analysis results indicate that commonly used fault diagnosis techniques do not meet the application performance requirements in complex power grid environments. Therefore, it is necessary to analyze these scenarios and application conditions, and propose more reliable and adaptable fault diagnosis models. This is of great significance for improving the efficiency of GCI design and is also a research hotspot in this field. In summary, there have been many studies on this type of device, but the theory and practical application have not been closely integrated, and further in-depth research is needed in the future.

This study discusses the structural composition and principles of GCI, and conducts simulation analysis to provide guidance for the optimization design of such devices. Our objective is to elucidate effective methodologies for readers to comprehend and utilize these devices. We focus on critical issues such as the design and optimization of inverter parameters for diverse operating conditions and performance standards, enhancement of inverter stability and efficiency, and the advancement of fault diagnosis and protection techniques for inverters. However, we must concede certain study limitations. Primarily, while our research predominantly relies on simulation and theoretical analysis, these methodologies may not encapsulate the complexity inherent in real-world operational environments. Grid and load conditions in practical settings may surpass our model's complexity, potentially limiting the applicability of our findings in certain scenarios. Secondly, constraints related to technology and resources may prevent us from considering all conceivable application environments and technical requirements. Although we strive to identify the most representative and prevalent circumstances, we acknowledge the potential omission of certain unique or exceptional cases.

The organization of this thesis proceeds as follows: Chapter 2 presents an in-depth analysis of the working principle and characteristic parameters of the grid-connected inverter, investigating its basic mode and parameters along with the corresponding implications on its performance and stability. Chapter 3 offers a comprehensive review of inverter performance and stability, along with strategies for enhancing these facets. Chapter 4 summarizes the primary research outcomes and noteworthy observations, suggesting potential research avenues, with specific emphasis on unresolved issues and challenges meriting further exploration.

2 The Working Principles and Key Parameters of Grid-connected Inverters.

Chapter 2.1 is an introduction to the basic operating modes of the inverter and explains the key steps of the inverter operation. Chapter 2.2 is an introduction to the key parameters of the inverter and details the impact of changes in each key parameter on the inverter.

2.1 Basic Operation Mode

The grid-connected inverter, as a key device connecting renewable energy and the power system, has a complex and precise operating mechanism. Its basic operating mode aims to achieve efficient energy conversion from direct current (DC) to alternating current (AC), while ensuring the quality of energy during the conversion process and the stability of the system. The core of the DC to AC conversion process in the grid-connected inverter is its ability to convert DC electricity from renewable energy sources (such as solar panels) into AC electricity[4]. This conversion process involves several key steps:

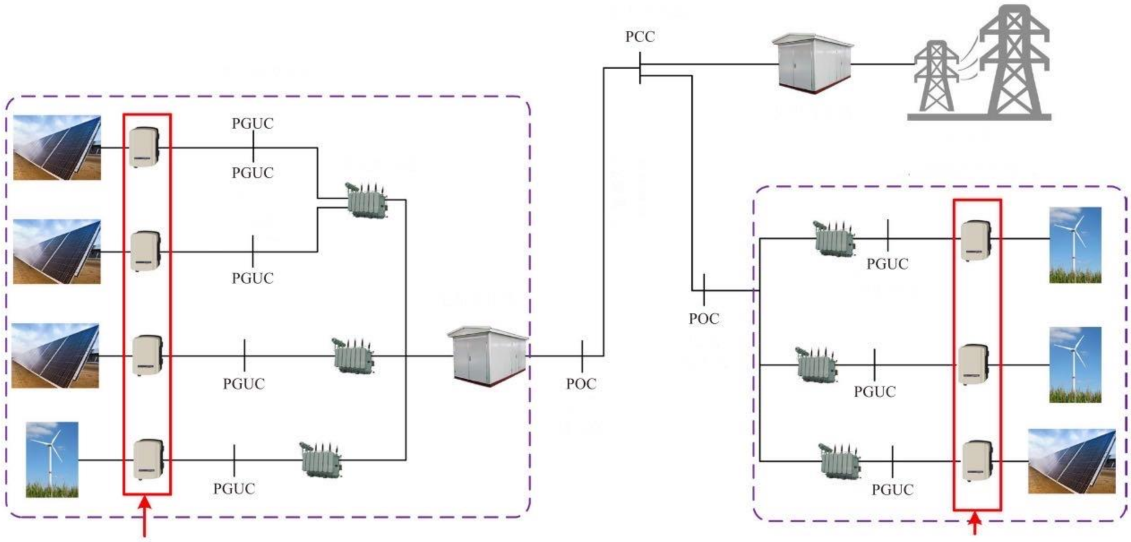


Figure1 Typical structure diagram of the high-penetration new energy grid-connected power generation system. (Review and Perspectives on Control Strategies for Renewable Energy Grid-connected Inverters, Heifei University of Technology)

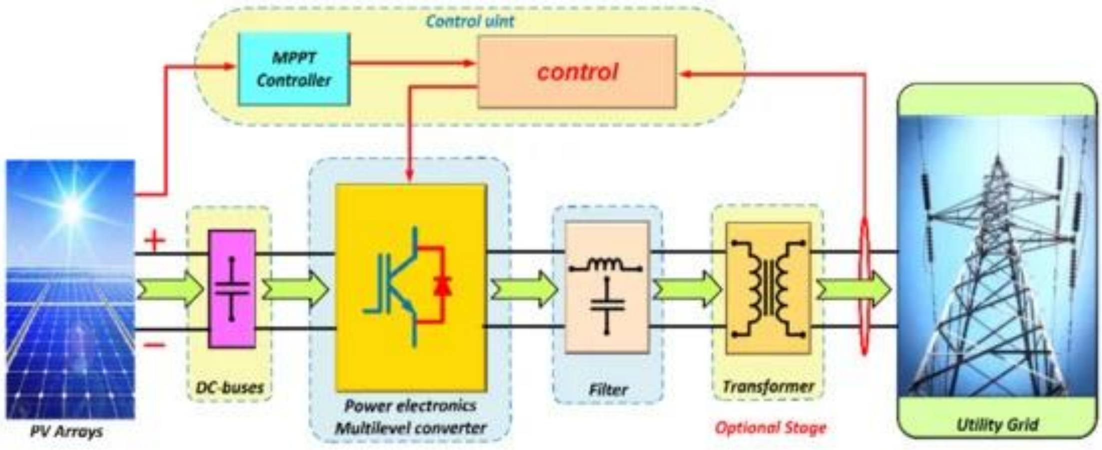


Figure 2 A photovoltaic (PV) system with power electronics and the needed control. (Review of Multilevel Inverters for PV Energy System Applications, USM)

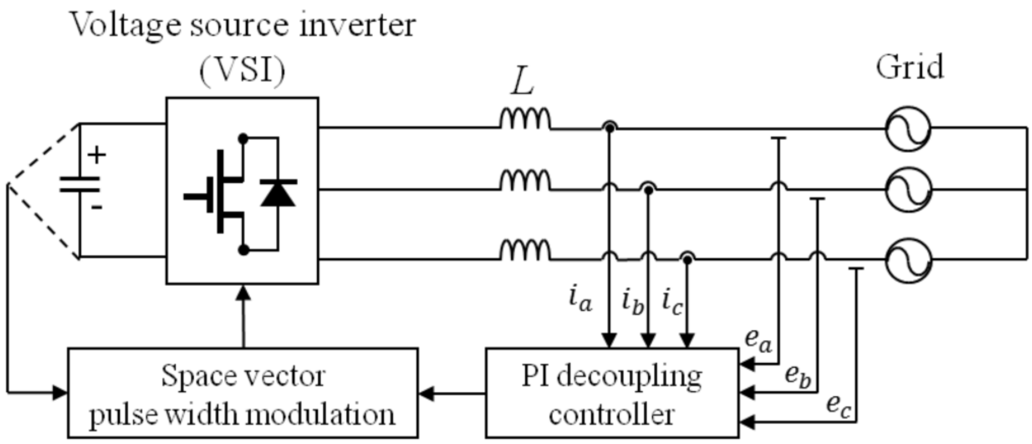


Figure 3 Block diagram of three-phase grid-connected inverter. (An Improved Current Control Strategy for a Grid-Connected Inverter under Distorted Grid Conditions, Seoul National University of Science and Technology)

Figure 1 shows that both wind and solar power require inverters connected to the main grid. It shows that the inverter is the key to realizing the integration of new energy power generation into the grid. Figure2 shows the components of a system for solar energy conversion including the PV cells, the power converters, and the control unit for the regulation of the power extracted from the PV cells. Figure3 shows a whole configuration of three-phase grid-connected inverter with an *L* filter.

2.1.1 DC input stage

The direct current (DC) input stage primarily encompasses two components. The initial component relates to energy sourcing and regulation, focusing on the origin of energy and the inverter's regulatory mechanisms. The subsequent sections discuss the voltage stability of the inverter and its influencing factors.

- Energy and regulation: The type and regulation of energy directly determine the operating mode of GCI. Under this operating condition, direct current is input to the inverter. After changes in environmental conditions, the input current will also undergo certain changes, such as significantly different output currents under different light intensities and temperatures. To better absorb solar energy and improve system efficiency, the Maximum Power Point Tracking (MPPT) tracking mode is generally selected during operation. In this mode, the system adjusts the input electrical parameters to achieve maximum output power [5]. In this tracking mode, regardless of how the environmental conditions change, the output power reaches the highest level. To meet this requirement, it is necessary to apply efficient and sensitive control systems, and in addition, it is necessary to conduct in-depth research on the characteristics of the power supply [6].

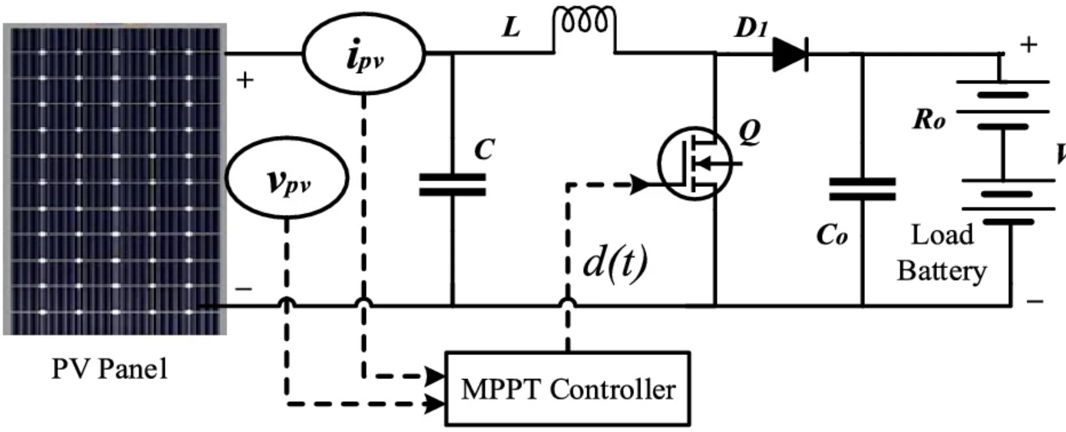


Figure 4 Photovoltaic system based on single pole MPPT control. (Improved Level 2 MPPT scheme)

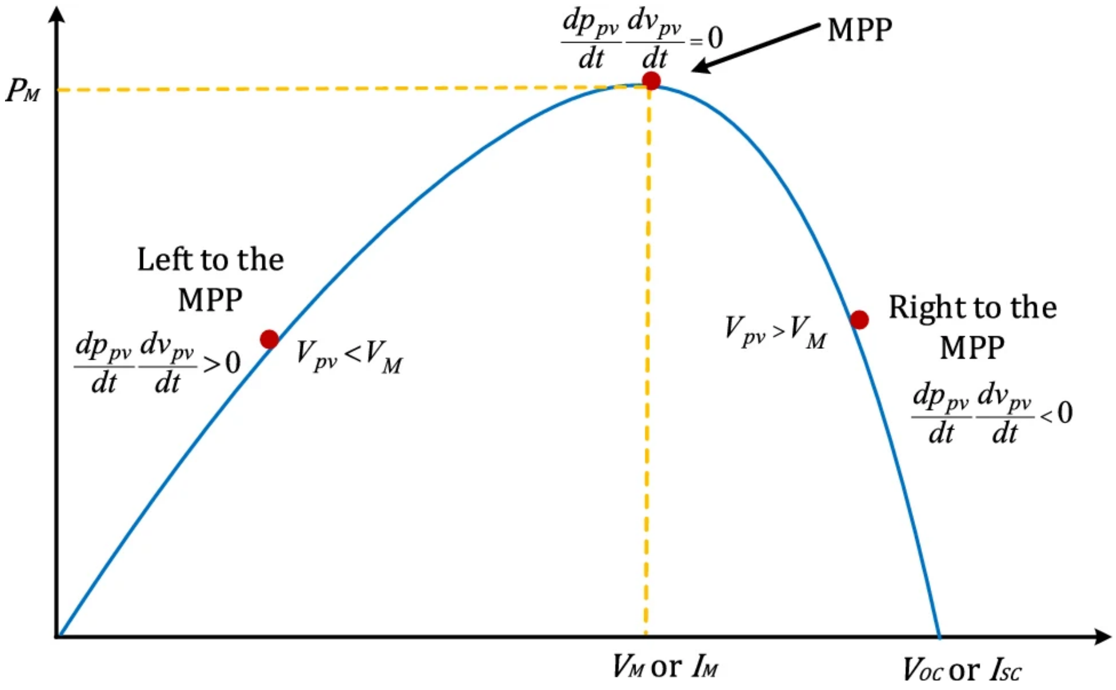


Figure 5 P-V feature curve of photovoltaic system. (An improved 2-level MPPT scheme for photovoltaic systems using a novel high-frequency learning based adjustable gain-MRAC controller, Scientific Reports)

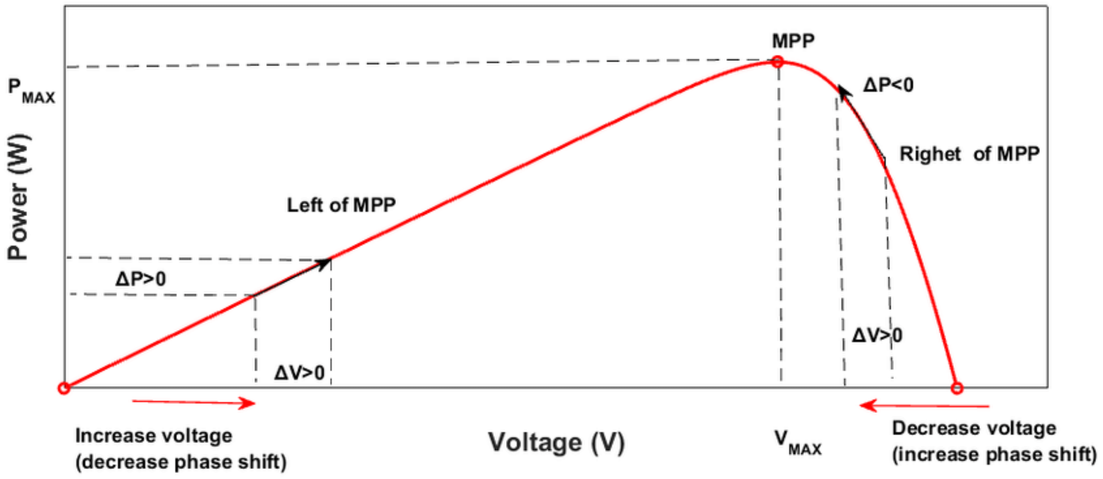


Figure 6 Behavior of Fixed Frequency MPPT algorithm with P-V curve (New MPPT Technique using Phase-shift Modulation For LLC Resonant Micro-inverter, Menoufia University, Egypt)

Figure 4 shows a photovoltaic system using a unipolar MPPT control scheme, Figure 5 shows the P-V characteristic curve of the photovoltaic panel, and Figure 6 shows the MPPT principle. A decision to reduce the phase shift is made when the extracted power from the photovoltaic panel falls below the Maximum Power Point (MPP), suggesting a progression towards the MPP. In contrast, a higher than MPP reading implies deviation from the optimal point.

- Voltage stability is crucial for inverter operation. The direct current (DC) input must be maintained at a stable level to prevent fluctuations that can adversely impact inverter performance and power output quality. To ensure stability, the inverter may integrate a DC-DC converter—a device designed to regulate and maintain the DC input voltage within desired thresholds. Operating in a switching mode, the DC-DC converter transforms the variable input into a constant, predefined voltage level, thereby augmenting system stability and efficiency[7]. Moreover, it safeguards the inverter's internal components from damage due to voltage overloads or underloads.

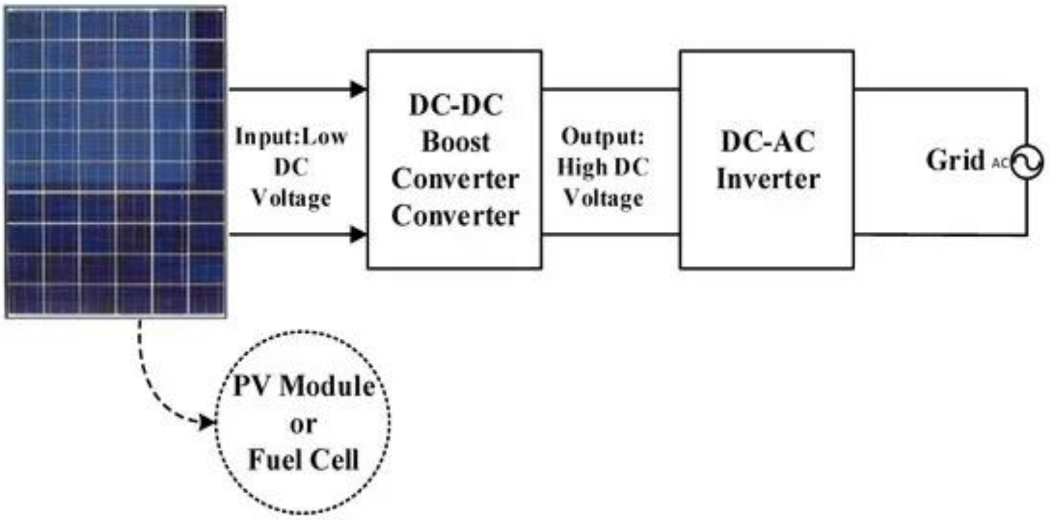


Figure 7 DC-DC converter (An Efficient Design of High Step-Up Switched Z-Source (HS-SZSC) DC-DC Converter for Grid-Connected Inverters)

Figure 7 shows an example of the use of a DC-DC converter in a circuit.

2.1.2 Switching transition stage

The switching conversion stage comprises primarily of two stages. The initial stage pertains to the switching action, providing a comprehensive explanation of the switching behaviour within the inverter. The subsequent part focuses on generating AC waveforms and provides an in-depth explanation of the AC waveforms generated by the inverter.

- Switching Action: Inside the inverter, the switching action is the key process that converts the direct current source into an alternating current source. The switching elements in the inverter (such as power electronic transistors) are driven by the control system to switch rapidly at specific time intervals, thereby converting direct current into alternating current. The core of this process lies in the precise control of the switching action, which is usually achieved by advanced control algorithms (for example, Pulse Width Modulation, PWM)[8]. The PWM control strategy can precisely control the on and off times of the switch, thereby controlling the amplitude and frequency of the alternating current and achieving precise control of the output electric energy[9].

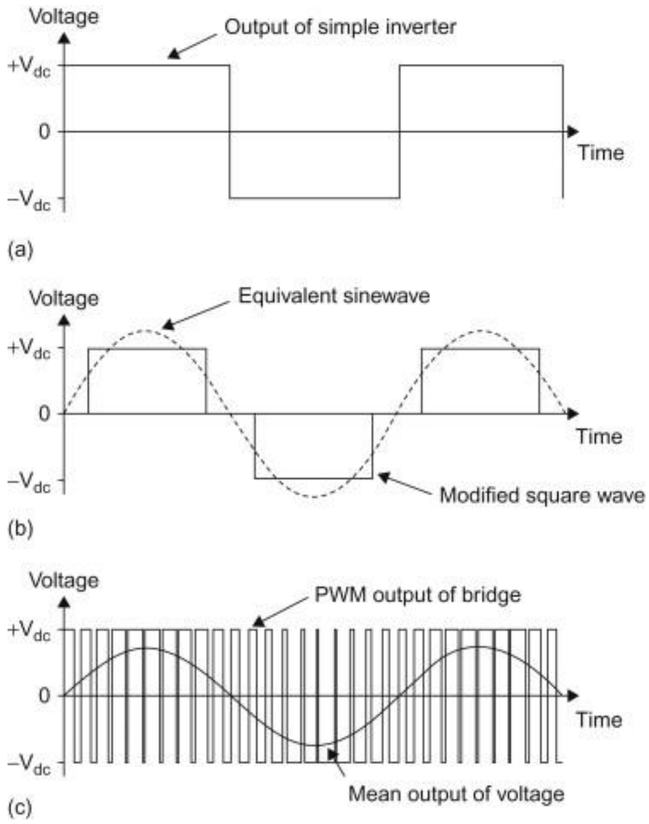


Figure 8 The output of a single-phase inverter is characterized by (a) simple square wave switching and (b) a PWM-driven quasi-sinusoidal output. (3.1 Single-Phase Inverters, System Electronics)

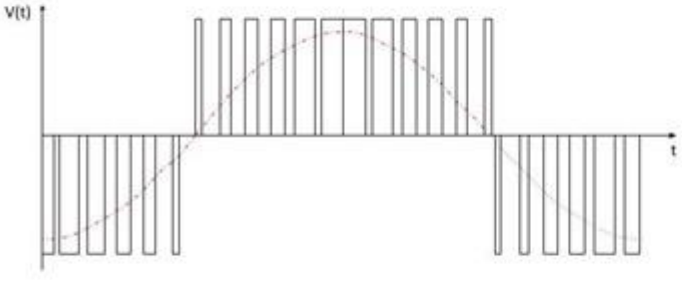


Figure 9 Pulse Width Modulation (How D.C. to A.C. Inverters Work, Steven McFadyen)

The switch of the inverter can simply alternate at the required frequency of the AC, as shown in Figure 8(a). This simple switching scheme has the advantage of simplicity, but it cannot control the load voltage, and the resulting waveform will have a high harmonic content. The root mean square (r.m.s) value of the equivalent sine wave is the same as the modified square wave. This is sometimes referred to as single pulse width modulation. By modulating the duty cycle in the appropriate manner, as shown in Figure 8(c), the average output voltage can vary in a sinusoidal manner over the switching period. The modulation frequency has been reduced. Figure 9 shows, in Pulse Width Modulation (PWM), the width of each pulse is varied, so that the overall electrical effect is similar to that of a sine wave.

- Generation of AC Waveforms: By precisely controlling the switching devices, the inverter can generate different shapes of AC waveforms, such as square waves, modified square waves, or waveforms close to sine waves. The choice of waveform depends on the design and application requirements of the inverter. For example, for some basic applications, it might only be necessary to produce square waves. However, in most cases, we aim to generate waveforms close to sine waves, as sine waves are common in nature and power systems, and they can minimize power loss and electromagnetic interference[10].

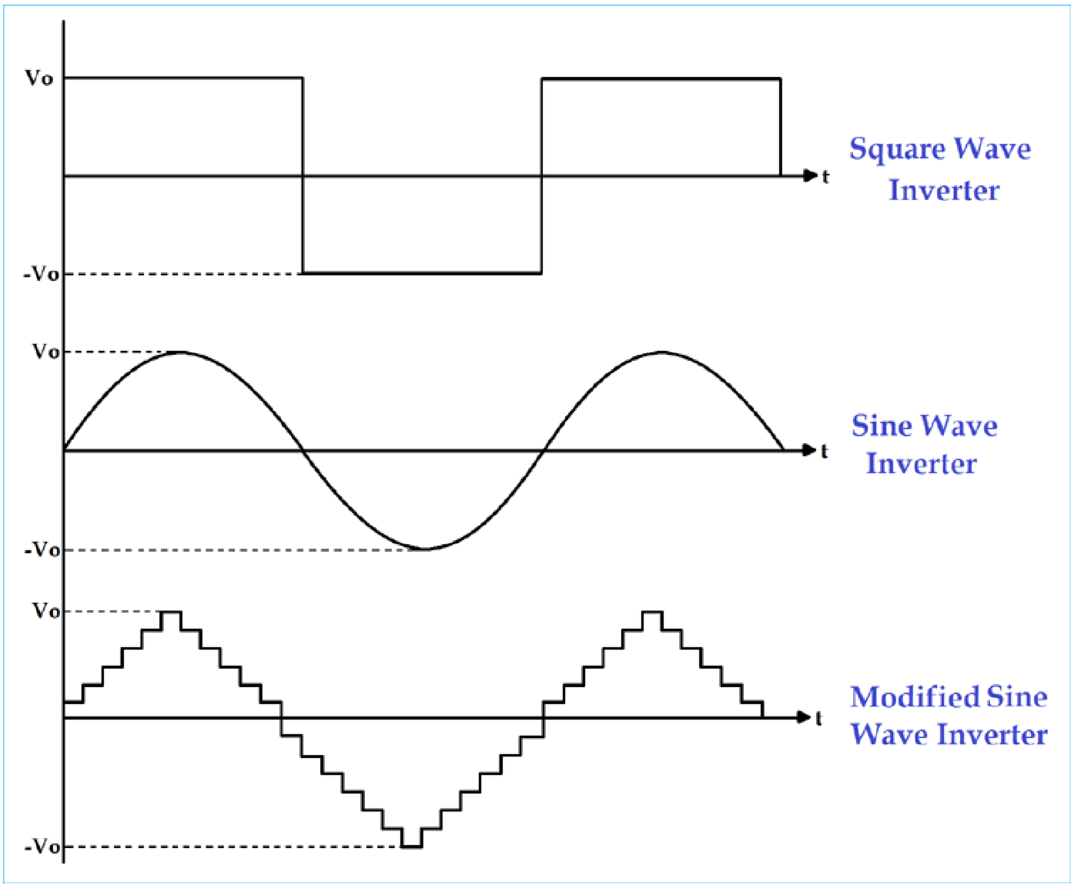


Figure 10 Inverters that output different types of waves. (Introduction to Different Types of Inverters, Ravi Kansagara)

Figure 10 shows different types of waves output by different types of inverters.

2.1.3 Waveform shaping and filtering

The filtering process consists of two primary stages. The initial stage involves filtering out harmonic components. The subsequent stage is grid-connected operation, where the inverter relies on advanced control strategies to achieve voltage and frequency synchronization with the power grid.

- Filtering process: The AC electricity generated during the switch conversion stage contains high-frequency harmonic components. These harmonics can degrade the quality of the electricity and may cause interference to the power grid and other devices. Therefore, it must be processed through a filter. Common types of filters include LC (inductor-capacitor) and LCL (inductor-capacitor-inductor) filters[11]. The purpose of these filters is to reduce the impact of harmonics, making the output AC electricity closer to the ideal sine wave[12]. The process of filter design and selection is intricate, necessitating the consideration of a multitude of factors including grid impedance, inverter switching frequency, filter size, and associated cost[13].

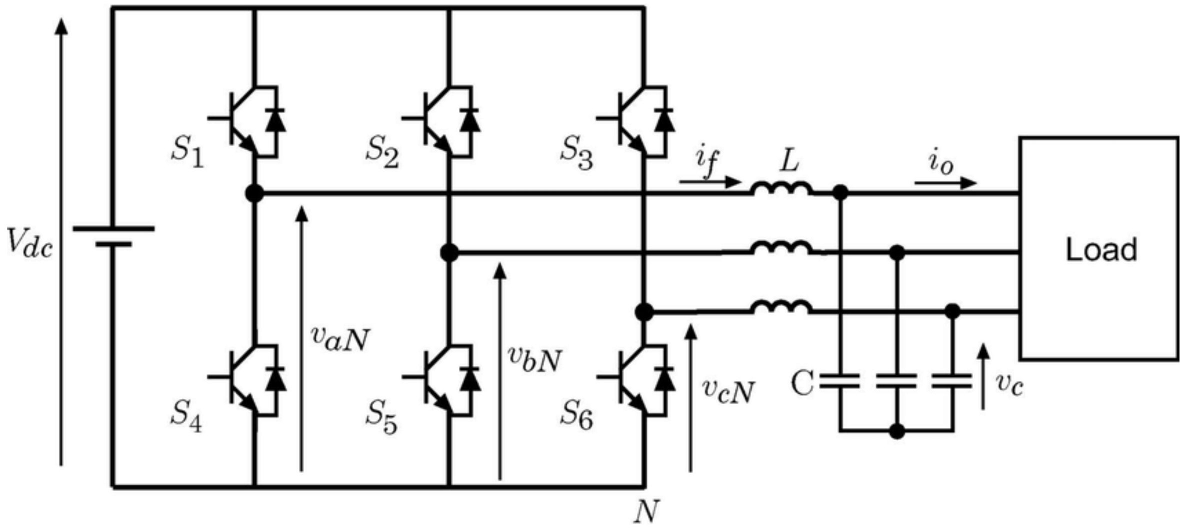


Figure 11 Three-phase inverter with LC filter (Implementation of model predictive control for three-phase inverter with output LC filter on eZdsp F28335 Kit using HIL simulation.)

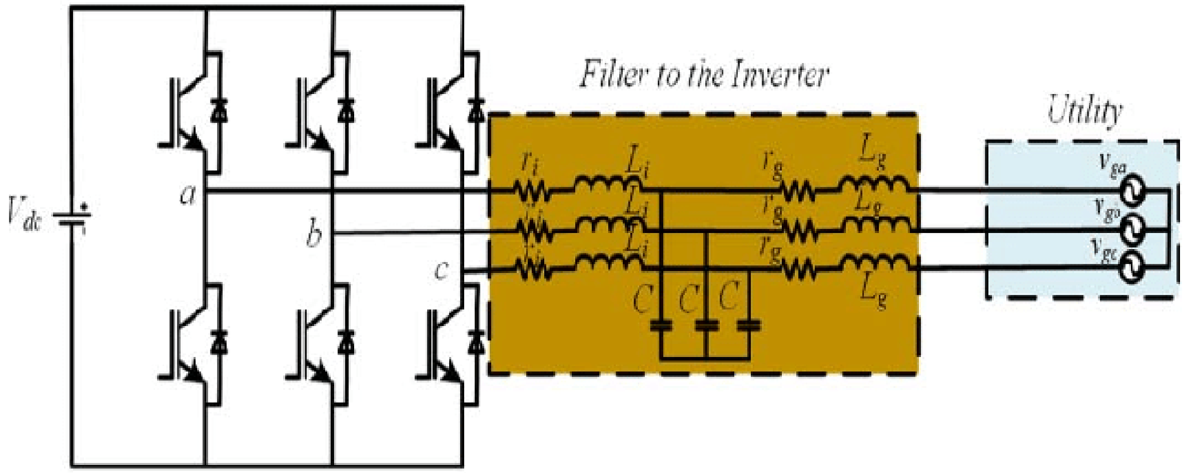


Figure 12 Three-phase inverter with LCL filter(Control of a Three-Phase Inverter under Unbalanced Grid Conditions, Missouri University of Science and Technology)

Figures 11 and 12 are models of a three-phase inverter with an LC filter and a model of a three-phase inverter with an LCL filter respectively.

- The inverter needs to control its output to synchronize with the voltage of the power grid during operation in order to improve the reliability of the power grid and avoid energy losses issues. When performing synchronous control, methods such as phase-locked loop (PLL), direct power control (DPC), sliding mode control, etc. can be selected, and there are significant differences in control accuracy and sensitivity among different modes. During grid connection, it is also necessary to ensure compliance with safety and efficiency requirements. In the event of a power grid fault, the inverter needs to be immediately disconnected to provide a certain level of protection. This passage provides a concise overview of five key control strategies:
  Phase-Locked Loop (PLL): It belongs to a feedback control system, in which the phase comparator compares the phase of the input and output signals, determines the error signal, and then adjusts the oscillation frequency through this signal. After multiple adjustments, synchronization effect can be achieved. According to the investigation, this technology has been widely applied in the fields of radio and telecommunications, and has shown good results in improving signal quality.

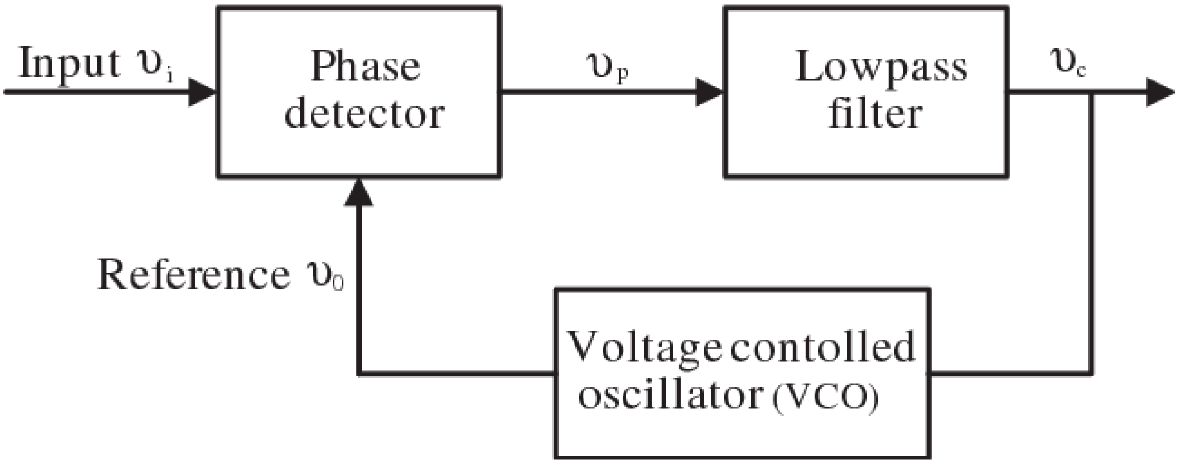


Figure 13 Schematic diagram of phase-locked loop operation.

Figure 13 is a block diagram of a simplified PLL. A phase-locked loop (PLL) is a feedback system that responds to changes in the frequency or phase of an input signal by adjusting the frequency of a voltage-controlled oscillator (VCO) until it matches the input signal. Therefore, from an attribute perspective, it is a feedback system. After continuous adjustment, PLL can control the frequency difference of the signal to zero [14]. In terms of measuring signal frequency, the accuracy can reach a very high level, but there is also a delay. Another advantage of the PLL is that it is insensitive to harmonics and noise, due to its low-pass filter and feedback loop. In this system, the phase detector is the most important component, which directly affects the accuracy of frequency measurement.

Vector control: In the field of motor control, this technology is widely used. In practical applications, vector control technology can precisely adjust the parameters related to motor speed, torque, and speed, thus greatly improving the operational accuracy of the system. When vector control is used, it is necessary to simplify the motor into a two-phase orthogonal structure, and then analyze it using mathematical methods to provide corresponding control equations. In this mode, the current and voltage related parameters of the motor can be accurately adjusted, which also improves the sensitivity of the motor's response. According to relevant information, this control technology also demonstrates high application value in the field of energy management in the system [15]. Accurately adjusting the parameters of each stage of motor operation significantly improves energy efficiency and demonstrates significant advantages in energy conservation. For example, in vector control, adjusting the motor speed and torque can achieve energy-saving effects. In this control mode, the inverter can efficiently and sensitively respond to complex load changes and disturbances, ensuring stable system performance. In industrial automation and precision machining of parts, the advantages of vector control mode are more obvious.

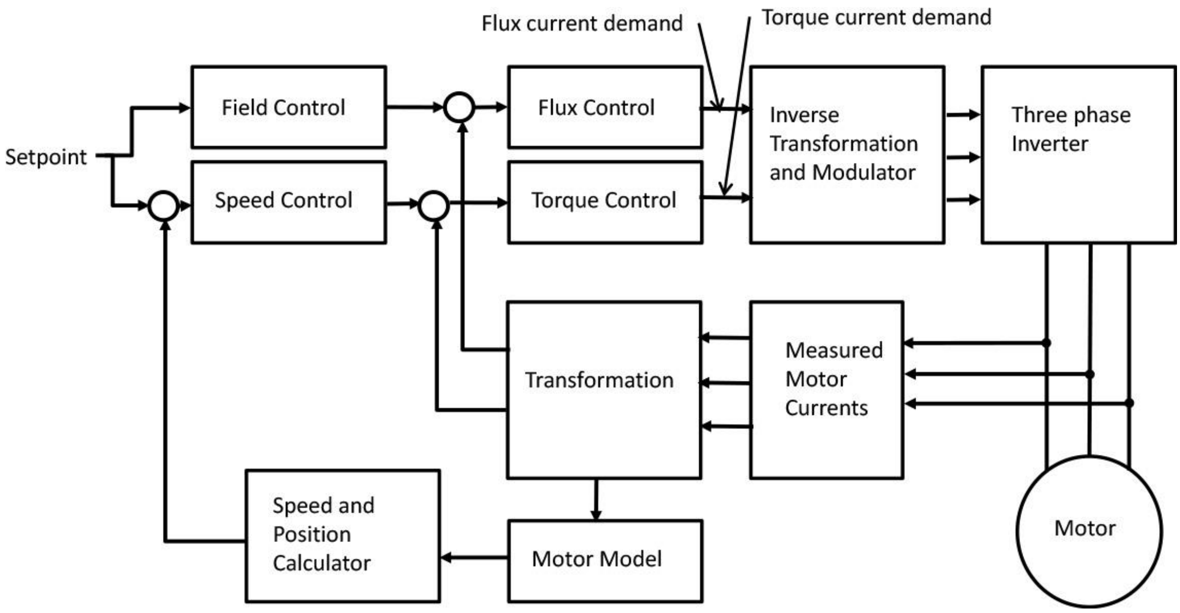


Figure 14 Vector Control System Block Diagram [16]

Figure 14 shows a simplified vector control schematic.

Direct Power Control (DPC): Direct Power Control (DPC) represents an advanced power control strategy quintessential for inverter systems, designed to instantaneously adjust power transmission to align with electric grid demands. DPC's foremost benefit is its rapid response capability, enabling swift adaptation to power system fluctuations—this is especially pivotal in renewable energy systems where power output can rapidly vary due to environmental conditions. By modulating the inverter's switching state, DPC accomplishes precise regulation of active and reactive power; the former governs the system's energy output, while the latter influences voltage and system stability. Through meticulous control over these power types, DPC not only promotes efficient inverter operation across diverse load scenarios but also bolsters grid stability. Furthermore, DPC exhibits remarkable versatility in managing the non-linear attributes and uncertainties inherent in power systems, thus ensuring effective operation even within intricate grid dynamics. This adaptability renders DPC exceptionally suited to renewable energy systems with frequent fluctuations, such as those harnessed from wind and solar sources.

Predictive control: This control mode can achieve the effect of actively responding to fluctuations, while significantly improving energy conversion efficiency. This method can dynamically anticipate the system and provide targeted control and adjustment based on the obtained results. Based on the collected historical data, predict the power grid and load for a period of time in the future, and then control it in advance. The introduction of this control technology in inverters has significant advantages, as explained in detail below [17]. Firstly, it is beneficial for GCI to actively adapt to changes in the power grid and load, providing support for improving the stability of power grid operation. In complex power grid operating conditions and nonlinear load environments, the advantages of this control mode are more obvious. The relevant experimental research results indicate that under predictive control mode, the performance of the inverter in responding to external fluctuations is significantly improved. During the operation, the voltage and frequency fluctuations of the power grid are predicted in advance, and then the output is adjusted in advance, which can significantly improve the stability of the power grid operation. When controlling clean energy systems, this technology has more significant advantages and can also meet application performance requirements well under nonlinear conditions. It can also improve the energy efficiency of the system, and after optimizing the control strategy, energy can be transmitted more efficiently.

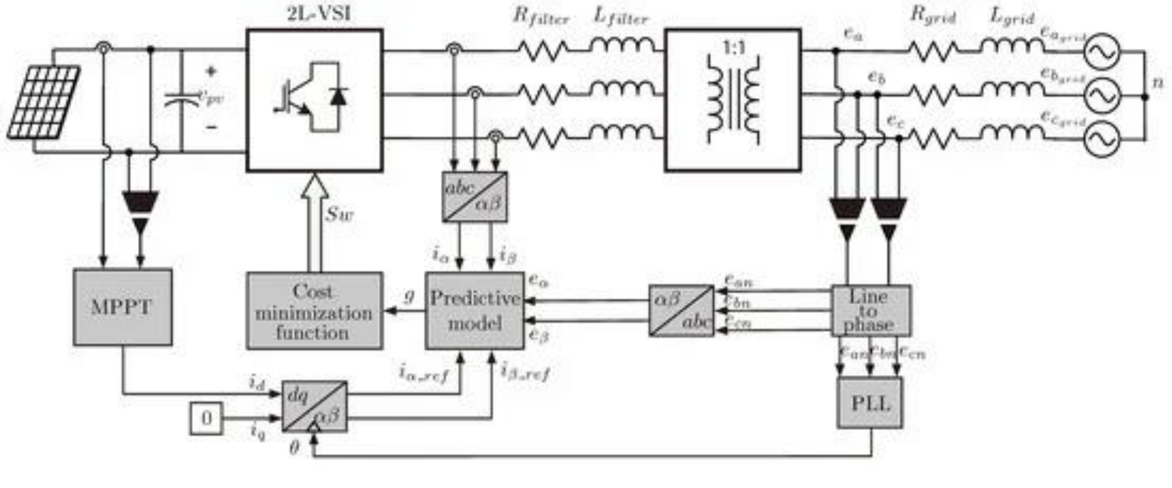


Figure 15 A model predictive current control method. (Predictive Control with Current-Based Maximum Power Point-Tracking for On-Grid Photovoltaic Applications, University of Talca)

Figure 15 is a scheme diagram of a model predictive current control method.

Sliding Mode Control (SMC): It is a typical nonlinear control strategy that can improve the response level of inverters under random disturbances and uncertain operating modes, thereby maintaining stable operation of the power grid. The key part of SMC is the sliding mode. According to extensive application experience, the robustness of this control can reach a high level, and it exhibits high adaptability under nonlinear conditions; It mainly controls the system to maintain its position in the synovial membrane, which can avoid the influence of random interference in the environment and ensure that the system exhibits high anti-interference performance. During the operation of the inverter, under sliding film control, it can work reliably under various complex power grid and load conditions. To achieve this, it is necessary to set up a high-performance sliding mode to ensure that the output of GCI is within a reasonable range and provide support for the operation of the power grid. In order to respond efficiently and sensitively to grid disturbances and load changes, the input of the inverter needs to be adjusted to quickly rebuild the sliding mode so that it enters a new stable state in a short time. This technology has clear advantages where high reliability and robustness are required, such as in industrial automation and critical infrastructure, where SMC ensures power supply continuity and reliability. The operational performance of equipment can undergo significant changes under small differences, and in severe cases, it can also cause malfunctions; Therefore, sliding film control can ensure that the inverter operates smoothly even in the face of severe fluctuations in the power grid and load.

GCI is widely used in power systems, and its main function is to convert direct current into alternating current to meet relevant grid connection requirements; These systems can collect clean energy during operation, convert it into a certain form, and output current to the power grid, thereby achieving the purpose of energy transmission. Accurate control is required at all stages in order to improve energy conversion efficiency and ensure the stability of the power grid operation. The main function of the initial inverter is to optimize the energy harvesting process, such as controlling through MPPT mode to output as much energy as possible, without considering environmental factors. In the subsequent development process, its role has undergone significant changes, requiring precise duty cycle control during the energy conversion stage to effectively improve efficiency, reduce interference with the power grid, and improve operational reliability. When the inverter outputs, it is also necessary to accurately adjust voltage and frequency related parameters to ensure grid compatibility and efficient operation of the entire system. After a power grid failure, the inverter needs to be quickly disconnected to provide safety protection, prevent further expansion of the fault range, and prevent power grid damage. The inverter needs to be strictly based on regional standards during operation, and safety and efficiency should also be considered in order to fully play its role and also facilitate long-term reliable operation. To surmise, the role of an inverter significantly overreaches the simplistic act of energy transformation, representing instead a system of considerable integration and meticulous control. It is incumbent upon such systems to continuously refine and innovate to stay abreast of dynamic technological and ecological benchmarks, thereby ensuring a secure, proficient merge of renewable energy with the electrical grid.

2.2 Key Parameter

The performance and stability of a grid-connected inverter mainly depends on its design and operating parameters, which mainly include switching frequency, switching circuit design, control strategy, filter design, and load and grid conditions, etc[18]. In the following discussion, the impact of each parameter on the inverter will be introduced individually.

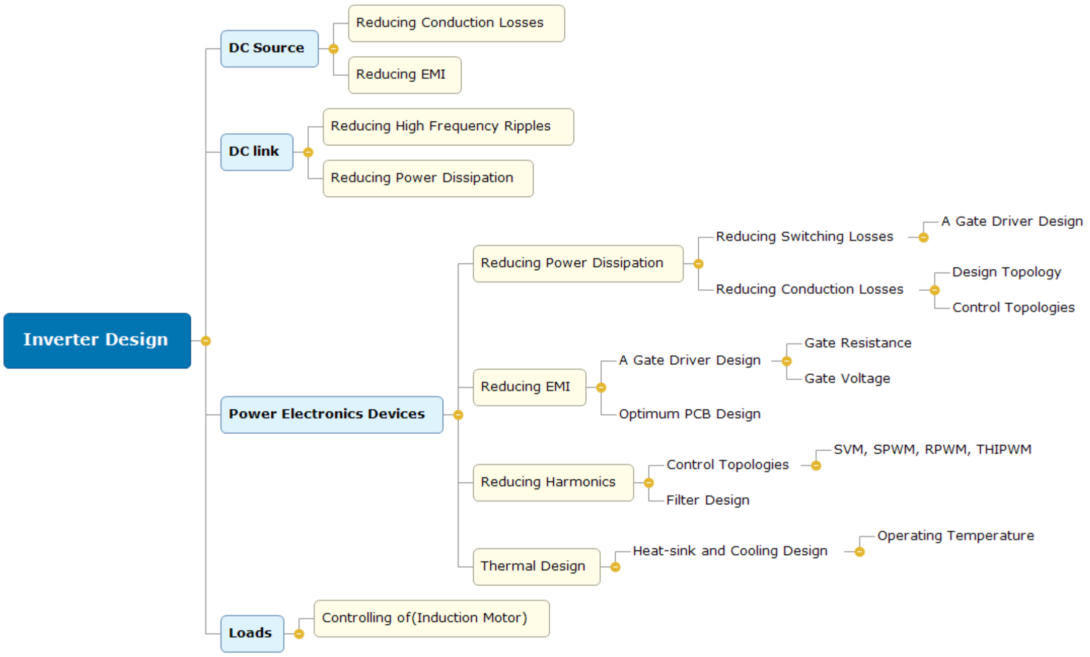


Figure 16 The main design parameters of power inverters. (Three-Phase Voltage Source Inverter with Very High Efficiency Based on SiC Devices, H. Muhsen)

Figure 16 shows the main design parameters of power inverters

2.2.1 Switching frequency

The switching frequency is a pivotal parameter in grid-tied inverter design, with direct implications for inverter efficiency and voltage quality. A trade-off exists regarding the frequency: elevated switching frequencies can yield voltage waveforms with closer resemblance to an ideal sine wave, thus improving power quality, diminishing current harmonics, and curbing damage to electrical equipment. Conversely, increased frequencies impose rigorous demands on switching devices due to the associated energy losses incurred during operation, which escalate with the frequency, thereby compromising inverter efficiency. Comparative analysis shows that electromagnetic interference may intensify as the frequency increases, which requires a significant improvement in the electromagnetic compatibility of the system and stronger noise resistance performance. After increasing the switching frequency, the volume of the inverter will decrease, and the cost will also decrease to varying degrees, making it more convenient for equipment integration. Therefore, when setting the switching frequency, it is necessary to comprehensively analyze all factors and then optimize the results obtained from the pattern.

2.2.2 Design of the switching circuit

This section mainly introduces the design of switching circuits. The design process involves many aspects such as the selection of switching components, the design of the drive circuit, and the formulation of the protection circuit. Rated voltage, current capacity, and loss characteristics are all performance parameters of switching devices, and comprehensive analysis is required when selecting them. The key factors to consider in the design process of the driving circuit include signal waveform, level, frequency, etc., to ensure that the system can be accurately activated. To better meet the requirements of protection performance, it is necessary to conduct a comprehensive analysis of factors related to overvoltage, overcurrent, and short circuit, in order to control the equipment from being damaged under certain impact conditions and meet safety requirements. A scientifically efficient switching circuit is beneficial for improving the efficiency and sensitivity of system operation, and the loss of switching components is also reduced.

2.2.3 Control strategies

Control strategies determine the response speed and accuracy of an inverter to changes in the power grid and load. When controlling inverters, different control models can be selected. Currently, commonly used models include proportional integral (PI), pulse width modulation (PWM), and sliding mode control, each of which has a certain range of applications. The following are specific explanations. PI control is relatively simple, but it lacks robustness against parameter shifts and disturbances [19]. PWM mode exhibits high adaptability to nonlinear systems, but requires a high level of computer performance. Sliding mode control stands out for its exceptional robustness to variable parameters and disruption. However, it also has complexity and high-frequency oscillation issues, which pose significant constraints on its application. To better meet the performance requirements of applications, it is necessary to improve the dynamic response and sensitivity of the inverter, but in this case, the complexity of the system will also significantly increase [20]. Overall, specific analysis of system performance, stability, and cost requirements should be conducted to optimize the selection of control modes.

2.2.4 Filter design

The configuration of the filter plays a crucial role in determining the output voltage waveform and quality of the inverter. The high-frequency harmonics output by the oscillator during operation are filtered to obtain a signal that approximates a sine wave, which is of great significance for improving system performance. The key factors to consider in filter design are inductance and capacitance. For the former, factors related to inductance value, current carrying capacity, and frequency response characteristics need to be considered, while for the latter, capacitance value and voltage endurance, and frequency behavior need to be analyzed. When arranging filters, it is necessary to analyze the current path, harmonic suppression performance and the refinement of the voltage waveform in order to effectively improve signal quality. Under a reasonable design scheme, the size of the filter is significantly reduced, the cost is also reduced, and the operating life is extended.

2.2.5 Grid interface

The grid interface is closely related to the grid connection mode of the inverter, and also determines its response performance. The key factors to consider in this design include connection points, wiring methods, and protection modes. For the first factor, it is necessary to analyze the voltage level, current level, and frequency of the grid , while for the second factor, it is necessary to analyze the power grid structure, load layout, etc. To improve the protection effect, it is necessary to analyze the power grid accidents and overheating related situations in detail, in order to effectively avoid interference caused by faults and improve the reliability of equipment operation. When the grid interface design is very reasonable, the inverter can be connected to the grid for operation more stably, and the performance of the grid will also be improved.

GCI needs to balance various factors and continuously optimize and improve during design. In the design phase, it is necessary to optimize the switching frequency, switching circuit, etc., and select appropriate filters based on the interference of clutter. In addition, it is necessary to analyze environmental factors and operating conditions in order to optimize the design of control strategies and power grid interfaces. In this design process, it is also necessary to consider factors related to inverter efficiency and output voltage stability, and control the balance of inverter efficiency, power quality and cost, reliability, robustness of the equipment.

3 Performance and Stability

The performance of grid-tied inverters is primarily reflected in the quality of their output voltage, efficiency, response speed, and stability. The quality of its output voltage can be reflected through voltage deviation. Efficiency refers to the power conversion efficiency of the inverter in transforming direct current (DC) power to alternating current (AC) power. Response speed indicates how quickly the inverter can react to changes in load and grid conditions. Stability is specifically manifested as the ability to meet the required performance under various loads and power grid conditions. The following is a specific analysis of the inverter's performance.

3.1 Output Voltage Quality

When evaluating the performance of a grid-tied inverter, one of the main factors to consider is the quality of the output voltage. This indicator is closely related to the stability of the power grid and the effective utilization of electric energy, and mainly depends on the proportion of harmonics in the output voltage. Ideally, the inverter's output voltage should be a pure sine wave to minimize potential damage to the grid and connected load equipment. However, in practice, due to the switching characteristics of the components and load nonlinearity, the output voltage of an inverter always contains certain harmonic components. If the harmonic distortion rate is too high, this can lead to not only wastage of electrical energy but also potential damage to the grid and load equipment, or it might even trigger grid failures. Voltage deviation is another important indicator of voltage quality. Under ideal conditions, its output voltage should be completely consistent with the set value. However, under actual conditions, the two are not completely consistent due to factors related to load changes and power supply voltage fluctuations. When the voltage deviation exceeds a certain range, the normal operation of the equipment will be significantly affected, and in some cases, serious faults may also occur. Components such as voltage stability, symmetry of the voltage waveform, instantaneous voltage fluctuations, and flicker are also crucial aspects of voltage quality. Voltage stability refers to the inverter's ability to maintain a stable output voltage despite changes in load and supply voltage. Instantaneous voltage fluctuations specifically reflect the magnitude of instantaneous changes in output voltage, which directly affects the operational stability of the load equipment.

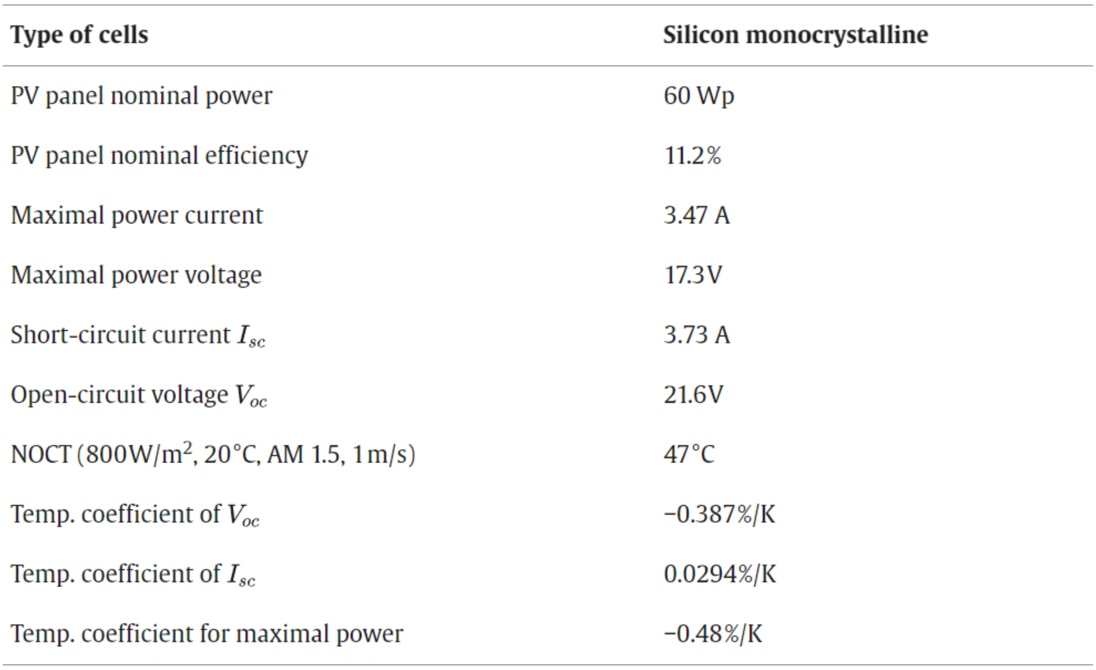
3.2 Efficiency

The efficiency of grid-tied inverters, a critical metric of energy conversion proficiency, mirrors the extent of energy dissipation during the conversion from direct current (DC) to alternating current (AC). The efficiency of inverters has a significant impact on the operating costs of the system, so it is necessary to ensure that its efficiency is controlled within a reasonable range. Enhancing efficiency remains a focal point throughout inverter design and production. The performance of inverters is closely related to various factors, such as the performance of switch components and the resistance of cables, as well as the control mode. Circuit optimization is of great significance in improving the operational efficiency of the system, and should be a key consideration in the design process. During the design process, various types of loss pipelines should be minimized as much as possible, circuit topology should be optimized, and scientific and reasonable control modes should be selected to minimize energy dissipation levels. Based on extensive experience, it is known that under the conditions of using high-performance IGBT or MOSFET transistors, switch losses can be significantly reduced. After appropriate optimization of the circuit structure, energy loss will also be significantly reduced, and conversion efficiency will be significantly improved. Maximum Power Point Tracking (MPPT), an advanced control approach, is vital for maintaining peak operational efficiency, particularly in variable-input energy systems like photovoltaics, by adapting to fluxes in environmental conditions [21]. In addition, it is necessary to ensure that the inverter maintains continuous high efficiency under different load conditions. Ultimately, the efficiency improvement of grid-connected inverters covers many aspects, including improving circuit architecture, components, internal resistance mitigation and optimizing strategic control.

3.3 Response Speed

At the same time, the response speed of the inverter can affect the accuracy of tracking load changes, energy collection efficiency and energy output. For example, in photovoltaic systems, when weather conditions change, the inverter needs to respond and adjust quickly to continue to obtain maximum energy input and output. Rapid response largely depends on the inverter's control strategy. Advanced algorithms can monitor power supply and load changes in real time, and with the inverter's adaptive control, millimeter-level efficient responses can be achieved[22]. Moreover, the system's dynamic capabilities significantly influence response rapidity. Inverter designs should cater to swiftly shifting operational demands while ensuring efficiency and stability, often involving the fine-tuning of circuit architecture, the integration of fast-operating high-grade components, and robust thermal regulation to maintain component efficacy[23]. In conclusion, optimizing response speed in grid-tied inverters relies on advanced control methodologies, systemic design enhancements, and meticulous component selection.

Table 1 Table of Technical characteristics of ISF-60/12 PV panel. (Performance evaluation of single-stage photovoltaic inverters under soiling conditions)



Type of cells	**Silicon monocrystalline**
PV panel nominal power	60 Wp
PV panel nominal efficiency	11.2%
Maximal power current	3.47 A
Maximal power voltage	17.3V
Short-circuit current I_{sc}	3.73 A
Open-circuit voltage V_{oc}	21.6V
NOCT (800W/m^2, 20°C, AM 1.5, 1 m/s)	47°C
Temp. coefficient of V_{oc}	−0.387%/K
Temp. coefficient of I_{sc}	0.0294%/K
Temp. coefficient for maximal power	−0.48%/K

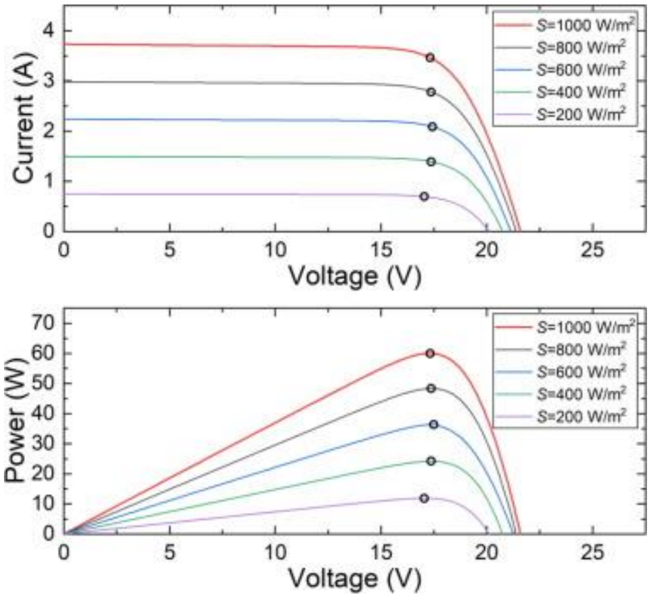


Figure 17 Solar irradiation influence on PV panel current–voltage (top) and power-voltage (bottom) characteristics with cell temperature *T* = 25℃. (Performance evaluation of single-stage photovoltaic inverters under soiling conditions)

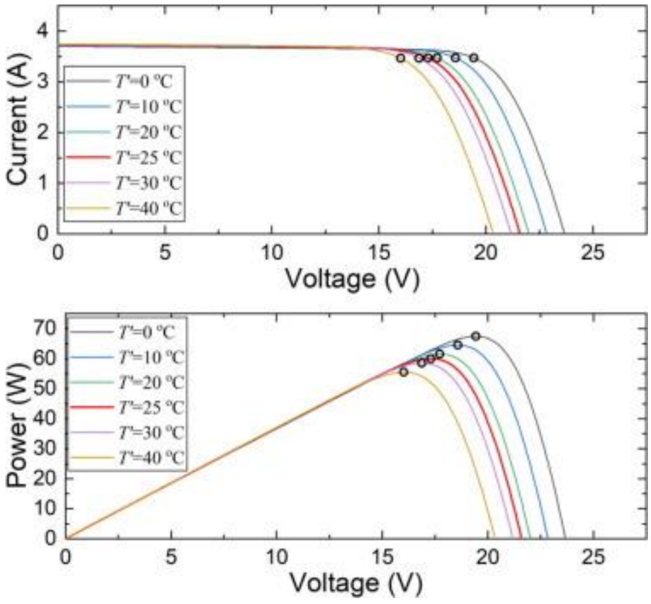


Figure 18 Cell temperature influence on PV panel current–voltage (top) and power-voltage (bottom) characteristics under incident irradiation. *S*=1000 W/ m2. (Performance evaluation of single-stage photovoltaic inverters under soiling conditions)

Table 1 shows the table of technical characteristics of ISF-60/12 PV panel. Figure 17 and 18 shows the impact of solar radiation and battery temperature on the current, voltage, and power of photovoltaic panels.

3.4 Stability

The stability of grid-tied inverters stands as a pivotal metric of performance, gauged by their steady operation across diverse conditions and in the face of faults. Stability is intrinsically tied to the inverter's reliability and longevity, exerting a profound influence on the safety and operational efficacy of the power grid. Stability is closely related to the hardware performance of the inverter, and is also influenced by the control mode. In general, a higher overload tolerance should be set to avoid faults caused by overload conditions [24]. In addition, in the control process, it is also necessary to prevent issues related to device overheating. To meet this requirement, an efficient thermal management mode needs to be set up, which can quickly respond when the temperature exceeds a certain limit. To improve the protection sensitivity of the system, it is necessary to set overvoltage and overcurrent reasonably, which can automatically protect the inverter under large impact conditions and avoid damage. Control strategies are another bedrock of stability, mandating robust and adaptive functionalities within the inverter. Robustness enables the inverter to respond to changing conditions and modeled differences, while adaptability allows the control strategy to be automatically recalibrated based on grid changes and load changes. These require high requirements for control algorithms, and in order to effectively improve control performance, control technologies related to fuzzy logic, adaptive control, and artificial intelligence can be selected during the design process. The fault diagnosis performance of inverters is also of great significance. In the event of a fault, it is necessary for them to efficiently determine the cause of the fault and respond promptly. Predicting and identifying faults in advance, and doing a good job in response, is of great significance for handling faults. At the same time, isolation work should be done well to avoid further expansion of the fault range and adverse effects [25]. The stability of GCI is a key factor to consider in the system design process, requiring comprehensive analysis and optimization in terms of software, hardware, and control modes.

3.5 Optimization of Control Strategies

Control strategies are integral to the performance and stability of grid-tied inverters. In the control process, it is necessary to ensure that the inverter can operate efficiently under various complex conditions and will not have a significant impact on the power grid [26]. After continuous optimization, a high-performance control scheme can be developed, which can significantly improve its response sensitivity and improve more efficient tracking of power grid changes, providing support for improving power grid stability. The main factors that need to be considered in the design process of control strategies are control structure, model selection, and parameter settings [27]. At present, in the field of inverter control, model predictive control (MPC) has shown high predictive performance, effectively improving the dynamic capacity of inverters. It can also operate smoothly under complex nonlinear conditions, and the utilization efficiency of system resources is greatly improved. The advantage of adaptive control is that it can efficiently and sensitively adjust relevant control parameters according to system changes, but this also puts higher requirements on control algorithms. Fuzzy control leverages fuzzy logic to handle uncertainties and nonlinearities, imparting robustness to the control process, yet its design and implementation demand considerable expertise. The integration of these strategies can better cope with complex changes, but the complexity of the control system will also significantly increase, thus requiring a reasonable balance [28]. After optimizing the control mechanism, not only the output voltage quality of the system is significantly improved, but also the overall performance and reliability of the power system can be improved.

3.6 Refine of Design

Optimization design: When optimizing the design of an inverter, multiple factors need to be considered, including component type, circuit configuration, thermal management, component selection, and control strategy. Therefore, in order to better meet the performance requirements of inverters in all aspects, careful planning is needed to determine the basic scheme and continuously optimize and adjust it. Below are delineated key aspects of inverter design refinement:

- Optimization of circuit layout: Circuit layout is a key consideration, and the reliability of the circuit structure and inverter is closely related. Streamlining the circuit layout can minimize wire lengths and resistance, consequently diminishing line losses and bolstering conversion efficiency. Optimizing the circuit structure can also increase the service life of the system and reduce the probability of system failure.
- The importance of thermal design: Thermal design is also a key factor to consider in the design process, which is closely related to the performance of the system. Scientific thermal design strategies can help reduce the operating temperature of equipment, while also reducing the occurrence of overheating and failures. Under optimal thermal conditions, the device can also operate efficiently, and the conversion efficiency will be improved to varying degrees. Therefore, targeted optimization is needed for the thermal design scheme.
- Efficacy of Thermal Design: Thermal design is a pivotal element in the engineering of grid-tied inverters, as it directly influences performance and stability. Under reasonable heat dissipation conditions, the operating temperature of the device can be effectively reduced, thereby improving stability. In addition, a reasonable heat dissipation solution is also conducive to controlling the increase in semiconductor resistance and avoiding the adverse effects of increased resistance on device operation. Therefore, reasonable thermal design is of great significance and is also a key factor to consider in the design process.
- Adaptability of control strategies: At the heart of grid-tied inverter design are control strategies, whose adaptability critically affects system performance and stability. A highly adaptable strategy can efficiently adapt to complex grid and load changes, improve output power quality, and reduce system failure rates. A highly adaptive control strategy is beneficial for improving operational consistency under various operating conditions, thereby improving system reliability, and also providing support for the functionality of the inverter.

In summary, a comprehensive analysis of the above factors is required in the design of inverters, followed by detailed optimization to ensure that they can respond efficiently and sensitively under various complex stochastic conditions, providing support for the smooth operation of the power system.

3.7 Impact of Grid Interactivity

GCI needs to interact efficiently with the power grid during operation to adapt to grid demand and minimize the impact of clean energy grid connection on the power grid. To meet these requirements, it is necessary to do a good job in frequency regulation, phase synchronization, and control voltage fluctuations within a reasonable range. These are of great significance for improving the stability of the power grid and directly determine its work efficiency. Frequency adjustment is a key factor that needs to be considered when interacting with the inverter. The purpose is to control the frequency between the inverter and the grid to facilitate the coordinated operation of the two. The difference in frequency should be within a small range. If it is large, it can have a significant impact on the stability of the power grid and may even lead to faults in some cases. Phase synchronization mainly requires that the voltage phase of the inverter and the power grid meet certain synchronization requirements, thereby providing support for the transmission of electrical energy. Without proper phase coherence, energy losses may ensue, compromising grid performance. During the voltage control process, it is necessary to accurately adjust the output voltage based on the fluctuation of the power grid voltage, in order to control the stable operation of the power grid and avoid obvious impacts. The output voltage of the inverter should be within a certain range. If it exceeds the range, it will significantly affect the balance of the power grid, and in severe cases, it may lead to device damage. Overall, reasonable frequency regulation, phase synchronization, and voltage control are of great significance for the interaction between the two, and can also better adapt to changes in the power grid, providing support for improving the operational performance of the power grid. These are key considerations in the design process.

3.8 Ultra-High-Capacity Inverters

The capacity of the inverter is closely related to its working performance. Increasing the capacity appropriately can increase the power generation, but it may also bring certain adverse effects. Based on practical application experience, it has been found that the advantage of ultra-high capacity inverters is that they can efficiently convert energy during peak periods of light energy. However, tThey often operate at part of their maximum power point, reducing their efficiency, especially when operating below their optimal capacity. When the light intensity is poor, the startup duration of the large capacity inverter will also increase, and its operating and maintenance costs will also increase. Overcapacity can lead to more severe wear and tear, significantly affecting its lifespan. However, in areas with consistently good lighting conditions, the advantage of large capacity inverters is evident, as they can efficiently convert energy over a long period of time. With the improvement of technological level and a large number of applications, the application advantages of large capacity inverters are also clearly demonstrated[29]. Therefore, in practical applications, it is necessary to conduct a comprehensive analysis of various factors, while improving energy collection efficiency and considering its drawbacks and limitations.

4 Conclusions

This article introduces the modeling of photovoltaic systems with grid connected inverters and further analyzes the future research directions in this field, as well as the challenges that humans will face. Based on parameter analysis, further propose relevant solutions to improve inverter efficiency and stability. Next, the article elaborates on the current design status of grid inverters, specifically involving the selection of inductors and capacitors, circuit layout enhancement, thermal design, and other aspects. In practical applications, the scientific design of the above devices can ensure the high-quality output, fast response, and stable operation of the inverter, thus ensuring the overall stability of the power system. In addition, this article also discusses in detail the improvement of control strategies. During this process, a series of advanced control theories and technologies are presented, such as Model Predictive Control (MPC), Adaptive Control, and Fuzzy Control. Fully applying these theories and technologies to practice can undoubtedly improve the dynamic and static performance of inverters, reduce the adverse effects of power grid and load changes on the entire system, and thus extend the service life of the system. From the current situation, there are still many unresolved issues in the field of inverter research, such as the unsatisfactory efficiency and stability of inverters, especially in complex power grid scenarios and fluctuating load conditions, where their performance will be greatly reduced. Further optimization is needed in the future. With the increasing call for environmental protection from humans, developing inverters with low energy consumption has become a trend. In practical applications, the performance and stability of inverters are directly related to energy utilization efficiency. Therefore, in the future, humans still need to continuously innovate in technology to improve the performance of inverters and achieve minimum energy consumption. In summary, this study can provide reference for enterprises to design and optimize grid connected inverters, and has certain practical significance. Future endeavors should persist in investigating the practical application challenges of grid-connected inverters and devising innovative solutions to further scientific and technological advancements in this domain.

References

[1] Naga Lakshmi Thotakura, Mohd. Hasan Ali, 2022. Smart Inverters and Controls for Grid-Connected Renewable Energy Sources.

[2] Ali Q. Al-Shetwi, M.A. Hannan, Ker Pin Jern, M. Mansur, T.M.I. Mahlia, 2020. Grid-connected renewable energy sources: Review of the recent integration requirements and control methods.

[3] J. Rocabert, R. Capó-Misut, R. S. Muñoz-Aguilar, J. I. Candela and P. Rodriguez, 2019. Control of Energy Storage System Integrating Electrochemical Batteries and Supercapacitors for Grid-Connected Applications

[4] Ngoc-Bao Lai, Kyeong-Hwa Kim, 2016. An Improved Current Control Strategy for a Grid-Connected Inverter under Distorted Grid Conditions.

[5] Pankaj Sahu, Rajiv Dey, 2021. An improved 2-level MPPT scheme for photovoltaic systems using a novel high-frequency learning based adjustable gain-MRAC controller. Scientific Reports volume 11, Article number: 23131 (2021).

[6] Nehmedo Alamir, Mohamed A. Ismeil, Mohamed Orabi, 2017. New MPPT technique using phase-shift modulation for LLC resonant micro-inverter. In: Power Systems Conference (MEPCON), 2017 Nineteenth International Middle East.

[7] Rahul Kumar, Ramani Kannan, Narinderjit Singh Sawaran Singh, Ghulam E Mustafa Abro, Nirbhay Mathur, Maveeya Baba, 2022. An Efficient Design of High Step-Up Switched Z-Source (HS-SZSC) DC-DC Converter for Grid-Connected Inverters.

[8] J. Neil Ross, 2012. System Electronics. In Practical Handbook of Photovoltaics (Second Edition).

[9] Steven McFadyen, 2014. How D.C. to A.C. Inverters Work.

[10] Ravi Kansagara, 2018. Introduction to Different Types of Inverters.

[11] Carlos Gurrola-Corral, Juan Segundo, Miguel Esparza, Roel Cruz, 2020. Optimal LCL-filter design method for grid-connected renewable energy sources.

[12] Ihab S. Mohamed, Sherif A. Zaid, M.F. Abu-Elyazeed and Hany M. Elsayed, 2016. Implementation of model predictive control for three-phase inverter with output LC filter on eZdsp F28335 Kit using HIL simulation. June 2016International Journal of Modelling Identification and Control 25(4):301-312.

[13] Vikram Roy Chowdhury, Subhajyoti Mukherjee, Pourya Shamsi, Mehdi Ferdowsi, 2017. Control of a three-phase inverter under unbalanced grid conditions. In: 2017 IEEE Energy Conversion Congress and Exposition (ECCE). 10.1109/ECCE.2017.8096537.

[14] Spark Xue, Bogdan Kasztenny, Ilia Voloh, Dapo Oyenuga, 2007. Power System Frequency Measurement for Frequency Relaying. In: Western Protective Relay Conference At: Spokane, WA.

[15] Arangarajan Vinayagam1, K. S. V. Swarna1, Sui Yang Khoo1, Aman Than Oo1, Alex Stojcevski, 2017. PV Based Microgrid with Grid-Support Grid-Forming Inverter Control-(Simulation and Analysis)

[16] Vector Drive Control System Block Diagram, Vector Control. https://www.invertekdrives.com/support/iknow/vfd-fundamentals/vector-control-13

[17] Carlos Muñoz, Marco Rivera, Ariel Villalon, Ariel Villalon, Carlos R. Baier, Javier Munoz, Roberto Ramírez, Patrick Wheeler, 2021. Predictive Control with Current-Based Maximum Power Point-Tracking for On-Grid Photovoltaic Applications.

[18] H. Muhsen, 2016. Three-Phase Voltage Source Inverter with Very High Efficiency Based on SiC Devices.

[19] Teodorescu, R., Liserre, M., & Rodriguez, P. (2011). Grid converters for photovoltaic and wind power systems. John Wiley & Sons.

[20] Mohd. Hasan Ali, Naga Lakshmi Thotakura, 2022. Smart Inverters and Controls for Grid-Connected Renewable Energy Sources.

[21] Hemant Patel, Manju Gupta, Aashish Kumar Bohre, 2016. Mathematical modeling and performance analysis of MPPT based solar PV system.

[22] Milutin P. Petronijevic a, Ivana Radonjic b, Marko Dimitrijevic a, Lana Pantić b, Martin Calasan c, 2023. Performance evaluation of single-stage photovoltaic inverters under soiling conditions.

[23] Manel Hlaili, Hfaiedh Mechergui, 2016. Comparison of Different MPPT Algorithms with a Proposed One Using a Power Estimator for Grid Connected PV Systems.

[24] Behrooz Mirafzal, Aswad Adib, 2020. On Grid-Interactive Smart Inverters: Features and Advancements.

[25] Massawe, Henry Benedict, 2013. Grid Connected Photovoltaic Systems with SmartGrid functionality.

[26] Kumari Sarita, Ramesh Devarapalli, Pankaj Rai, 2020. Modeling and control of dynamic battery storage system used in hybrid grid.

[27] Tazay, Ahmad F., 2017. Smart Inverter Control and Operation for Distributed Energy Resources.

[28] Peter Unruh, Maria Nuschke, Philipp Strau, Friedrich Welck, 2020. Overview on Grid-Forming Inverter Control Methods.

[29] Yaosuo Xue, Michael Starke, Jin Dong, Mohammed Olama, Teja Kuruganti, Jeffrey Taft, Mallikarjun Shankar, 2018. On a Future for Smart Inverters with Integrated System Functions.