

Optimization of Decoupling Technology for Control and Stability Enhancement in Photovoltaic Inverters

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Abstract: In solar power systems, photovoltaic (PV) inverters play a crucial role in converting DC power generated by solar panels into AC power for grid integration. The development of decoupling technologies is essential for enhancing system efficiency, ensuring stable operation, and prolonging equipment lifespan. This paper begins by outlining the application context and theoretical foundations of decoupling technology in PV inverters, emphasizing its potential advantages in reducing weight, enhancing overcurrent protection capabilities, and improving system reliability. The paper then addresses the primary challenges encountered during the decoupling process of inverters. These challenges include increased control complexity, energy loss, and electromagnetic compatibility (EMC) issues, all of which present clear targets for subsequent resolution strategies. In response to these challenges, innovative solutions are proposed. By introducing advanced control strategies and optimizing circuit design, the control process can be simplified, and energy losses minimized. Additionally, methods for improving EMC are explored to ensure stable operation of decoupled inverters under various working conditions. The effectiveness and feasibility of the proposed solutions are demonstrated through experimental validation and simulation analysis, providing robust technical support for practical applications. In conclusion, the paper summarizes the research progress in decoupling technology for PV inverters and forecasts future trends. As technological innovation continues, decoupled PV inverters are expected to play a more significant role in improving energy conversion efficiency, reducing costs, and extending service life, thereby providing strong support for sustainable green energy development. Future research will focus on further refining decoupling strategies to accommodate higher power levels and more complex system environments.

Keywords: Photovoltaic Inverters, Decoupling Technology, Life Expectancy, Lightweighting, Overcurrent Protection.

1. Introduction

With the growing global emphasis on renewable energy, solar photovoltaic power generation has become a key component of the energy transition due to its clean and renewable nature. As the core element of solar power systems, the performance of photovoltaic (PV) inverters directly influences the efficiency, stability, and reliability of the entire system. The introduction of decoupling technology addresses many of the challenges faced by traditional PV inverters, particularly in

achieving more efficient energy conversion, enhancing system stability, and reducing equipment maintenance costs.

The output characteristics of solar panels vary under different lighting conditions, necessitating the use of maximum power point tracking (MPPT) technology to maximize power extraction [1]. However, a contradiction exists between this control strategy and the power frequency ripple generated during grid connection, resulting in power fluctuations and instantaneous power imbalances. Traditional decoupling methods, such as using electrolytic capacitors, can temporarily address this issue. Nevertheless, electrolytic capacitors have limited lifespans, increase system weight, hinder lightweight design, and constrain improvements in overcurrent protection capabilities [2, 3]. Therefore, developing high-efficiency, long-life, and lightweight decoupling strategies is crucial to advancing the commercial application of solar photovoltaic power generation technology.

In recent years, microinverters have gained popularity due to their advantages of individualized control, high efficiency, and easy maintenance. However, the power decoupling problem is particularly prominent in microinverters, with the limited lifespan of electrolytic capacitors being a major bottleneck restricting widespread adoption. Researchers have been exploring new decoupling circuit designs, such as staggered flyback microinverters [4, 5], which effectively reduce capacitor ripple and extend service life by dynamically adjusting the charging and discharging strategies of decoupling capacitors. Additionally, innovations in topologies, such as the introduction of Zeta circuits [6, 7] or improved flyback converters, and the adoption of advanced control strategies, such as three-phase grid-connected decoupling control and space vector pulse width modulation (SVPWM) technology [8, 9], have further improved the decoupling performance of microinverters, optimized system efficiency, reduced harmonic content, and enhanced grid-connected quality.

The Background and Significance section of this study aims to highlight the critical role of PV inverter decoupling technology in improving system performance, reducing costs, and extending equipment lifespan. Understanding the context of these challenges underscores the necessity of enhancing decoupling technologies and sets the stage for the analysis and discussion of solutions in subsequent chapters. Additionally, this section looks forward to the future development of decoupling technology, offering researchers and engineers new directions for exploration and innovation. By doing so, it seeks to elevate photovoltaic inverter technology to new heights and contribute significantly to the global green energy transition.

2. PV inverter section

The issue of longevity is a major challenge in PV inverter decoupling technology, particularly in microinverters. Traditional decoupling methods, such as the use of electrolytic capacitors, have partially addressed the problem of power fluctuations, but the limited lifespan of electrolytic capacitors has become a bottleneck for sustainable system performance. The capacity of an electrolytic capacitor generally determines its ability to store and release energy, and its relatively short lifespan is a significant problem. Over time, the performance of electrolytic capacitors deteriorates, leading to a reduction in capacity and an increase in ripple, which can negatively affect the stable operation of the entire inverter system.

Weight reduction is another critical issue for PV inverters, especially for microinverters, where compactness and portability are essential competitive advantages. While traditional decoupling methods, such as using electrolytic capacitors, can achieve effective power decoupling, their relatively large size and weight limit the overall reduction in the inverter's weight. The weight of electrolytic capacitors not only increases equipment costs but can also complicate installation and transportation, thereby limiting their broader adoption in distributed solar energy systems.

Overcurrent protection is a critical concern in the decoupling process of PV inverters. In applying decoupling technology, precise current control is key, as overcurrent can not only degrade system

performance but also damage internal components and shorten the device's lifespan. Traditional decoupling methods, such as using electrolytic capacitors, help stabilize current, but their capacity and tolerance limitations make overcurrent protection challenging. Excessive current can cause the capacitor

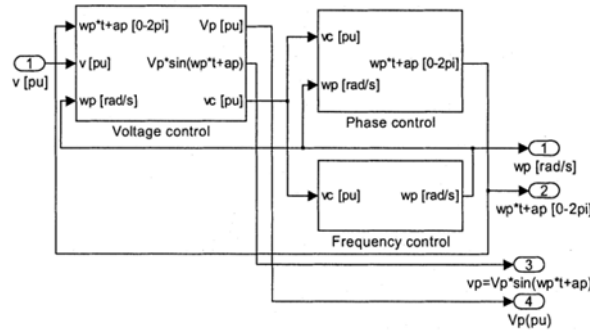


Figure 1: Schematic diagram of a phase-locked loop system.

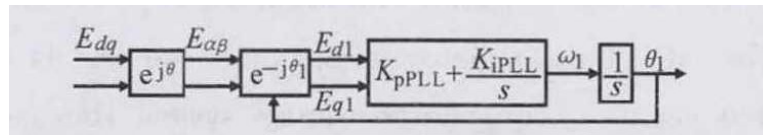


Figure 2: Typical phase-locked loop control block diagram.

to overheat, lead to voltage collapse, or even cause the electrolytic capacitor to rupture, posing a threat to the entire system.

3. Solutions to the Problem of Decoupling

3.1. Solutions to longevity problems

Addressing the longevity issue in PV inverter decoupling is a critical task in advancing microinverter technology. Traditional decoupling methods, such as the use of electrolytic capacitors, have resolved power fluctuation problems in the early stages of system development, but the limited lifespan of electrolytic capacitors has become a major factor restricting stable system operation. To overcome this challenge, researchers have shifted their focus to new decoupling circuit designs and improvements in control strategies.

The introduction of staggered flyback microinverters marks a significant breakthrough in addressing the longevity problem. The dynamic charge-discharge strategy employed by these inverters not only reduces output power fluctuations but also decreases the required decoupling capacity, thereby indirectly extending the capacitor's service life. Through precise control of the charge-discharge process, the capacitor can efficiently store and release energy at different power stages, effectively reducing its workload and prolonging its lifespan within the system.

Innovations in circuit topologies, such as the adoption of Zeta circuits or the optimization of flyback converters, also play a key role in solving the longevity issue. The Zeta circuit's unique inductive structure allows for efficient temporary energy storage in the inductor, reducing the dependence on electrolytic capacitors and mitigating the aging effects associated with capacitors. Additionally, the improved design of flyback converters optimizes the magnetic circuit layout, reducing stress on the capacitor and further extending its service life.

Modernizing control strategies is also crucial for increasing the lifespan of the system's components. The implementation of more accurate maximum power point tracking (MPPT)

algorithms can track the maximum power point of photovoltaic cells more efficiently, reducing the frequency of charging and discharging in decoupling capacitors and indirectly prolonging their service life.

Compared to traditional PI controllers, the use of advanced PI controllers with active damping can significantly reduce speed and position tracking errors caused by changes in load torque and inertia during the operation process. This improved control method enhances the operational performance of the inverter system and provides effective suppression of load disturbances.

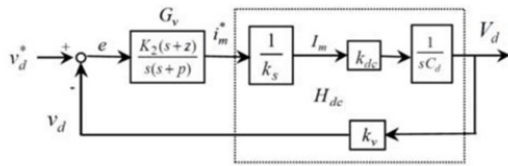


Figure 3: Schematic diagram of a voltage loop controller.

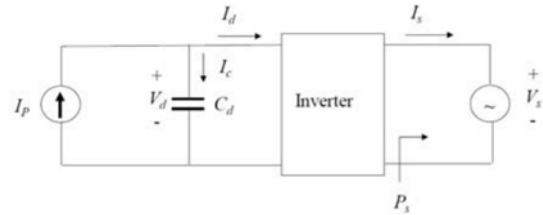


Figure 4: Schematic diagram of the operation of the inverter under normal operating conditions.

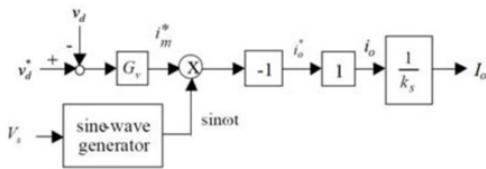


Figure 5: Voltage control structure diagram.

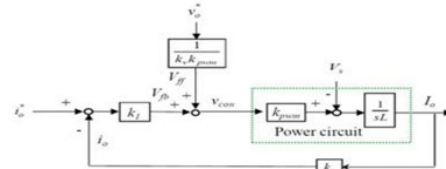


Figure 6: Current feedback control structure.

Additionally, phase-locked loop (PLL) systems [12] have shown strong capabilities in suppressing grid disturbances in the middle and low-frequency ranges (as shown in figure 1). The most commonly used PLL method achieves phase locking by controlling the phase error to zero within the synchronous rotating coordinate system.

Within the bandwidth of the controller (as shown in figure 2), increasing the gain of the current loop can effectively avoid reaching the system's peak response point, while outside the bandwidth range, the system accurately reflects the circuit characteristics. This enables finer control over current and voltage, reducing unnecessary energy losses and slowing the degradation of electrolytic capacitors.

To verify the effectiveness of these new circuits and strategies, researchers frequently use simulation tools such as MATLAB to construct detailed inverter models that simulate performance under different operating conditions. Simulation analysis allows researchers to evaluate key parameters such as ripple, capacitor lifespan, and energy efficiency, ensuring the proposed solutions are both theoretically sound and practically feasible. The experimental data provides a reliable foundation for optimizing decoupling technology, helping researchers iteratively refine designs to achieve longer-lasting decoupling inverters.

One challenge associated with inverter operation is the high working temperature. While many substations in China adopt passive heat dissipation methods, transitioning to active heat dissipation could improve inverter performance. However, active cooling requires additional power consumption, which may reduce system efficiency despite the potential for improved lifespan.

3.2. Solutions to the lightweight problem

In the process of decoupling photovoltaic (PV) inverters, lightweight technology is of paramount importance, especially for microinverters, where lightness and portability are key competitive advantages. Traditional decoupling methods, such as the use of electrolytic capacitors, are effective for power decoupling, but their weight and size hinder the reduction of overall device weight. To address this bottleneck, researchers and engineers have explored innovative circuit designs and control strategies aimed at reducing the capacity and weight of capacitors while maintaining system performance.

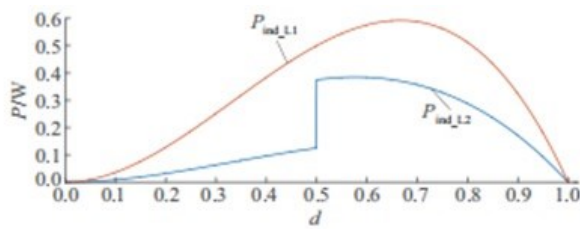


Figure 7: Comparison of AC power between the new inverter and the traditional inverter.

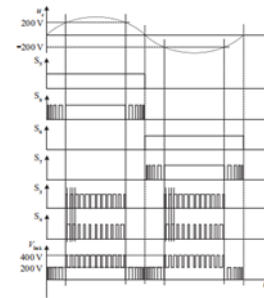


Figure 8: Timing diagram of switching device control.

The staggered flyback microinverter is one such innovation that provides stable decoupling while significantly reducing the need for large capacitors by dynamically adjusting the charging and discharging behavior of the decoupling capacitor. This approach not only reduces the weight of the device but also indirectly improves the overall system lifespan by decreasing capacitor usage. The core of this design is its flexibility in adjusting to actual power needs, which minimizes reliance on capacitors and enables a lighter device.

Innovations in circuit topologies, such as the adoption of Zeta circuits, have also contributed to the lightweighting of inverters. Zeta circuits use a unique inductive structure to temporarily store and efficiently transfer energy, reducing the dependence on electrolytic capacitors during the decoupling process, and thereby further decreasing the weight of the device. Similarly, optimized designs for flyback converters, such as improved magnetic circuit layouts and structural adjustments, reduce the importance of capacitors in the system, facilitating overall weight reduction.

Control strategy optimization also plays a key role in reducing the weight of PV inverters. Efficient maximum power point tracking (MPPT) algorithms can more accurately track the maximum power point of photovoltaic cells, reducing the frequency of charging and discharging of decoupling capacitors and thereby lowering the demand for large capacitor capacities. Additionally, the use of intelligent PI controllers and phase-locked loop (PLL) systems enhances the control accuracy of current and voltage (as shown in figure 3), lessening the need for large capacitors and consequently reducing the overall weight burden.

To verify the effectiveness of these lightweight strategies in practical applications, researchers frequently use simulation tools such as MATLAB for detailed modeling and analysis. By simulating the performance of decoupling circuits under various operating conditions, they can accurately calculate the weight and volume of the device, as well as evaluate the workload of capacitors (as shown in figure 4). This ensures that the proposed strategies are effective in reducing weight without compromising system performance. Experimental data and simulation results provide designers with accurate comparisons, enabling them to select the most appropriate lightweight solution for real-world applications.

3.3. New topology circuit

In Ref. [11], a control strategy based on the unipolar sinusoidal pulse width modulation (SPWM) method is proposed, which offers fewer switching events, higher efficiency, and lower harmonic content in the output SPWM waveform. This approach effectively reduces system losses.

The control principle is illustrated in figure 5. In the inverter control process, the grid output current is tracked using proportional-resonant (PR) control, which provides an improved sinusoidal response. For power decoupling control, the decoupling control algorithm described in this section is used to obtain the necessary capacitor voltage. The DC input voltage is then connected in series with the capacitor input voltage to achieve a higher V_{link} voltage, ensuring the normal operation of the inverter control. The control timing of the switching devices is depicted in figure 6.

Compared to traditional single-phase inverter topologies, the new topology reduces the alternating current (AC) power in the inductor by 35.6% on a year-over-year basis, and the volume of the inductor is reduced by 28% under the same experimental conditions. This results in reduced switching losses and a smaller heat sink volume, contributing to enhanced efficiency and improved thermal management.

4. Discussion

Future research will focus on more durable capacitor materials, optimized circuit structures, and smarter control algorithms to significantly improve the service life of photovoltaic (PV) inverters while maintaining the benefits of decoupling technology. These advancements will not only accelerate the commercial application of microinverter technology but also provide more stable and reliable power conversion equipment for distributed solar energy systems, offering robust hardware support for the global green energy transition.

As the demand for lightweight designs continues to increase, future research and development will concentrate on thinner and lighter capacitor materials, more compact circuit designs, and advanced control algorithms to further reduce the weight of PV inverters and enhance their competitiveness in portable and distributed solar systems. For example, new types of film capacitors and inductive materials with high energy storage densities may be introduced to replace traditional electrolytic capacitors. Additionally, the use of intelligent control strategies, such as real-time optimization through machine learning algorithms, will enable more precise current control, reducing the system's reliance on capacitors.

Through innovations in circuit design, optimized control strategies, and advanced material technologies, the decoupling technology of PV inverters is progressing toward lighter weight and greater efficiency. These developments will not only facilitate installation and transportation but also align with the trend toward miniaturization and high efficiency in green energy systems. Such advancements have significant implications for promoting the widespread application of solar energy technology.

5. Conclusion

This paper introduces a new type of photovoltaic inverter whose decoupled circuit design has been significantly optimized. With the introduction of the Zeta circuit, the topology and structure of the circuit are improved, thus improving the overall performance.

In the decoupling circuit design, the Zeta circuit is used to convert the power pulsation into the voltage pulsation on the small-capacity capacitor, which greatly reduces the low-frequency harmonic current on the DC input side and achieves good power decoupling. This design not only saves costs, but also reduces volume.

In terms of circuit topology and structure optimization, the introduction of Zeta circuit makes the circuit simpler and the control more flexible. At the same time, the design also realizes the single stage lift inverter, which enhances the ability to resist the input side disturbance.

In the aspect of control strategy upgrading, this paper adopts advanced control algorithm to improve transformer life, achieve light weight and overcurrent protection. Through precise control, the inverter can maintain efficient and stable operation in different environments, thus extending the service life of the transformer. In addition, the design also realizes the lightweight of the inverter by optimizing the circuit structure and improves its portability and application range. At the same time, the addition of overcurrent protection function further guarantees the safe operation of the inverter.

In summary, the new photovoltaic inverter proposed in this paper has achieved remarkable results in decoupling circuit design, circuit topology and structure optimization and control strategy upgrading, which provides a new idea and method for the development of photovoltaic inverters.

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