Design and research of photovoltaic modules in energy routers based on cascaded H-bridge

Mingjie Pan¹, Xiang Li², Da Xie¹*, and Chenghan Zhao¹

¹Department of Electrical Engineering, Shanghai Jiaotong University, Minhang District, Shanghai, 200240, China
²Institute of Electrical, Shanghai Dianji University, Minhang District, Shanghai, 200240, China
*xieda@sjtu.edu.cn

Abstract. Aiming at the shortcomings of traditional photovoltaic modules in energy routers, a new structure of cascaded H-bridge photovoltaic module is designed in this paper, including photovoltaic cell module, Boost/Buck module with inertial energy links, and chain H-bridge module. The maximum power point tracking (MPPT) control algorithm and the chain cascaded H-bridge control algorithm are studied, and the control angle table of the full chain 12H-bridge and the missing chain 11H-bridge is given. A 12H-bridge cascade model is built in the EMTP simulation software to verify the feasibility of the H bridge cascade output and it proves that its harmonic content is small and the power quality is high. Finally, a chain cascaded photovoltaic panel is produced, showing that it can output AC power smoothly. Comparing the daily power generation of the new photovoltaic module and the traditional photovoltaic module, it proves that it has more power generation and better irradiance tracking performance.

1. Introduction

The photovoltaic module is an important link to the energy router. Traditional photovoltaic modules are made up of multiple silicon units connected in series, which convert solar energy into direct current with a certain voltage level, and then convert the direct current into alternating current that meets the requirements of the grid through a grid-connected inverter.

This photovoltaic power generation system, however, has certain limitations and deficiencies. First of all, because the system adopts the silicon unit series structure, once a piece of silicon unit fails, the string will not be able to effectively output power and have poor reliability[1]. Secondly, traditional photovoltaic power generation is significantly affected by environmental factors such as temperature and light intensity[2]. Thirdly, most photovoltaic power plants currently use centralized or string inverters and cannot achieve optimal power output and energy management for each photovoltaic module. In addition, various inverters composed of high-frequency electronic switches generally contain certain components of harmonics, which reduce the power quality of the power grid.

In order to solve the above problems, scholars have done a lot of research work. Paper [3] proposes an improved hybrid modulation strategy for the unbalanced output power of the photovoltaic panels on the DC side of the H-bridge module due to environmental factors. Paper [4-5] proposed a voltage equalization strategy for the problem of uneven DC bus voltage caused by the independent MPPT adjustment of each level of the cascaded grid-connected inverter. Paper [6] uses a three-level circuit on the solar photovoltaic inverter, which greatly reduces the harmonic content of the output voltage and
greatly improves the power quality. The above papers mentioned introduce a multilevel converter into the photovoltaic power generation system, which realizes the MPPT of a single photovoltaic module and reduces the harmonic content, but the voltage equalization problem of DC side commonly exist.

In this paper, a new structure of cascaded H-bridge photovoltaic module and its control algorithms are designed, and simulation and experimental analysis are performed to verify the feasibility of the structure and the correctness of the theory. The main innovations of this paper are as follows: (1) Boost/Buck circuit and H-bridge circuit are added to the traditional photovoltaic module and the output terminals are cascaded, realizing low-harmonic and high-quality sine wave output. (2) The distributed constant voltage MPPT control algorithm, inertial energy control and chain H-bridge control algorithm are proposed to enhance the ability of the new photovoltaic module to output AC power smoothly and improve its power generation efficiency.

2. Structure of photovoltaic modules based on cascaded H-bridges

Figure 1 shows the structure of 3H-bridge cascaded photovoltaic module. It is based on the traditional photovoltaic module, adding three sets of Boost/Buck (hereinafter referred to as B/B) circuit and H-bridge circuit, and cascade the output end of the H-bridge circuit.

Figure 1. Structure of H-bridge cascaded photovoltaic module.

The photovoltaic module is composed of photovoltaic cells connected in series, usually 60 pieces. Every 20 pieces are connected in parallel with a diode to prevent partial shading, which will cause hot spots or battery breakdown. The B/B circuit is composed of a supercapacitor $C_1$ with inertial energy storage and a traditional B/B circuit. The supercapacitor is mainly used to store or release energy to ensure that photovoltaic modules can still output voltage in harsh environments. The traditional B/B circuit is used to realize the MPPT function. The function of the H-bridge circuit is to convert direct current into alternating current. In this paper, the output terminals of the three H-bridge circuits are cascaded to form a 3H-bridge cascaded photovoltaic module. All levels of cascaded H-bridges output higher voltages through superposition, and the pulse width can be changed by controlling the trigger angle of the cascaded H-bridges, thereby changing the waveform of the output voltage.

3. Control algorithms of chain cascaded photovoltaic modules

3.1. Distributed constant voltage MPPT control algorithm

Traditional photovoltaic modules use centralized MPPT control. However, the photovoltaic modules differ in parameters and solar irradiance, so they cannot work at the optimal power at the same time, which causes serious energy loss. In this paper, the distributed MPPT control is adopted, that is, the MPPT control is added to each string of photovoltaic modules, thus reducing the energy loss and improving the power generation efficiency. In addition, the traditional MPPT control algorithm is mainly based on the detection method of voltage and current, and the accuracy of the sensor has a great influence on the determination of the maximum power point. Therefore, the constant voltage
method is used for MPPT control in this paper, and no current detection link is required, which simplifies the control process. The specific control algorithm flow is shown in Figure 2.

The collecting device compares the collected voltage $U_0$ with the reference voltage $U_0^*$. When the two voltages are not equal, the duty cycle of the B/B circuit is adjusted to keep the MPPT output at all times. Under normal working conditions, each module exhibits the same external characteristics, which makes the output voltage under MPPT control basically the same. When each string of photovoltaic modules works at the maximum power point, the 3H cascaded photovoltaic modules also work near the maximum power point of the system (taking into account the error), so as to realize the MPPT control of the cascaded system.

3.2. Inertial energy control
In order to improve the grid-friendliness of the cascaded multi-level photovoltaic system and avoid the impact of large fluctuations in solar power on the output voltage, the energy stored on the supercapacitor can be released every time the power drops suddenly to maintain the stable output of the photovoltaic system.

Assuming that the initial voltage of the supercapacitor $C$ is $V_{c0}$, and the voltage after changing the duty cycle is $V_{c1}$, the energy released by the inertial energy link $\Delta E$ can be expressed as:

$$\Delta E = \frac{1}{2} C (V_{c0}^2 - V_{c1}^2)$$

(1)

From equation (1), under the energy increment $\Delta E$, the output voltage of the cascaded H-bridge photovoltaic module changes from $V_0$ to $V_1$, and the changed voltage $V_1$ can be expressed as:

$$V_1 = \sqrt{V_0^2 - \frac{2 \times \Delta E}{C}}$$

(2)

3.3. Control algorithm of chain H-bridge
With $n$ H-bridge photovoltaic modules cascaded, there are a total of $3n$ H-bridge chain links. First, the DC voltage detection circuit uploads the collected DC voltages of the $3n$ H bridges to the main control unit. The main control unit judges the working status of each chain link according to the received voltage, and obtains the number of effective chain links. Then, according to the current number of effective chain links, the principle of equivalence of impulse area is used to calculate the switching tube trigger angle of each link, and the received voltage data is sorted. The chain links are numbered in the order of their voltages from high to low, so that the chain links with larger energy output more, which can balance the DC side voltage. Finally, the host will issue the total chain number and the sequence number of the chain link to the controller of each chain link. The basic principle of the chain control algorithm is shown in Figure 3.

The working status of each H-bridge chain link can be judged according to the change of the output voltage of each string of photovoltaic modules. When the power of the photovoltaic panel is sufficient, the module is at full power output and the voltage is in the best state. When the photovoltaic panel is
shaded for a short time, the output power drops, and the supercapacitor discharges to maintain the series current and maintain the proper output power. At this time, the DC voltage drops. When the photovoltaic panel is completely shaded, there is almost no power output. At this time, the bypass diode is turned on, and the terminal voltage is only the forward voltage of the diode.

In this paper, taking the 12H-bridge composed of 4 cascaded photovoltaic panels as an example, the trigger angle of the switch tube is calculated when 12-link operation and 11-link operation are performed, and the results are shown in Table 1. The trigger angle of each switch tube in the subsequent 12H-bridge cascade simulation circuit can be obtained from this table.

| Type | 12H | 11H |
|------|-----|-----|
| Number | Conduction angle | Extinction angle | Conduction angle | Extinction angle |
| 1     | 0.039 | 179.961 | 0.038 | 179.962 |
| 2     | 10.342 | 169.658 | 12.233 | 167.767 |
| 3     | 10.360 | 169.640 | 25.325 | 154.675 |
| 4     | 18.130 | 161.870 | 38.574 | 141.426 |
| 5     | 22.336 | 157.664 | 39.712 | 140.288 |
| 6     | 28.210 | 151.790 | 51.387 | 128.613 |
| 7     | 33.573 | 146.427 | 63.139 | 116.861 |
| 8     | 40.138 | 139.862 | 73.237 | 106.763 |
| 9     | 46.601 | 133.399 | 81.248 | 98.752 |
| 10    | 55.852 | 124.148 | 86.807 | 93.193 |
| 11    | 67.577 | 112.423 | 89.641 | 90.359 |
| 12    | 79.279 | 100.721 | —       | —       |

4. Simulation and experimental analysis

4.1. Simulation analysis

In order to verify the effectiveness of the control algorithms of the cascaded H-bridge photovoltaic modules, a 12H-bridge cascade model is built in the EMTP simulation software. The simulation model replaces photovoltaic components with capacitors and maintains the voltage across the capacitor at about 12V. Figure 4 shows the output voltage waveform of the cascaded H-bridge. Here, the normal operation of the 12H-bridge chain and the operation of the 11H-bridge chain when some modules are missing due to the failure of the chain are given.

As seen in Figure 4, the output waveform is a sine wave formed by stepwise superposition. In the case of 12H-bridge cascaded, the output waveform is basically sine wave, and stable output can be achieved. When one chain is missing, the output voltage wave becomes 11 level, and the 11 chain link can still achieve a fitted sine wave output.

In order to verify that the chain circuit can effectively eliminate the harmonic content, the FFT analysis of the voltage waveform under normal chain operation is carried out. The time-domain diagram and frequency-domain diagram are shown in Figure 5. From the frequency-domain diagram, it can be seen that there are basically no harmonics in the output waveform.
4.2. Experimental analysis
In order to verify the effectiveness of the new module board structure and control strategy designed in this paper, actual hardware tests are carried out. B/B circuit modules and H-bridge modules containing inertial energy are added to the existing photovoltaic panels, as shown in Figure 6. Each H-bridge module consists of 4 MOSFETs. The optocoupler is triggered by the GPIO of the control chip STM32, and then the switch tube is driven by the optocoupler, and finally the required output signal is generated. Table 2 shows the parameters of the experimental device.

| Type                        | Parameter                        |
|-----------------------------|----------------------------------|
| Photovoltaic panels CNPV-250p | Open circuit voltage 37.6V; Short circuit current 8.55A |
| Supercapacitor              | 2.5V, 1F                         |
| Winding inductance          | 10uH                             |
| Control chip of H-bridge    | STM32F103C8T6                    |
| MOSFET                      | HM3207B                          |

In order to verify the control strategy proposed, the output voltage of the B/B circuit is tested first. Figure 7 shows the boost waveform of the output voltage. It can be seen that when the output voltage of a string of photovoltaic modules is 5V, it can be increased to about 12V by adjusting the MPPT control of the B/B circuit, indicating that the B/B circuit can achieve a stable boost.
can be seen from Figure 8 that the output waveform contains three levels of positive, negative, and zero, and the H-bridge can output AC voltage stably regardless of whether it is under load or no load.

On the basis of the test of single H-bridge mentioned above, in order to verify the feasibility of the multi-module photovoltaic panel chain cascaded scheme, the grid-connected test of the 12H-bridge cascaded photovoltaic modules is carried out. Figure 9 shows the output voltage of the photovoltaic panel and the system. From the test waveform, it can be seen that the waveform is a high-quality sine wave, which captures the phase of the power grid well and keeps it consistent all the time.

In order to verify the power generation effect of chain cascade photovoltaic panels, the daily power generation of chain cascade photovoltaic panels and traditional photovoltaic panels are compared. Figure 10 is a comparison chart of the daily power generation curve of the new module panel (blue line) and the traditional photovoltaic panel (red line). It can be seen that the chain cascade can capture light energy well and generate more power than traditional photovoltaic panels. Furthermore, the new panels have considerable benefits due to the reduction of the cost of the inverter.

5. Conclusions
In this paper, the structure of the 3H-bridge cascaded photovoltaic module is first designed, and then its control strategy is studied. Finally, the feasibility of the proposed new photovoltaic module is verified through simulation and experiment. The following conclusions are obtained:

(1) The chain cascaded structure can replace the inverter and convert the direct current of the photovoltaic cell into alternating current. Using low withstand voltage switching devices can achieve high-voltage output, eliminating the cost of the inverter, thereby reducing the cost of PV power plants.

(2) When the photovoltaic cell is mismatched or the solar panel is blocked or lack of link, the cascaded structure can still operate through the communication of the corresponding angle. Therefore, the n-k missing link control technology improves the reliability of photovoltaic power generation.
Acknowledgments
The research in this paper was supported by Research on Energy Systems of Smart Park. Research and Demonstration on Key Technologies of Multi-functional Energy Router of Shanghai Science and Technology Commission (18DZ1203700)

References
[1] Yang H T, Huang C M, Huang Y C, et al. A weather-based hybrid method for 1-day ahead hourly forecasting of PV power output[J]. IEEE transactions on sustainable energy, 2014, 5(3): 917-926.
[2] Crăciun B I, Kerekes T, Séra D, et al. Frequency support functions in large PV power plants with active power reserves[J]. IEEE Journal of Emerging and Selected Topics in Power Electronics, 2014, 2(4): 849-858.
[3] Wang Fusheng, Zhang Dehui, Dai Zhiqiang, et al. A hybrid control scheme of cascaded H-bridge inverters for grid-connection photovoltaic systems[J]. Transactions of China Electrotechnical Society, 2016, 31(s1):137-145.
[4] Wang Shuzheng, Zhao Jianfeng, Yao Xiaojun, et al. Power balanced controlling of cascaded inverter for grid-connected photovoltaic systems under unequal irradiance conditions[J]. Transactions of China Electrotechnical Society, 2013, 28(12):251-261.
[5] Bailu Xiao, Ke Shen, Jun Mei, et al. Control of cascaded H-bridge multilevel inverter with individual MPPT for grid-connected photovoltaic generators[C]. IEEE Energy Conversion Congress and Exposition, Raleigh, USA: IEEE 2012: 3715-3721.
[6] Yu Y, Konstantinou G, Hredzak B, et al. Power balance optimization of cascaded H-bridge multilevel converters for large-scale photovoltaic integration[J]. IEEE Transactions on Power Electronics, 2016, 31(2): 1108-1120.