Photovoltaic grid-connected inverter based on super capacitor energy storage MMC

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Abstract. In order to improve the reliability of grid-connected operation of photovoltaic power generation systems, this paper proposes a photovoltaic grid-connected inverter based on supercapacitor energy storage MMC. Compared with traditional battery energy storage devices, the converter has the advantages of environmental friendliness, high energy storage efficiency, and long service life. The control strategy of the system is divided into three parts: carrier phase shift modulation strategy (CPS-SPWM), voltage balance control strategy and super capacitor charging control strategy. Finally, the feasibility of the proposed photovoltaic grid-connected inverter and its control strategy is verified in MATLAB/Simulink. The results show that the system can realize the photovoltaic grid-connected inverter process, realizes soft switching, and has high Energy storage efficiency.

1. Introduction

Photovoltaic power generation is greatly affected by the natural environment and has the characteristics of randomness, intermittence and instability. If it is directly connected to the grid, it will cause severe fluctuations in the voltage amplitude and frequency of the grid, and deterioration of power quality, which will seriously affect the safe and stable operation of the grid. Installing energy storage devices to reduce the rate of change of active power is an effective method to solve the problem of active power impact. Commonly used energy storage devices, such as batteries, have the advantages of high energy density and stable output voltage, but they also have problems such as long charging time, short cycle life, and serious environmental pollution, which severely restrict their use in photovoltaic power generation systems. Modular multilevel converter (MMC) is a new type of multilevel converter that has emerged in recent years. It is widely used in grid-connected systems due to its high degree of modularity and easy cascading expansion[1]. At present, there have been studies on integrating energy storage units into MMC as energy buffers. However, these studies are mainly focused on the application of battery-based energy storage MMC.

As a new type of energy storage element, supercapacitors have the advantages of high working efficiency, fast charging and discharging speed and long service life. In addition, with the rise of electric vehicles, charging devices based on supercapacitors have received extensive attention. However, there are relatively few studies on the use of supercapacitor energy storage devices in the electrical field. To this end, this paper proposes a photovoltaic grid-connected inverter and its control strategy based on Super Capacitor Energy Storage Based MMC (MMC-SCES). In order to improve the efficiency of the energy storage system, the LLC resonant converter is used as the connection
device between the MMC and the super capacitor to manage the voltage of the super capacitor [2-3]. On the one hand, this new inverter can be used as a grid-connected inverter, and on the other hand, it can provide a super capacitor charging device as a high-quality charging source for electric vehicles. In order to verify the feasibility of the proposed new inverter, this paper builds a 15-level MMC-SCES simulation model in MATLAB/Simulink. According to the simulation results, the system can stably output three-phase approximately sinusoidal alternating current, which can meet the requirements of Grid-connected process. The voltage of the super capacitor in the energy storage device is stable, and the resonant converter realizes soft switching, which helps to improve the efficiency of energy storage.

2. The topological structure of MMC-SCES system

The topology of the super capacitor energy storage system MMC-SCES is shown in Fig. 1. Its main inverter loop is similar to the traditional MMC topology, consisting of three parallel phase units with a common bus, and each phase unit is divided into two upper and lower phases. Bridge arms, each bridge arm is formed by connecting n half-bridge sub-modules (SM) and 1 bridge arm inductance L in series. Among them, the connection point of the upper and lower bridge arm inductances is used as the AC output terminal. When working, the input quantity of the upper and lower bridge arm sub-modules can be adjusted to achieve a three-phase AC voltage output similar to a sine wave. Among them, $U_{dc}$ is the DC bus side voltage of the system, $i_{pa}$, $i_{pb}$, and $i_{pc}$ are the upper arm currents of each phase respectively; $i_{na}$, $i_{nb}$, and $i_{nc}$ are the lower arm currents of each phase respectively; $i_a$, $i_b$, $i_c$ are the three-phase output currents; $U_a$, $U_b$, $U_c$ are three-phase output voltage.

Different from the traditional MMC, each super capacitor SC in this topology is connected in parallel to the DC end of each sub-module SM through a DC/DC converter, so each sub-module can be used as a distributed energy storage unit. The DC/DC converter in this system uses a full-bridge LLC resonant converter, which has the advantages of easy realization of soft switching and low switching loss, which is beneficial to improve the energy storage efficiency of MMC-SCES.

![Figure 1. MMC-SCES topology.](image)

3. Control strategy of MMC-SCES system

The control strategy of MMC-SCES system is mainly divided into three parts. They are the modulation strategy of MMC, the voltage equalization control strategy of MMC, and the charging control strategy of supercapacitors.

The modulation strategy of MMC uses carrier phase-shifted pulse width modulation (CPS-PWM). This modulation method can obtain a higher equivalent switching frequency at a relatively low switching frequency, effectively reducing the switching loss, and the output voltage has good harmonic characteristics effectively reduce the size of the filter. Its basic principle is to equip N sub-modules in a single bridge arm of MMC with N triangular carriers with equal amplitude and $2\pi/N$ phase differences in sequence, and then compare these N triangular carriers with the same sine wave.
modulated wave to obtain $N$ PWM pulses, these PWM pulses are the control signals of the $N$ sub-modules on the bridge arm. In order to ensure that at any time, the sum of the number of sub-modules put in the upper and lower arms of each phase is always $N$, the sine modulation waves of the upper and lower arms of each phase unit are equal in size, the frequency is the same, and the phase difference is $180^\circ$[4].

There are a large number of floating capacitors in MMC. In order to ensure the quality of the converter's output voltage waveform, it is necessary to balance the capacitor voltage of each sub-module to ensure the stable operation of the system [5]. The capacitor voltage equalization control strategy includes two parts: the capacitor voltage balance control in the phase unit and the capacitor voltage balance control in the bridge arm.

1) Taking phase a as an example, the capacitance balance control block diagram of the phase unit is shown in Fig. 2(a). The input of the voltage outer loop is the average voltage $u_{ca}$ calculated by each sub-module in the phase. It follows the reference value $U_{cref}$ of the capacitor voltage, and its output is used as the given value $i_{ciref}$ of the current inner loop, that is the circulating current reference value. The current inner loop still uses a PI regulator, and its main function is to suppress the interphase circulating current of the MMC. The input is based on the circulating current value $i_{ciref}$ calculated by the upper and lower arm currents $i_{a1}$ and $i_{a2}$, and the output value $U_{Aref}$ is the capacitance voltage balance control correction value.

2) The control block diagram of the capacitor voltage balance in the bridge arm is shown in Fig. 2(b), in which $u_{ca}$ is the actual value of the capacitor voltage of each sub-module of phase a. After they are compared with the voltage reference value $U_{cref}$, the capacitance voltage correction value $U_{Bjaref}$ is obtained after proportional amplification. And its positive and negative depends on the direction of the upper and lower bridge arm currents, suppose the upper bridge arm current is $i_{a1}$. The last two voltage corrections are added to the sinusoidal modulation wave to achieve voltage equalization between the capacitors.

![Figure 2. MMC voltage balance control (a) Phase unit capacitor voltage balance control (b) Bridge arm capacitor voltage balance control.](image)

The charging control strategy of the supercapacitor uses the PI control algorithm. According to the supercapacitor voltage $u(t)$, it is compared with the reference voltage $U_{sc}$, and the difference $e(t)$ between the two is adjusted by the PI regulator to output the LLC resonant converter control signal $c(t)$. 
4. System Simulation
To verify the feasibility of the MMC-SCES energy storage system and its control strategy proposed in the previous article, a 15-level system simulation model was built in MATLAB/Simulink, as shown in Fig. 4. Fig. 5 is the simulation model of LLC resonant converter. The specific parameters of the simulation model are shown in Table 1.

Table 1. MMC-SCES simulation parameters

| Parameters                                      | Parameter Values |
|------------------------------------------------|------------------|
| Input bus voltage /kV                          | 3                |
| Number of sub-modules of single bridge arm     | 15               |
| Bridge arm inductance /mH                       | 1                |
| Sub-module capacitance /mF                      | 6                |
| Modulation ratio                                | 0.9              |
| Rated frequency /Hz                             | 50               |
| SM capacitor nominal voltage /V                 | 100              |
| Super capacitor capacitance /nF                 | 200              |
| SC nominal voltage /V                           | 3                |
Figure 5. Simulation model of LLC resonant converter.

Fig. 6 shows a multi-level stepped voltage waveform close to a sine wave output by the AC side of the MMC-SCES. The amplitude is 1.5kV, the frequency is 50Hz, the three-phase voltage waveforms are the same, and the phases are sequentially different by 120°. It can be seen that under the adopted CPS-SPWM control strategy, the amplitude and frequency of the output voltage on the AC side are stable at the rated value of the power grid during steady-state operation under the adopted CPS-SPWM control strategy, which ensures the quality of power supply and can realize inverter and grid connection.

Figure 6. MMC-SCES output three-phase voltage waveform.

The voltage waveform of each SM capacitor in the MMC is shown in Fig. 7. It can be seen that the voltage of each SM capacitor fluctuates around 200V, and the fluctuation range is within 10%. The voltage balance between the capacitors is realized, and the voltage equalization control strategy adopted is verified effectiveness.

Figure 7. SM capacitor voltage waveform.
From the super capacitor charging voltage waveform shown in Fig. 8, it can be seen that after the output voltage of the LLC converter is adjusted by PI, the voltage of the super capacitor can be stabilized at 3V, with good dynamic characteristics, high robustness, and stable energy storage. It can be seen from the voltage and current waveforms of the MOS tube shown in Fig. 9 that the voltage and current of the switching tube realize soft switching, so it can effectively reduce the switching loss and improve the efficiency of the switching converter [6-7].

![Figure 8. Super capacitor charging voltage.](image)

![Figure 9. Voltage and current waveforms of LLC resonant converter MOS tube.](image)

5. Conclusion
In order to reduce the negative impact of the instability of the photovoltaic power generation system on the grid, this paper proposes a photovoltaic grid-connected inverter based on a supercapacitor energy storage device and its control strategy. The system has the advantages of less environmental pollution and fast charging and discharging speed. In addition, the use of LLC resonant converter to manage the voltage of the super capacitor improves the efficiency of the energy storage system. The system model is built in MATLAB/Simulink. According to the simulation results, it can be seen that under the proposed control strategy, the inverter can realize the inverter grid-connected process, which verifies the feasibility and effectiveness of the proposed new photovoltaic inverter.

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