Study of Power Decoupling Technology Based on Impedance Source Converter

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Abstract. Z-source Inverter (ZSI) is widely used in renewable energy, electric vehicle charging systems, and other fields because of its voltage boost ability and good decoupling characteristics. However, ZSI is prone to problems such as Direct Current (DC) link voltage fluctuation and output current harmonics during operation, which affect stability and dynamic performance. This paper systematically reviews the existing ZSI power decoupling methods, including capacitance decoupling, inductance decoupling, hybrid decoupling, and decoupling based on the control strategy. By analyzing the traditional schemes and their improvement measures (such as parameter optimization and parallel resonant network) in detail, the performance and, advantages and disadvantages of each method are evaluated. In addition, hybrid decoupling strategies and advanced control strategies (such as instantaneous reactive power control (ISR), multi-resonant converter control (MRC), fuzzy control, and neural networks) are introduced, and future research directions and technical challenges are discussed to further improve the performance of ZSI.

Keywords: Z-Source Inverter (ZSI), Power Decoupling, Capacitance Decoupling, Inductance Decoupling, Hybrid Decoupling

1 Introduction

In recent years, the renewable energy and electric vehicle market has shown a rapid growth trend, which has promoted the development of power conversion technology. Due to its unique topology, ZSI can achieve boost function and good power decoupling without the use of transformers, so it is widely used in solar photovoltaic, wind power, and electric vehicle charging and other fields [1-5]. Studies have shown that ZSI achieves power decoupling through the built-in impedance network, which can effectively eliminate DC link voltage fluctuations and output current harmonics and significantly improve the stability and dynamic performance of the system [6, 7]. The proposed studies further show that the benefits of ZSI in these applications are not limited to its high efficiency and compact design but also its superior performance in responding to input voltage and load changes.

With the rapid development of the market, ZSI is also being used more widely in the field of new energy. However, the existing ZSI power decoupling technology still has some challenges, such as capacity limitations, large volume, and high cost of capacitive

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and inductive decoupling methods. To overcome these limitations, researchers have proposed a variety of improvement measures, including parameter optimization, parallel resonance networks, hybrid energy storage technology, and a variety of control strategies [8]. In this paper, existing ZSI power decoupling methods are systematically reviewed, and future research directions and technical challenges are discussed to further improve the performance of ZSI.

2 The Working Principle and Challenge of Z-source Inverter

2.1 Basic structure and topology of ZSI

The basic structure of the ZSI includes an impedance network, a Boost circuit, and a traditional voltage source three-phase inverter (VSI). The impedance network typically consists of two inductors, L1 and L2, and a capacitor C, which is used to create an impedance isolation layer between the AC（Alternating Current） output and the DC input. Common ZSI topologies are single-stage ZSI and multistage ZSI [9, 10]. The basic structure of the ZSI is shown in Fig. 1.

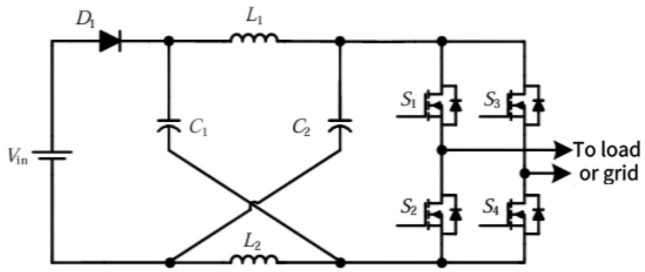

Fig 1. The basic structure of an ZSI [11]

Fig. (1) By adding a Z-source impedance network to the traditional voltage source-type inverter topology, it is possible to couple the boost and inverter in a primary circuit.

The single-stage ZSI is designed to realize the boost and inverter functions in a single converter stage. Although this design greatly simplifies the structure, it also brings control complexity. This approach is especially suitable for small and medium power applications because the impedance network and Boost circuit can be integrated into a single module, which not only improves the compactedness of the system but also enhances its reliability.

Multistage ZIS achieve more precise control by using multiple converter stages, which can provide higher output voltages and better decoupling, but their structure is relatively more complex. Multistage ZSI is more suitable for high-power applications because it can deal with the input voltage and load changes more effectively and improve the dynamic response speed of the system. Although the structural complexity of the multilevel ZSI increases, the performance of the system is significantly improved.

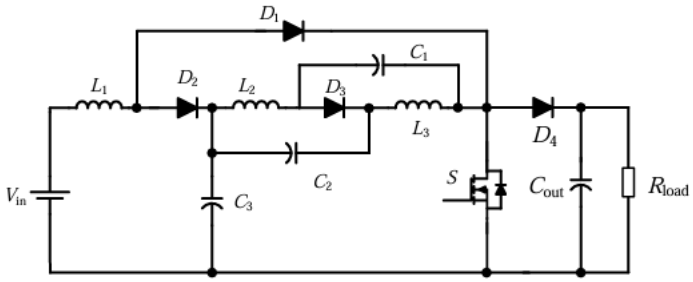

Fig 2. Improved quasi-Z-source converter topology [11]

On the basis of the original quasi-Z source converter, a layer of quasi-Z source impedance network is cascaded again in FIG. (2), which effectively improves the boost ratio but increases the number of devices, which has an impact on the efficiency of the system.

2.2 Common power decoupling problems of ZSI

In practical applications, the main power decoupling problems faced by ZSI mainly include the following aspects. First of all, DC link voltage fluctuation is a key problem. This fluctuation is mainly caused by changes in input voltage and load. DC link voltage fluctuation can lead to system voltage instability, which seriously affects the stability and reliability of the system. Especially in renewable energy applications, the input voltage varies greatly, which increases the risk of voltage fluctuations. Secondly, the problem of output current harmonics is also an important issue to pay attention to. This is due to the nonlinear characteristics of ZSI. The harmonic component in the output current will reduce the quality of the power supply, increase the loss of the system, and affect the normal operation of the load equipment. Finally, the problem of power noise can not be ignored. This noise can come from various electronic devices inside the system, such as switching devices, inductors, and capacitors. The effect of power noise may spread throughout the power grid, thus affecting the quality and stability of the grid. In addition, the noise may also cause electromagnetic interference (EMI), which affects the electromagnetic compatibility (EMC) of the system. These problems need to be considered and solved in the design and application of ZSI to ensure the stable operation and high efficiency of the system.

3 Power Decoupling Technology Basis

3.1 Frequency domain analysis method

Frequency domain analysis methods, such as Fourier transform and linear time-invariant system theory, are critical to understanding and evaluating the frequency response of systems and are especially suitable for analyzing the decoupling performance of zero sequence injection (ZSI) in different frequency segments. By Fourier transform, time domain signals can be converted into frequency domain signals, revealing the harmonic components and frequency characteristics of the system and providing a basis for designing impedance networks and control strategies. The linear time-invariant system theory applies to the analysis of the linear part of ZSI. By establishing the transfer function of the system, the frequency response of the system can be analyzed, and the impedance network parameters can be optimized to evaluate the stability and dynamic performance of the system.

The Fourier transform is a mathematical tool for converting a signal in the time domain into a signal in the frequency domain. By Fourier transforming the system signal, the complex time domain waveform can be decomposed into multiple frequency components so that the characteristics of each frequency component can be analyzed in detail. This analysis method not only helps to identify the harmonic components in the system but also reveals the influence of different frequency segments on the system performance.

Linear time-invariant systems (LTI) theory assumes that the system is linear at all points in time and that its properties do not change over time. This makes it possible to analyze the frequency response of the system by establishing its transfer function. The transfer function is a complex function that describes the output response of the system with inputs of different frequencies. With the transfer function, the gain and phase characteristics of the system can be calculated, thus optimizing the impedance network parameters. LTI theory is especially suitable for analyzing the linear part of ZSI, and through frequency response analysis, the stability, dynamic performance, and decoupling effect of the system can be evaluated.

3.2 Traditional control strategy

Traditional control strategies, which mainly include proportional-integral (PI) control and proportional integral differential (PID) control, although simple and effective, are less flexible when dealing with complex nonlinear problems. By adjusting the proportional and integral parameters, PI control can achieve the basic stability control of the system, but the dynamic response is slow when dealing with rapidly changing inputs and loads. PID control on the basis of PI control increases the differential link and improves the dynamic response speed of the system, but it is still difficult to deal with complex nonlinear problems, and the parameter adjustment is more complicated.

Proportional integral (PI) control is a widely used control strategy by adjusting the proportional (P) and integral (I) parameters to achieve system stability control. The basic principle is to process the error signal (that is, the difference between the expected value of the system and the actual value) through the proportion and integration links to generate the control signal. PI control can realize the basic stability control of the system and is suitable for static or slowly changing working conditions. The capacitive decoupling method can reduce voltage fluctuation and current harmonics effectively by adjusting PI controller parameters. However, the dynamic response speed of the PI controller is slow, and it is difficult to adjust the system parameters in time for the rapidly changing input and load, which leads to the performance of the system being reduced.

Proportional integral differential (PID) control adds a differential (D) link based on PI control to improve the dynamic response speed of the system by monitoring the instantaneous changes of the system in real time. The basic principle is to process the error signal through the three links of proportion, integral, and differential to produce a more accurate control signal. PID control not only inherits the advantages of PI control, such as realizing the basic stability control of the system, but also improves the dynamic response speed of the system through the differential link, which is suitable for fast dynamic change conditions. However, the parameter adjustment of PID control is more complicated, and it is necessary to optimize the three parameters of proportion, integral, and differential at the same time to avoid excessive oscillation or slow response of the system. In addition, PID control still has certain limitations when dealing with complex nonlinear problems.

4 Overview and Performance Comparison of Decoupling Methods

4.1 Traditional decoupling methods

4.1.1 Capacitive decoupling

Capacitive decoupling is a decoupling method widely used in DC links that reduces voltage fluctuations in the DC link by using capacitors in the circuit to absorb and release energy fluctuations. The capacitive decoupling method is simple and easy to implement and can provide good decoupling results, especially over a wide frequency range [12, 13].

The decoupling effect of capacitive decoupling depends mainly on the capacitance value and characteristics of the capacitor, such as equivalent series resistance (ESR) and equivalent series inductance (ESL). When the voltage or current in the DC link fluctuates, the capacitor can absorb or release this part of the energy by charging and discharging, thereby reducing the voltage fluctuation. Low ESR and low ESL capacitors can improve high-frequency response and stability and reduce energy loss.

However, capacitive decoupling has some limitations in high-power applications. Capacitors have limited energy storage capacity, making it difficult to meet demand in high-power applications. In high-frequency applications, the volume and weight of capacitors are larger, increasing the burden on the system. High-performance capacitors have a higher cost, further increasing decoupling costs.

4.1.2 Inductive decoupling

Inductive decoupling reduces voltage fluctuations in the DC link by using inductors in the DC link to smooth energy fluctuations. The inductive decoupling method shows a good decoupling effect in a low-frequency band and has high energy density, but it has certain limitations in high-frequency applications [12, 13].

The decoupling effect of inductance decoupling mainly depends on the inductance value of the inductor and the core material. When the current in the DC link fluctuates, the inductor can smooth this part of the current through magnetic energy storage, thus reducing the voltage fluctuation. The magnetic core material with high permeability can improve the energy storage capacity and reduce the volume of the inductor while reducing the core loss. Choosing the appropriate inductance value can ensure that the inductance can provide an effective decoupling effect under different working conditions.

However, inductance decoupling has some limitations in high-frequency applications. The volume and weight of inductors increase the burden on the system. The dynamic response speed of the inductance decoupling method is slow, and it is difficult to quickly cope with the changes in input voltage and load. The cost of high-performance inductors is higher, especially large-capacity inductors.

4.2 Improvement of the decoupling method

4.2.1 Improvement of capacitance decoupling

The improvement measures of capacitor decoupling mainly focus on the optimization of capacitor parameters, the introduction of the parallel resonant network, and the design of segmented capacitors, which not only improve the decoupling performance of capacitors but also optimize the cost and volume [14].

Optimization of capacitor parameters By selecting the appropriate capacitor value and material, the energy storage capacity of the capacitor can be significantly improved, and the harmonic content can be reduced. For example, the use of low ESR and low ESL capacitors can improve the high-frequency response capacity and stability of the capacitor and reduce energy loss. Choosing the right capacitance value can ensure that the capacitor can provide an effective decoupling effect under different working conditions. The introduction of a parallel resonant network can provide additional energy storage and filtering functions at specific frequencies, effectively reducing voltage fluctuations and output current harmonics in the DC link. Through rational design of the parallel resonant network, the decoupling effect of multiple frequency segments can be realized, and the overall performance of the system can be improved. The segmented capacitor design divides the large capacitor into several small capacitor modules, which not only improves the energy storage capacity of the capacitor but also reduces the volume and weight, and realizes more flexible control. The segmented design can dynamically adjust the configuration of the capacitor according to the actual needs of the system, which improves the dynamic response speed of the system.

4.2.2 Improvement of inductance decoupling

The improvement measures of inductance decoupling mainly focus on the optimization of inductance parameters, the introduction of parallel resonant circuits, and the design of segmented inductors. These measures not only improve the decoupling performance of inductors but also optimize the cost and volume [14].

The optimization of inductance parameters usually selects the appropriate inductance value and core material, which can significantly improve the decoupling performance of inductance and reduce the volume. For example, the use of magnetic core materials with high permeability can improve the energy storage capacity of the inductor and reduce the volume while reducing the core loss. Choosing the right inductance value can ensure that the inductance can provide an effective decoupling effect under different working conditions. The introduction of a parallel resonant circuit can provide additional smoothing and filtering functions at specific frequencies, effectively reducing voltage fluctuations and output current harmonics in the DC link. Through the rational design of parallel resonant circuits, the decoupling effect of multifrequency segments can be realized, and the overall performance of the system can be improved. The segmented inductor design divides the large inductor into several small inductor modules, which not only improves the decoupling performance of the inductor but also reduces the volume and weight and realizes more flexible control. The segmented design can dynamically adjust the configuration of inductors according to the actual needs of the system and improve the dynamic response speed of the system.

4.3 Hybrid decoupling scheme

The hybrid decoupling scheme combines the advantages of capacitive decoupling and inductive decoupling, which can reduce DC link voltage fluctuation and output current harmonics more effectively and improve system performance. In the hybrid decoupling scheme, the hybrid decoupling capacitor and inductor are to apply the capacitor and inductor to the DC link at the same time through the fast response and smooth characteristics of the capacitor, as well as the high energy density and long-term energy storage capacity of the inductor, to achieve a more comprehensive decoupling effect. The capacitor can quickly absorb and release instantaneous energy fluctuations, while the inductor can smooth the energy fluctuations in the low-frequency band, and the synergistic effect of the two significantly improves the decoupling effect and efficiency of the system.

The introduction of energy storage batteries and supercapacitors further improves the performance and stability of the hybrid decoupling scheme. With their high energy density, energy storage batteries can provide additional energy storage and are suitable for applications that require long-term energy storage. Supercapacitors, on the other hand, have a high power density and fast response capability, which is suitable for applications that require fast dynamic response. The innovative topology design is an important part of the hybrid decoupling scheme. By optimizing the topology of the circuit, more efficient energy management and decoupling can be achieved. The use of novel components, such as solid-state capacitors and high-performance inductors, can further optimize the performance of the system.

5 Advanced Control Strategy

5.1 Instantaneous reactive power control (ISR)

Instantaneous Reactive Power Control (ISR) is an advanced control strategy that can quickly respond and adjust the reactive power of the system under high-frequency conditions, thereby improving the stability and dynamic performance of the system. ISR monitors the instantaneous reactive power of the system in real time and dynamically adjusts the control parameters according to the monitoring results to achieve precise control of the reactive power.

The working principle of ISR is to reduce voltage fluctuations and current harmonics by monitoring the instantaneous reactive power of the system in real time and dynamically adjusting control parameters according to the monitoring results. This control method is especially suitable for occasions of rapid dynamic changes, such as electric vehicle charging systems and power converters in smart grids. By precisely controlling reactive power, ISR can improve the stability and dynamic performance of the system, ensuring that the system can still operate reliably under rapidly changing working conditions. ISR is widely used in electric vehicle charging systems, smart grids, and high-frequency power converters.

5.2 Multi-resonant converter control (MRC)

By introducing multiple resonant networks to achieve finer Control, Multi-Resonant Converter Control (MRC) can effectively reduce harmonic content and voltage fluctuations in different frequency segments and improve the reliability of the system. MRC works by introducing multiple resonant networks into the converter circuit, which provides additional filtering and decoupling functions in different frequency segments. By reasonably designing the parameters of the resonant network, the decoupling effect of multiple frequency segments can be realized, and the overall performance of the system can be improved. MRC applications are widely used in aerospace systems, high-frequency power converters, and high-precision control systems.

5.3 Fuzzy control

Fuzzy control is a control method based on fuzzy logic, which can provide stable control effects in uncertain and complex environments. By using fuzzy logic rules, the control parameters can be dynamically adjusted according to the state of the system to improve the adaptability and response speed of the system. Its working principle is to dynamically adjust the control parameters according to the system state through the fuzzy logic rules. Fuzzy logic rules are described by a series of fuzzy sets and membership functions.

6 Future Research Directions and Technical Challenges

6.1 Hybrid Energy storage technology [15]

Hybrid energy storage technology combines the advantages of multiple energy storage components (such as capacitors, batteries, and ultracapacitors) to provide more efficient energy management and decoupling under different conditions. By optimizing the parameters of energy storage components by optimizing the parameters of capacitors, batteries, and ultracapacitors, the overall performance and efficiency of the system can be significantly improved. Introducing New Types of Energy Storage Elements Using new types of energy storage elements, such as solid-state batteries and high-energy density capacitors, can further reduce the size and weight of the system and improve energy density and lifetime. Innovative topologies Through innovative design, more efficient energy management, and decoupling effects can be achieved.

6.2 Optimize existing components

Optimizing the parameters and structure of existing components, such as using new materials and technologies to manufacture capacitors and inductors, can significantly reduce the volume and weight of components and improve their performance. The use of novel materials, such as gallium nitride (GaN) and silicon carbide (SiC), can significantly improve the performance of capacitors and inductors, reduce the volume and weight, and improve the overall efficiency of the system. The introduction of new manufacturing technologies, such as micro and nanomanufacturing and 3D printing, can enable finer component designs and improve the reliability and stability of the system. Through innovative topological design, more efficient energy management and decoupling effects can be achieved.

7 Conclusions

As an efficient and flexible power converter, an ZSI is widely used in renewable energy and electric vehicle charging systems. However, its power decoupling technology still faces the problems of DC link voltage fluctuation, output current harmonics, and power noise. This paper systematically reviews the existing ZSI power decoupling methods, including capacitive decoupling, inductive decoupling, hybrid decoupling, and control strategy-based decoupling methods and analyzes the performance advantages and disadvantages of each method in detail. By means of parameter optimization, parallel resonant network, and hybrid energy storage technology, the decoupling effect and dynamic performance of the system are significantly improved. In addition, advanced control strategies such as instantaneous reactive power control (ISR), multi-resonant converter control (MRC), fuzzy control, and neural networks are introduced in this paper to further improve the stability and efficiency of ZSI. Future research directions will focus on hybrid energy storage technologies, optimization of existing components, and innovative control strategies to overcome current challenges and drive further development of ZSI technology.

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