

Comparative Analysis and Outlook of Centralized, String, and Micro Photovoltaic Inverters in Power Generation Systems

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Abstract. With the rise of renewable energy, optimizing photovoltaic (PV) inverter topologies—centralized, string, and micro inverters—is crucial for enhancing solar power efficiency and reliability in modern power systems. This paper introduces the classification of photovoltaic inverters into centralized, string, and micro inverter. It also introduces the respective topologies and working principles, analyzes the efficiency of the three topologies in the power system, the centralized inverter is affected by natural and equipment factors, the device of string inverter is easy to lose, and affects the introduction of the Maximum Power Point Tracking (MPPT) algorithm of the micro-inverter, then briefly describes the advantages and disadvantages of the three topologies, and then leads to an optimization analysis of the three structures, and, finally, presents the challenges and opportunities that the PV inverter may face in the future in the application of the PV. Finally, it introduces the challenges and opportunities that PV inverters may face in the application of PV power generation systems in the future, and makes a future outlook.

Keywords: Photovoltaic Inverters; Efficiency; MPPT.

1. Introduction

In this era of rapidly changing information technology, the digital age has come. Photovoltaic power generation also came into being and developed rapidly, and now China has become a big country of photovoltaic power generation. By the end of 2018, China's installed capacity of photovoltaic power generation had reached 174 million kilowatts, an increase of 34% over the same period of the previous year, and the national photovoltaic power generation capacity increased by 50% over the same period of the previous year [1]. In order to increase profits and enhance efficiency, the optimization and improvement of PV inverters has become an important part of improving the efficiency of PV power generation.

2. Principle and Structure Analysis of Inverter Circuit in Photovoltaic Panels

2.1. Working Principle

Photovoltaic inverters eliminate current fluctuations and electromagnetic interference by constructing an inverter bridge. In it, the current is rectified and filtered through specific devices such as IGBT, FRD, DSP, capacitors, inductors, etc., which are used to convert DC into AC [2]. The working principle of the traditional inverter is shown in Fig. 1.

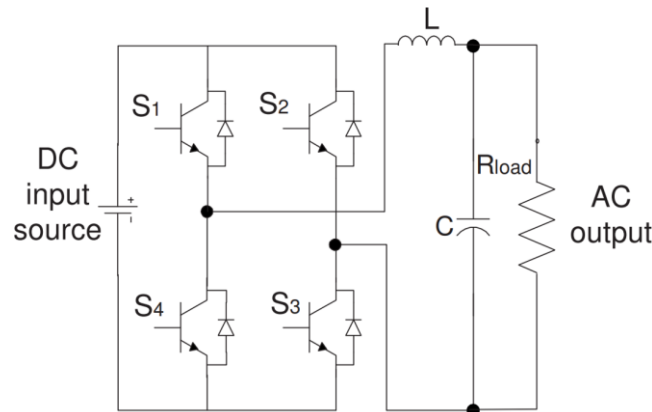


Fig. 1 Inverter working principle

However, due to the existence of many nonlinear devices and loads in the photovoltaic inverter system, there are a large number of useless harmonics in the output waveform, which reduces the propagation efficiency and quality of the power grid. The followings Fig.2 lists a simulation design diagram of passive filter Simulink [3].

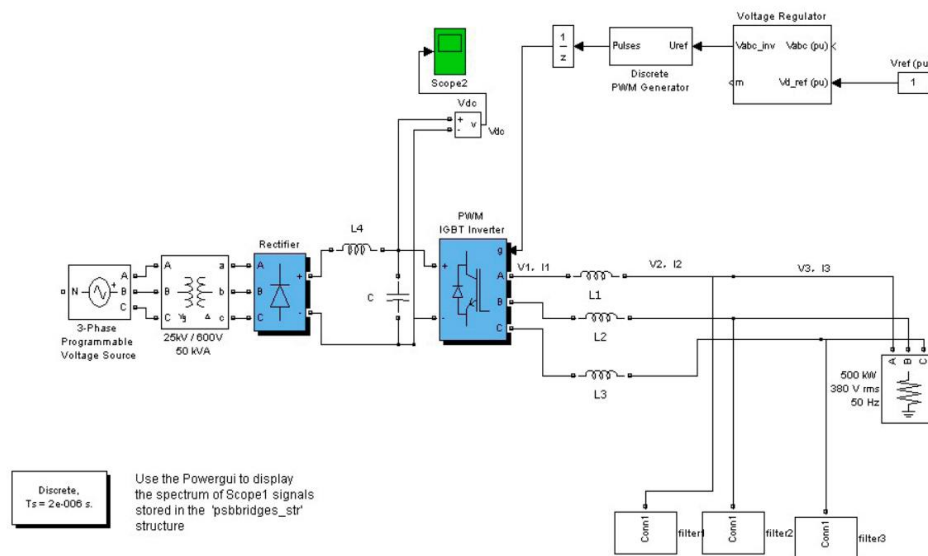


Fig. 2 Simulation model of an intersection-direct system

For photovoltaic inverters there are usually centralized, string, micro inverters, etc.

2.2. Structural classification analysis

2.2.1 Centralized Inverter

The centralized inverter technology is used to improve the quality of power by connecting multiple PV modules in parallel in series to the DC side of the same centralized inverter circuit, by using a three-phase IGBT power module and a digital signal processing converter to make the waveform closer to a sinusoidal waveform [4]. Because of the materials used and the way of integration of the centralized inverter circuit, the biggest advantage and feature for it is the higher output power and lower cost of the system [4]. It is shown in Fig.3 [5].

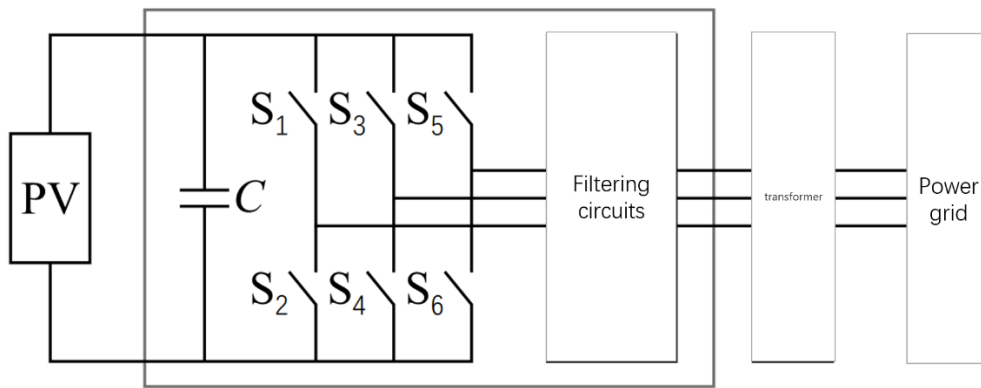


Fig. 3 Centralized three-phase two-level inverter topology [5]

2.2.2 String Inverter

String inverter usually adopts modular design, usually using multiple shared MPPT to form a string inverter, and then through multiple such inverters to form a collective to output to the grid. Due to its special series connection, good scalability and shadow resistance and easy maintenance and installation make string inverters basically applicable to all occasions [6]. The system scheme is shown in Fig.4 [5].

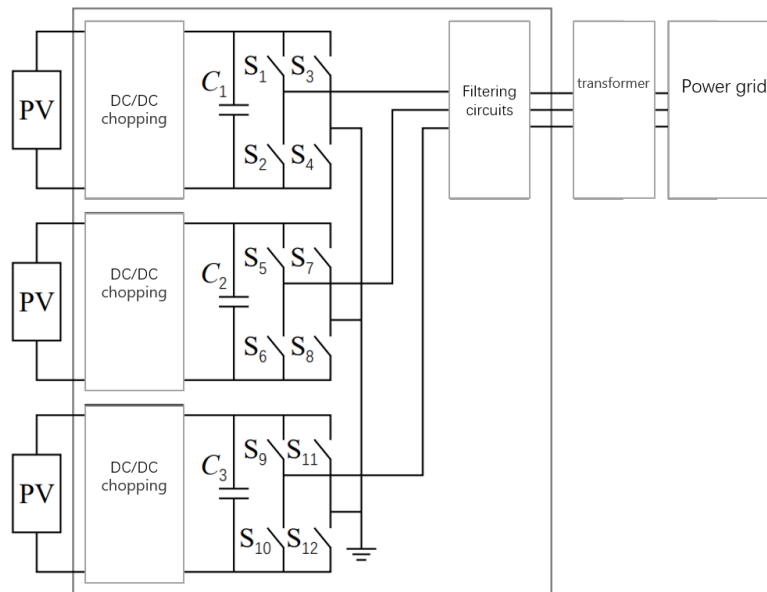


Fig. 4 String multi-branch modular inverter topology [5]

2.2.3 Microinverter

Solar photovoltaic panels transmit the generated DC energy to the microinverter, and the maximum power point of the microinverter detects the output voltage and current of the photovoltaic panels by tracking, while the inverter converts the DC energy to AC energy, and achieves the home power supply standard by adjusting the output voltage and frequency, and of course, the microinverter is usually equipped with a monitoring system to monitor the performance of the solar power system, including the PV panel output power, inverter operation status, etc. The following is a staggered parallel flyback topology made with Simulink as shown in Fig. 5 [7].

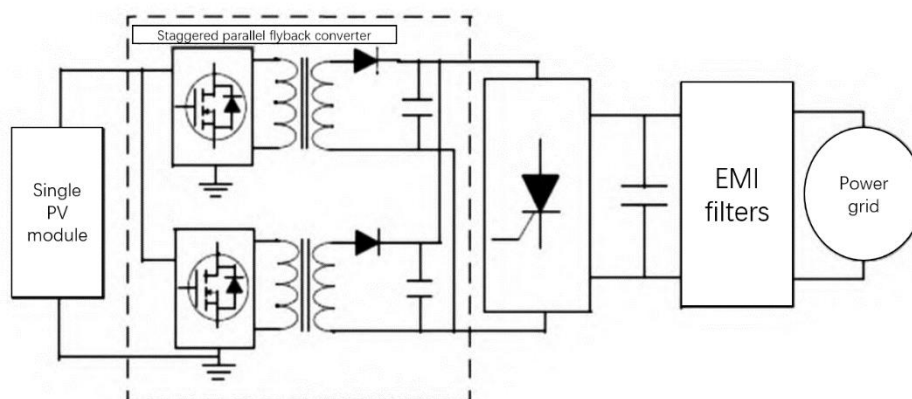


Fig. 5 Topology of interleaved parallel flyback [7]

3. Efficiency analysis for centralized, string and micro inverters:

3.1. Centralized inverters affected by two main factors: natural and equipment factors

Natural factors are multi-faceted and complex, the amount of solar radiation, temperature and humidity, dust, etc. can be a factor affecting the efficiency, we can usually only approximate the calculation and simulation of specific values, through these data to analyze the fluctuation trend of efficiency. For example, the absorption of the atmosphere will affect the conversion rate of photovoltaic modules, it will lead to the attenuation of the amount of radiation, so the sun angle of the high and low will affect the amount of radiation absorbed by the photovoltaic inverter, the midday altitude angle of the power generation will be large, and vice versa, in the morning and evening will be small. The temperature and humidity also affect the power, how high the temperature will lead to high component temperature, energy consumption increases, making the power drop; the same moisture saturation degree is too high in the air will affect the solar panel reflective surface of the reception, thus affecting its power generation. The effect of dust is more intuitive and serious, according to experimental data, when dust covers the surface of the PV module, it will make the efficiency drop at least 10% or more, and in severe cases, it will lead to a drop of more than 30% [1]. In a case study of a 6kWh PV system in Austin, Texas, the effect of 50% and 100% shading of a module is shown in Fig.6 [8].

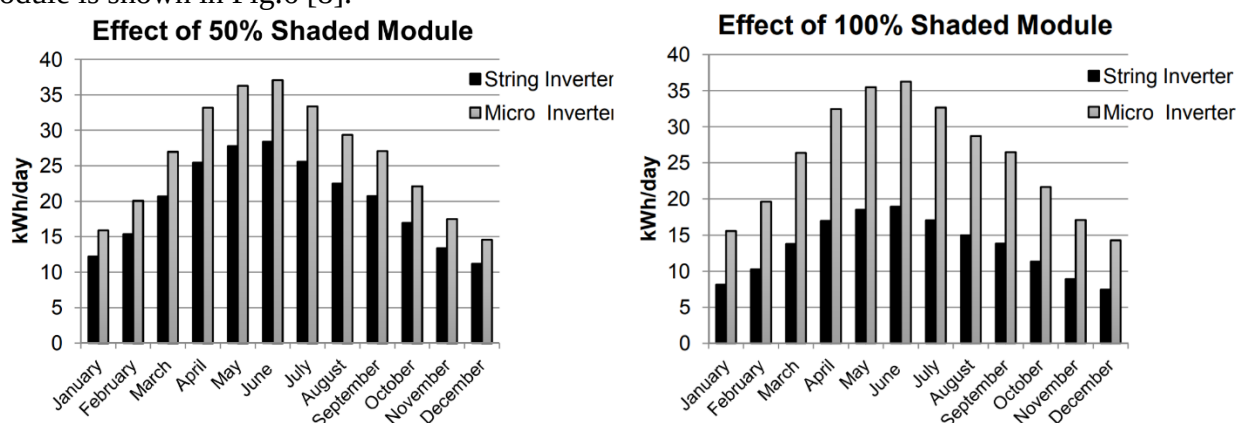


Fig.6 Example of complete module shading impact on the energy production [8]

Evaluating the exact cost of lost energy due to shading effect is very complex because shading depends on many factors' location, surroundings, time of day and season of the year. And the impact of equipment problems is even more diverse, component installation matching, system parameter tuning settings, control methods, losses and equipment failure. For example, conventional PV power generation has a DC side voltage rating of 1000 V. When the DC voltage side and AC voltage side

rise respectively, there is a significant decrease in the volume and loss of the inverter LCL filter, which leads to higher power generation efficiency [7].

3.2. Losses in string inverter devices

As string PV inverters are supported by multicore power generation technology, the system power generation faults in the inverter are being reduced, so the probability of efficiency reduction due to device failures is also decreasing [6]. So the loss of the device becomes the main factor that affects the efficiency of the string inverter as shown in Table 1 [9].

Table 1. Losses of Major Components

Critical devices	Quantity (single)	Wastage (W)	Derating design junction temperature T _{jdmax} (°C)	Derating design device case temperature T _c (°C)	Crust thermal resistance (°C/W)	Remarks
Inverter module	3	498.8 × 3=1496.4	175	120	0.11	
Boost module	6	86.24 × 6=517.44	140	113	0.26	
Boost inductor	3	80 × 3=240	150	—		Derating according to the corresponding insulation level
Inverter inductance	3	90 × 3=270	150	—		Derating according to the corresponding insulation level
Total				2523.8W		

3.3. For the MPPT algorithm affecting the efficiency of microinverters

There are also various factors that affect the efficiency of the microinverter, the performance of semiconductors, thermal design, topology of the circuit and MPPT algorithm are all factors that affect the microinverter, the following describes the MPPT algorithm for the microinverter.

3.3.1 Disturbance observation method

It is one of the most commonly used algorithms for MPPT, which calculates the power by measuring the instantaneous output current voltage from the PV cell, and then calculates the difference by comparing the change in output voltage and current at the same time. For example, P1 is the output power at time point t1, so that the output voltage increases U, P2 is the output power at time point t2 of the next cycle, the difference between the two output powers is $\Delta U = P2 - P1$, if the perturbation step $\Delta U > 0$, the output power of the PV cell will be larger in the arrival of the next time point, which has a correct direction of the perturbation and can be continued to perturbation so that the output voltage increases U. If the perturbation step $\Delta U < 0$, the PV cell's output power will become larger in the next time point, which has a correct direction and can continue to perturbation so that the output voltage increases U; if the perturbation If the perturbation $\Delta U < 0$, the output power of the PV cell will become smaller when the next time point comes, then the perturbation has a wrong direction and decreases the output voltage U, and it is necessary to add a new perturbation in the opposite direction to it. Continuously performing the above steps, the effect of the PV cell operating near the maximum power point can be achieved after constant perturbation. The control flow of the specific perturbation observation method is shown in Fig. 7 [10].

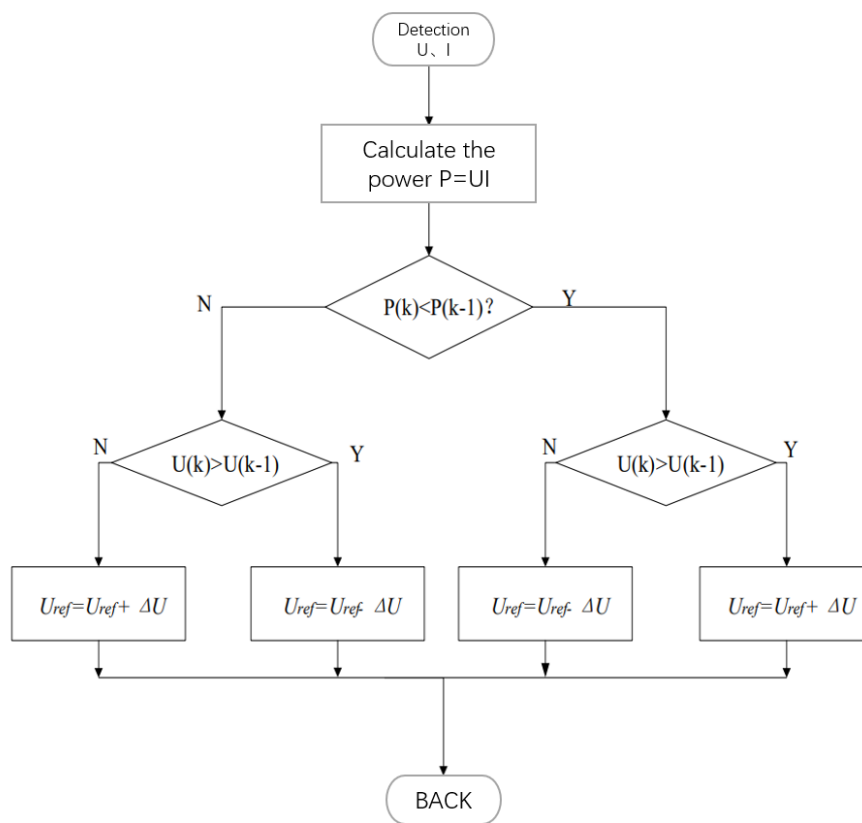


Fig. 7 Block diagram of the flow of the traditional perturbation observation method

3.3.2 Conductivity increment method

By analyzing the P-U output characteristic curve with reference, the conductance is compared with the maximum power point of the P-U characteristic curve, and then the direction of the interference at the next moment is predetermined, as shown in Fig.8 [11].

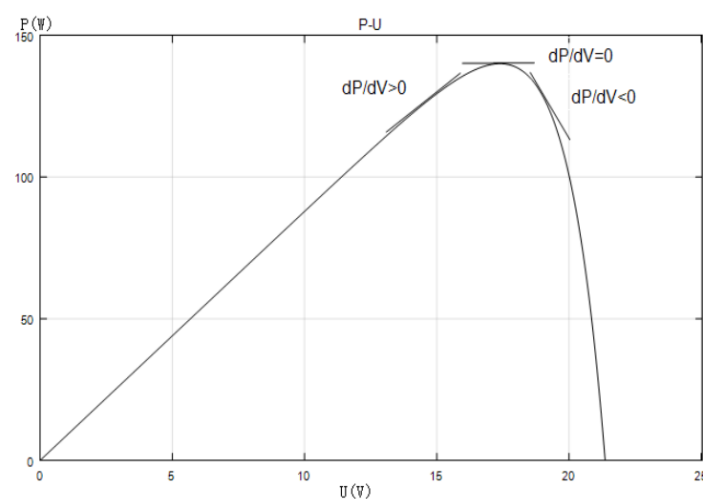


Fig. 8 PV cell P-U output characteristic curve and dP/dV variation characteristics

Corresponding to the above figure, the power-voltage rate of change on both sides of the maximum power point has the sign of the opposite direction, which is relative to each other, and the corresponding expressions are as follows:

$$dp/dp = 0, \text{ at the maximum power point}$$

$$\begin{aligned} dp/dp > 0, & \text{Maximum power point to the left} \\ dp/dp < 0, & \text{Maximum power point to the right} \end{aligned}$$

Due to this $\frac{dP}{dV} = \frac{d(IV)}{dV} = I + Vd(I)/dV$, it can be obtained from the maximum power point that: $\frac{dI}{dV} = -I/V$; the left side of the maximum power point: $\frac{dI}{dV} > -I/V$, the output voltage of the PV cell needs to be increased; similarly, the right side of the maximum power point: $\frac{dI}{dV} < -I/V$, the output voltage of the PV cell can be decreased. Obviously, the maximum power point tracking can be achieved by determining dI/dV and $-I/V$ relationship to whether or not to increase the voltage [10].

3.3.3 Hybrid MPPT measurement method

Tracking MPPT using Perturb and observe (P&Q) receives poor performance due to interference from environment and other factors, moreover, these methods always trade-off between tracking speed and power oscillations, higher tracking due to longer step size, speed leads to the size of the operating point of high power oscillations. Reduction in power oscillations small step size leads to slow tracking speed. So, Hybrid MPPT measurement method based on Incremental conductance (InC) is proposed by the team of Hadeed Sher et al. Hybrid MPPT method is basically a two-stage algorithm that utilizes the fast-tracking feature of offline MPPT method. The conventional P&O method. the P&O method is used for the proposed hybrid MPPT works in very small step size and the hybrid MPPT method is basically a two-stage algorithm that utilizes the fast-tracking feature of the offline MPPT method The conventional P&O method. the P&O method is used for the proposed hybrid MPPT works in very small step size so that the voltage and power oscillations are quite less [12].

3.4. Recommendations for the selection of centralized and string PV inverters

If it is a large ground power station, and the layout of PV modules is more regular, with less shading, centralized inverter may be a more economical choice. For distributed PV projects, especially rooftop projects, with complex module orientation and shading, string inverters can better ensure power generation efficiency and system stability. If there are high requirements for system flexibility and future expansion, string inverters are more advantageous. If you have enough budget and focus on power generation efficiency and system adaptability, you can give priority to string inverters. In conclusion, when choosing an inverter, you need to consider the project size, site conditions, budget, power generation efficiency requirements and other factors.

4. Efficiency optimization analysis and future prospects

4.1. Efficiency optimization analysis

Liang Changsheng scholars analyzed the advantages of centralized photovoltaic inverters, and proposed that centralized photovoltaic inverters can improve the capacity of the inverter as well as the effect of operating power, and can be flexibly adjusted. However, it also has obvious disadvantages, in the structure, centralized PV inverter occupies more space position and presents obvious single point of failure phenomenon [6]. Similarly in the application, MPPT voltage range is narrower and cannot monitor the operation of each and every module. Yehya Amari proposed that inverter topology with less transformers can be introduced in PV applications which can improve the system efficiency. Reducing the impact caused by the drawbacks [13].

Mokhtar Aly analyzed the advantages of string PV inverters such as high efficiency, low cost, light weight and smaller size. But in application, string grid-connected inverters also have obvious disadvantages [14]. Christian A. Rojas proposed a leakage current reduction modulation method and fault tolerant control method based on a novel NPC topology. The leakage current of the inverter can be effectively reduced to improve the efficiency [15].

Zhang Congfeng scholars analyzed the advantages of microinverters, microinverters can maximize the performance and advantages of solar cells, and because of its system failure protection function,

the efficiency of maintenance and overhaul will be greatly improved [16]. Bao Xiyong and other scholars also proposed that microinverters can be configured in each photovoltaic panel, the components are connected in parallel, which can effectively solve the problem of shadow shading impact on power generation, and is mostly used in residential roofs, courtyards and other photovoltaic power generation systems [17]. However, microinverters also have obvious disadvantages, its construction cost is higher, the individual module power conversion efficiency is slightly lower, microinverter life is shorter and other defects [16]. In terms of optimization, P. Sanjeevikumar used a novel power decoupling scheme applied to single-stage microinverters to replace large electrolytic capacitors to extend the life of microinverters. The microinverters will also be integrated into PV panels to give the microinverters a low-profile profile and optimize the microinverters by using planar magnetic components and increasing the switching frequency [18].

4.2. Challenges and future prospects

As one of the core components of PV power generation system, the development and progress of PV inverter technology, such as improving the efficiency of PV power generation as well as its reliability, are of great significance for the application of PV power generation in China. With the transformation of the global energy structure and the growing demand for renewable energy, the development of PV inverter technology is promising, mainly reflected in the following aspects

The efficiency of PV inverter directly affects the overall performance of PV power generation system. In the future, the improvement of inverter efficiency will mainly rely on the application of new materials and technologies. A. L. M. Toussi in order to improve the conversion efficiency and power density of inverters, proposes to introduce some wide bandgap semiconductor materials, such as siliconized carbon (SiC) and gallium nitride (GaN) [19].

Nowadays, all industries are beginning to enter the era of intelligence, and our country is no exception. With the application of artificial intelligence as well as the Internet of Things (IoT) technology, photovoltaic inverters will become more and more intelligent. Intelligent inverters are capable of autonomous monitoring, fault diagnosis and maintenance, and can even optimize the operating parameters of the power generation system through big data analysis to improve the power generation efficiency and system reliability. D. Zakzewski proposed a PID and fuzzy logic based intelligent controller with fast response and stability, accurately locating the maximum power operating point and generates the maximum power, which significantly improves the power generation efficiency and system reliability [20].

Modular design is one of the important trends in the future development of PV inverters. Modular design not only improves product flexibility and maintainability, but also reduces production and maintenance costs. Future inverters will focus more on modular design to adapt to different sizes and demands of PV power systems. P. Ganesh designed an inverter to improve the efficiency of the inverter by adding switches and DC sources in a modular multilevel inverter [21].

5. Conclusion

This paper mainly introduces three topologies of PV inverters, which are classified as centralized, string and microinverters, and analyzes the principle and structure, then analyzes their efficiency, and then analyzes the optimization of the efficiency, and looks forward to the future trend of PV inverters, which has both challenges and opportunities. As the core component of PV power generation system, PV inverter will play a significant role in its technological progress and market development. Through in-depth analysis of the technology trends of high efficiency, intelligence and modularization, we can foresee that future PV inverters will make significant progress in enhancing power generation efficiency, reducing system cost and improving system reliability. In addition, with the popularization of distributed PV systems and the system's energy storage capacity, PV inverters will play a more important role in the management of energy. Policy support and the development of standardization will also provide the industry with a good development environment and clear technical specifications.

However, the development of PV inverters also faces many challenges, including technical difficulties, market competition and environmental requirements. Only through continuous technological innovation and market development can PV inverter manufacturers stand out in the fierce market competition and promote the continuous development of the industry. In conclusion, the future of PV inverters is full of opportunities and challenges. We need to continue to promote technological progress and industrial development through continuous research and practice, and contribute to the realization of the wide application of global renewable energy and sustainable development. It is expected that in the near future, PV inverter technology can be applied in more fields and on a wider scale, making greater contributions to the optimization of global energy structure and environmental protection.

Authors Contribution

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

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