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Method to Suppressing the Leakage Current Phenomenon of Non-Isolated Three-Level Photovoltaic Grid-Connected Inverters

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Abstract. With the increasing dominance of photovoltaic power generation in renewable energy, non-isolated three-level photovoltaic grid-connected inverters are widely used. However, due to their topology and the existence of parasitic capacitors, inverters can cause leakage current problems, which can cause grid current distortion and bring security risks. Two leakage current suppression strategies are summarized in this paper: improved inverter model prediction direct power control strategy and active zero sequence current injection-based control method. The improved inverter model predicts that the direct power control strategy has higher control precision and response speed and can effectively suppress the leakage current while ensuring the output power of the inverter. However, the output voltage is unstable in the two optimized structures. The principle of the control method based on active zero sequence current injection is simple and easy; the hardware of the inverter is less changed and can effectively reduce the leakage current and improve the safety of the photovoltaic power generation system, but it needs to add additional control lines of the injection current, and its cost will increase.

Keywords: Three-Level Four-Bridge Inverter, Active Zero Sequence Current Injection

1 Introduction

Photovoltaic power generation systems can be divided into off-grid type and grid-connected type two. A grid-connected photovoltaic power generation system is a power system that converts direct current into alternating current directly through an inverter and connects to the power grid to form mutual support with the power grid. It has the advantages of a wide application range, good flexibility, and high security. Non-isolated three-level grid-connected photovoltaic inverters are commonly used in the rectification equipment of photovoltaic systems connected to the grid. Because it does not use line frequency transformers and high-frequency transformers, the non-isolated three-level photovoltaic grid-connected inverter has the characteristics of high efficiency, small size, and low weight.

The metal shell of the photovoltaic system equipment is in contact with the ground

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to generate parasitic capacitance, also known as stray capacitance. The presence of parasitic capacitors can cause the current to bypass the inverter through the ground and directly into the grid, resulting in leakage current problems. Leakage current will cause current distortion of the power grid, magnetic field interference, and even cause injury to personnel. Significant progress has been made in some control methods. For example, Wang's research pointed out that the new carrier modulation strategy of dual-carrier modulation can be used to reduce the leakage current, and Zhang's research pointed out that the problem of leakage current can also be reduced by improving the cascade H5 topology [1, 2]. However, the existing technology still has certain limitations. Leakage current suppression not only requires efficient control strategies but also needs to be optimized according to the needs of practical applications.

This paper aims to review the leakage current suppression methods of non-isolated three-level grid-connected photovoltaic inverters, with emphasis on two more effective control strategies. It aims to provide theoretical support and practical reference for future research direction and technical application.

2 Generation Mechanism and Influencing Factors of Leakage Current

2.1 Topological structure

In the topology of voltage source inverters, the number of output voltage levels is different, which can be divided into two-level inverters, three-level inverters, five-level inverters, and so on. The topology of different inverters is also different, and the corresponding leakage current intensity is also different. However, the structure of a five-level inverter is more complex, and its cost is higher than other types of inverters. Compared with the two-level inverter, the use frequency of the device is lower, and the corresponding service life is longer than that of the two-level inverter. At the same time, the three-level inverter can output more layers of stepped power, which is closer to the sinusoidal waveform after modulation, and the harmonic content in the output power will be relatively low, and the quality will be higher [3]. Therefore, the research on three-level inverters has more practical significance.

2.2 Parasitic capacitance, common-mode voltage, and common-mode current

In the non-isolated PV grid-connected system, the electric energy is transferred between the PV array and the grid through the line. Since the earth and the photovoltaic panel can be regarded as two parallel panels that are approximately parallel, there will be parasitic capacitance between the photovoltaic panel and the earth. A common mode loop will be formed between the PV array, grid-connected converter, and grid. The high-frequency pulsating common-mode voltage generated by the power switch tube in the converter during operation will generate common-mode current on the parasitic capacitor. These common-mode currents will enter the grid through the circuit and cause a leakage current phenomenon, thus affecting the stability and safety of the grid [4].

3 Leakage Current Suppression Method

3.1 Add a common mode filter

Adding a common mode filter is a traditional method for leakage suppression. Common-mode filters suppress leakage currents by incorporating capacitors and inductors into the circuit to form common-mode impedance. This control strategy can effectively suppress common-mode interference, is easy to install, and has low cost, but its suppression effect on differential mode interference is limited [5].

Common-mode filters can be divided into first-order, second-order, and third-order filters. Specifically, the role of common-mode filters can first reduce the common voltage and thus reduce the common-mode current and finally reduce the leakage current intensity [6]. Second, the common mode noise can be suppressed, and then the anti-interference ability of the system can be improved. The third common mode filter can reduce the transient voltage in the circuit and thus improve the reliability of the system.

3.2 Optimal control strategy

The leakage problem can also be controlled by optimal control strategies, including improved model Predictive Control (MPC), virtual vector synthesis and over-modulation strategy based on virtual space vector modulation [7].

The FCS-MPC algorithm is an advanced control strategy (Fig. I) capable of efficiently controlling nonlinear, multivariable systems. In the MPC algorithm, leakage current suppression can be achieved by adding a common-mode voltage control term to the cost function [8]. The MPC algorithm strategy does not need a modulator and has a small amount of computation and a fast response speed. However, the switching frequency is not fixed, the control accuracy is low, and there will be problems such as difficult design and difficulty to guarantee the power quality of the network.

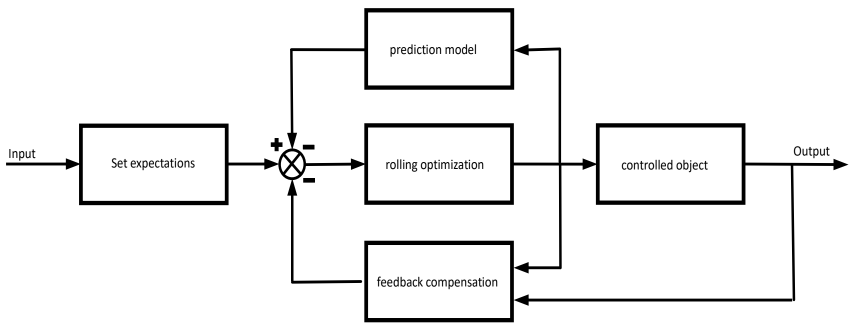

Fig. 1. Schematic diagram of MPC control strategy [3].

Virtual vector synthesis is a control strategy based on Space Vector modulation (SVM). The leakage current can be effectively suppressed by selecting the switching vectors that make the common-mode voltage fluctuation smaller to synthesize the virtual vector. Feng Hui proposed to reduce the number of IGbts with switching state changes by optimizing the synthesis method of virtual vectors [8], thereby reducing switching loss and error and finally improving the working efficiency of the inverter and reducing the leakage current intensity. The SVM strategy can realize multi-objective optimization control, which can optimize other control objectives while realizing common mode voltage suppression. However, it is greatly affected by dead zone and control delay and has a strong dependence on the system model.

3.3 Improved topology of three-level four-bridge inverter

Fig. 2 shows the basic topology of the basic three-level four-bridge arm inverter (hereinafter referred to as the basic structure). Compared with the two-level three-phase four-bridge arm inverter and the three-level three-phase three-bridge arm inverter, the mathematical model of the three-level four-bridge arm inverter is more complex. This complexity stems from its special topology, which contains four bridge arms, each consisting of two switching devices and two diodes in reverse parallel [9].

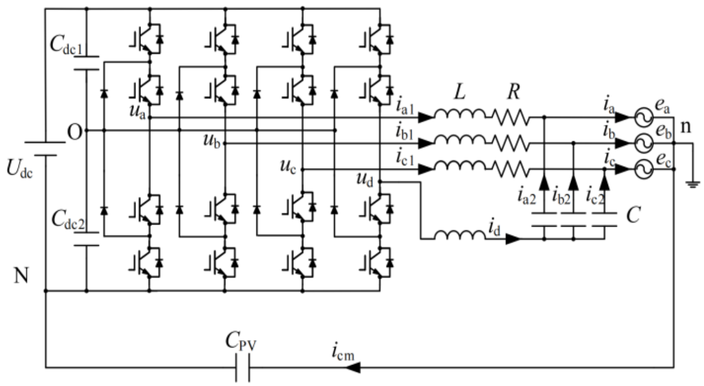

Fig. 2. The basic structure of three-level four-bridge inverter grid-connected schematic diagram [3]

In the Fig. 2, the grid voltage represents the grid-connected current, which represents the voltage of each inverter bridge arm output to point N (j=a, b, c, d) According to the derivation of Yang Kaiwen, the conclusion can be obtained [3]

$$4u_{cm} = L\frac{di_{cm}}{d_t} + i_1R + \frac{1}{C}\int i_d dt + e + \frac{4}{C_{pv}}\int i_{cm}dt \quad (1)$$

According to equation (1), the equivalent circuit Fig. 3 can be drawn:

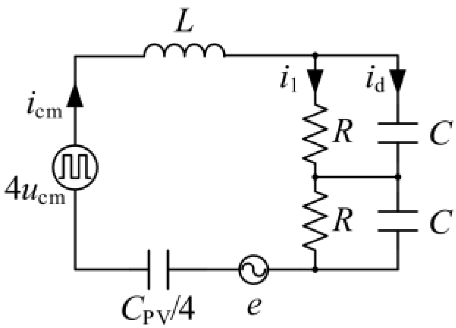

Fig. 3. Equivalent circuit [3]

Finally, it is concluded that there are two ways to suppress the leakage current intensity. First, starting from the excitation, the leakage current is indirectly suppressed by reducing the common-mode voltage change rate through the control strategy, as shown in 3.1 and 3.2. Second, optimize the circuit structure to suppress leakage current from the hardware circuit principle [3].

The topology of the traditional three-level, four-bridge arm inverter is shown in Fig. 4:

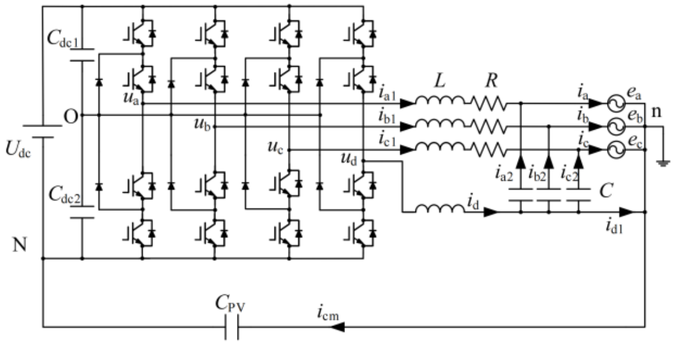

Fig. 4. Traditional three-level four-bridge inverter topology [3]

According to the paper of Kaiwen Yang, the final formula (2) and the equivalent circuit diagram Fig. 5 can be obtained.

$$4u_{cm} = L\frac{di_{cm}}{dt} + i_1 R + \frac{4}{C_{PV}}\int i_{cm} dt \qquad (2)$$

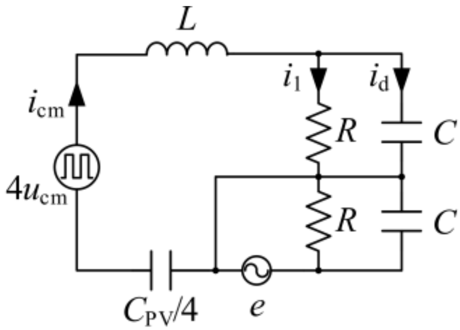

Fig. 5. Traditional topological equivalent circuit diagram [3]

Compared with Fig. 3, in the traditional topology, the grid-side power supply and some components are short-circuited, and the excitation sources are reduced from two to one so as to reduce the leakage current [3]. However, this structure introduces other currents at the grid side neutral point, causing interference to the grid side current and producing greater distortion.

Based on the traditional topology, Kaiwen Yang proposed two optimized topologies to reduce the leakage current intensity. The first optimization topology (referred to as optimization 1) connects the common midpoint of the filter capacitor to the midpoint O of the two capacitors on the DC side, as shown in Fig. 6

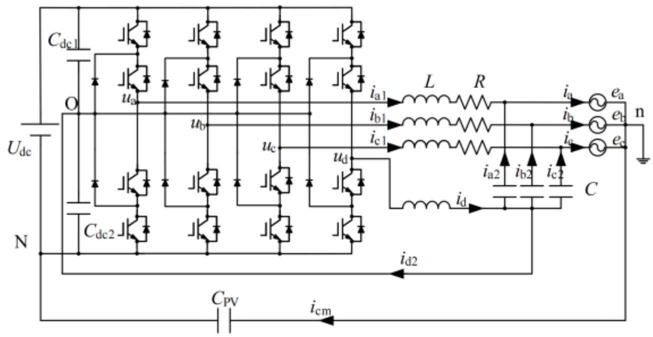

Fig. 6. Optimization 1 Schematic diagram [3]

Its corresponding final expression (3) (4) and equivalent circuit diagram in Fig. 7 below

$$4u_{cm} = L\frac{di_1}{dt} + i_1R - \frac{1}{C}\int i_2dt + 4U_{ON} + L\frac{di_d}{dt} \qquad (3)$$

$$4u_{cm} = L\frac{di_1}{dt} + i_1R + L\frac{di_d}{dt} + e + \frac{4}{C_{PV}}\int i_{cm}dt + \frac{1}{C}\int i_2dt \qquad (4)$$

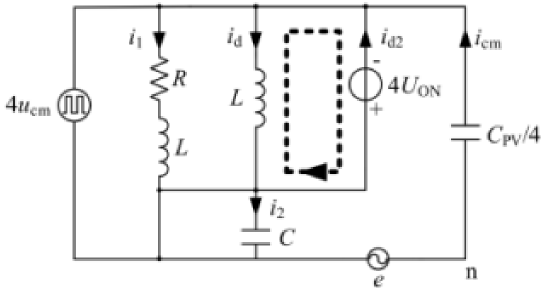

Fig. 7 Optimize 1 equivalent circuit [3]

In optimization 1, the influence of DC excitation source is ignored, and the current generated by the excitation source is diverted by multiple branches, so that the leakage current is reduced, and the leakage current is suppressed theoretically. However, since the branch where the output current of the fourth bridge arm is located has only one inductor, the impedance is too small, which leads to the DC side current flowing back to the fourth bridge arm, as shown by the dotted line in Fig. 7, resulting in the potential drift of the midpoint of the DC side, resulting in the instability of the output voltage and affecting the system operation [3].

The second optimization (referred to as optimization 2) uses the same control strategy as optimization 1 by series resistors in the branch from the filter capacitor to point O on the DC side, as shown in Fig. 8.

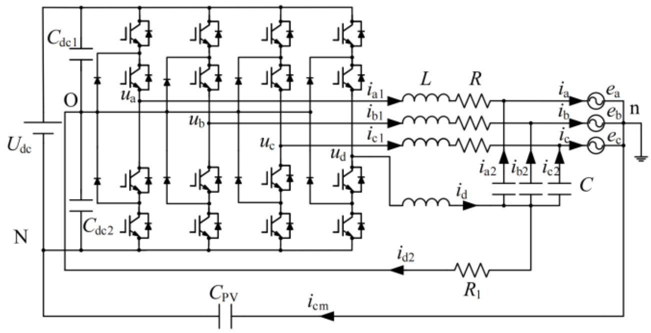

Fig. 8 Optimization 2 schematic diagram [3]

The final expression (5) given by Yang and the equivalent circuit diagram Fig. 9

$$4u_{cm} = L\frac{di_1}{dt} + i_1R - \frac{1}{C}\int i_1R + 4U_{ON} + L\frac{di_d}{dt} + 4i_{d2}R_1 \quad (5)$$

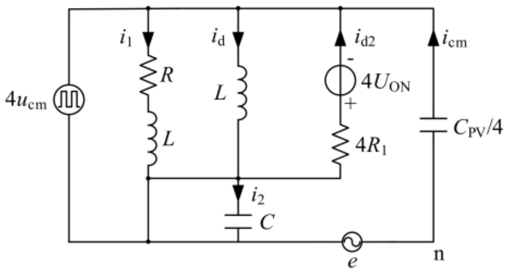

Fig. 9 Optimize 2 equivalent circuits [3]

By means of series resistance, the circulation problem caused by too small branch impedance is eliminated. The selection of the resistance value of the series resistance needs to be calculated according to the overall circuit parameters and other components parameters and output power.

4 New Leakage Current Control Method Based on Active Zero Sequence Current Injection

Wang Xiuyun innovatively proposed a new leakage current control method based on active zero-sequence current injection to control leakage current [4].

4.1 Topological structure

The leakage current control method proposed by Wang Xiuyun is different from the traditional three-level four-bridge arm inverter. As shown in Fig. 10, this method increases the capacitance at the negative end of the DC bus to form an active zero-sequence loop, which limits the leakage current to form a circulation inside the filter capacitor and inverter to avoid leakage current flowing into the grid.

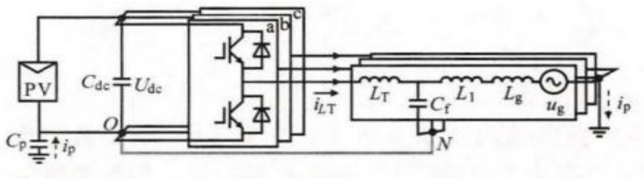

Fig. 10. Topology of non-isolated PV grid-connected inverter based on active zero sequence loop [4]

4.2 Analysis of leakage current mechanism

The leakage current control method can weaken the common mode current by actively injecting the active zero sequence current into the loop. The equivalent common mode circuit is shown in Fig. 11.

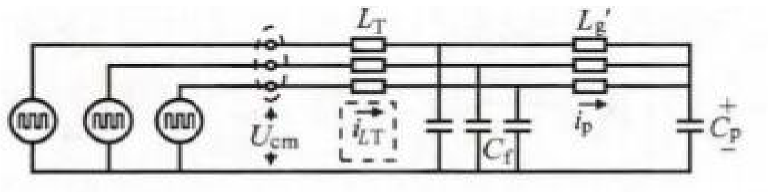

Fig. 11 Equivalent common mode circuit [4]

4.3 Control strategy

The new leakage current control method based on active zero-sequence current injection is mainly composed of three parts: grid-connected control, active zero-sequence current control and active damping control, and its control block diagram is shown in Fig. 12.

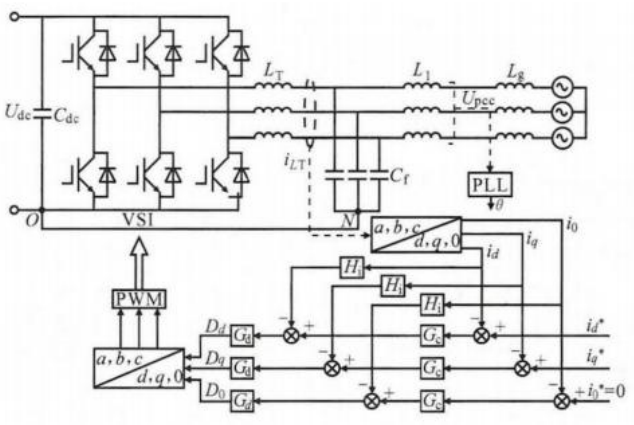

Fig. 12 Leakage current suppression control method [4]

4.4 Defects and optimization

Traditional zero-sequence current injection uses SVPWM control method. When controlling the midpoint potential of three-level Midpoint Clamp (NPC) inverter, it needs to adjust the action time of redundant small vectors in each small sector, which is relatively complex. Xie Jijin proposed the strategy of setting the midpoint potential threshold and introducing a hysteresis loop to optimize the injected zero-sequence components. This optimization strategy effectively reduces the switching loss while controlling the midpoint potential [10].

5 Conclusion

This paper systematically reviews a variety of effective leakage control strategies, including adding common-mode filters to filter noise, optimizing control strategies to improve system response efficiency, improving circuit topology to reduce leakage generation, and adopting a novel leakage control technique based on active zero-sequence current injection. These methods show their respective advantages and limitations according to different application scenarios and requirements. In particular, the active zero-sequence current injection technique innovatively offsets the common-mode current by injecting a specific current into the circuit, thereby theoretically eliminating the effect of leakage current to the maximum. Although this method has some drawbacks in terms of cost and circuit complexity, its unique control concept opens up a new research direction in the field of leakage current control and shows great research potential and application prospects, which is worthy of further exploration and optimization.

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