Research Status and Future Prospect of Z Source Inverter Leakage Current Suppression

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Abstract. Z-source inverters (ZSI) have been widely used in photovoltaic grid-connected applications because of their high efficiency and low cost. However, due to the lack of electrical isolation, such inverters are prone to leakage current (LC), affecting the safety and stability of the system. This paper reviews the current research status of ZSI LC suppression and focuses on the design of new ZSI and its advantages in reducing LC. Through the innovation of the new circuit structure and control strategy, the new inverter effectively eliminates the high-frequency common mode voltage (CMV), thus significantly reducing the LC. In addition, the application of silicon carbide power devices in improving power efficiency is also introduced, and the effectiveness of the proposed scheme is verified by experiments. Future research directions include further optimization of inverter topologies, development of new modulation strategies, and exploration of more efficient LC suppression techniques to improve the reliability and safety of ZSIs.

Keywords: Z-Source Inverter (Zsi), Leakage Current Suppression, Silicon Carbide Power Devices

1 Introduction

With the increase in the global demand for renewable energy, photovoltaic systems have been rapidly developed as a clean and efficient energy solution. The Z-source inverter (ZSI) plays a crucial role in the photovoltaic power generation system. Through its unique Z-source impedance network and through the state control mechanism, it can realize both the boost function and the inverter function on the DC side so as to ensure that the input voltage range matches the target AC voltage. Compared with traditional inverters, ZSIs not only eliminate additional booster or buck circuits but also effectively avoid low-order harmonics caused by dead time [1]. Because of its simple structure, low cost, and high power density, ZSIs have been widely used in the field of photovoltaic grid connection. However, the leakage current (LC) problem of ZSI has become an important factor restricting its wide application. Leakage current may not only interfere with the normal current flow of the power grid but also may produce electromagnetic fields, which will affect the stability of the power grid and the quality

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of the power supply. Therefore, how to effectively suppress the LC in ZSIs has become the focus of research.

In recent years, scholars have proposed a variety of solutions to address this challenge. For example, by improving the circuit topology, such as introducing auxiliary switches or adopting novel modulation strategies, the CMV can be effectively reduced, thus reducing the LC. Yue et al. proposed an FSS-MPC strategy based on an adjacent voltage vector. By introducing the idea of switching sequence, the traditional finite set model predictive control (FCS-MPC) strategy solves the problem that the current harmonic distribution is irregular due to the fixed switching frequency, and the control accuracy depends on the high sampling frequency [2]. The experimental results show that the FSS-MPC strategy has better performance in reducing switching times, reducing current harmonics, and improving control precision, and can effectively reduce LC. Zhang proposed a single-phase lift type double-ended common ground ZSI, that is, a three-switch double-ended common ground ZSI, which can effectively bypass the parasitic capacitance between the photovoltaic panel and the earth by grounding the negative terminals of the input and output terminals, thereby eliminating the problem of LC [3]. Bradaschia et al. adopted a method that synthesized three odd or even vectors as reference vectors to suppress the fluctuation of CMV so as to achieve the purpose of suppressing LC. However, this method has some disadvantages, including a smaller modulation system, larger output current harmonics, and narrow output range [4]. Although there are many methods to effectively suppress LC in ZSIs, they still face certain limitations and challenges.

In this paper, the latest progress in reducing the LC of transformerless quasi-Z-source inverters (QZSI) will be discussed in detail, and their performance in practical applications will be analyzed. At the same time, this paper also looks forward to the future research direction, including further optimization of circuit design, development of new control strategies, and exploration of more efficient LC suppression technology in order to provide valuable references and suggestions for academia and industry.

2 Etiology of the LC Issue

2.1 ZSI structure

The core of the ZSI is an impedance network composed of inductors (L) and capacitors (C), which is often referred to as the "Z-source network." This network is connected between the inverter's DC input voltage and AC output voltage, forming an X-shaped structure. Compared with traditional voltage source inverters and current source inverters, ZSIs have higher flexibility and adaptability. It is capable of handling a wider range of input voltages and can maintain a stable output under different load conditions.

2.2 Working principle of ZSI

The Z-source network consists of two inductors (L1, L2) and two capacitors (C1, C2), forming an X-shaped network. This network can not only store energy but also change the impedance characteristics of the circuit under different working states so as to achieve the function of boosting or reducing voltage. When the upper and lower power switches of the inverter bridge are on at the same time, the circuit is in a straight state. In this case, the DC side voltage is equal to the input voltage, and the inverter bridge can be used as the current source of the DC link to realize the voltage boost function. In other states, the inverter bridge is not in a straight-through state, at which time the circuit behaves as a zero vector or open state and can be output as a voltage source. By adjusting the duty cycle (D0) of the through state, the ZSI can realize the rise and fall of the DC side voltage. For example, in the straight-through state, the input voltage can be raised higher than the output voltage by adjusting the duty cycle. In the non-straight-through state, the DC side voltage can be reduced to match the load demand.

ZSIs are usually controlled by pulse width modulation (PWM) technology to achieve accurate regulation of the output voltage. In addition, advanced methods such as fuzzy control and neural network control can be used to improve the performance and stability of the system. Due to their unique ability to boost and reduce pressure, ZSIs are widely used in new energy vehicles, energy storage systems, renewable energy grid connections, and other fields. It is particularly suitable for applications requiring wide-range voltage regulation and high reliability.

2.3 Causes of LC of ZSI

ZSI in grid-connected applications, because its common-mode Voltage (CMV) refers to the change in the average voltage of two or more signals relative to a Common reference point in the circuit, it is easy to generate high-frequency LC. The LC mainly comes from the resonant network composed of a photovoltaic panel parasitic capacitor and output filter inductor and capacitor. Specifically, the generation of LC is mainly due to the coupling effect between the parasitic capacitance in the photovoltaic system and the grid. When the common-mode voltage changes, these parasitic capacitors form a loop, resulting in LC. The LC usually appears as a high-frequency component, and its magnitude is closely related to the change in CMV. In addition, due to the high switching frequency of traditional QZSIs, the CMV changes rapidly, resulting in an increase in LC.

Due to non-ideal conditions or factors, there is a switching time scale delay between the voltage Pulse of the bridge arm of the inverter and the Pulse Width Modulation (PWM) digital signal, which will increase the influence of low-frequency harmonics on the grid-connected current (GCC). In addition, pulse delay also weakens the suppression effect of common-mode voltage, resulting in an increase in high-frequency common-mode leakage current (CMLC). After the AC with more harmonics is incorporated into the power grid, the power generation quality and conversion efficiency of the system will be reduced, resulting in the normal operation of power equipment [5].

3 Modulation Strategy and Control Methods

In power electronic systems, especially in the field of photovoltaic grid-connected inverters, common mode LC is a problem that needs attention. Common mode LC may produce electromagnetic interference, affecting the stability and security of the system. In order to reduce this LC, engineers have effectively suppressed the LC by improving the topology, adopting new modulation strategies, and modeling predictive control. For the LC problem of ZSI, the method of real-time prediction of LC and optimization of switching state and dynamic suppression of CMV fluctuation are often used to further reduce LC. The research shows that the model predictive control can effectively reduce the peak LC.

3.1 Topology optimization method

A new Z-source photovoltaic grid-connected inverter (ZPGCI) was proposed by Dai et al. The circuit structure is optimized by introducing coupled inductors to reduce volume and improve reliability [6]. The inverter adopts a transformerless topology, combining the advantages of the quasi-Z-source bridge inverter, such as allowing the bridge arm straight through and high DC voltage utilization, while solving the problems of the traditional quasi-Z-source bridge inverter, such as large volume, low reliability, and high high-frequency common mode LC.

Specifically, the new ZPGCI winds two inductors in reverse on the same magnetic core, and when the LC flows through the two coils, the magnetic flux is generated in the same direction, which is superimposed in the magnetic core, representing a high impedance and blocking the current flow. In addition, because ZPGCI has the same common-mode voltage throughout the supply cycle and does not contain high-frequency AC voltage, ZPGCI can effectively suppress LC problems caused by high-frequency changes in common-mode voltage. The experimental waveform shows that the peak value of ZPGCI's common mode LC (item) in one power supply cycle is about 52mA, much less than 300mA, which verifies the correctness of the new ZPGCI and theoretical derivation [6].

In addition to the above advantages, the new ZPGCI also reduces the weight and cost of the ZSI and further improves the reliability of the system due to the low thermal stress of the components in the coupled inductance Z-source network. In addition, when connected to the power network, the ZPGCI does not need to install bulky power frequency isolation transformers, which makes the system more concise and efficient in design. Despite these advantages, there are still high costs, complex control, and thermal stress management problems.

Choi et al. designed an efficient transformerless inverter based on quasi-Z-source topology. By introducing a bidirectional switch synchronized with the frequency of the power grid, the inverter provides a low-frequency channel for the common mode current and effectively filters out the high-frequency component of the CMV, thus achieving the purpose of suppressing LC [7]. In addition, by applying the SiC mosfet in the inverter, the overall efficiency of the system is increased by 2%. They also designed a coordinated control algorithm for DC link voltage and grid-connection current to ensure stable grid-connection over a wide input voltage range. The test of a 1kW prototype showed that the LC decreased from 120mA in the traditional scheme to 15mA (87.5% reduction) after the addition of a bidirectional switch, which proved the leading role of the topology change [7].

3.2 Control strategy optimization method

Song proposed a new class of single-phase and three-phase topologies, which solved the problems of large on-off losses and commutation and enhanced the conversion efficiency and reliability [5]. Specifically, ZSIs in single-phase, three-phase, and AC-AC power conversion scenarios are deeply studied in this paper. In the aspect of single-phase ZSI, three topologies, basic type, simplified type, and lift type, are proposed. Among them, the simplified type only uses two power switches, and the input and output are common, while the lift and pressure type realizes the single-stage lift and pressure function through three power switches. In the aspect of three-phase ZSI, a new topology and soft start strategy are proposed to optimize the circuit structure and improve reliability.

In addition, to solve the problem of the closed-loop control system, Song also proposed a control strategy of input voltage feedforward plus output voltage peak feedback to realize the decoupling control of the DC side and AC side, which has the advantages of simple implementation, stability and steady-state error of output voltage [5]. The results show that the active harmonic suppression strategy based on pulse correction can overcome the negative influence of pulse delay on the elimination effect of CMV and low-frequency harmonic of GCC. When combined with the phase-shifted zero-common-mode pulse width modulation strategy, compared with the traditional space vector PWM method, the peak value of CMLC is reduced by 81%, and the low-frequency harmonic amplitude of GCC is reduced to within 0.024A, which can simultaneously eliminate high-frequency CMLC and suppress low-frequency harmonic of GCC in photovoltaic grid-connected inverter system [5].

In order to achieve further performance optimization of traditional inverters, Yue proposed an improved finite switching sequence model predictive direct current control strategy [8]. This strategy reduces the CMLC through a carefully designed switching action. It uses three adjacent non-zero vectors and through vectors to form a switching sequence. A variety of current and voltage waveforms can be realized by combining or switching various non-zero vectors. A new type of switching sequence is formed by combining nonzero vectors and through vectors skillfully. This switching sequence can effectively reduce the common mode LC and the change rate of CMV while ensuring the normal operation of the system. This helps to improve the electromagnetic compatibility of the system, reduce electromagnetic interference, and improve the overall performance and stability of the system.

In addition, because the position and number of inductor current ripple are closely related to the through vector, the choice of through vector has an important effect on the shape and size of the inductor current ripple. Therefore, the four-segment pass-through insertion method is chosen as the design method of the switch sequence. That is, instead of simply inserting the pass-through vector continuously into the switch sequence, it is divided into four segments and cleverly inserted between different non-zero working vectors. The purpose of this is to reduce the ripple of inductive current by optimizing the switching action while keeping the system working properly and possibly bringing other performance improvements. The design method can flexibly adjust the switch sequence according to the specific system requirements and constraints (such as the requirements of inductor current ripple, the number, and position of through vector, etc.) so as to achieve better system performance. At the same time, the switching loss can be reduced, and the efficiency of the system can be improved by inserting different through vectors in sections.

The model predictive current control of the existing finite switch sequence and the improved finite switch sequence proposed by Yue are compared experimentally. The experimental results verify the effectiveness of Yue's proposed control strategy in the multi-objective optimization of three-phase energy storage type Z-source grid-connected PV inverters[8].

3.3 Modulation strategy optimization method

By analyzing the working principle of three-phase, three-level, four-bridge ZSI and the factors affecting its common-mode voltage amplitude and system LC, Guo et al. proposed a new carrier modulation strategy based on two carriers [9]. Under traditional carrier modulation and traditional space vector modulation, it can be seen that the CMV changes at high frequency by observing the CMV and phase voltage waveform. Under the CMV with high frequency changes, the parasitic capacitance voltage cannot remain constant, and it is often difficult to achieve the ideal suppression effect, and the system LC cannot be effectively suppressed. Therefore, the idea of keeping the CMV and coefficient a and b constant by precisely controlling the on-off state of the switch is put forward to suppress the LC. The vectors obtained by this modulation method are all vectors with constant common-mode voltage, so that the common-mode voltage remains constant and the LC is effectively suppressed. After experimental verification, the maximum value of the LC waveform is only 102mA, which is much smaller than the standard of VDE0126-01-01 which is lower than 300mA [9]. It is proved that the scheme is effective, the principle is simple and clear, the implementation is relatively easy, and has certain practical application significance.

Negar et al. proposed a new modulation method, CA SVM, to suppress the LC of grid-connected three-phase qZSI [10]. The method analyzes CMV harmonics based on Fourier transform, effectively removes the low frequency harmonics of CMV, and filters the high frequency harmonics by changing the distribution of the high frequency harmonics combined with the high frequency notch filter, thus eliminating the LC and significantly reducing the adverse effects of harmonics on the protection device. Specifically, the CMV harmonics are analyzed in detail by Fourier transform, and then the CMV low-frequency harmonics in qZSI are almost completely removed by modulation strategy. At the same time, the proposed modulation method changes the distribution characteristics of high frequency harmonics on the frequency axis, so that these high frequency harmonics can be effectively filtered through the designed high frequency notch filter. Finally, the modulation method, CA SVM, is successfully applied to the grid-connected three-phase qZSI system, which realizes the effective suppression of LC and greatly reduces the possible adverse effects of harmonics on the protection device

Qin proposed a new modulation strategy to suppress the CMLC of the system. In this method, 6 large vectors, 6 medium vectors, 1 zero vector and 3 through vectors are used to synthesize the reference voltage vector [11]. After the through phase is selected reasonably, the through state is injected into the zero vector to achieve the boost function. The experimental waveform shows that both the amplitude and the rate of change of the common-mode voltage are reduced, which proves the effectiveness of the strategy. This strategy can keep the common-mode voltage within a certain range and suppress the CMLC of the system. An optimal modulation strategy is designed for non-isolated quasi-Z-source three-level photovoltaic inverters.

4 Conclusion

ZSIs overcome the limitations of traditional inverters in terms of voltage control, boost capability and load adaptability through their unique Z-type network and bridge arm straight-through function. This makes it have significant application advantages in the fields of new energy power generation, electric vehicles, energy storage systems and UPS. It can be seen that ZSIs occupy a major position in many fields. The suppression of LC is one of the key problems in Z-source PV inverters, and many studies have proposed different topologies and control strategies to solve this problem. For example, by improving the H-bridge topology, adopting a new coupling inductor topology, and introducing auxiliary switches, the common mode LC is effectively reduced. The control strategies used in different studies have their advantages and disadvantages in suppressing LC.

However, the current technology still has limitations, some topologies can reduce LC, but may affect the efficiency of the system or increase the hardware complexity. In addition, some control strategies may not be effective under certain conditions, such as dead zone time, which has a large effect on the LC. LC suppression of ZSIs is of great significance for ensuring the safety of photovoltaic systems, improving efficiency and reliability, meeting industry standards, and addressing complex environmental challenges. The selection of inverter products with efficient LC suppression is the key to ensure the safe and stable operation of photovoltaic systems. Through continuous technological innovation and optimization, such as improving control algorithms to solve these problems, the performance and safety of photovoltaic grid-connected systems can be significantly improved.

Future research will continue to explore new inverter topologies and modulation strategies to further reduce LC. For example, by improving circuit topology design (such as transformerless QZSI) and optimizing modulation technology (such as dual-carrier modulation strategy), the generation of LC can be effectively suppressed. At the same time, common-mode voltage control will be the focus of research, by controlling the common-mode voltage and improving the switching sequence to reduce the LC, such as changing the common-mode impedance or adopting a specific modulation strategy to keep the common-mode voltage constant. In addition, for the problem of LC caused by high-frequency CMV, future research will pay more attention to the suppression effect in practical applications, combined with experimental verification and simulation analysis, to ensure the effectiveness of the proposed solution in practical scenarios.

References

1. Dai, Y., Zhang, H.: A transformerless Z-source photovoltaic grid-connected inverter with coupled inductor coil. Micro & Nano Letters, 2024, **19**(2).
2. Yue, Y.H., Qu, A.W.: Finite switching sequence model predictive control for quasi-Z-source inverter. Power Electronics Technology, 2022, **56**(08): 23-26+44.
3. Zhang, X.Y.: Research on single-phase buck-boost type dual-end common ground Z-source inverter. Yanshan University, 2022.
4. Bradaschia, F., Cavalcanti, M.C., Ferraz, P.E.P., et al.: Modulation for three-phase transformerless Z-source inverter to reduce leakage currents in photovoltaic systems. IEEE Transactions on Industrial Electronics, 2011, **58**(12): 5385-5395.
5. Song, X.L.: Research on active harmonic suppression technology for three-phase three-level photovoltaic grid-connected inverter. University of Electronic Science and Technology, 2024.
6. Dai, Y.Z., Tang, H., Liu, M.X., et al.: A Z-source photovoltaic grid-connected inverter and its common-mode leakage current suppression. Journal of Solar Energy, 2024, **45**(03): 517-522.
7. Choi, Y.W., Yang, K.M.: Transformerless Quasi-Z-Source Inverter to Reduce Leakage Current for Single-Phase Grid-Tied Applications. Electronics, 2019, **8**(3): 312.
8. Yue, Y.H.: Multi-objective optimization control of three-phase energy storage quasi-Z-source photovoltaic grid-connected inverter. Fuzhou University, 2022.
9. Guo, X.Q., Yang, Y., Wang, B.C.: Leakage current suppression in three-phase three-level four-bridge Z-source inverter. Journal of Solar Energy, 2020, **41**(02): 325-332.
10. Negar, N., Mokhtar, Y., Reza, M.Z.: A modulation method for leakage current reduction in a three-phase grid-tie quasi-Z-source inverter. IEEE Transactions on Power Electronics, 2019, **34**(6): 5439-5450.
11. Qin, C.W.: Research on high-performance control technology of three-level photovoltaic inverter system. Shandong University, 2019.