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Comparative Analysis of Grid-Connected Inverter for Photovoltaic Generation

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Abstract: The global energy mix is currently facing a major transformation, with the non-renewability of traditional fossil energy sources such as coal, oil and natural gas and environmental pollution becoming increasingly prominent. This paper presents an in-depth comparison between different grid-connected photovoltaic (PV) inverters, focusing on the performance, cost-effectiveness, and applicability of these two inverter technologies in PV grid-connected applications. These inverters are highly adaptable to dynamic grid conditions and provide significant harmonic suppression, but the relatively high initial cost is their major drawback. The study also explores optimization methods for filtering techniques, as well as future directions for inverter technology, including the application of smart materials, advanced control algorithms and new semiconductor materials. It is found that LCL-type inverters and three-phase inverters with active power filter have their own advantages, and the selection should be based on specific application needs, cost budget and power quality requirements. In the future, with the continuous progress of technology, we expect that the inverter technology can realize higher efficiency and better power quality to meet the increasing demand for grid-connected PV system.

Keywords: Photovoltaic generation, grid-connected inverter, active power filter, harmonic.

1. Introduction

The global energy mix is currently facing a major transformation, with the non-renewability of traditional fossil energy sources such as coal, oil and natural gas and environmental pollution becoming increasingly prominent. With the serious challenges of global climate change and environmental degradation, clean, renewable energy has become an important alternative to fossil fuels. New energy sources include solar, wind, hydro, biomass, etc., with solar energy being the leading new energy source due to its virtually unlimited supply and low environmental impact.

Photovoltaic (PV) power generation utilizes solar cells to convert sunlight directly into electricity, which has the advantages of being clean and non-polluting, with low operation and maintenance costs, and can be installed on rooftops or open spaces without taking up additional land resources. In

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addition, advances in photovoltaic technology have led to increasing conversion efficiency and decreasing costs, making it increasingly competitive on a global scale [1-3].

Photovoltaic power generation systems, as shown in Figure 1 and Figure 2, are mainly categorized into two types of structures, with transformer and without transformer (transformerless). Transformer structure usually includes PV arrays, inverters and transformers, and is suitable for large-scale grid-connected systems, which can increase the voltage level of the system, but increases the system cost and energy loss. The structure without transformer directly converts DC power to AC power, which reduces the energy conversion link and improves the system efficiency, and is suitable for small and medium-sized grid-connected or off-grid systems [5-8].

Figure 1: Photovoltaic system without transformer [2].

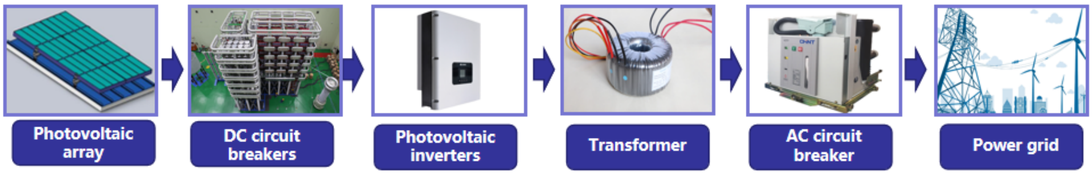

Figure 2: Photovoltaic system with transformer [2].

Filter makes one of the core components of the PV grid-connected system, and its main role is to reduce the harmonics generated during the inverter work process, and effectively improve the overall quality of power [8-10]. In the photovoltaic grid-connected more widely used filtering methods are two: one is passive filtering; the second is active filtering. Passive filtering with the help of inductors, capacitors and other components to build filtering circuit, has the advantages of simple structure, low network cost, but in a particular frequency may produce harmonics, the stability of the whole system has an impact. Active filtering technology can realize the effective control of harmonics in the power grid, which is suitable for various occasions requiring fast response and precise control. The current mainstream active filtering methods for inverters include the following as shown in Figure 3.

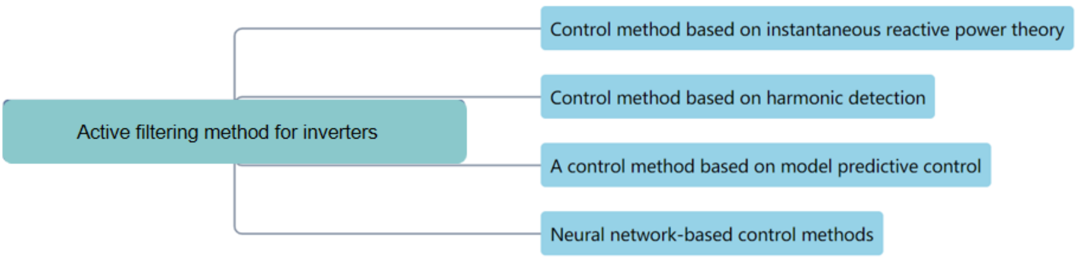

Figure 3: Mainstream Inverter Active Filtering Methods [4].

2. PV Inverters with Active Power Filters

2.1. Principle and Classification of Active Power Filters

When integrating into power systems, eliminating harmonics and compensating for reactive power are two core tasks. Active Power Filters (APFs) have shown their unique advantages in this regard. Unlike passive filters, APFs use active elements such as transistors and switches to generate a waveform that is opposite to the harmonic or disturbance signal, thereby canceling out unwanted signals and achieving more efficient filtering effects. These filters are of great value in engineering applications due to their excellent anti-interference capabilities.

After more than forty years of development and research, APFs have evolved into various types to meet diverse engineering needs. Engineers can categorize the topological structure of APFs from five different dimensions: the number of phases of the power source, the method of connection, the voltage level, the number of PWMs, and the type of energy storage elements. This classification method provides convenience for engineers, enabling them to select the most suitable APF model according to specific application scenarios. This is shown in Figure 4.

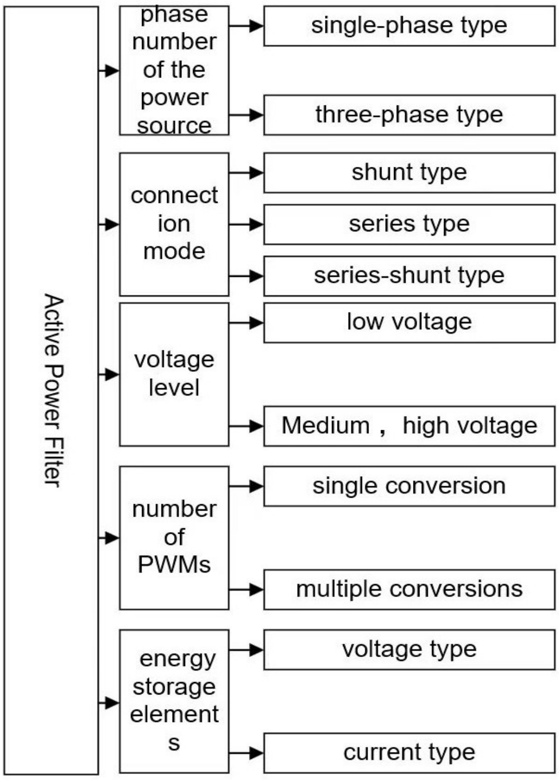

Figure 4: Classification of APF [5].

In the configuration of power systems, the topology of Active Power Filters (APFs) can be classified as single-phase or three-phase systems based on the number of phases of the power source. For three-phase systems, the design of APFs can be further refined into three-phase three-wire or three-phase four-wire systems. Particularly, three-phase four-wire APFs are more suitable for environments with high harmonic currents or where there is a three-phase imbalance. In applications with low power requirements, such as below 100kVA, single-phase APFs are a more common choice. However, when it comes to medium to high power demands, that is, 100kVA and above, three-phase APFs become the more appropriate solution.

In power systems, the topological structure of Active Power Filters (APFs) can be categorized into three main types based on their connection to the grid: series type, shunt type, and hybrid type. This classification helps in selecting the appropriate type of APF for different application scenarios. The shunt-type APF focuses on compensating harmonic currents and reactive currents in the power grid. It has the advantages of simple design, easy operation, and mature control technology, thus being widely applied in the industrial field. However, the research challenge lies in how to simultaneously improve dynamic response speed and steady-state performance. A shunt-type APF typically consists of four main parts: a signal processing module, a current calculation module, a switch tube control module, and an inverter module. The series-type APF is very sensitive to harmonic voltages in the power grid, but due to its low fundamental frequency impedance, it is not suitable for large-capacity reactive power compensation because it cannot generate enough reactive current. Additionally, LC filters need to be designed for specific frequency harmonics and cannot achieve dynamic compensation for other frequency harmonics. The hybrid-type APF combines the advantages of series and shunt APFs and is particularly suitable for medium to high voltage systems. Experiments have proven that this type of filter not only provides good filtering effects but also has high reliability and minimal impact on power supply to the load. In terms of hardware circuits, an APF usually consists of a power amplifier, a controller, and a transformer connected to the power grid. The controller is responsible for detecting the harmonic signals generated by nonlinear loads and calculating the corresponding reverse signals, which are then output to the power amplifier. The role of the power amplifier is to superimpose this reverse signal onto the original signal to eliminate harmonics. This hardware design enables the APF to effectively compensate for harmonic and reactive currents in the power grid, thereby improving the quality of electrical energy.

The design and application of Active Power Filters (APFs) can be distinguished into two major categories based on the voltage levels they are suitable for: low voltage and medium to high voltage. In low voltage and low power applications, APFs are widely popular due to the simplicity of their structure and the ease of implementing control methods. However, limited by power devices, these APFs produce significant ripple in the output current and have low efficiency and high harmonic distortion rates in medium to high voltage and high power applications, which restricts their use in these fields. To adapt APFs to medium to high voltage and high power application environments, engineers often employ multi-level converter technology. This technology includes four common circuit structures: Neutral Point Clamped (NPC), Flying Capacitor (FC), Cascaded H-bridge (CHB), and Modular Multilevel Converters (MMC). APFs with these multi-level converter structures can improve system efficiency, reduce harmonic distortion, and make them more effective in medium to high voltage and high power applications. For example, in low voltage applications, a two-level shunt APF based on a half-bridge structure is a common design choice. In medium to high voltage applications, to enhance efficiency and reduce harmonic distortion, engineers adopt more complex multi-level converter designs. These designs not only improve the performance of APFs but also expand their scope of application in power systems. Through the application of these technologies, APFs can provide more efficient and cleaner electricity for power systems at different voltage levels.

In the design of Active Power Filters (APFs), the topological structure of APFs can be divided into single-PWM converter and multi-PWM converters based on the number of PWM converters. This classification reflects the flexibility and efficiency of APFs in different application scenarios. Multi-PWM converter APFs are constructed by paralleling multiple PWM converters, a design that allows each converter to operate at a lower switching frequency, thereby enhancing system stability and enabling higher power ratings [1].

For instance, the design of a dual-PWM converter APF is a typical example, achieving high capacity and high-efficiency conversion through switching devices with low switching frequencies. However, this design also presents some challenges. When multiple converters share the same DC-

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side capacitor, circulating currents may arise, affecting the even distribution of power among the modules. If left uncontrolled, these circulating currents could negatively impact system stability. Therefore, when designing multi-PWM converter APFs, appropriate measures need to be taken to optimize the circuit and reduce circulating currents, ensuring an even distribution of power. This may involve adjustments to the circuit topology, improvements in control strategies, or the adoption of more advanced converter technologies. Through these methods, the overall performance of APFs can be enhanced, ensuring that they provide stable and efficient power filtering services in a variety of application scenarios.

In the design of Active Power Filters (APFs), the type of energy storage element is one of the key factors that distinguish different APF topologies. Based on this criterion, APFs can be classified into two main forms: voltage-type and current-type. Voltage-type APFs typically use capacitors as energy storage elements on the DC side [2]. while current-type APFs tend to employ inductors. In industrial applications [3]., voltage-type APFs are more favored due to their lower losses; the losses of capacitors are usually lower than those of inductors, which gives voltage-type APFs an advantage in efficiency. However, current-type APFs face some challenges when extending to multi-level structures. This topology requires a higher switching frequency, which not only increases the complexity of the design but also limits its application range in high-voltage and high-capacity scenarios. Therefore, the use of current-type APFs in these specific applications is not as widespread as that of voltage-type APFs.

Overall, voltage-type APFs are widely popular due to their use of capacitors on the DC side, while current-type APFs face certain design and application challenges because of their use of inductors on the DC side. These differences influence the selection and application of APFs at different voltage and power levels.

2.2. Prospects of Active Power Filters

APF is currently still in the theoretical exploration stage and has not been widely applied in practice. Despite this, APF has shown great potential in improving power quality and reducing harmonic pollution in the power grid. It is anticipated that in the future, APF will integrate multiple functions, such as harmonic suppression, power factor correction, and voltage distortion compensation, and will implement these functions through advanced control strategies.

With the rapid development of power electronics technology, especially with the popularization of photovoltaic inverters and switch-mode power supplies, the problem of ultra-high frequency harmonics is becoming increasingly prominent. Therefore, the study of APFs that can effectively suppress these ultra-high frequency harmonics will become a hot topic for future research. In terms of controller design, digital signal processor (DSP) chips tailored for different control schemes are expected to enhance the performance and cost-effectiveness of the controllers. Although intelligent control methods, such as predictive control and neural networks, have already been applied in APF research, their use in actual engineering is not yet widespread. Therefore, establishing a practical APF model is an urgent task at present, and the improvement of APF’s dynamic performance is also a potential hot topic for future research.

In high-voltage and high-power applications, the Modular Multilevel Converter (MMC) has shown promising prospects, but it may encounter three-phase AC power grid imbalances in high-voltage direct current (HVDC) transmission systems. The resulting uneven distribution of arm energy and internal circulating current issues. Solving these problems will help promote the further development of high-voltage and high-capacity APFs. The development of power electronic systems has led to widespread power quality issues, which will propel APFs to play a greater role in enhancing the power quality of electrical systems and to evolve towards a diversified direction. The multifunctionality of APFs, including harmonic isolation, reactive power compensation, voltage

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regulation, and their application in medium and high voltage power systems, all require further research and development. At the same time, finding a balance between improving filtering performance, increasing efficiency, and reducing costs is also an important direction for future research.

3. PV Inverter with Passive Filters

3.1. Classification of Passive Filters

A passive filter comprises passive components such as resistors, capacitors, and inductors. The common passive filters include L-type, LC-type, and LCL-type filters. The types of passive filters are shown in Figure 5.

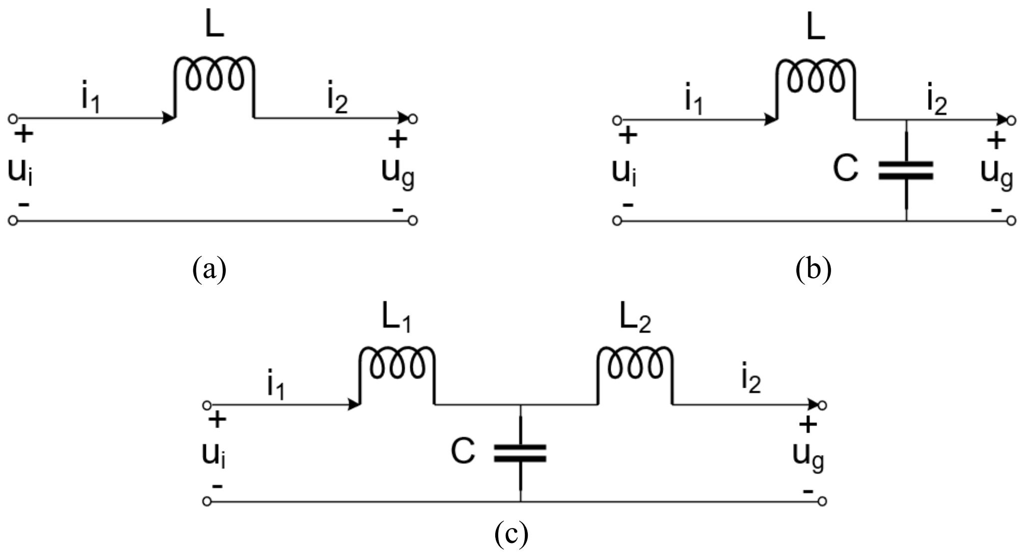

Figure 5: Different passive filters for PV inverter: (a) L-type, (b) LC-type, (c) LCL type [7].

An L-type filter, as shown in Figure 5(a), uses only inductors for filtering, and the larger the inductance, the more significant the effect. However, it will increase the size and weight of the filter and affect the dynamic response speed. An LC-type filter, as shown in Figure 5(b), is often used in independent inverter operation scenarios, and its harmonic suppression ability in the high-frequency range is better than that of the L-type filter [7]. However, its performance in other frequency ranges is the same as that of the L-type filter. There is no significant difference among the three in the lower frequency range, but the effect of the L-type filter is inferior to the other two in the higher frequency range. Under the same conditions, the performance and inductance of the LCL-type filter, as shown in Figure 5(c), are superior. The LCL-type filter has a significantly higher performance than the above two, and the required inductance is much smaller than that of the L-type filter, which makes the circuit size and weight smaller, making it more suitable for operation in high-power environments.

LCL filters are prone to resonance at specific frequencies, causing the output waveform changed. Causes include harmonic sources in the system, the interaction between the inverter and the grid, and the interaction between inverters [8]. Its intensity is closely related to the parameters of the inverter and the grid, such as the distance between the transmission line and the grid when connected, the grid impedance, the number and parameters of the inverters, and the type and order of the background harmonics [8]. Resonance can cause instability in the system, which may cause inverters to trip without reason, affecting the stable operation of the grid. In severe cases, resonance can damage the equipment and cause the deterioration in power quality.

System damping can be introduced to solve the resonance problem of LCL filters. It can significantly attenuate the resonance peaks and slow down the phase shift. There are generally two solutions for this, passive damping and active damping.

3.2. Passive Damping

Passive damping introduces damping directly into the circuit by adding resistors in series and parallel to suppress resonance peaks. For the LCL circuit, there are six places where resistors can be placed. The most widely used method is connecting the filter capacitor in series with a resistor while connecting the filter capacitor in parallel with a resistor has the best damping effect [7]. The position for placing resistors is shown in the Figure 6. Passive damping is suitable for suppressing resonance in single-inverter grid-connected systems. For the capacitor-series-resistor scheme, the greater the damping resistance, the more obvious the reduction of the resonance peak, but the high-frequency signal will also be attenuated. The capacitor-shunt-resistor scheme effectively reduces the peak, and the low-frequency and high-frequency characteristics are retained. The attenuation of the resonance peak will increase as the damping resistance decreases. However, decreasing the damping resistance leads to an increase in power consumption, resulting in a decrease in efficiency. The realization method is simple, and no complex control algorithms are required. It can effectively suppress high-frequency harmonics and improve system stability. However, the resistor consumes energy, resulting in a decrease in efficiency. It has a poor effect on suppressing low-frequency harmonics. It is suitable for large-power scenarios because it is easy to implement and does not require changes to the control strategy. But the resistor will cause additional losses.

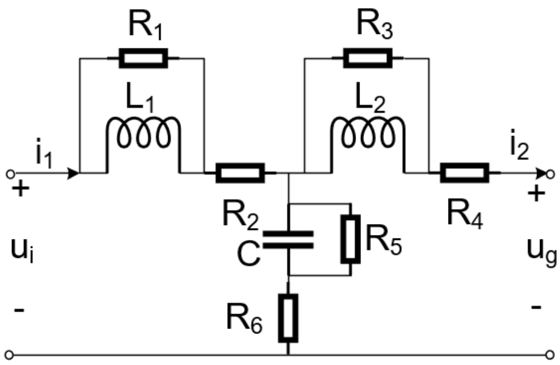

Figure 6: Position for placing resistors [7].

3.3. Active Damping

Active damping (AD) is a method that replaces actual resistors with virtual resistors without changing the circuit topology and uses control algorithms to provide feedback and generate negative resonance peaks to achieve damping effects, thus avoiding the power loss caused by actual resistors and simultaneously suppressing resonance peaks. Common methods include notch filter active damping control and state variable feedback active damping control [7].

Notch filter active damping control: By introducing notch filters into the control loop, the method effectively suppresses specific frequency harmonics and improves the power quality of the system. The design and implementation are relatively simple and suitable for various inverter systems. It can significantly improve system stability and reduce the impact of resonance peaks [8].

State-variable feedback active damping control utilizes state-variable feedback to control the system state precisely and with good adaptability. It can improve the system's dynamic response performance and quickly suppress resonance phenomena [9]. However, the design and

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implementation are relatively complex and require a comprehensive modeling and analysis of the system state.

Compared with passive damping, active damping does not require additional physical resistance, avoiding additional power loss in the system. The system damping is increased by the control algorithm, improving the system's operating efficiency [10]. The parameters can be adjusted by software to adapt to different working conditions and requirements. The active damping can effectively suppress the resonance peak and improve the stability and power quality of the system.

However, the use of notch filters requires knowledge of the system resonant frequency, but due to its change with various factors, the damping effect is weakened, making it unsuitable for actual use. The control algorithm for state variable feedback active damping control is complex, and the requirements for the inverter control circuit are high. In addition, high-frequency noise is amplified in the system's differential operation, and the digital control differential can only be approximated, which will weaken the active damping [7].

Active damping is suitable for systems that require high efficiency and low loss. The control algorithm generates virtual resistance to avoid the additional loss of passive damping, improving system efficiency and stability. It is often used in applications where high system response speed and harmonic suppression are required.

4. Comparison and Outlook

In PV grid-connected inverters, APFs and passive filters have their own advantages and limitations in terms of harmonic suppression. Passive filters have a simple structure and lower cost, but may resonate with the grid at specific frequencies, affecting system stability. Their design is usually based on a specific harmonic frequency and is less adaptable to frequency changes. In contrast, active filters can dynamically compensate for harmonics in the grid, providing a more flexible and effective solution. APFs achieve real-time compensation of harmonics by monitoring the grid conditions in real time and injecting currents equal in size and opposite in direction to the harmonic currents. However, the complex control algorithms and high cost of APFs are the main obstacles to their wide application.

To address the issue of passive filters that may resonate at specific frequencies, future research could explore the application of smart materials such as piezoelectric materials or shape memory alloys in filters, which can dynamically adjust their physical properties according to the real-time conditions of the grid to optimize the filtering effect and reduce the risk of resonance. In addition, by integrating advanced sensors and control algorithms, passive filters can respond more intelligently to grid changes, improving their adaptability and stability. For example, machine learning algorithms are used to predict and adapt to dynamic changes in the grid and optimize filter parameters for more accurate harmonic suppression.

Although active filters have good harmonic suppression capability, their high manufacturing cost prevents them from being used on a large scale. Reducing the manufacturing cost of active filters is one of the key research directions in the future. The use of new semiconductor materials such as silicon carbide and gallium nitride in active filters can increase the switching frequency and reduce the loss in the conduction process, which is conducive to further improving the reliability and comprehensive performance of active filters. The application of artificial intelligence control strategy to active filters can significantly improve the adaptive ability and response speed of active filters, which in turn provides higher stability in the complex electronic network environment.

5. Conclusion

In this paper, an in-depth and systematic comparative study of LCL-type grid-connected PV inverters and three-phase PV inverters with filtering function has been carried out, which clarifies the performance differences and applicability differences between the two types of inverters in the field of grid-connected PV applications. The study shows that the LCL inverter has the advantages of low cost and simple structure in the process of practical application, and has a high economy in practical application, especially suitable for the application in the field of cost-sensitive, but lower requirements for power quality. harmonic components, which helps to improve the power quality. Three-phase PV inverters with filter functions can effectively compensate for harmonics in the power grid with the help of integrated active power filters, thus improving power quality. These inverters are able to dynamically process changes in the grid, providing increased flexibility and adaptability, as well as better harmonic suppression. APF inverters have a higher initial investment cost, but can effectively improve power quality and stability, resulting in greater long-term benefits for the entire system. APF inverters have important applications in precision industries, data centers, and other areas with high power quality requirements. In addition to being able to respond to changes in the power grid in a more timely and flexible manner, inverters containing APFs can output more stable power, but also increase the complexity of the calculations and the loss of the switch itself.

Authors Contribution

All the authors contributed equally and their names were listed in alphabetical order.

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