Analysis on unbalanced compensation of star-connected Cascade H-bridge inverter

Lingyun Fan 1, a, Yunhao Jiang 1 and Sian Fang 2

1 Hubei Key Laboratory for High-efficiency Utilization of Solar Energy and Operation Control of Energy Storage System, Hubei University of Technology, Wuhan, 430068, China
2 Wuhan Wuxin Electrical Technology Co. LTD, Wuhan, China

fanlingyun@hbut.edu.cn

Abstract. In unbalanced compensation current situation, it is necessary to take appropriate control strategies to ensure that the star connection cascade static reactive power generator of the dc side voltage balance, the commonly used methods for injecting zero sequence voltage, this paper introduce current unbalance degree to analyze the compensation ability of plant, gives the scope of compensation is derived, by means of simulation demonstrate the validity of the derived, for the star connection series H bridge the application and selection of multilevel SVG has the significance.

Keywords: Cascade H bridge, high voltage SVG, unbalanced compensation.

1. Introduction

With the continuous development of electric power industry, all kinds of nonlinear and impact loads increase greatly, which puts forward higher requirements for power quality control. Static var Generator (SVG) plays an important role in improving power quality and compensating reactive power due to its good compensation effect, fast response speed, small volume of energy storage element and low harmonic content. Among them, series H-bridge multi-level SVG has attracted much attention due to its advantages such as easy modular extension, independent of each inverter unit, no need for multiple transformer access, and fewer switching devices required under the same output level.

The basic constant dc side voltage of each H bridge module of star connected cascade H bridge multilevel SVG is the premise of safe and reliable operation of the device. The causes of dc side voltage imbalance can be divided into 1. SVG itself is mainly caused by the difference in device losses and the different charging and discharging time of each module. 2. System voltage imbalance and compensation current imbalance will lead to different voltages borne by each switching device. When the imbalance is serious, the voltage on the switch device will even exceed the withstand voltage level, resulting in device burn out. In order to solve this problem at home and abroad scholars put forward many control method, while the control method is different, but the overall train of thought are superimposed in the cascade multilevel SVG H bridge negative sequence current and zero sequence voltage, based on negative sequence current and dc voltage balance control method could introduce additional negative sequence current in power grid [1-2], pollute the power grid.
Literature [3-4] is a composite utilization of two kinds of control, in which [3] is a composite utilization of zero sequence voltage and negative sequence current under the star, which can improve the balance control ability of the DC side. But the control is complex and the time to reach equilibrium is long. Literature [5] gives a control method based on zero-sequence voltage, which has good control effect but does not analyze the compensation limit. Literature [6] analyzes the key factors affecting the rated voltage of SVG under unbalanced condition based on zero-sequence voltage control, and deduces the negative sequence current compensation capability and range of the device under a certain grid voltage. However, the derivation of zero-sequence voltage in this paper is based on SVG side voltage and current. In this paper, based on the control in reference [5], the compensation ability and scope of control negative sequence current are studied.

2. Dc side balance control in the case of unbalance
The main circuit structure of H-bridge cascade SVG is shown in Figure 1. A, B, and C are connected in a three-phase star. Each phase is composed of N identical H-bridge modules in series, and then connected to the power grid by connecting reactor L. In the figure, $U_{sa}$, $U_{sb}$ and $U_{sc}$ are the three-phase grid voltage respectively. $I_{ca}$, $I_{cb}$ and $I_{cc}$ are the three-phase output current of series multilevel SVG respectively. $I_i$ (i = a, b, c) is the incoming inductance of SVG when it is connected to the power grid. $U_{dc-i}$ (i = a, b, c; k=1,2,3...n) is the voltage value of equivalent DC side capacitance of each H bridge module.

![Fig. 1 Main circuit structure of star-connected H-bridge SVG](image)

The control is divided into DC side voltage control and current tracking control. The DC side voltage control adopts hierarchical control. The first layer controls the stability of the total voltage on the DC side, the second layer controls the stability of each phase, and the third layer controls the stability of each module of the cascade H bridge. Current tracking control keeps the current generated by SVG consistent with the current generated by the system.
Layer 1 control

Current tracking control

Layer 2 control

Layer 3 control

Positive and negative sequence
Current separation module

Fig. 2 General control block diagram of the system

The third layer control is discussed in detail in literature [5]. This paper mainly focuses on phase control and discusses the control ability of phase control to unbalanced current. Due to its own loss and imbalance of the system will make the voltage of each phase difference, if not effectively controlled will make the voltage is too high beyond the rated value damage components. When the grid voltage is asymmetric, negative sequence components are included. Let the grid voltage be:

\[ u_{ns} = \sqrt{2} U_p \sin(wt) + \sqrt{2} U_n \sin(wt + \varphi) \]

\[ u_{ns} = 2 U_n \sin(wt - 120^\circ) + \sqrt{2} U_n \sin(wt + \varphi + 120^\circ) \]

\[ u_{ns} = \sqrt{2} U_n \sin(wt + 120^\circ) + \sqrt{2} U_n \sin(wt - \varphi - 120^\circ) \]

Where \( U_p \) is the effective value of the positive sequence component of the phase voltage; \( U_n \) is the effective value of the negative sequence component of the phase voltage; \( \varphi \) is the initial phase of the negative sequence component of phase voltage. The output current of SVG when compensating reactive current and negative sequence current is:

\[ i_{ns} = \sqrt{2} I_p \cos(wt - 120^\circ) + \sqrt{2} I_n \sin(wt + 120^\circ + \phi) \]

\[ i_{cc} = \sqrt{2} I_p \cos(wt + 120^\circ) + \sqrt{2} I_n \sin(wt - 120^\circ + \phi) \]

In the formula, \( i_s \) is the effective value of positive sequence current, \( i_n \) is the effective value of negative sequence current, \( \varphi \) is the initial phase of negative sequence current, the phase of positive sequence A phase of grid voltage, and the absorbed power of each phase is:

\[ p_{ns} = U_p I_p \sin(2wt) + U_p I_n \cos(\varphi - \phi) - U_p I_n \cos(2wt + \varphi + \phi) + U_n I_p \sin(\varphi + \phi) + U_n I_n \sin(2wt + \varphi) + \]

\[ p_{ob} = U_p I_p \sin(2wt - 240^\circ) + U_p I_n \cos(\phi - 120^\circ) - U_p I_n \cos(2wt + \varphi + \phi) + U_n I_p \cos(\varphi - \phi) - U_n I_n \cos(2wt + \varphi + 120^\circ) + U_n I_p \sin(\varphi - 120^\circ) + U_n I_n \sin(2wt + \varphi) \]

\[ p_{ob} = U_p I_p \sin(2wt + 240^\circ) + U_p I_n \cos(\phi + 120^\circ) - U_p I_n \cos(2wt + \varphi + \phi) + U_n I_p \cos(\varphi - \phi) - U_n I_n \cos(2wt + \varphi + 120^\circ) + U_n I_p \sin(\varphi + 120^\circ) + U_n I_n \sin(2wt + \varphi) \]
The average power absorbed by each phase of SVG converter within each grid cycle is as follows:

\[ p_e = U_e I_e \cos(\phi) + U_a I_a \cos(\varphi - \phi) + U_c I_c \cos(\varphi) \]
\[ p_n = U_e I_e \cos(\phi - 120^\circ) + U_a I_a \cos(\varphi - \phi) + U_c I_c \cos(\varphi + 120^\circ) \]
\[ p_p = U_e I_e \cos(\phi + 120^\circ) + U_a I_a \cos(\varphi - \phi) + U_c I_c \cos(\varphi - 120^\circ) \]

(4)

Add the three formulas in (4) to get:

\[ p_e + p_n + p_p = 3U_e I_e \cos(\varphi - \phi) \]

(5)

The deviation of each phase absorption relative to the average power is:

\[ \Delta p_e = U_e I_e \cos(\phi) + U_a I_a \cos(\varphi - \phi) \]
\[ \Delta p_n = U_e I_e \cos(\phi - 120^\circ) + U_a I_a \cos(\varphi + 120^\circ) \]
\[ \Delta p_p = U_e I_e \cos(\phi + 120^\circ) + U_a I_a \cos(\varphi - 120^\circ) \]

(6)

From equations (4) - (6), it can be seen that the power offset is generated by positive sequence voltage and negative sequence current, negative sequence voltage and positive sequence current, and the total three-phase power remains unchanged, indicating that it only causes the power transfer between the three phases, and does not affect the active power absorbed from the grid on the DC side. We can generate power offset by injecting a zero-sequence voltage. So that the three-phase voltage and current return to a vertical relationship. The action principle of zero sequence voltage is shown in Figure (3), where \( U_n \) (i=a,h,c) is the voltage of each phase, and the components of positive sequence, negative sequence and zero sequence are respectively \( U_a^+ \), \( U_n^- \), \( U_o^- \) and \( I_n^- \) are the output currents of SVG. Without injecting zero sequence voltage, some meet to absorb power from the grid, making the voltage rise, while other phases release energy, making the DC side voltage decrease. Under the action of zero sequence voltage, the corresponding voltage and current are vertical, the DC side does not absorb active power, and the DC side remains stable.

![Diagram](image)

Fig.3 Let the expression for the zero sequence voltage be

\[ u_0 = \sqrt{2} U_0 \sin(\omega t + \Theta) \]

(7)

In the formula, \( \Theta \) is the initial phase of zero sequence voltage, referring to the phase of \( a \) of grid voltage; \( U_0 \) is the effective value of zero sequence voltage, and the average periodic power generated by zero sequence voltage is:

\[ \bar{\Delta p}_a = U_0 I_p \sin(\Theta) + U_0 I_n \cos(\phi - \Theta) \]
\[ \bar{\Delta p}_n = U_0 I_p \sin(\Theta + 120^\circ) + U_0 I_n \cos(\phi - \Theta + 120^\circ) \]
\[ \bar{\Delta p}_c = U_0 I_p \sin(\Theta - 120^\circ) + U_0 I_n \cos(\phi - \Theta - 120^\circ) \]

(8)

From the sum of the three formulas in Equation (8), it can be seen that the injection of zero sequence voltage can only change the power between the three phases, so that the power redistribution between the three phases cannot change the total power. Due to the linear correlation of the three formulas, analysis of two of them can be obtained as follows:
\[ u_0 = \frac{3\sqrt{2} \Delta \rho_{I_p}^0 \cos\phi - 2\sqrt{6} \Delta \rho_{I_n}^0 I_p - \sqrt{6} \Delta \rho_{I_n}^0 I_n - 2\sqrt{6} \rho_{I_p}^0 I_p \sin\phi - \sqrt{6} \rho_{I_n}^0 I_n \sin\phi}{3(I_n + I_p)(I_n - I_p)} \sin(\omega t) + \]
\[ \frac{2\sqrt{6} \Delta \rho_{I_p}^0 I_p \cos\phi + \sqrt{6} \Delta \rho_{I_n}^0 I_p \cos\phi + 3\sqrt{2} \rho_{I_p}^0 I_p \sin\phi - 3\sqrt{2} \rho_{I_n}^0 I_p \cos(\omega t)}{3(I_n + I_p)(I_n - I_p)} \]

Formula (9) can be reduced to
\[ u_0 = \frac{3\sqrt{2} \Delta \rho_{I_p}^0 K \cos\phi - 2\sqrt{6} \Delta \rho_{I_n}^0 I_p - \sqrt{6} \Delta \rho_{I_n}^0 I_n - 2\sqrt{6} \rho_{I_p}^0 K \sin\phi - \sqrt{6} \rho_{I_n}^0 K \sin\phi}{3(K_i + 1)(K_i - 1)} \sin(\omega t) + \]
\[ \frac{2\sqrt{6} \Delta \rho_{I_p}^0 K \cos\phi + \sqrt{6} \Delta \rho_{I_n}^0 K \cos\phi + 3\sqrt{2} \rho_{I_p}^0 K \sin\phi - 3\sqrt{2} \rho_{I_n}^0 K \cos(\omega t)}{3(K_i + 1)(K_i - 1)} \]

It can be seen that the magnitude of the zero sequence voltage is related to the imbalance degree of the initial phase current of the negative sequence voltage, but the injection of the zero sequence voltage may overmodulate in the compensation of the negative sequence, so the compensation ability of the negative sequence current can be reflected in the imbalance degree of the current. Assuming that the modulation ratio under the rated voltage condition is kept at 0.8, in order to avoid over-modulation, the voltage ratio of SVG output should not be greater than 1.25 to the system voltage, and \( K_i \) should not exceed 28% by calculation. The star structure can only be used in the case of small balance.

3. The simulation analysis

In order to verify the accuracy of theoretical derivation and quantitative analysis in this paper, the Matlab/Simulink simulation tool was used to build a simulation model of star-connected h-bridge multi-level SVG. The simulation parameters are shown in Table 1.

| parameter | Numerical value | parameter | Numerical value |
|-----------|----------------|-----------|----------------|
| Dc voltage simulation diagram/kV | 10 | Switching frequency/kHz | 24 |
| The grid frequency/Hz | 50 | Connect the reactance/mH | 3 |
| Number of modules in each phase cascade N | 12 | Connect the reactance/V | 850 |
| Dc measure capacitance/μF | 5000 | |

The system compensates with SVG at 0.1s, and compensates with reactive power at 0.1s-0.3s when the load of the system is balanced, as shown in FIG. 4. It can be seen that the imbalance degree at this time is 0 and the DC side voltage is balanced. Three-phase current balance of the system. Load imbalance in 0.3 s, \( K_i = 10.9\% \) at this time, the dc side to balance, unbalanced system by the start of the current compensation to the balance state, within the scope of the compensation, 0.6 s increasing load imbalance, at this time \( K_i = 16.2\% \), SVG can still run normally, within the scope of the compensation, 0.9 s continue to increase the load imbalance, the imbalance is beyond the scope of the system to adjust, \( K_i = 28.5\% \), beyond the compensation limits of system design, the dc side voltage is not in balance, current can compensate the system into balance.
In the case of $K_i = 0$

**Fig. 4** DC voltage simulation diagram

**Fig. 5** System current simulation diagram

**Fig. 6** Positive and negative sequence currents simulation diagram

In the case of $K_i = 10.9\%$

**Fig. 7** DC voltage simulation diagram
In the case of $K_i = 16.2\%$

Fig. 8 system current simulation diagram

Fig. 9 Positive and negative sequence currents simulation diagram

Fig. 10 DC voltage simulation diagram

Fig. 11 System current simulation diagram

Fig. 12 Positive and negative sequence currents simulation diagram
In the case of $K_i = 28.5\%$

![DC voltage simulation diagram](image1)

**Fig. 13** DC voltage simulation diagram

![System current simulation diagram](image2)

**Fig. 14** System current simulation diagram

![Positive and negative sequence currents simulation diagram](image3)

**Fig. 15** Positive and negative sequence currents simulation diagram

### 4. Summary

The influence of current imbalance on dc side voltage control is considered in this paper. In this paper, the phase-to-phase control of injected zero-sequence voltage is further derived. In the case of introducing the degree of imbalance, it can be seen that the magnitude of zero-sequence voltage is related to the current imbalance and the initial phase of negative sequence current. The star structure is more suitable for the occasions with small current imbalance due to the advantages of the structure, which provides the basis for the design of the parameters of star connection equipment.

### Acknowledgements

This research was financially supported by the Leading Projects for Green Industry Technology (ZZTS2016003), the Major Project of Hubei Collaborative Innovation Center for High-efficiency Utilization of Solar Energy (HBSKFZD2015002) and Hubei Provincial Technology Innovation Special Major Project "Research on High-efficiency Flexible Electric Power Conversion Equipment and Its Application in Transportation" (Project Number: 2019AAA018).
References

[1] Zhao Bo, Guo Jianbo, Zhou Fei Chain STATCOM phase DC voltage balance control strategy [J]. Chinese journal of electrical engineering, 2012, 32 (34):36-41.

[2] Chou S F, Wang B S, Chen S W, et al. Average power balancing control of a STATCOM based on the cascaded H-bridge PWM converter with star configuration [J]. IEEE Transactions on Power Electronics, 2013, 50(6):3893-3901.

[3] Ji Zhendong, ZHAO Jianfeng, Sun Yichao, et al. Dc side voltage balance control for cascade grid-connected inverters with zero and negative sequence voltage injection [J]. Chinese journal of electrical engineering, 2013, 33 (21):9-17.

[4] Ji Zhendong, ZHAO Jianfeng, Sun Yichao, et al. Voltage balance control on dc side of triangle-connected chain-link H-bridge inverter [J]. Journal of electrical technology, 2013, 28 (12):191-206.

[5] He Yingjie, Fu Yabin, Duan Wenyan. Research on voltage equalization control method of star-connected h-bridge cascade SVG dc side [J]. Chinese journal of electrical technology, 2016, 31(11):13-21.

[6] Luo Rui, HE Yingjie, LIU Yunfeng. Analysis on unbalanced Compensation of star-connected H-bridge Multi-level Static reactive power Generator [J]. Chinese Journal of Electrical Engineering, 2012, 38(03):861-869.