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Stability of LCL grid-connected inverter under weak current network

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Abstract. With the development of energy generation technology, In today's weak grid environment, the research on the stability of grid-connected inverters is becoming more and more important, whose main task is to improve grid-connected current. The paper concludes the widely-used control strategy of LCL grid-connected inverter, including adjusting inverter parameters, introducing a filter, voltage source admittance control strategy, and passive/active damping method. This paper compares the different effects of upgrading strategies of LCL inverters and recognizes their advantages and limits. For example, the passive/active damping method not only can effectively suppress resonance peak, but can also preserve amplitude-frequency characteristics of low and high-frequency bands. However, the gain in low frequency or the harmonic in high frequency may be reduced. Then, the paper discusses future development trends and technical challenges faced by LCL grid-connected inverters. In principle, effective suppression of high-frequency resonance is the key to improving system stability. From the perspective of control strategy, improving system stability is as important as adopting advanced algorithms. Finally, the paper raises practical advice about increasing Inverter efficiency.

1 Introduction

In order to effectively address climate change on a global scale, it is crucial to prioritize the development of clean and low-carbon energy sources as a key strategy for transforming the energy sector. As the scale of new energy generation technology continues to expand, the development and application of renewable energy technology is particularly important. As the core component of the new energy power generation system, grid-connected inverter plays a decisive role in improving the efficiency and power quality of the whole power generation system. In particular, research has primarily centered around the LCL grid-connected inverter because of its excellent high-frequency harmonic filtering ability and low system inductance requirement.

However, as a third-order system, LCL grid-connected inverter has the challenge of high-frequency resonance and stability control. If these problems are not solved, the performance of grid-connected inverters will be seriously affected, especially in a weak grid environment. To address these issues, researchers have conducted extensive research exploring a variety

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of optimal control strategies, including adjusting inverter parameters, applying voltage source admittance control strategies, and passive damping methods.

This article will discuss these optimization control strategies in detail and evaluate their effectiveness and applicability in practical applications. By synthesizing the existing research results, this paper aims to provide a systematic analysis method to evaluate the stability of LCL grid-connected inverters in weak grid environments and explore the limitations of existing strategies and potential directions for future research, so as to provide theoretical and technical support for the stable and efficient operation of new energy power generation systems

2 LCL grid-connected inverter circuit

2.1 Circuit topology structure diagram

As the current energy shortage becomes increasingly prominent, grid-connected inverters can be used as power conversion interfaces based on new energy public grids such as wind energy and nuclear energy and distributed generation [1]. However, due to a series of problems such as frequency deviation and fluctuation effect of harmonic current generated by inverter on power grid voltage, LCL filter has good harmonic suppression ability, so it is widely used. The Figdepicts the topology of an inverter connected to an LCL grid.

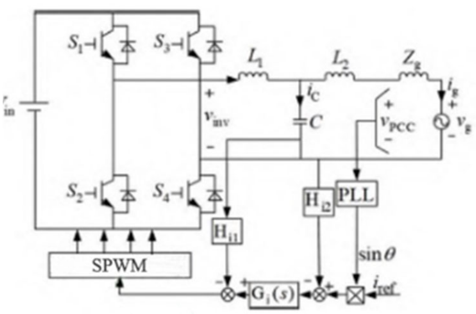

Fig. 1. LCL grid-connected inverter structure [2].

2.2 Equivalent circuit

Most of the existing research results are based on NORTON equivalent circuit for system analysis, as demonstrated in Fig2.

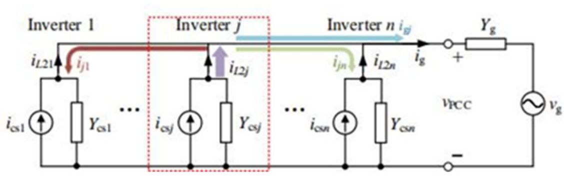

Fig. 2. Equivalent circuit of grid-connected system under weak current network [3].

3 Analysis of specific control policies

3.1 Active disturbance rejection control

This method is a kind of method to select inductance and capacitance parameters of LCL inverter and adjust the inverter parameters. In order to reduce the harmonic current generation reasonably, so as to reduce the impact of resonance on the power grid. Active disturbance rejection control, because of its good control performance, has been effectively utilized in a wide range of control systems. At present, this control method has become the research direction of many scholars in the field of grid-connected inverters. In recent years, we can see that Song proposed the first-order ADRC method for active power filters. Although this method solves the contradiction between the rapidity and overshoot of the system, it still fails to involve the design of higher-order ADRC[2]. In the subsequent studies, scholars like Din proposed a grid-connected current control strategy based on third-order Linear ADRC (LADRC)[4]. This method greatly enhances the stability of the parameter change of grid-connected inverter, and because it includes the observer ESO, the system can control the decoupling current by itself, and the effectiveness of this method has been verified. In Xu's research [5], based on the complex structure and difficult parameter setting of traditional LADRC control, an innovative reduced order linear ADRC control method is proposed, which takes the side voltage of grid-enabled inverter as the control quantity and the side current of inverter as the output quantity.

Compared with the research results of the above two scholars, the three-order LADRC control method proposed by Ding has better control effect and lower output harmonic content. In terms of harmonic filtering effect, it is also far better than the reduced order LADRC control method, and the reduced order LADRC controller proposed by Xu scholars will be simpler in design and parameter setting and can realize more efficient control of LCL grid-connected inverters. However, these two methods can not solve the problems of system parameter design and tuning. In addition, the current researches on this method are still mostly system simulation experiments. In the future, the research on this method should focus on the design of active disturbance rejection parameters and continue to study more suitable parameter optimization strategies, such as the application of neural network analysis methods.

3.2 New phase locked loop control strategy

Nowadays, new energy power generation under high permeability has become an inevitable trend of development, nonetheless, high permeability frequently causes the grid-connected common coupling point's equivalent grid impedance to fluctuate significantly, making the grid show weak or even very weak grid characteristics. Many scholars have proposed many solutions to the problem of system instability caused by the coupling of current loop, phase-locked loop and grid impedance of grid-connected inverters. In Cao's research [6], based on SOGI-PLL and APF-PLL, which are commonly used in single-phase applications at present, the research only focuses on the performance of PLL itself. The FF-SO-SOGI-PLL, which has a stronger suppression effect on the disturbed signal, and the CCF-MFOF-PLL, which is improved on the traditional APF-PLL, is improved to enhance its suppression capability of the PLL in inverter impedance and the harmonic of the grid side. These two PLL enhancement techniques significantly increase the stability of grid-connected inverters in weak current networks and expand the system's stability region, but they only further optimize the parameter adaptive characteristics, and fail to fundamentally solve the problem of reduced robustness of the system under weak current networks. Moreover, many complex situations encountered in practical applications, such as power grid failure, frequency disturbance, low voltage crossing, and grid-connected mode switching, are not considered. In the study of Yang, a feedforward function of grid voltage is constructed that can totally remove the impact of PLL on the system's output impedance, after which a grid-connected inverter's impedance reshaping control approach based on grid voltage feedforward is suggested[7]. The research of Ge also starts by solving the fundamental problem of system robustness reduction under weak current network[8]. By analyzing the coupling principle between PLL and the current loop, the reasons for system robustness decline when grid impedance and PLL bandwidth change are deeply analyzed, and on this basis, the PLL transfer function is reconstructed by constructing a pre-link. A new phase locked loop (PLL) control structure is proposed, and the parameter design method is given. With the help of this method, not only the problem of decreasing system robustness with the increase of PLL bandwidth can be effectively solved, but also the parameter design is made easier and the system can still run stably under extremely weak current network. Both modeling and experimentation are used to confirm the viability of this approach.

To sum up, in weak current networks, the proportion feedforward of grid voltage will to some extent reduce the system's stability margin when improving the harmonic suppression ability. Further considering the negative damping introduced by the PLL link, it will significantly lower the low-frequency output impedance of the grid-connected inverter's phase margin, seriously affecting the stability of the grid connected inverter[9]. In recent years, the research on the coupling mechanism between PLL, current loop and power grid impedance continues to develop, and this direction is still a research hotspot, but there are few studies on the strategy to achieve the balance of these three parts. Future research direction should consider further in-depth research on the decoupling control strategy between these three parts.

3.3 Passive/active damping method

Passive damping and active damping are two categories of resonant damping for LCL filters. The passive/active damping method is mainly used to solve the resonant peak problem of LCL filter in grid-connected inverters.

Passive damping is a common passive damping method that is realized through series or parallel resistance of inductive or capacitor branches of LCL filter [10]. Among these six basic passive damping methods, capacitor shunt resistance has the best damping effect. However, the capacitor parallel resistor technique is impractical because of the very small voltage drop of the inductor, the capacitor voltage being very close to the power grid voltage, and the capacitor voltage being directly supported by the parallel resistor, resulting in a very substantial loss. In contrast, the method of capacitor series resistance is widely used because of its low loss. The book also mentions four methods to improve the traditional passive damping method, but due to the increase in the type and number of components required by the improved circuit, the complexity, volume and cost of the circuit are also increased. Furthermore, it is rarely employed in real-world applications due to its detrimental effects on the filter's high-frequency harmonic attenuation capability and low frequency gain. In recent years, the passive damping method has been used to connect series or parallel resistors on the inductance and capacitance of a filter to achieve the damping effect. The passive damping method is less commonly used due to its accompanying energy loss and increased cost[11] There are few researches on this method.

The active damping method realizes the effect of adding damping through the control algorithm. When compared to the passive damping approach, the active damping method can increase the system's operational efficiency and prevent adding more power loss to the passive resistance[12]. At present, the common active damping methods are reactive power control, grid-connected current negative feedback control, sliding mode method and adaptive control method. Each of these active damping methods has its advantages and disadvantages. Although the reactive power control method is simple to operate, it will increase the cost. Although the negative feedback control method of grid-connected current has faster response speed, it requires higher control precision of the negative feedback link. Although the control precision based on the sliding mode control method is high, the requirements of the sliding mode surface and parameters are strict. Finally, although the method based on adaptive control has strong adaptive adjustment ability, it has precise requirements for model parameters and control algorithms.

Based on the traditional active damping method, various scholars have made a lot of progress in its improvement and innovation research direction. Because the capacitor shunt resistance of LCL filter has the best damping effect on the resonance of grid-connected LCL filter of a single inverter, the research on the capacitor shunt virtual resistance to suppress the resonance of multi-inverter grid-connected system started earlier and is also one of the main research directions at present. Grid-connected current feedback active damping method is a common active damping method. In the research of Dong Guangde et al. [13], in order to make the virtual impedance present positive resistance characteristics at high frequencies to suppress LCL resonance spikes and enhance the stability of the system, a highly robust active damping strategy with grid-connected current feedback is proposed. The potential mid-frequency resonance instability in the system using the traditional GCFAD strategy is effectively avoided. As for the innovation of new methods, Wang Hanwen and other scholars proposed a new control strategy based on grid-connected current and common coupling voltage feedback, which not only provides active damping to suppress LCL resonance, but also reduces the use of sensors, and a strong adaptability to a wide range of power grid impedance changes [14]. The traditional high-pass filter HPF(highpass filter) active damping technology of a single grid current feedback loop does not take into account the influence of impedance changes in the weak grid, and this strategy not only maintains the advantages of saving sensors, but also effectively suppresses the harmonics of grid-connected current and maintains good stability throughout a wide range of grid impedance changes. Also in the study of Shi Mingming et al. [15], a grid-connected inverter design idea with an integrated active damper function was proposed, which has a good damping resonance effect and significantly improves system stability.

The active damping approach has the benefit of being able to effectively inhibit without contributing to further energy loss. The drawback is that when combined with the voltage feedforward technique, the numerous improved active damping algorithms that have been proposed to improve the suppression effect can occasionally be overly complex, placing a heavy demand on the inverter's control circuit[16]. Therefore, to sum up, the improvement of traditional active damping method is no longer a research hotspot, and the future research direction in this field is mainly to innovate new methods. With the in-depth research on resonance monitoring and detection in multi inverter grid-connected systems, intelligent active dampers with online resonance monitoring and active resonance suppression functions will undoubtedly be a future research hotspot[17].

4 Conclusion

With the creation of new power systems and energy grid structures, grid-connected inverters are used more and more widely.

At present, LCL grid-connected inverter control stability is faced with many challenges in a weak grid environment. From the principle point of view, the key to improve the stability of the system is to effectively suppress the high-frequency resonance. This involves not only the precise control requirements for the internal the inverter's circuit parameters but also the consideration of the external grid environment. Therefore, in terms of control strategy, in addition to adopting advanced algorithms, the stability of the system in dynamic changes is improved. From the perspective of practical application, the cost problem can not be ignored. In the pursuit of technological breakthroughs, it is also necessary to pay attention to cost control, and strive to take the best practical application plan to enhance the common stability of the whole system without increasing too much cost.

Looking forward to the future, in the specific research direction of LCL grid-connected inverter control stability inverters, this research can pay attention to the following aspects: First, we should focus on the development of high-performance control strategies suitable for weak grid environments to further improve the stability and actual work efficiency of inverters; Secondly, we can pay attention to the hardware design and optimization of the inverter, for example, by improving the circuit topology, optimizing key parameters and other measures to further improve the performance and reliability of the inverter. Finally, environmental adaptability of the inverter is strengthened to ensure the practicability of the strategy, so that it can make the inverter run stably in various practical application environments.

Therefore, to sum up, in order to improve the performance of the entire system in the new energy power generation and promote development of the new energy industry, it is necessary to study the stability of LCL grid-connected inverters in a weak grid environment

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