Research on the Unbalanced Compensation of Delta-connected Cascaded H-bridge Multilevel SVG

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***Abstract*—The paper presents the application of Delta-connected cascaded H-bridge multilevel SVG under unbalanced compensation currents or unbalanced supply voltages. Clustered balancing control for delta-connected SVG can be realized by injecting a zero-sequence current to the delta-loop. But zero-sequence current injection may cause the high peak phase current which may break converter switches. The aim of this paper is to analyze the key factors that affect the maximum output current of the SVG with injecting zero-sequence current and acquire the quantitative relationship between unbalance compensation capability, the unbalance degree of the supply voltage, the initial phase of negative-sequence voltage, the unbalance degree of the compensation current and the initial phase of negative-sequence current. On this foundation, the valid compensation range of delta-connected SVG under unbalanced conditions is obtained. Furthermore, the compensation characteristic of the negative-sequence current is deduced with the certain supply voltage and the influence of supply voltage variation on the maximum output current for SVG is also considered with the certain compensation current. Finally, the correctness of the relevant theoretical analysis is verified by simulation and experiment.**

***Index Terms*—Delta-connected cascaded H-bridge multilevel SVG, zero-sequence current, unbalance degree.**

I. Introduction

In recent years, with more and more impulsive and fluctuating load connected to the power system, voltage fluctuation, flicker and voltage unbalance problems are increasingly serious, which are serious threats to the safe and stable operation of the power system. Therefore, there is an urgent need to install power quality improvement devices in the system. Among power quality improvement devices, static var generator (SVG) due to good compensation, fast response, small energy storage component size and low harmonic content and so on, has been widely applied [1-3]. Among the SVGs family, the cascaded H-bridge multilevel SVG has been receiving considerable attention due to the advantages of easy modular expansion, independent inverter units, no need for multiple transformer access and less switching devices required at the same output level [4-7]. The cascaded H-bridge multilevel SVG has two different structures, namely star and delta. When the asymmetrical loads are compensated, the star-connected SVG is required to output both reactive and negative-sequence currents, and offset occurs at neutral-point of the star-connected SVG. When the severely asymmetrical loads are compensated, a smaller command voltage in one phase of the star-connected SVG is required to output and the cluster needs a small number of H-bridge modules, but a larger command voltage in other phase of the star-connected SVG is required to output and the cluster needs a larger number of H-bridge modules. Therefore, it is not suitable for the star-connected SVG to compensate the severely asymmetrical load. For the delta-connected SVG, the H-bridge modules in each cluster can be independently controlled, which is equivalent to the change of the asymmetrical load structure. The delta-connected SVG can quickly and accurately compensates symmetrical and asymmetrical loads well, which is impossible for the star-connected SVG to realize. For above reasons, the delta-connected SVG is chosen as the emphases for research in this paper.

Delta-connected cascaded H-bridge multilevel SVG has many advantages that many other topologies don't have, but there are also some defects in the delta-connected SVG. Among them, cluster voltage control is difficult for the design of SVG control system. In practical applications, the parallel loss and the switching loss of the H-bridge module, and the conduction inconsistency between the trigger pulses of the switching device will lead to the imbalance of the dc-link voltage. If corresponding measures are not taken to control the dc-link voltage, the imbalance of the dc-link voltage will not only affect the compensation effect of SVG, but also threaten the safe and stable operation of the SVG. Taking aim at the above mentioned problem, many control strategies have been put forward by experts and scholars. The split phase control method [8][9], the equilibrium component method [10] and the zero-sequence current injection method [11-15] are three main methods currently used for cluster voltage control in the delta-connected

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SVG. Among the methods, zero-sequence current injection method has received extensive attention because the zero-sequence current only flows in the loop and does not affect the output compensating line current of the device.

The control strategies based on the zero-sequence current superposition introduce zero-sequence current into the output phase current of the delta-connected cascaded H-bridge multilevel SVG to guarantee dc-link voltage balancing, which increase the output phase current. So the unbalanced range in which SVG can operate reliably is limited when the rated output phase current is decided. At present, the most of the literature focuses on researching the control strategies, and only a few literatures have given a quantitative analysis on the compensating capability of the star-connected cascaded H-bridge multilevel SVG, and there is rarely introduction about quantitative analysis on the compensating capability of the delta-connected cascaded H-bridge multilevel SVG. For the star-connected SVG, in the work presented in [16], the compensation ability of the negative-sequence current was analyzed under the symmetrical grid voltage, but the compensation ability under the asymmetrical grid voltage was not studied. In [17], the compensation capacity under the condition of simple negative-sequence current was quantitatively analyzed, but the research on the whole compensation domain was lacking. For the delta-connected SVG, in [18], it was discussed that the reactive power rating is related to the voltage unbalance factor and phase angle of negative-sequence voltage, but ignored the effect of the unbalanced compensation currents. In addition, in the work presented in [19], it indicates that both the star-connected SVG and delta-connected SVG exhibit a singularity in the solution of the zero-sequence component, which in turn limits the operational range, but it didn't exactly give the unbalanced compensation ability and range for two configurations with zero-sequence component injection.

At present, there is no comprehensive quantitative analysis on compensation ability of the delta-connected cascaded H-bridge multilevel SVG. Therefore, the aim of this paper is to analyze the key factors that affect the maximum output current of the SVG under unbalanced conditions, and give the valid compensation range of delta-connected SVG. At the same time, the compensation characteristics of the negative-sequence current are deduced under the certain supply voltage and the influence of the variation of the supply voltage on the maximum output current of the SVG is also discussed under the certain compensation current. The results of the analysis are verified by simulation and experiment.

II. Cluster Voltage Control Under Unbalanced Conditions

A. Control Principle Based on Superposition of Zero-sequence Current Component

The system configuration of the delta-connected cascaded H-bridge multilevel SVG is depicted in Fig. 1.

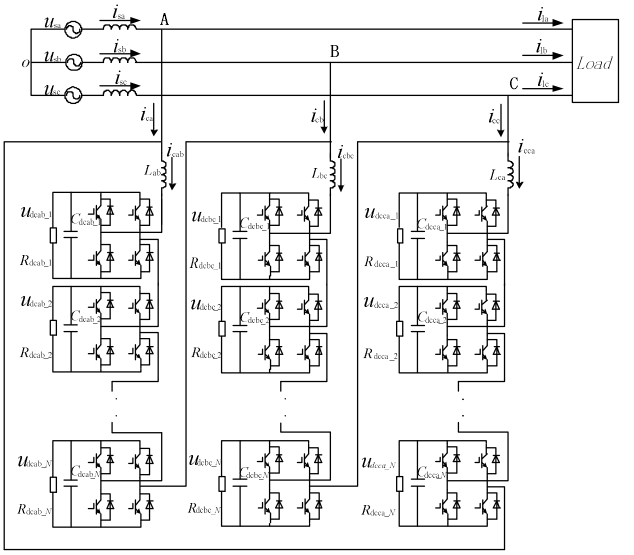

Fig.1. Delta-connected cascaded H-bridge multilevel SVG system configuration

Three phases of A, B and C are in delta configuration, and each phase consists of N identical H-bridge modules in series, and then is connected to the grid by interface inductance L_i(i=ab,bc,ca) The voltages of the three-phase system are u_{sa}, u_{sb}, u_{sc} and the currents of the three-phase system are i_{sa}, i_{sb}, i_{sc}. The output line currents of SVG are i_{ca}, i_{cb}, i_{cc}, and the output phase currents of SVG are i_{cab}, i_{cbc}, i_{cca}, and the load currents are i_{la}, i_{lb}, i_{lc}, u_{dci_k}（i=ab,bc,ca， k=1,2,3,…,N）represents dc-link voltage of H-bridge module, and R_{dci_k}, C_{dci_k}（i=ab,bc,ca， k=1,2,3,…,N） represent the resistance equivalent to the power loss and DC capacitor of each H-bridge module respectively.

Referring to Fig. 1, the voltage of each phase leg of delta-connected cascaded H-bridge multilevel SVG under unbalanced supply voltage can be written as

$$\begin{aligned} u_{sab} &= \sqrt{2}U_p \sin(\omega t) + \sqrt{2}U_n \sin(\omega t + \varphi) \\ u_{sbc} &= \sqrt{2}U_p \sin(\omega t - 120°) + \sqrt{2}U_n \sin(\omega t + \varphi + 120°) \\ u_{sca} &= \sqrt{2}U_p \sin(\omega t + 120°) + \sqrt{2}U_n \sin(\omega t + \varphi - 120°) \end{aligned} \quad (1)$$

Where, U_p, U_n are the effective values of positive and negative-sequence components of voltage, and φ is the initial phase of negative-sequence voltage. Similarly, the current flowing through each phase leg is shown as follows:

$$\begin{aligned} i_{cab} &= \sqrt{2}I_p \sin(\omega t + \gamma) + \sqrt{2}I_n \sin(\omega t + \phi) \\ i_{cbc} &= \sqrt{2}I_p \sin(\omega t + \gamma - 120°) + \sqrt{2}I_n \sin(\omega t + \phi + 120°) \\ i_{cca} &= \sqrt{2}I_p \sin(\omega t + \gamma + 120°) + \sqrt{2}I_n \sin(\omega t + \phi - 120°) \end{aligned} \quad (2)$$

Where, I_p, I_n are the effective values of positive and negative-sequence components of current, and γ, ϕ are the initial phase of positive and negative-sequence current respectively.

According to (1) and (2), the average power flow at each phase in one cycle can be calculated by (3).

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$$\begin{aligned}\overline{p_{\mathrm{ab}}} &= U_{\mathrm{p}}I_{\mathrm{p}}\cos\gamma + U_{\mathrm{n}}I_{\mathrm{n}}\cos(\phi-\varphi) \\ &\quad + U_{\mathrm{p}}I_{\mathrm{n}}\cos\phi + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi) \\ \overline{p_{\mathrm{bc}}} &= U_{\mathrm{p}}I_{\mathrm{p}}\cos\gamma + U_{\mathrm{n}}I_{\mathrm{n}}\cos(\phi-\varphi) \\ &\quad + U_{\mathrm{p}}I_{\mathrm{n}}\cos(\phi-120^\circ) + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi+120^\circ) \\ \overline{p_{\mathrm{ca}}} &= U_{\mathrm{p}}I_{\mathrm{p}}\cos\gamma + U_{\mathrm{n}}I_{\mathrm{n}}\cos(\phi-\varphi) \\ &\quad + U_{\mathrm{p}}I_{\mathrm{n}}\cos(\phi+120^\circ) + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi-120^\circ)\end{aligned} \tag{3}$$

It can be seen from (3) that the average power absorbed by each phase can be divided into two parts: $\overline{p}$ is the same part of the phase cluster power flows and $\overline{\Delta p_i}$ is the deviation of the phase cluster power flows, and the relationship between two parts is shown as follow,

$$\overline{p_i} = \overline{p} + \overline{\Delta p_i} \,(i = \mathrm{ab,bc,ca}) \tag{4}$$

Where,

$$\overline{p} = U_{\mathrm{p}}I_{\mathrm{p}}\cos\gamma + U_{\mathrm{n}}I_{\mathrm{n}}\cos(\phi-\varphi) \tag{5}$$

$$\begin{cases}\overline{\Delta p_{\mathrm{ab}}} = U_{\mathrm{p}}I_{\mathrm{n}}\cos\phi + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi) \\ \overline{\Delta p_{\mathrm{bc}}} = U_{\mathrm{p}}I_{\mathrm{n}}\cos(\phi-120^\circ) + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi+120^\circ) \\ \overline{\Delta p_{\mathrm{ca}}} = U_{\mathrm{p}}I_{\mathrm{n}}\cos(\phi+120^\circ) + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi-120^\circ)\end{cases} \tag{6}$$

Assuming that there is no converter power loss, which is reasonable because power loss is so small that it can be ignored in the real installation. In order to maintain cluster voltage balancing, it is necessary to superimpose the zero-sequence current into the delta-connected cascaded H-bridge multilevel SVG to ensure the zero active power flow. Phasor diagram showing how to find out zero-sequence current is shown in Fig. 2, $\boldsymbol{U}_{\mathrm{s}i}(i=\mathrm{a,b,c})$ and $\boldsymbol{U}_{\mathrm{s}i}(i=\mathrm{ab,bc,ca})$ are the phase voltage and line voltage phasors on point of common coupling (PCC) respectively, the relationship between the two can be written as

$$\begin{bmatrix}\boldsymbol{U}_{\mathrm{sab}} \\ \boldsymbol{U}_{\mathrm{sbc}} \\ \boldsymbol{U}_{\mathrm{sca}}\end{bmatrix} = \begin{bmatrix}\boldsymbol{U}_{\mathrm{sa}} - \boldsymbol{U}_{\mathrm{sb}} \\ \boldsymbol{U}_{\mathrm{sb}} - \boldsymbol{U}_{\mathrm{sc}} \\ \boldsymbol{U}_{\mathrm{sc}} - \boldsymbol{U}_{\mathrm{sa}}\end{bmatrix} \tag{7}$$

$\boldsymbol{I}_{ci}\ (i=\mathrm{ab,bc,ca})$ and $\boldsymbol{I}_{ci}\ (i=\mathrm{a,b,c})$ refer to the output compensation phase and line currents phasors of SVG respectively, the relationship between the two is shown in (8). $\boldsymbol{I}_{ci}\ (i=\mathrm{ab,bc,ca})$ can be resolved into positive-sequence component ($\boldsymbol{I}_{ci}^{\mathrm{p}}$) and negative-sequence component ($\boldsymbol{I}_{ci}^{\mathrm{n}}$) without introducing zero-sequence component. $\boldsymbol{I}_{ci}\ (i=\mathrm{ab,bc,ca})$ can be expressed by (9)

$$\begin{bmatrix}\boldsymbol{I}_{\mathrm{ca}} \\ \boldsymbol{I}_{\mathrm{cb}} \\ \boldsymbol{I}_{\mathrm{cc}}\end{bmatrix} = \begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}} - \boldsymbol{I}_{\mathrm{cca}} \\ \boldsymbol{I}_{\mathrm{cbc}} - \boldsymbol{I}_{\mathrm{cab}} \\ \boldsymbol{I}_{\mathrm{cca}} - \boldsymbol{I}_{\mathrm{cbc}}\end{bmatrix} \tag{8}$$

$$\begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}} \\ \boldsymbol{I}_{\mathrm{cbc}} \\ \boldsymbol{I}_{\mathrm{cca}}\end{bmatrix} = \begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}}^{\mathrm{P}} \\ \boldsymbol{I}_{\mathrm{cbc}}^{\mathrm{P}} \\ \boldsymbol{I}_{\mathrm{cca}}^{\mathrm{P}}\end{bmatrix} + \begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}}^{\mathrm{n}} \\ \boldsymbol{I}_{\mathrm{cab}}^{\mathrm{n}} \\ \boldsymbol{I}_{\mathrm{cab}}^{\mathrm{n}}\end{bmatrix} \tag{9}$$

Obviously, $\boldsymbol{I}_{ci}(i=\mathrm{ab,bc,ca})$ and $\boldsymbol{U}_{si}(i=\mathrm{ab,bc,ca})$ are not perpendicular without introducing the zero-sequence current component ($\boldsymbol{I}_{ci}^{0}$), which will cause some clusters to absorb energy from the grid and dc-link voltage is rising, and the other clusters release energy to the grid and the dc-link is decreasing. After introducing $\boldsymbol{I}_{ci}^{0}$, $\boldsymbol{I}_{ci}(i=\mathrm{ab,bc,ca})$ can be written as

$$\begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}} \\ \boldsymbol{I}_{\mathrm{cbc}} \\ \boldsymbol{I}_{\mathrm{cca}}\end{bmatrix} = \begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}}^{\mathrm{P}} \\ \boldsymbol{I}_{\mathrm{cbc}}^{\mathrm{P}} \\ \boldsymbol{I}_{\mathrm{cca}}^{\mathrm{P}}\end{bmatrix} + \begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}}^{\mathrm{n}} \\ \boldsymbol{I}_{\mathrm{cab}}^{\mathrm{n}} \\ \boldsymbol{I}_{\mathrm{cab}}^{\mathrm{n}}\end{bmatrix} + \begin{bmatrix}\boldsymbol{I}_{\mathrm{cab}}^{0} \\ \boldsymbol{I}_{\mathrm{cab}}^{0} \\ \boldsymbol{I}_{\mathrm{cab}}^{0}\end{bmatrix} \tag{10}$$

Where,

$$\boldsymbol{I}_{\mathrm{cab}}^{0} = \boldsymbol{I}_{\mathrm{cbc}}^{0} = \boldsymbol{I}_{\mathrm{cca}}^{0} \tag{11}$$

At moment, $\boldsymbol{I}_{ci}(i=\mathrm{ab,bc,ca})$ is perpendicular to the corresponding terminal voltage $\boldsymbol{U}_{si}(i=\mathrm{ab,bc,ca})$. In the view of phasor, zero-sequence current is introduced to change the phase angle of the fundamental component of the phase current inside the triangle without affecting $\boldsymbol{I}_{ci}(i=\mathrm{a,b,c})$. By selecting the proper zero-sequence current component, the phase current can be perpendicular to the line voltage respectively, and the active power flowing each phase leg is zero, and cluster voltage is kept balancing.

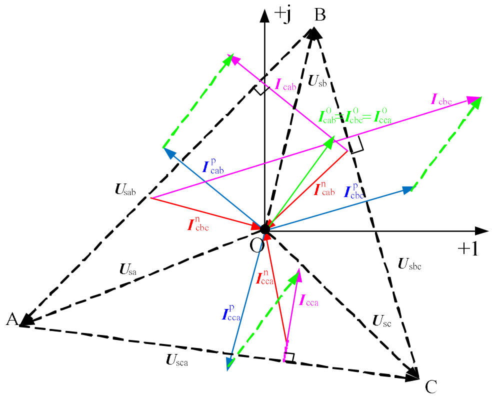


Fig.2. Phasor diagram showing how to find out zero-sequence current

Setting the zero-sequence voltage is

$$i_0 = \sqrt{2} I_0 \sin(\omega t + \delta) \tag{12}$$

Where, I_0 is the effective value of zero-sequence current; δ is initial phase of zero-sequence current. With injecting zero-sequence current, the average active power absorbed by each phase leg can be expressed by

$$\overline{p_i} = \overline{p} + \overline{\Delta p_i} + \overline{\Delta p_i^{0}} \,(i = \mathrm{ab,bc,ca}) \tag{13}$$

Where,

$$\overline{p} = U_{\mathrm{p}}I_{\mathrm{p}}\cos\gamma + U_{\mathrm{n}}I_{\mathrm{n}}\cos(\phi-\varphi) \tag{14}$$

$$\begin{cases}\overline{\Delta p_{\mathrm{ab}}} = U_{\mathrm{p}}I_{\mathrm{n}}\cos\phi + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi) \\ \overline{\Delta p_{\mathrm{bc}}} = U_{\mathrm{p}}I_{\mathrm{n}}\cos(\phi-120^\circ) + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi+120^\circ) \\ \overline{\Delta p_{\mathrm{ca}}} = U_{\mathrm{p}}I_{\mathrm{n}}\cos(\phi+120^\circ) + U_{\mathrm{n}}I_{\mathrm{p}}\cos(\gamma-\varphi-120^\circ)\end{cases} \tag{15}$$

$$\begin{cases}\overline{\Delta p_{\mathrm{ab}}^{0}} = U_{\mathrm{p}}I_{0}\cos\delta + U_{\mathrm{n}}I_{0}\cos(\delta-\varphi) \\ \overline{\Delta p_{\mathrm{bc}}^{0}} = U_{\mathrm{p}}I_{0}\cos(\delta+120^\circ) + U_{\mathrm{n}}I_{0}\cos(\delta-\varphi-120^\circ) \\ \overline{\Delta p_{\mathrm{ca}}^{0}} = U_{\mathrm{p}}I_{0}\cos(\delta-120^\circ) + U_{\mathrm{n}}I_{0}\cos(\delta-\varphi+120^\circ)\end{cases} \tag{16}$$

The power loss of the device is ignored and the overall active power flows is zero, we can get (17) easily as follow:

$$\sum_{i=ab,bc,ca} \overline{p_i} = 3\overline{p} = 3(U_p I_p \cos\gamma + U_n I_n \cos(\phi-\varphi)) = 0 \quad (17)$$

At the same time, in order to maintain the cluster voltages of three phases basically constant, it is necessary to ensure that the active power flowing through each phase leg is zero. Due to the restriction of the existing (17), the zero-sequence current only needs to satisfy (18).

$$\begin{cases} \overline{p_{ab}} = 0 \\ \overline{p_{bc}} = 0 \end{cases} \quad (18)$$

Based on equation (13)—(18), the expression of zero-sequence current can be obtained as follows.

$$\begin{aligned} i_0 &= \sqrt{2} I_0 \sin(\omega t + \delta) \\ &= \sqrt{2}\left[\frac{-U_n U_n I_p \cos(\gamma - 2\varphi) + U_p U_p I_n \cos\phi - U_p U_n I_n \cos(\phi+\varphi) + U_p U_n I_p \cos(\gamma-\varphi)}{(U_n - U_p)(U_n + U_p)}\right]\sin\omega t \\ &+ \sqrt{2}\left[\frac{U_n U_n I_p \sin(\gamma - 2\varphi) - U_p U_p I_n \sin\phi - U_p U_n I_n \sin(\phi+\varphi) + U_p U_n I_p \sin(\gamma-\varphi)}{(U_n - U_p)(U_n + U_p)}\right]\cos\omega t \end{aligned} \quad (19)$$

B. Influence Factors of Zero-sequence Current Component

According to (19), it can be obviously seen that the zero-sequence current of the delta-connected cascaded H-bridge multilevel SVG under unbalanced conditions is affected by the factors such as U_p, U_n, I_p, I_n, γ, ϕ, φ. In order to facilitate the quantitative research on zero-sequence current, it is necessary to further analyze the key factors. The unbalance degree of supply voltage and compensation current is defined in (20) respectively.

$$K_u = U_n / U_p, \quad K_i = I_n / I_p \quad (20)$$

Equation (14) can be rewritten as

$$\begin{aligned} i_0 &= \sqrt{2} I_0 \sin(\omega t + \delta) \\ &= \sqrt{2} I_p\left[\frac{-K_u K_u \cos(\gamma - 2\varphi) + K_i \cos\phi - K_u K_i \cos(\phi+\varphi) + K_u \cos(\gamma-\varphi)}{(K_u - 1)(K_u + 1)}\right]\sin\omega t \\ &+ \sqrt{2} I_p\left[\frac{K_u K_u \sin(\gamma - 2\varphi) - K_i \sin\phi - K_u K_i \sin(\phi+\varphi) + K_u \sin(\gamma-\varphi)}{(K_u - 1)(K_u + 1)}\right]\cos\omega t \end{aligned} \quad (21)$$

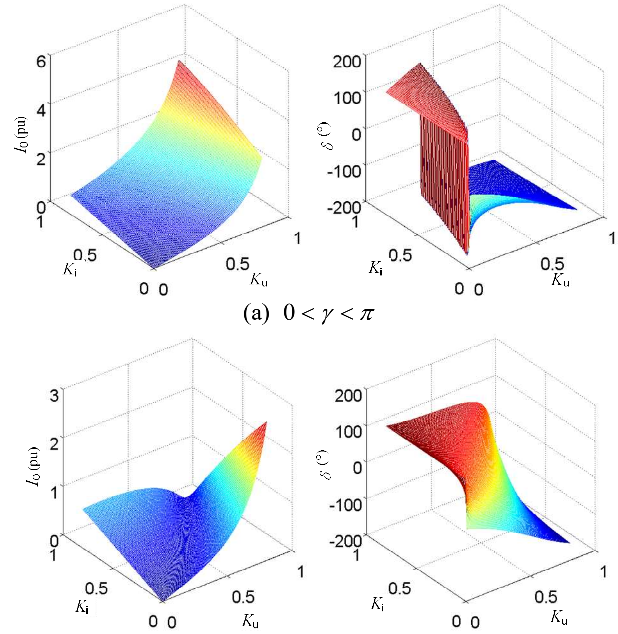
The equation (21) shows that a practical limitation exists in delta-connected SVG, with an infinite zero-sequence current requirement needed under specific operating conditions. In other words, the zero-sequence current i_0 tends to infinity when K_u tends to 1. Substituting (20) into (17) and solving (17) to get the relationship between K_u, K_i, γ, ϕ and φ as follow:

$$\gamma = \begin{cases} \pi - \mathrm{acos}(-K_u K_i \cos(\phi - \varphi)) & 0 < \gamma < \pi \\ \pi + \mathrm{acos}(-K_u K_i \cos(\phi - \varphi)) & \pi < \gamma < 2\pi \end{cases} \quad (22)$$

Substituting (22) into (21), it is found that the capacitive and inductive characteristics of the positive-sequence current (the value range of γ) have an important impact on the zero-sequence current. In addition, the zero-sequence current of the delta-connected cascaded H-bridge multilevel SVG under unbalanced conditions is determined by the five factors. In addition to the effective value of positive-sequence current I_p, the other four factors are: K_u is the unbalance degree of the supply voltage, K_i is the unbalance degree of compensation current, φ is the initial phase of the negative-sequence voltage component of supply voltage, and ϕ is the initial phase of negative-sequence current component of compensation current. Zero-sequence current is satisfied by

$$i_0 = I_p g(K_u, K_i, \phi, \varphi) \quad (23)$$

According to the functions shown in (21) and (23), the quantitative relationships of the unitary value of the amplitude(based on the rating current of the power grid) and phase of zero-sequence current, the unbalance degree of supply voltage and the unbalance degree of compensation current are shown in Fig. 3.



(a) $0 < \gamma < \pi$

(b) $\pi < \gamma < 2\pi$

Fig.3. The amplitude and phase change of zero-sequence current of delta-connected cascaded H-bridge multilevel SVG

III. Unbalanced Compensation Range

Regardless of line loss, the maximum values of current flowing through three-phase legs and output voltage of the delta-connected cascaded H-bridge multilevel SVG are shown in (24) and (25) respectively with injecting zero-sequence current.

$$I_{max} = \max\{|i_{cab} + i_0|, |i_{cbc} + i_0|, |i_{cca} + i_0|\} \quad (24)$$

$$\begin{aligned} U_{max} = \max\{ & |u_{sab} + j\omega L_{ab}(i_{cab} + i_0)|, \\ & |u_{sbc} + j\omega L_{bc}(i_{cbc} + i_0)|, \\ & |u_{sca} + j\omega L_{ca}(i_{cca} + i_0)|\} \end{aligned} \quad (25)$$

Where, '| |' represents phasor modulo operation.

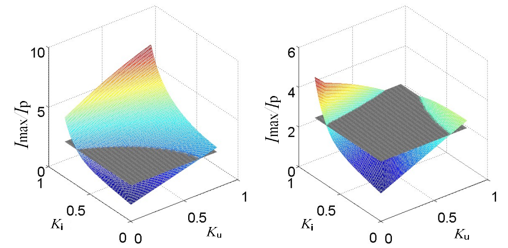
Substituting (1), (2) and (21) into (24), the functional relationship between the maximum output current amplitude of the delta-connected cascaded H-bridge multilevel SVG and each variable is obtained by

$$I_{\max} / I_{\mathrm{p}} = G(K_{\mathrm{u}}, K_{\mathrm{i}}, \phi, \varphi) \qquad (26)$$

When compensating the negative-sequence current, it is necessary for the delta-connected cascaded H-bridge multilevel SVG to inject the zero-sequence current to maintain cluster voltages balance, which is likely to cause the variation of output voltage or current of some phase legs, and result that the output voltage or current exceeds the rated value and device is damaged. However, in engineering practice, the voltage fluctuation caused by the zero-sequence current in the inductor is very small relative to the voltage on point of common coupling (PCC), whose influence on the output voltage of the device can be neglected. Because the device is prone to overcurrent rather than overvoltage after injecting the zero-sequence current and $I_{\max}/I_{\mathrm{p}}$ can accurately reflect the status of output current of each phase leg, $I_{\max}/I_{\mathrm{p}}$ is chosen as the standard to measure the unbalance compensation ability of the delta-connected cascaded H-bridge multilevel SVG in this paper. Only when the value of $I_{\max}/I_{\mathrm{p}}$ is smaller than the rated value, the SVG can operate normally.

According to the functional relationship shown in (26), it can be seen that the output current level $I_{\max}/I_{\mathrm{p}}$ is mainly affected by four factors: the unbalance degree of the supply voltage K_{u}, the initial phase of the negative-sequence voltage component of supply voltage φ, the unbalance degree of the compensation current K_{i} and the initial phase of negative-sequence current component of compensation current ϕ. when the other parameters are decided, the quantitative relationship between the output current level $I_{\max}/I_{\mathrm{p}}$, the unbalance degree of the supply voltage K_{u} and the unbalance degree of the compensation current K_{i} can be obtained by MATLAB numerical analysis method, as shown in Fig. 4.

When the output current level $I_{\max}/I_{\mathrm{p}}$, is determined by the limitation of the SVG itself, such as the maximum current that can flow through switching devices and so on, there is a plane paralleling to the K_{u} and K_{i} axes along the rated value of $I_{\max}/I_{\mathrm{p}}$,. Only the unbalanced operating range below the plane is the area where the device can operate reliably. From the point of view of practical application, when the output rated current of the device and the unbalance degree of the compensation current are determined, in order to ensure the safe and stable operation of the device, it is necessary to control the unbalance degree of the supply voltage in the proper range. In addition, the rated output current of delta-connected cascaded H-bridge multilevel SVG is affected simultaneously by K_{u} and K_{i}, and the influence of K_{u} is more significant. Scilicet, the delta-connected SVG is more sensitive to the unbalance degree of the supply voltage and appears more preferable choice for industrial application, such as arc furnaces, where the converter aims to exchange both positive- and negative-sequence current and the loads typically connected to relatively strong grids.

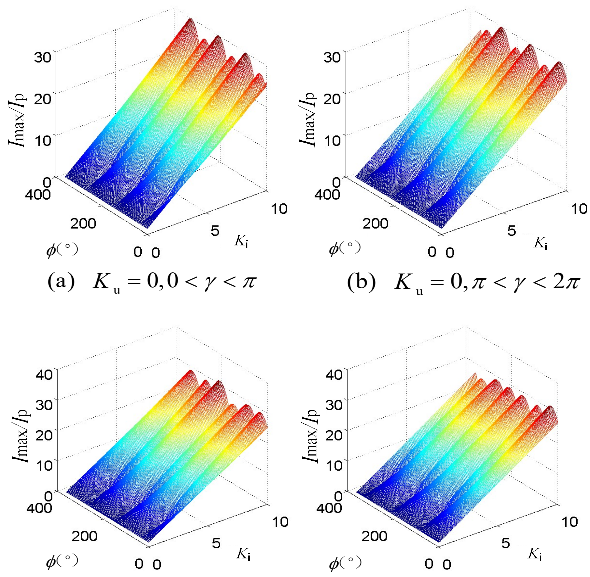


(a) $0<\gamma<\pi$ (b) $\pi<\gamma<2\pi$

Fig.4. Variation of output current level of delta-connected cascaded H-bridge multilevel SVG with the change of K_{u} and K_{i}

Similarly, when the other parameters are decided, the relationship between the output current level $I_{\max}/I_{\mathrm{p}}$, the unbalance degree of the compensation current K_i and the initial phase of the negative-sequence current component ϕ is shown in Fig. 5.

As illustrated in Fig. 5, the output current level $I_{\max}/I_{\mathrm{p}}$ is increasing with the increase of the proportion of negative-sequence current component in the compensation current. In the case of Fig. 5(a), assuming that the rated output current of the device is 1000A and the value of I_{p} is 250A, the rated output current level of the device is 4. In order to ensure the safe and stable operation of the device, by means of calculation, the value of K_{i} must be less than 44 %. Comparing Fig. 5(a) and Fig. 5(b) (or Fig. 5(c) and Fig. 5(d)), it can be found that when the output current level reaches the maximum value, the phase difference between the initial phase of the negative-sequence current component ϕ in two figures is 180°, which indicates that the capacitive and inductive characteristics of the positive-sequence current have no influence on the maximum output current of the device. In addition, Fig. 5 shows that, when the supply voltage is symmetrical (K_{u}=0), $I_{\max}/I_{\mathrm{p}}$ occurs periodic change with the variation of ϕ; when the supply voltage is asymmetric (K_{u}=0.1), $I_{\max}/I_{\mathrm{p}}$ occurs aperiodic change with the variation of ϕ.



(a) $K_{\mathrm{u}}=0, 0<\gamma<\pi$ (b) $K_{\mathrm{u}}=0, \pi<\gamma<2\pi$
(c) $K_{\mathrm{u}}=0.1, 0<\gamma<\pi$ (d) $K_{\mathrm{u}}=0.1, \pi<\gamma<2\pi$

Fig.5. Variation of output current level of delta-connected cascaded H-bridge multilevel SVG with the change of K_{i} and φ

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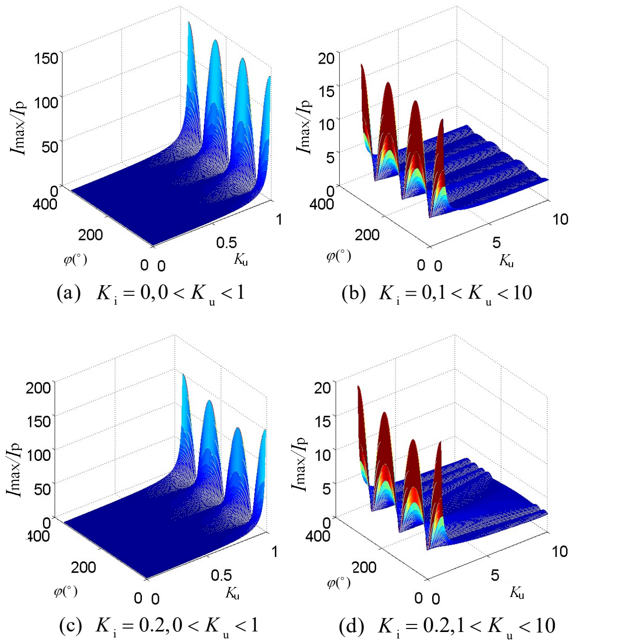
when the other parameters are decided, in the same way, the relationship between the output current level I_{max}/I_p, the unbalance degree of the supply voltage K_u and the initial phase of the negative-sequence voltage component φ is shown in Fig. 6 (Because the graphics with $0<\gamma<\pi$ and $\pi<\gamma<2\pi$ are similar, we choose the graphics with $0<\gamma<\pi$). As illustrated in Fig. 6, I_{max}/I_p reaches the maximum value at the vicinity where K_u is 1: when 0< K_u <1, the output current level I_{max}/I_p increases with the increase of negative-sequence voltage; when 1<K_u<10, the output current level I_{max}/I_p decreases first and then tends to be stable and remains greater than 2.2(K_i=0) or 2.4(K_i=0.2). But the proportion of negative-sequence voltage component is too high when 1<K_i<10, and it is not suitable for practical application. In addition, Fig. 6 shows that, when the compensation current is symmetrical (K_i=0), I_{max}/I_p occurs periodic change with the variation of φ; when the compensation current is asymmetric (K_i=0.2), I_{max}/I_p occurs aperiodic change with the variation of φ.

Therefore, in the case of a certain compensation current, it is necessary for delta-connected cascaded H-bridge multilevel SVG to consider K_u. If the voltage at the point of common coupling does not meet the requirements, it is very likely to affect the cluster voltage balance and the output current value of the device is very high, and then damage device. For the safe and stable operation of the device, the delta-connected cascaded H-bridge multilevel SVG should be applied where the K_u is relatively low.



(a) $K_i=0, 0<K_u<1$ (b) $K_i=0, 1<K_u<10$ (c) $K_i=0.2, 0<K_u<1$ (d) $K_i=0.2, 1<K_u<10$

Fig.6. Variation of output current level of delta-connected cascaded H-bridge multilevel SVG with the change of K_u and φ

IV. SIMULATION AND EXPERIMENTAL RESULTS

A. Simulation Results

In order to verify the accuracy of the theoretical derivation and quantitative analysis in this paper, a simulation model of delta-connected cascaded H-bridge multilevel SVG is built by using Matlab/Simulink. The simulation parameters are shown in Table. I.

TABLE.I

PARAMETERS OF SIMULATION

Variables	Symbol	Value
Line-to-line rms voltage	u_s	10(kV)
Grid frequency	f	50(Hz)
Cascaded cell number	N	12
DC bus capacitor	C_{dc}	4700(uF)
Switching frequency	f_{sw}	10(kHz)
Couple inductor	L	6(mH)
Nominal DC voltage	u_{dc}^*	1000(V)

The simulation model uses three layers voltage control system and the control block diagram is shown in Fig. 7. The whole control system is divided into three layers: the first layer is the overall dc-link voltage control, which is responsible to maintain the sum of dc-link voltage of all H-bridge modules constant; the second layer is the cluster voltage control, which is achieved by superimposing the zero-sequence current component i_0^* so that the active power between three-phases legs is zero, and i_0^* can be obtained by (18), positive and negative-sequence components of the measured signals are estimated using delayed signal cancellation (DSC)technique [20]; the third layer is the individual voltage control, which is achieved by exchanging energy among each H-bridge module within each phase leg, The individual voltage control in this paper is based on the method in [13]. As shown in Fig. 7, $u_{dc}^*$is the dc-link voltage reference value, $\bar{u}_{dc}$ is the total dc-link voltage average, i_{la}, i_{lb}, i_{lc} are three phase load currents. i_{cd}, i_{cq} and i_{c0} refer to compensation current component in d, q and 0 axis respectively, i_{cd}^*, i_{cq}^* are the command value corresponding to the preceding component in d and q axis, U_p, U_n and φ represent the effective values of positive and negative-sequence components of supply voltage and the initial phase of negative-sequence voltage respectively, I_p, I_n and ϕ represent the effective values of positive and negative-sequence components of compensation current and the initial phase of negative-sequence current respectively.

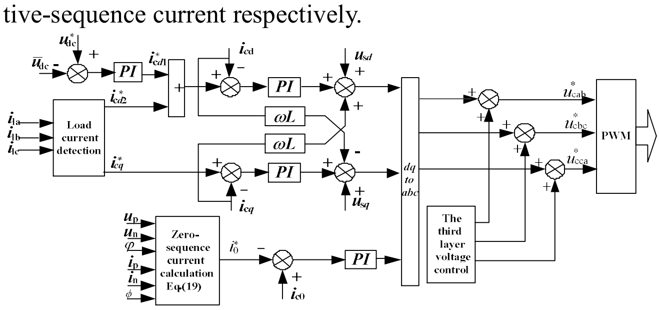
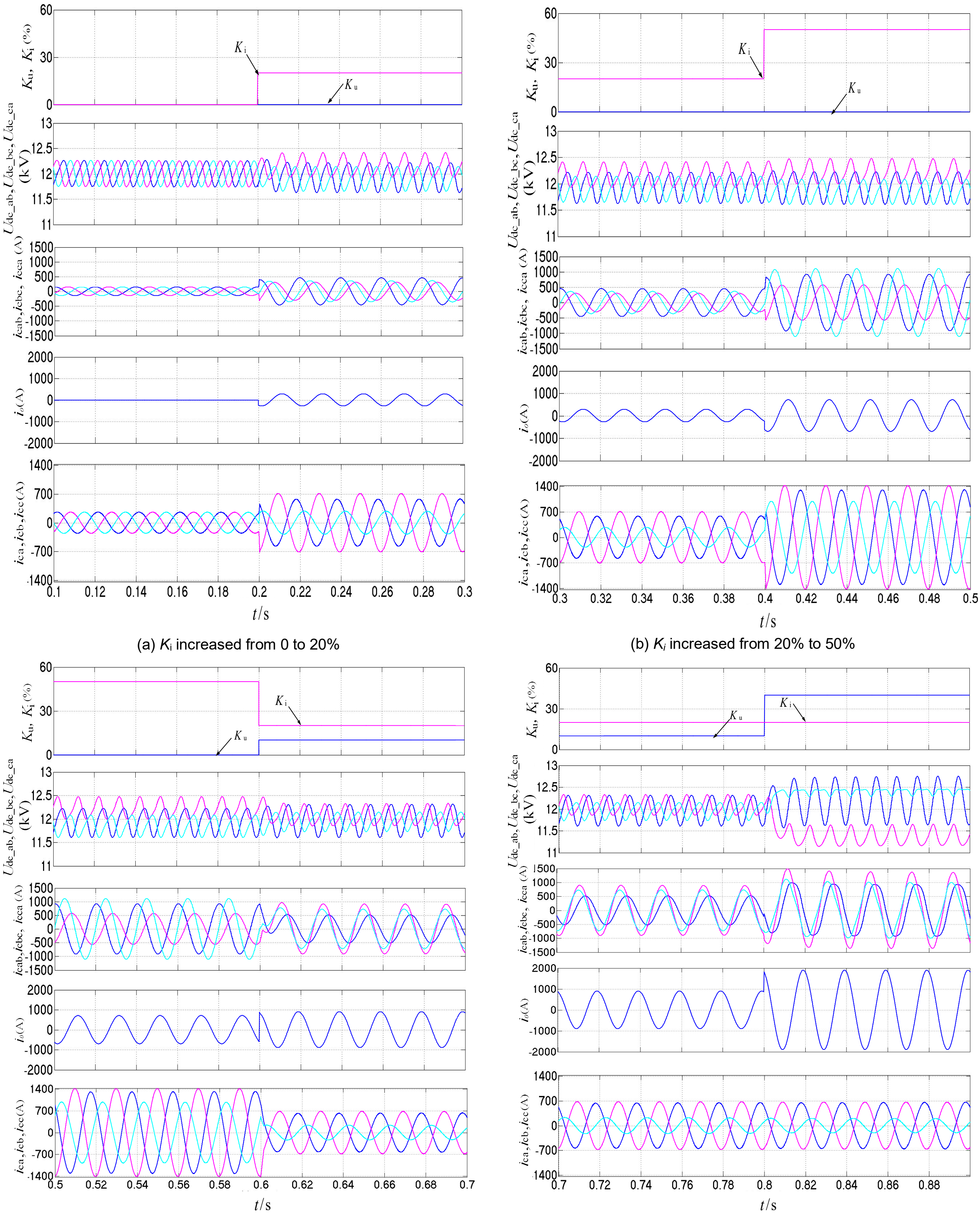


Fig.7 The block diagram of the total control system

The simulation results are shown in Fig. 8, which are divided into five stages. *Stage I* (t<0.2s): The unbalance degrees of the supply voltage and compensation current were zero, only the positive-sequence reactive current was compensated, as illustrated in Fig. 8(a), the dc-link voltage and compensation current also can be kept balance without injecting the zero-sequence current, which was consistent with the theory. *Stage II* (0.2s<t<0.4s): In this stage, the unbalance degree of the supply voltage was still zero, but the unbalance degree of the



(a) K_i increased from 0 to 20%

(b) K_i increased from 20% to 50%

(c) K_i decreased from 50% to 20% and K_u increased from 0 to 10%

(d) K_u increased from 10% to 40%

Fig.8 Partial enlargement waveforms during sudden change of unbalance degree

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compensation current changed from 0 to 20%, then the SVG need to compensate reactive and negative-sequence current at the same time. It was necessary for the SVG to inject the corresponding zero-sequence current to achieve the cluster voltage balance control, as shown in Fig. 8(a). *Stage Ⅲ*(0.4s<t<0.6s): The unbalance degree of the compensation current increased from 20% to 50%, which was more than the designed maximum unbalance degree 44%, as shown in Fig. 8(b). After the mutation, the maximum value of the output phase current exceeds its rated value 1000A. *Stage Ⅳ*(0.6s<t<0.8s): The unbalance degree of the compensation current decreased from 50 % to 20%, the unbalance degree of the supply voltage increased from 0 to 10%. At this stage, the zero-sequence current was adjusted, and the cluster voltage reached stable state again, as shown in Fig. 8(c). *Stage Ⅴ*(0.8s<t<1s): The unbalance degree of the compensation current was still 20%, the unbalance degree of the supply voltage changed from 10% to 40%, SVG cannot maintain cluster voltage balance, and the amplitude of the output phase current is much larger than its rated value, and the output line current does not change after the mutation, indicating that the injected zero-sequence current flows only inside the triangle and has no effect on the output line current, as shown in Fig. 8(d).

As illustrated in Fig. 8, whether the delta-connected cascaded H-bridge multilevel SVG can send out the negative-sequence current and maintain the cluster voltage balance or not, it is related to the unbalance degree of the supply voltage and the compensation current. When the unbalance degree of the supply voltage or the compensation current increase, the injected zero-sequence current amplitude increases significantly, which will result that the output current of some legs exceeds their rated value.

In addition, in order to maintain the cluster voltage balancing, it is necessary to inject the corresponding zero-sequence current when the unbalance degree of the supply voltage and the compensation current change within the rated range. The waveforms of the zero-sequence current and the cluster voltage are shown in Fig. 8. With injecting corresponding zero-sequence current, the cluster voltage is maintained at a stable value 12kV, which verifies the accuracy of theoretical calculation of zero-sequence current.

B. Experiment Results

Theoretic analysis results are necessary to be further verified by the actual circuits. The main controllers of experiment platform are DSP and FPGA. DSP is TMS320F28335 of TI Company, which is dedicated to realize the control algorithm of the entire system. FPGA is Cyclone II series EP2C35F484C8 of Altera Company, which mainly generates the PWM gating signals and the other achieves communications and protections. The basic parameters of the experiment are as follows: the supply voltage amplitude is 100V, the supply voltage frequency is 50Hz, the inductance value is 6mH, the number of H-bridge module in each phase is two, and the dc-link voltage of the H-bridge module is 60V.

The control strategy adopted in the experiment is consistent with the simulation. The experimental results are shown in Fig. 9—12. Fig. 9 indicates the waveforms of supply voltage in AB phase and the compensating current in SVG when load with smaller unbalance degree mutates into load with larger unbalance degree. Fig. 10 shows the waveforms of zero-sequence current and dc-link voltage of each cluster in SVG when load with smaller unbalance degree mutates into load with larger unbalance degree. Fig. 11 shows the waveforms of supply voltage in AB phase and the compensating current when load with larger unbalance degree mutates into load with smaller unbalance degree. Fig. 12 shows the waveforms of zero- sequence current and dc-link voltage of each cluster in SVG when load with larger unbalance degree mutates into load with smaller unbalance degree. It can be observed that when the load mutated, the injected zero-sequence current is adjusted in time to ensure that the SVG can accurately compensate the reactive and negative-sequence current and stabilize the dc-link voltage near the reference value. In addition, the introduction of zero-sequence current will lead to reactive and negative- sequence current amplitude changes, which is likely to cause overcurrent and damage device. Therefore, it is necessary to limit the unbalance degree of compensation current within a proper range in the mutation test.

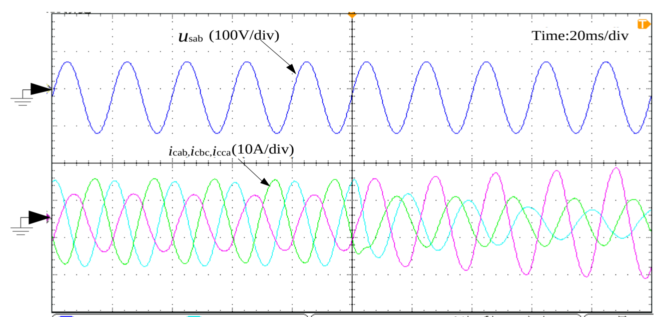

Fig.9 The waveforms of supply voltage in AB phase and the compensating current when load with smaller unbalance degree mutates into load with larger unbalance degree

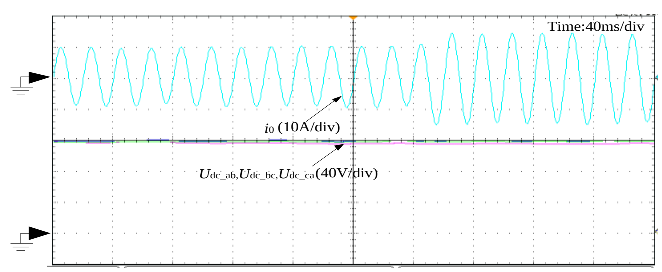

Fig.10 The waveforms of zero-sequence current and dc-link voltage of each phase when load with smaller unbalance degree mutates into load with larger unbalance degree

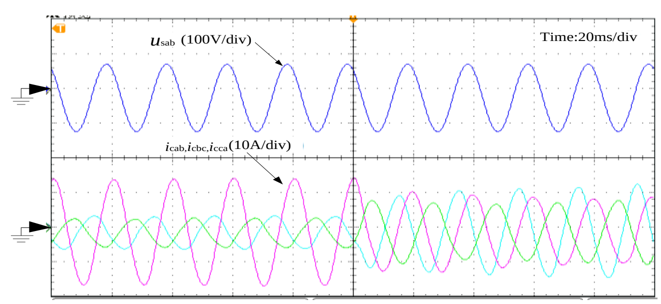

Fig.11 The waveforms of supply voltage in AB phase and the compensating current when load with larger unbalance degree mutates into load with smaller unbalance degree

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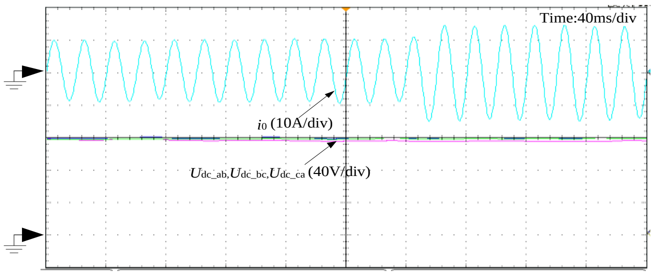

Fig.12 The waveforms of zero-sequence current and dc-link voltage of each phase when load with larger unbalance degree mutates into load with smaller unbalance degree

V. CONCLUSION

In this paper, the effect of unbalanced supply voltage and compensation current on the delta-connected SVG has been analyzed. Injecting zero-sequence current into the delta-loop allows maintaining cluster voltage balancing for the SVG. However, it has been shown that zero-sequence current injection may cause the high peak phase current which may break converter switches.In order to guarantee safe and reliable operation of the delta-connected SVG, whose maximum output current level I_{max}/I_p is chosen as the standard to measured its unbalance compensation capability and the valid compensation range under unbalanced conditions can also be obtained. The unbalance compensation range of the delta-connected structure is limited by the unbalance degree of the supply voltage, the initial phase of negative-sequence voltage, the unbalance degree of the compensation current and the initial phase of negative-sequence current. The quantitative relationship between unbalance compensation capability and other influence factors derived in this paper can provide a good theoretical basis for the parameter design and device selection of the delta-connected cascaded H-bridge multilevel SVG. In addition, the delta-connected SVG is more sensitive to the unbalance degree of the supply voltage than the unbalance degree of the compensation current， and it will be better way for industrial applications aiming at improving the power quality. The simulation and experimental results further verified the rationality and accuracy of the analysis.

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