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Study on neutral-point voltage balancing control in three-level grid-connected photovoltaic inverter

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Abstract. Three-level photovoltaic grid-connected inverters are widely used in the photovoltaic grid-connected systems because of their high efficiency and low harmonic characteristics. However, the major problem of the three-level inverter has always been its core challenge, significantly affecting its system reliability and performance. This study reviews the causes of neutral-point voltage imbalance, discusses three typical three-level inverter topologies, including neutral-point-clamped inverter, flying capacitor inverter, and cascaded H-bridge inverter, and compares their application effectiveness in neutral-point voltage balancing control. Then, it analyzes several common control methods, such as the modulation method based on space vector, model predictive control, and relatively new techniques for controlling virtual neutral-point voltage. The comparative analysis results show that space vector is easy to implement, but the neutral-point voltage fluctuates markedly; model predictive control exhibits strong dynamic response performance but has a high computational complexity; virtual neutral-point voltage does not rely on the real-time feedback of actual neutral-point voltage. In conclusion, this study makes a prospect for the development trends of neutral-point voltage balance control technologies and proposes possible development directions for further improving the performance of grid-connected photovoltaic inverters.

Keywords: three-level grid-connected photovoltaic inverter, neutral-point voltage balancing, control method

1. Introduction

As global resources are further depleted, the demand for renewable energy and resources grows accordingly. Solar energy, being a clean and sustainable form of energy, is widely applied and promoted. The grid-connected system is one of the major applications that utilize solar energy, with the core electronic component of grid-connected photovoltaic inverters.

Three-level grid-connected inverters feature advantages such as high-quality electrical output, high efficiency, and low voltage stress on power switching devices, which have become hot research topics in grid-connected photovoltaic inverters.

However, the issue of the imbalanced neutral-point voltage of three-level grid-connected photovoltaic inverters leads to problems such as output current distortion and uneven voltage on switching devices, severely affecting the performance and reliability of the system [1]. In the research conducted by Wang, focusing on the neutral-point voltage imbalance issue in the neutral point clamped (NPC) three-level inverter, a neutral-point voltage balancing control algorithm was introduced, and the imbalanced neutral-point voltage was avoided by improving the space vector pulse width modulation (SVPWM) strategy [2]. The experiment demonstrated that the algorithm could enhance the direct current (DC) voltage utilization of the inverter, improve the quality of the output waveform, and optimize the switching frequency, thereby effectively controlling the neutral-point voltage [2]. Wang proposed a neutral-point voltage balancing method based on model predictive control (MPC), which reveals the intrinsic mechanism by building a dynamic model of neutral-point voltage deviation to avoid the issue of neutral-point voltage deviation in three-level inverters [3]. After theoretical derivation and experimental exploration, the results show that MPC has significant advantages in improving the efficiency and stability of the system [3]. Cheng put forward a novel neutral-point voltage balancing control strategy, which can achieve dynamic control of neutral-point voltage while not changing the original modulation strategy [4]. Theoretical analysis and experiments proved the effectiveness of virtual midpoint voltage (VMV) in improving the accuracy of neutral-point voltage balancing [4].

Hence, studying the neutral-point voltage balancing control methods of three-level grid-connected photovoltaic inverters is of great significance both theoretically and practically.

To address the neutral-point voltage imbalance of inverters, this study primarily analyzes three typical three-level topologies, which are followed by detailed discussions of neutral-point voltage balancing control methods, including SVPWM, MPC, and VMV control. With a comparative analysis of these methods, this study aims to provide technical reference for improving the performance and reliability of three-level inverters.

2. Overview of unbalanced neutral-point voltage

A grid-connected power generation system mainly consists of a photovoltaic array, inverter, load, and grid [5]. Among them, the photovoltaic array functions as the source of the system, converting solar energy into DC electrical energy. Then, the inverter transforms DC electrical energy generated by the photovoltaic array into alternating current (AC), facilitating the electrical energy to be smoothly integrated into the grid. The load consumes the electrical energy for its practical application. The grid functions as the network for receiving and distributing electrical energy, delivering the electric power generated by the photovoltaic system to power consumption areas. Meanwhile, it provides supplemental power for the load when the power generated by the photovoltaic system is insufficient, thereby ensuring the stability and reliability of the power supply. The core electronic component is the grid-connected photovoltaic inverter.

Unbalanced neutral-point voltage could trigger a series of negative impacts, such as harmonic content increase of the output voltage, resulting in reduced efficiency and excessive heating of motors and other loads, and even issues like electromagnetic interference. Simultaneously, it could cause uneven voltage stress on some power-switching devices, disturbing their lifespan and the system's reliability. Additionally, the fluctuation of neutral-point voltage could lead to unbalanced charging and discharging of the DC-side capacitors, which accelerates capacitor aging and shortens their lifespan, further affecting the stable operation and performance of the system overall.

Main reasons for unbalanced neutral-point voltage:

Differences in circuit parameters. Neutral-point voltage imbalance can be caused by differences in the on-state resistance, reverse recovery characteristics of power switching devices, such as insulated-gate bipolar transistors (IGBTs), and parameters of the DC-side capacitors. The current distribution across the phases will be uneven during switching if the on-state resistance of the switching devices in bridge arms of each phase are not identical, which can generate neutral-point current and cause a deviation in the neutral-point voltage. In addition, if there are differences in the capacitance, equivalent series resistance (ESR), and equivalent series inductance (ESL) of the two capacitors on the DC side, the voltages of the two capacitors cannot remain consistent during the charging and discharging process, which will cause the imbalance of neutral-point voltage.

Factors of load characteristics. When the load is unbalanced, the magnitudes of the three-phase currents become unequal. This causes non-zero neutral-point currents, which lead to a shift in neutral-point voltage. For example, if there are differences in the impedance of the three-phase windings of the motor or uneven mechanical load driven by the motor during the operation process, the three-phase currents will become unbalanced, further affecting neutral-point voltage. In addition, the power factor of the load affects neutral-point voltage as well. A low power factor load increases the reactive component of the current, intensifying the imbalance in the neutral-point current and making the neutral-point voltage fluctuation more prominent.

Imperfect modulation strategy. If the chosen modulation strategy does not adequately account for balancing neutral-point currents, it may lead to fluctuations in the neutral-point voltage. Different modulation strategies can have varying effects on the neutral-point voltage.

3. Topology of three-level inverter

3.1. Neutral point clamped (npc) three-level inverter topology

NPC three-level inverter is developed based on the two-level inverter. It connects two equal capacitors in series on the DC side, with two clamping diodes linked between them [6, 7]. The topology is shown in Figure 1.

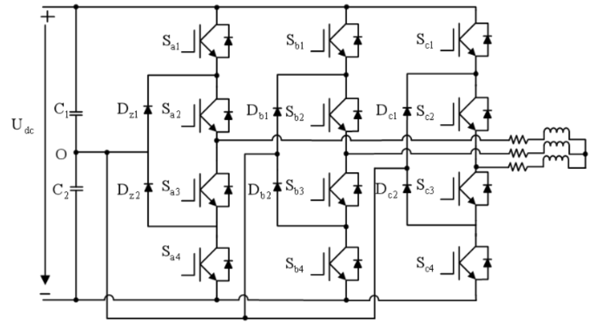

Figure 1. NPC three-level inverter topology [1]

According to Figure 1, NPC three-level inverters have three bridge arms, corresponding to phases a, b, and c. Each bridge arm consists of clamping diodes and power switching devices. The three different output levels of the three-level inverter are primarily achieved by controlling the on-off states of the power switching devices.

NPC topology produces better waveforms. During the commutation process of the three-level bridge arm, the variation of each voltage level is determined by the positive or negative neutral-point voltage. An additional level is introduced and converted into phase voltage. This helps levels of waveform variation smoothly transit towards a sine wave, thereby reducing harmonic distortion. Therefore, during the commutation process of the three-level bridge arm, each voltage level change is influenced by the positive or negative neutral-point voltage. The additional voltage level introduced during commutation results in each power semiconductor device experiencing this voltage. This increases voltages and power levels and provides certain benefits to the inverter. The NPC inverter has relatively low switching losses. Namely, it has lower switching losses when the voltages and phase currents on the DC side are the same. It allows for an appropriately increased switching frequency, further reducing harmonics. However, the NPC topology has its limitations. It has more power semiconductor devices and two clamping diodes, even more than those in two-level inverters. More components cause certain disruptions to the system. For example, issues such as output voltage distortion and even neutral-point voltage balancing might occur, causing damage to the two capacitors on the DC side of the components. The increase in components causes a certain degree of loss in each device [8, 9].

3.2. Fly-Capacitor (FC) three-level inverter topology

The FC three-level inverter topology uses a single capacitor to replace the two clamping diodes in the NPC inverter [1]. The topology is shown in Figure 2.

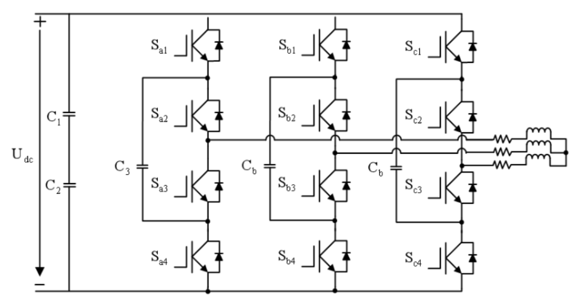

Figure 2. Topology of FC three-level inverter [1]

Each bridge arm of the FC inverter consists of four switching devices and two identical capacitors. Output with three voltage levels can be achieved by controlling the on and off states of switching devices, namely positive level, negative level, and zero level. The major advantage of FC three-level inverters is that their topology provides significant protection for switching transistors. Since it has strong control over both active and reactive power, it is better suited for high-voltage DC transmission systems. However, its major drawback lies in the high energy storage capacity it requires, which significantly adds complexity to the system control [10, 11]. To achieve the expected output level, equal charging and discharging of the storage capacitor is required.

3.3. Cascaded three-level inverter topology

A cascaded three-level inverter topology connects two identical single-phase full-bridge inverters in series. The single-phase topology is shown in Figure 3.

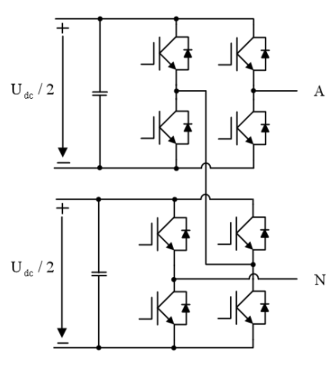

Figure 3. Single-phase cascaded three-level inverter topology [1]

Clamping diodes or capacitors are not required for cascaded three-level inverters. Correspondingly, issues such as neutral-point voltage deviation and voltage balancing in the intermediate DC link do not exist [12, 13]. Compared to the aforementioned two topologies, cascaded three-level inverter topology has distinct advantages.

In this topology, the DC side is powered by an independent voltage source, making voltage balancing easy and preventing neutral-point voltage imbalance. However, this introduces an inevitable drawback. The power supply requires multiple independent voltage sources with identical parameters, which is difficult to achieve in real-world scenarios. Even if the requirements are met, the operational cost would be significantly high.

4. Neutral-point voltage balancing control of three-level grid-connected photovoltaic inverters

4.1. SVPWM-based control method

Regarding the issue of neutral-point voltage imbalance occurred in the NPC three-level inverter, Wang conducted research and introduced the neutral-point voltage balance control algorithm by improving the SVPWM strategy [2]. This algorithm can increase the DC voltage utilization and output waveform quality, thereby achieving effective control of neutral-point voltage [2]. This research also proved the effectiveness of the proposed method through simulation and testing, offering insights into the issue of neutral-point voltage imbalance in the NPC three-level inverter.

Based on the concept of space vector, SVPWN converts the instantaneous values of the three-phase voltages into an equivalent rotating space vector. The inverter achieves this by generating different switching states. The main task is to project the target voltage vector onto the range of the six basic vectors and approximate it by using different switching combinations with varying time ratios. SVPWM implementation involves three steps, including determining the sector of the reference vector, calculating the duty cycle, and generating the switching sequence [2, 14].

4.2. MPC-based control method

Wang analyzed the issue of neutral-point voltage deviation of three-level inverters and proposed a neutral-point voltage balance method based on MPC by developing a dynamic model of neutral-point voltage deviation and uncovering its intrinsic mechanism [3]. To optimize the dynamic response and steady-state performance of the system, theoretical derivation and experiments were conducted. The experiment results show that MPC has significant advantages in improving system efficiency and stability [3].

Model predictive modulation is the control strategy developed based on the system model and optimized algorithm. It predicts the future states using a mathematical model, selecting an optimized control action based on the predicted results to attain the control objectives. Regarding the system model, the control state variables of the three-level inverter are typically the current vector or flux linkage vector, while the control variable is the inverter's switching state.

The objective function is defined based on the control objectives and can be optimized for different applications, such as current tracking, harmonic suppression, and loss minimization. There are four steps to implement MPC. The first step is sampling and state estimation, where the system's current state is determined using sensors to measure current, voltage, and other state variables. The second step is model prediction, where the state at the next time step is predicted for different control inputs based on the current state and system model. The third step is inputs optimization. The last step is the application of control inputs, where the most effective control input is applied to the inverter [15].

4.3. VMV-based control method

Cheng introduced the concept of VMV and established a new neutral-point voltage balance control strategy. This strategy can achieve the dynamic regulation of neutral-point voltage. Through theoretical analysis and experiment, Cheng provided the effectiveness of VMV in improving the neutral-point voltage balancing accuracy.

Different from the traditional method, the VMV-based control method enhances the robustness of the system and reduces hardware complexity by introducing VMV as a reference, instead of directly relying on the measurement of physical neutral-point voltage [16]. VMV is a reference value for neutral-point voltage generated by algorithms, simulating the neutral-point voltage under ideal conditions. It shifts the control objectives from the actual neutral-point voltage to the virtual one, thereby avoiding direct reliance on neutral-point voltage measurement. Three steps are involved to implement VMV modulation. The first step is VMV generation, which utilizes the total voltage of the DC bus capacitors and the characteristics of the load current. The second step is virtual voltage deviation calculation, which calculates the deviation between VMV and the ideal reference value. The last step is voltage balance control, which minimizes the neutral-point voltage deviation by adjusting the inverter’s switching states or modulation strategy in real-time.

4.4. Comparison of different control methods

Based on the aforementioned contents, the advantages and disadvantages of current neutral-point voltage balance control methods are summarized in Table 1. Characteristics of each method are analyzed. Different methods have distinct advantages, with some controlling at the hardware level and others controlling through model-based algorithms. However, there are also some drawbacks.

Table 1. Characteristics of different control methods

Control methods	Advantages	Disadvantages
SVPWM-based control method [17]	High DC voltage utilization; Low harmonic distortion; easy digital implementation; simple to implement.	Unfixed switching frequency; pronounced fluctuation of neutral-point voltage.
MPC-based control method [3, 15]	Swift response performance and fast parameter tracking; flexible handling of multivariable coupled systems and nonlinear constraints; no need for a modulator; low harmonic distortion.	High computational complexity and difficulty, especially at high switching frequencies, where the computational burden is significant; requires high accuracy of the system model, as model errors may affect control performance; and unfixed switching frequency.
VMV-based control method [18]	No need for an additional neutral-point voltage sensor, which reduces the measurement error of the system; no reliance on real-time feedback of the actual neutral-point voltage, and effectively addresses sensor failures and signal noise, making it more adaptable to load fluctuations and parameter variations; a relatively simple algorithm which reduces computational complexity.	A relatively novel method with a concept that remains somewhat vague compared to others.

5. Conclusion

In conclusion, this study systematically reviews the three-level grid-connected photovoltaic inverter topology and neutral-point voltage balance control methods. Through in-depth analysis of various literature, it is found that the neutral-point voltage balance control of the three-level grid-connected photovoltaic is a key factor in ensuring the stable and reliable performance of the system.

Regarding the inverter topology, NPC, FC, and cascaded three-level inverter topologies all have remarkable performance in enhancing power quality, reducing switching losses, and optimizing voltage utilization.

Existing studies have made significant progress in exploring the neutral-point voltage balance control methods of three-level grid-connected photovoltaic inverters. Multiple effective control strategies and technologies have been proposed and developed, such as MPC, VMV, and other advanced control strategies. These strategies have demonstrated distinct advantages and effects in various scenarios. For instance, MPC performs exceptionally in terms of dynamic response and steady-state performance optimization. However, there are still some technical bottlenecks and logical flaws, including the high complexity of control strategies, strict requirements on hardware, and insufficient robustness in practical applications. Future studies should explore more simple and efficient neutral-point voltage balance control methods with strong robustness, and these methods should be validated and optimized in real-world application scenarios. This will promote the sustainable development and application of three-level grid-connected photovoltaic inverter technology.

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