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Current Limit Strategy of Voltage Controller of Delta-Connected H-Bridge STATCOM under Unbalanced Voltage Drop

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Abstract – This paper presents the current limit strategy of voltage controller of delta-connected H-bridge static synchronous compensator (STATCOM) under an unbalanced voltage fault event. When phase to ground fault happens, the feasibility to heighten the magnitude of sagging phase voltage is considered by using symmetric transformation method in delta-structure STATCOM. And the efficiency to cover the maximum physical current limit of switching device is considered by using vector analysis method that calculate the zero sequence current for balancing the cluster energy in delta connected H-bridge STATCOM. The result is simple and obvious. Only positive sequence current has to be used to support the unbalanced voltage sag. Although the relationship between combination of the negative sequence voltage with current and zero sequence current is nonlinear, the more negative sequence current is supplying, the larger zero sequence current is required. From the full-model STATCOM system simulation, zero sequence current demand is identified according to a ratio of positive and negative sequence compensating current. When only positive sequence current support voltage sag, the least zero sequence current is needed.

Keywords: Cluster balancing control, Delta-connected H-bridge STATCOM, Symmetric component current, Unbalanced fault

1. Introduction

With an electric power being considered commodity, a demanding for higher stability and reliability of electric power system has been growing [1]. Nevertheless, with electric power system complexity and power system short circuit capacity being increasing, and the renewable energy being installed to the grid, the demand will be not able to satisfy. And various nonlinear loads might distort the power quality of the electric power system in distribution system. In this environment, the utility has to search alternatives for more optimal and profitable operation of the electric power system. One of alternative to enhance the power quality and voltage stability applies the power electronic based equipment such as flexible AC Transmission System (FACTS) by rapidly responding to system event [2-4].

A static synchronous compensator (STATCOM) is one of the parallel structure FACTS devices by supplying the reactive current from voltage source converter (VSC) which is able to synthesize the voltage magnitude and phase. It could mitigate the disturbance and improve the power quality at a faster rate comparing to the static VAR compensator (SVC). However the STATCOM technology was not attractive FACTS in a manner of installation cost before discovering the modular multilevel converter (MMC) technology. The MMC technology is also called as a cascade-H bridge converter in STATCOM technology field. The cascade-H bride topology has advantages such as easy scalability, low switching loss, low electromagnetic compatibility (EMC) concerns due to the sub-module (SM) switching comparing to conventional 2-level PWM VSC technology [5, 6].

Fig. 1 shows the configuration of cascade H-bridge STATCOM which is connected in delta structure. The STATCOM is connected to grid voltage (U_{aG}, U_{bG}, U_{cG}) through the wye-delta transformer and system impedance (L_s). The STATCOM is composed in three phase clusters in which numerous SM is connected in series. The SM is full-bridge converter whose terminal voltage can be

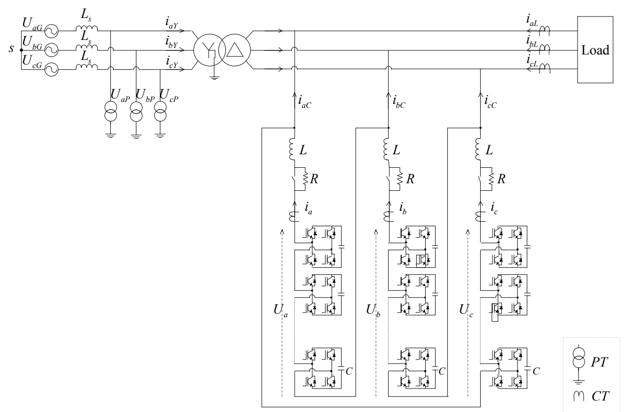

Fig. 1. The configuration of delta-connected H-bridge STATCOM

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positive, negative and zero DC capacitor voltage. From the combination of each SM terminal voltage (U_a, U_b, U_c), the magnitude and phase of cluster voltage can be synthesized through the inductance (L). It means that the STATCOM is able to supply positive and negative sequence current (i_{aC}, i_{bC}, i_{cC}) independently by controlling the voltage source. In case of unbalanced fault event, the STATCOM which is operational as a voltage regulator is able to support positive and negative sequence voltage by supplying corresponding current respectively. It is necessary to figure out the feasibility to heighten the particular phase voltage magnitude and the efficient current limit strategy in delta-connected H-bridge STATCOM. For example, the STATCOM can support voltage for the current source converter high-voltage direct current (CSC-HVDC) system. When an unbalanced fault event happens, the commutation fail can be occurred due to the particular phase voltage drop [7].

The main objective of this paper is to comprehensively investigate the efficient symmetric current limit for supporting the unbalanced voltage drop in delta-connected H-bridge STATCOM. This paper is organized as follows. Section 2 describes the theoretical analysis of delta-connected H-bridge STATCOM to calculate the zero sequence current. A general voltage controller and its current limit of STATCOM are introduced in Section 3. The combination of positive and negative sequence current is investigated to support the aforementioned unbalanced fault in Section 4. Section 5 shows the simulation result of proposed current strategy based on the full-model STATCOM, followed by concluding remarks.

2. Theoretical Analysis of Delta-connection H-bridge STATCOM

In order to operate the delta-connected H-bridge STATCOM, the theoretical analysis is necessary. Because of delta-connection, the H-bridge STATCOM has a circulating current through the cluster. The circulating current has a role of balancing the cluster voltage. It means that the delta-connected H-bridge STATCOM cannot support the zero sequence current to the PCC. Although the star-connected H-bridge can supply the zero sequence current to the grid, it depends on the transformer configuration. In order to theoretical analysis, the simple modeling is concerned that the delta-connected H-bridge STATCOM is connected to the ideal voltage source as below

$$\begin{aligned} u_a &= U_p \sin(\omega t) + U_n \sin(\omega t + \theta_n) \\ u_b &= U_p \sin(\omega t - 2\pi/3) + U_n \sin(\omega t + \theta_n + 2\pi/3) \\ u_c &= U_p \sin(\omega t + 2\pi/3) + U_n \sin(\omega t + \theta_n - 2\pi/3) \end{aligned} \tag{1}$$

where u_a, u_b ad u_c are phase voltages. U_p is positive sequence voltage magnitude. U_n and θ_n are negative sequence voltage magnitude and phase displacement, respectively. The current flowing through the cluster can be obtained as following

$$\begin{aligned} i_a &= I_p \sin(\omega t + \varphi_p) + I_n \sin(\omega t + \varphi_n) \\ i_b &= I_p \sin(\omega t + \varphi_p - 2\pi/3) + I_n \sin(\omega t + \varphi_n + 2\pi/3) \\ &\quad + I_0 \sin(\omega t + \varphi_0) \\ i_c &= I_p \sin(\omega t + \varphi_p + 2\pi/3) + I_n \sin(\omega t + \varphi_n - 2\pi/3) \\ &\quad + I_0 \sin(\omega t + \varphi_0) \end{aligned} \tag{2}$$

where I_p, I_n, and I_0 are symmetric component magnitude of cluster current, respectively. φ_p, φ_n and φ_0 are phase displacement of each symmetric component of cluster current. From the current component, it can be figured out that delta-connected H-bridge STATCOM supports the positive sequence current and negative sequence current independently. And zero sequence current is only used as a control freedom of the STATCOM for balancing the voltage between clusters.

From the cluster voltage and current, average power distribution of each cluster can be calculated.

$$\begin{aligned} \overline{P}_a &= avg(u_a i_a) = P_{pp} + P_{nn} + P_{pn,a} + P_{np,a} + P_{p0,a} + P_{n0,a} \\ \overline{P}_b &= avg(u_b i_b) = P_{pp} + P_{nn} + P_{pn,b} + P_{np,b} + P_{p0,b} + P_{n0,b} \\ \overline{P}_c &= avg(u_c i_c) = P_{pp} + P_{nn} + P_{pn,c} + P_{np,c} + P_{p0,c} + P_{n0,c} \end{aligned} \tag{3}$$

Each power components of (3) can be shown as following.

$$P_{pp} = \frac{U_p I_p}{2}\cos(\varphi_p), P_{nn} = \frac{U_n I_n}{2}\cos(\varphi_n - \theta_n) \tag{4}$$

$$\begin{aligned} P_{pn,a} &= \frac{U_p I_n}{2}\cos(\varphi_n), P_{pn,b} = \frac{U_p I_n}{2}\cos(\varphi_n - 2\pi/3) \\ P_{pn,c} &= \frac{U_p I_n}{2}\cos(\varphi_n + 2\pi/3) \end{aligned} \tag{5}$$

$$\begin{aligned} P_{np,a} &= \frac{U_n I_p}{2}\cos(\varphi_p - \theta_n), P_{np,b} = \frac{U_n I_p}{2}\cos(\varphi_p - \theta_n + 2\pi/3) \\ P_{np,c} &= \frac{U_n I_p}{2}\cos(\varphi_p - \theta_n - 2\pi/3) \end{aligned} \tag{6}$$

The common power distribution component (4) is the common loss of each cluster. It does not effect on unbalancing the cluster voltage. The positive sequence unbalanced power distribution (P_{pn}) can be generated by positive sequence voltage and negative sequence current. And the negative sequence unbalanced power distribution (P_{np}) is coming from negative sequence voltage and positive sequence current. It means that different power is consumed in different cluster. It causes the voltage unbalance between clusters.

From (5) and (6), the major factor of cluster unbalancing is the grid voltage unbalance degree and supplying unbalanced current degree. In order to balance the cluster voltage, the zero sequence current can be used.

$$\begin{aligned}
&P_{p0,a}+P_{n0,a} \\
&\quad=\frac{U_pI_0}{2}\cos(\varphi_0)+\frac{U_nI_0}{2}\cos(\varphi_0-\theta_n) \\
&P_{p0,b}+P_{n0,b} \\
&\quad=\frac{U_pI_0}{2}\cos(\varphi_0+2\pi/3)+\frac{U_nI_0}{2}\cos(\varphi_0-\theta_n-2\pi/3) \\
&P_{p0,c}+P_{n0,c} \\
&\quad=\frac{U_pI_0}{2}\cos(\varphi_0-2\pi/3)+\frac{U_nI_0}{2}\cos(\varphi_0-\theta_n+2\pi/3)
\end{aligned} \tag{7}$$

In (7), the positive and negative sequence unbalanced power distribution can be compensated by zero sequence current. As an example, the zero sequence current can be calculated in balanced voltage and unbalanced current circumstance.

$$\begin{aligned}
&\overline{P}_a=avg(u_ai_a)=P_{pp}+P_{pn,a}+P_{p0,a} \\
&=\frac{U_pI_p}{2}\cos(\varphi_p)+\frac{U_pI_n}{2}\cos(\varphi_n)+\frac{U_pI_0}{2}\cos(\varphi_0) \\
&\overline{P}_b=avg(u_bi_b)=P_{pp}+P_{pn,b}+P_{p0,b} \\
&=\frac{U_pI_p}{2}\cos(\varphi_p)+\frac{U_pI_n}{2}\cos(\varphi_n-2\pi/3)+\frac{U_pI_0}{2}\cos(\varphi_0+2\pi/3) \\
&\overline{P}_c=avg(u_ci_c)=P_{pp}+P_{pn,c}+P_{p0,c} \\
&=\frac{U_pI_p}{2}\cos(\varphi_p)+\frac{U_pI_n}{2}\cos(\varphi_n+2\pi/3)+\frac{U_pI_0}{2}\cos(\varphi_0-2\pi/3)
\end{aligned} \tag{8}$$

Because negative sequence voltage is not applied to the STATCOM, only negative sequence current cause the voltage difference of cluster. Therefore positive sequence unbalanced power distribution can be compensated by the positive sequence unbalanced power distribution from the zero sequence current. Normally STATCOM is used for reactive power compensation. The positive sequence phase displacement is $\pi/2$. Therefore, the common power distribution component is almost zero. The cluster average power distribution should be zero in order to prevent the STATCOM to be unstable. The solution of zero sequence can be easily calculated as

$$\begin{aligned}
&\varphi_p=\frac{\pi}{2} \\
&I_0=I_n \\
&\varphi_0=\pi-\varphi_n
\end{aligned} \tag{9}$$

However if both of cluster voltage and current are unsymmetrical, it is not easy to find out the solution of the zero sequence current by mathematical method.

3. Control Method of Delta-connected H-bridge STATCOM

3.1 Control overview of delta-connected H-bridge STATCOM

Fig. 2 shows the controller of delta connected H-bridge STATCOM. The controller can be divided into two parts. One part deals with the STATCOM system control whose output is phase reference voltage value. The other is phase voltage control in which the SM gate signal is generated. In first controller, independent five control freedom can be adjustable. Those are positive and negative symmetric components and zero sequence current. First of all, positive

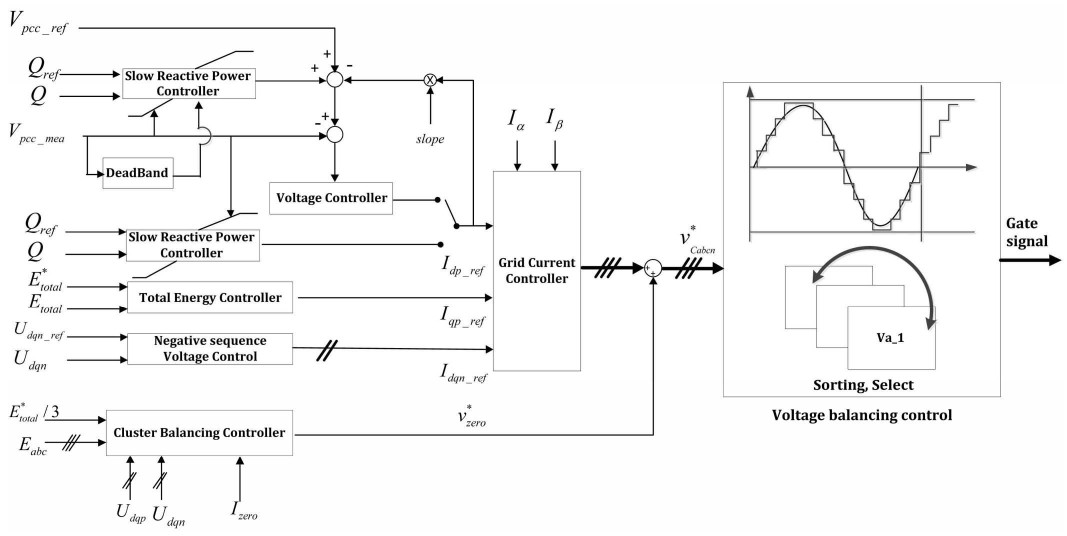

Fig. 2. The controller of STATCOM

sequence currents can be considered as system current. When the active current is aligned to the q-axis in synchronous frame, the total energy control of all DC capacitor in H-bridge SM (E_{total}) is realized by using q-axis positive sequence current (I_{qp_ref}). The d-axis positive sequence current in synchronous frame (I_{dp_ref}) is dealing with output reactive power. It is possible to control the reactive power directly (from Q_{ref} and Q) or generate the reactive current by voltage feed-back controller (from V_{pcc_ref} and V_{pcc_mea}). In general, the voltage controller can be selected into a main controller for coping with voltage variation [8]. In order for stable operation of various reactive power compensation devices, the dead band and droop control strategy can be applied as shown in Fig. 2.

Secondly, in order to compensate the unbalanced load current or the unbalanced voltage (U_{dqn_ref}), the negative sequence can be used (I_{dqn_ref}) [9]. The negative sequence current can be divided into two components (d-axis and q-axis) in synchronous frame as shown in Fig. 3. It means that each negative sequence current component can be controlled independently. These four independent current controller produce phase reference voltage by using feed-back controller comparing the reference value to measured one. Depending on the controller, measured current can be used in which is converted based on synchronous (I_d, I_q) or static (I_α, I_β) reference frame transformation. Regardless of the topology of STATCOM, aforementioned decoupled current controller is used. But the cluster balancing controller is unique one to cascade H-bridge STATCOM. Especially the circulating current is used for balancing the cluster voltage (E_{abc}) in delta-connected H-bridge STATCOM. As shown in (8), the zero sequence circulating current (I_{zero}) flows only inside the delta-connected three clusters and can be employed to transfer energy among the three different clusters not affecting the outside of STATCOM that is usually grid side. There are several conventional feed-back cluster balancing control methods [10-12]. The linear combination (V^*_{Cabc}) of the phase voltage reference value and the voltage reference value from cluster balancing control (V^*_{zero}) is processed to

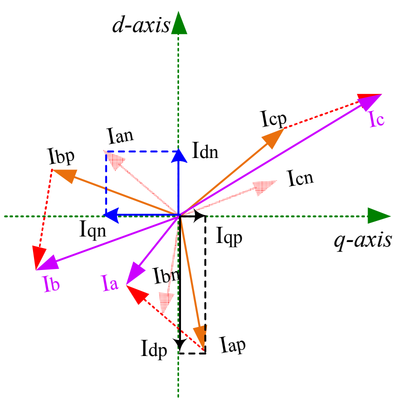

Fig. 3. Symmetric current component's phasor diagram and its 2-axis orthogonal component

determine the SM gate signals. Various SM voltage balancing controllers are PS-PWM (Phase shift- pulse width modulation) [13, 14], NLC (nearest level control) by using direct modulation, and indirect modulation [15]. In this paper, the NLC method is used because the number of SM is enough large.

3.2 Operation range of STATCOM and voltage controller

Fig. 4 shows the steady-state V-I characteristic curve of STATCOM in which the voltage controller is selected. As shown in Fig. 2, the voltage reference of voltage control is adjusted by slow reactive power control (ΔV_Q) to keep the STATCOM at an operating point with low losses. In general, the slow reactive power controller is operating under the voltage dead-band range. And, an adjustable droop characteristic is applied to the voltage reference to avoid a steady state operation at the limited of the controllable range. Although the grid voltage is not controlled exactly to the reference voltage value, the output current of STATCOM is controlled through the V-I characteristics curve [16]. This V-I characteristic is considered in balanced voltage sag or swell. It means that only positive sequence current is useful for compensating the grid voltage.

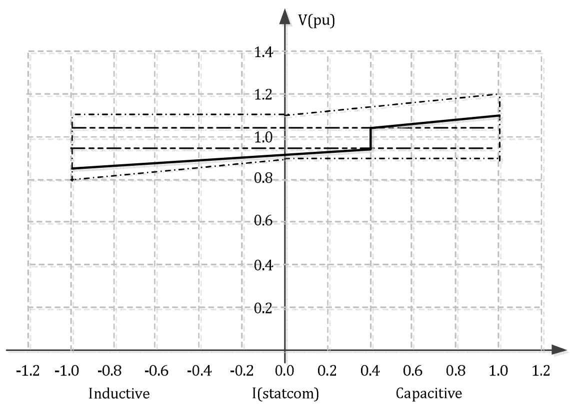

Fig. 4. V-I characteristic curve of STATCOM

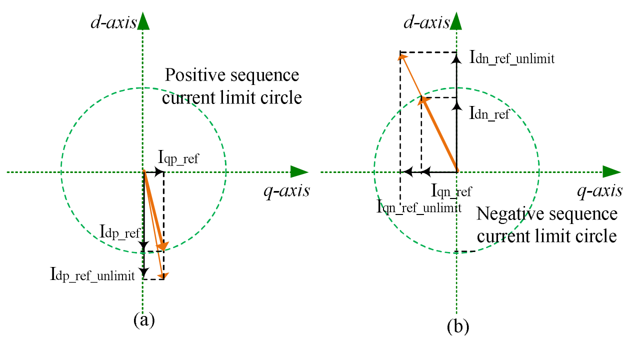

Fig. 5. (a) Positive sequence current limit, (b) Negative sequence current limit

3.3 Current Limit Strategy

The capacity of STATCOM is not infinite. In particular, current limit flowing through the cluster depends on the switching device specification and its rated capacity. As mention in before, STATCOM can control four-different current independently in high speed performance. To fulfill the above constraint and operate the STATCOM properly in any environments, the current limit strategy is necessary. This strategy is subject to change according to the role of STATCOM. The strategy is as following. First of all, the q-axis positive sequence current component is not limitable. Since only loss of STATCOM is reflected on the q-axis positive sequence current, the amount of reference current is relatively small comparing to compensation current (d-axis positive and dq-axis negative sequence currents). And, total energy of clusters should be sustained to operate STATCOM properly. From first limit strategy, only d-axis positive sequence current is limited by positive sequence current limit circle, as shown in Fig. 5(a). Second, limit ratio between d-axis positive sequence current component and negative sequence current component has to be determined. Third, when compensating negative sequence current is higher than the negative sequence current limit circle, d- and q-axes negative sequence current must be limited as an equal ratio as shown in Fig. 5(b).

It means that the only magnitude of negative sequence current is limited but the phase displacement of negative sequence current is fixed [9]. Finally, under the unsymmetrical voltage and current circumstance, the circulating current must be included for balancing the cluster voltage, as mentioned in section 2. Therefore, the compensation current should be decreased depending on the amount of circulating current.

4. Voltage Compensation by STATCOM

Fig. 6 shows the phasor diagram of grid unbalanced voltage. In general one-phase ground fault is occurred, an a-phase voltage is sagging and the rest is remained in rated value. If someone wants to compensate the sagging voltage as much as possible using STATCOM, it is necessary to identify the feasibility and efficiency in order for the special requirement.

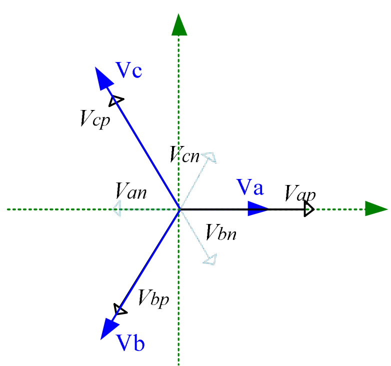

Fig. 6. Symmetric voltage component's phasor diagram when the one-phase fault occurs

4.1 Analysis of voltage compensation

When the magnitude of a-phase voltage is half (0.5 pu) comparing to the reset phase (1.0 pu), the positive, negative, and zero sequence voltage magnitude are 0.83 pu, 0.17 pu, and 0.167 pu respectively. Since the delta-connected STATCOM has an ability to compensate the positive and negative sequence voltage using positive and negative sequence current independently, it assumed that the magnitude of positive and negative sequence voltage is compensated under the current limit strategy in Section 3.2. In general, the short circuit capacity of grid is magnificent larger than the capacity of STATCOM, the compensated voltage is limited (in this example, it is assumed that only 0.05 pu voltage can be compensated).

- Case I: Only positive sequence voltage is increased. From Table 1, as the positive sequence voltage increase, the sagging phase voltage also increases.
- Case II: Only negative sequence voltage is decreased. From Table 2, as the negative sequence voltage decrease, the sagging phase voltage increases.
- Case III: Both positive and negative sequence voltage are adjusted in limitation 0.05 pu. The magnitude of sagging phase voltage is equivalent. The rest phase voltage magnitude is adjusted depending on ratio of positive and negative sequence voltage. However, angle distortion between phases becomes worse.

From the case study, the special requirement does not satisfy from the combination of positive and negative sequence voltage compensation. That is, no matter the kind of symmetric voltage, the compensated magnitude of the sagging phase voltage is equivalent.

Table 1. Positive sequence voltage compensation

Positive	0.89	0.88	0.87	0.86	0.85	0.84	0.83
Negative	0.17	0.17	0.17	0.17	0.17	0.17	0.17
a-phase	0.553	0.543	0.533	0.523	0.513	0.503	0.493

Table 2. Negative sequence voltage compensation

Positive	0.83	0.83	0.83	0.83	0.83	0.83	0.83
negative	0.17	0.16	0.15	0.14	0.13	0.12	0.11
a-phase	0.493	0.503	0.513	0.523	0.533	0.543	0.553

Table 3. Both positive and negative sequence voltage compensation

Positive	0.89	0.88	0.87	0.86	0.85	0.84	0.83
negative	0.17	0.16	0.15	0.14	0.13	0.12	0.11
a-phase	0.553	0.553	0.553	0.553	0.553	0.553	0.553
b-phase	1.058	1.043	1.028	1.013	0.998	0.984	0.969
angle	60	59.6	59.1	58.6	58.1	57.6	57.0

4.2 Circulating current calculation of delta-connected H-bridge STATCOM

When the PCC voltage has only positive sequence component, the circulating current for balancing the cluster energy can be calculated as shown in (9). However, it is difficult to figure out the influence of negative sequence voltage or combination of voltage and current from the mathematical calculation. One of methods to calculate the circulating current under above circumstance is vector analysis method in [17]. The vector analysis is based on the measured cluster voltage and current phasor vectors. From this circulating current calculation method, the feed-forward control design is achieved and this term is able to be additional input to a zero sequence controller in order to improve the disturbance rejection performance of a system.

When the output current component has only positive sequence and its magnitude is rated value, the zero sequence current can be calculated depending on the voltage distortion as shown in Fig. 7. The nonlinear relationship between zero sequence and negative sequence voltage is discovered. It means that it is difficult to find out the minimum zero sequence current trajectories directly under the sudden voltage distortion circumstance. However, as the amount of output current decreases, the magnitude of circulating current tends to be reduced in the distorted voltage circumstance as shown in Fig. 8. In Section 4.1, we focus on the magnitude of sagging phase voltage in assumption of equivalent compensation ability by supplying the corresponding symmetric current. In same condition, it is necessary to find out an additional current in cluster for sustainable operation of the STATCOM, that is zero sequence current. When only positive sequence current is compensated, the zero sequence current is required up to 0.16 pu from Table 4. In order to decrease the magnitude of negative sequence voltage, 0.88 pu zero sequence current is needed for balancing the cluster energies in Table 5. When the ratio of compensated symmetric current is different, the zero sequence gets more influence on the compensated negative sequence current in Table 6.

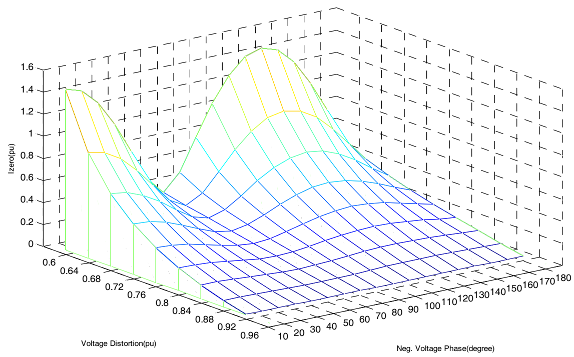

Fig. 7. Relationship between zero sequence current and distorted voltage (magnitude and phase displacement) under supplying only positive sequence current

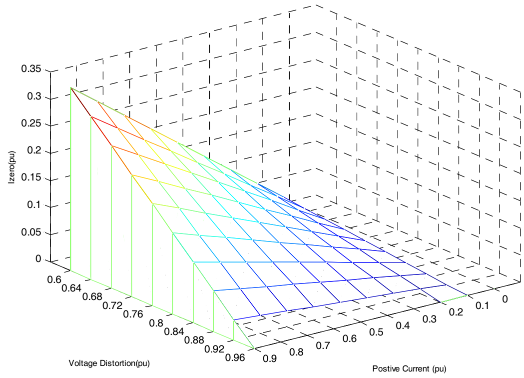

Fig. 8. Relationship between zero and positive sequence current under voltage distortion (Negative sequence voltage phase displacement is fixed as 180°)

Table 4. Positive sequence voltage compensation

Positive	0.89	0.88	0.87	0.86	0.85	0.84	0.83
Negative	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Zero-I	0.16	0.135	0.109	0.082	0.055	0.028	0.0

Table 5. Negative sequence voltage compensation

Positive	0.83	0.83	0.83	0.83	0.83	0.83	0.83
Negative	0.17	0.16	0.15	0.14	0.13	0.12	0.11
Zero-I	0.0	0.14	0.28	0.43	0.57	0.72	0.88

Table 6. Both positive and negative sequence voltage compensation

Positive	0.89	0.88	0.87	0.86	0.85	0.84	0.83
Negative	0.17	0.16	0.15	0.14	0.13	0.12	0.11
Zero-I	0.16	0.02	0.18	0.36	0.53	0.70	0.88

4.3 Current limit strategy under special voltage compensation requirement

In order to compensate the sagging phase voltage as much as possible using the delta-connected H-bridge STATCOM, the most effective way is only supplying maximum positive sequence current. Under the physical current limit of switching device, the maximum positive sequence is determined considering the zero sequence current.

$$\begin{aligned} I_{qp\_ref} &= I_{device\_limit} - I_{zero\_ref} \\ I_{dn} &= 0 \\ I_{qn} &= 0 \end{aligned} \tag{10}$$

where I_{dq_ref}, I_{dn_ref}, and I_{qn_ref} are positive sequence q-aixs reference current, negative sequence d-axis and q-axis reference current respectively. And, I_{device_limit} and I_{zero_ref} are device physical current limit and zero sequence for balancing the cluster. This result might be simple and obvious. However the current limit strategy is based on the two observations, as shown in Sections 4.1 and 4.2. First of all, if the total magnitude of symmetric voltage is compensated equivalently, the sagging phase voltage heightens same magnitude. And the magnitude of additional current for compensation tends to be larger when more negative sequence current is used.

5. Simulation Results

To verify the proposed current strategy under special voltage compensation requirement, the simulation has been developed by using the PSCAD/EMTDC software program. The simulation schematic in which the delta-connected H-bridge STATCOM is connected to the voltage source grid through the grid-impedance is illustrated in Fig. 1. Assume that the grid impedance is 5% of 100-Mvar system. The 100-MVAR STATCOM system is connected to the 345 kV grid-voltage via 39 kV transformer. The rated cluster current is 853 A. The full-model that dissembles the numerous SM in series is considered. The cluster balancing controller including the vector analysis feed-forward controller in Section 4.2 and feed-back controller in Fig. 2 are utilized. And, the proper SM voltage balancing controller is applied to reduce the switching frequency and keep SM voltages in a tolerance. In order to drop a single phase voltage, the fault impedance 10 Ω is installed in parallel. The STATCOM operating point is a capacitive 1 pu in state-state from the slow reactive power control. When the fault happens, the fast voltage control is activated under various current limit strategies.

When a single phase ground fault happen to the delta-connected H-bridge STATCOM, the measured zero sequence current can be captured in various current supplying situation in Figs. 9 and 10. The grid voltage distortion is 30%. The demand of zero sequence current is 0.35 pu when only positive sequence current is supplying.

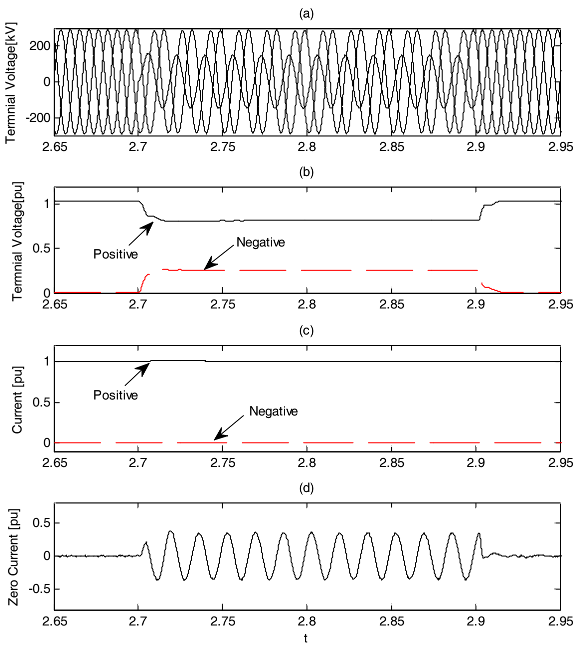

Fig. 9. Simulation result: (a) terminal voltage, (b) symmetric component of terminal voltage, (c) supplying symmetric currents (positive =1.0 pu, negative=0.0 pu), (d) measured zero sequence current of (c)

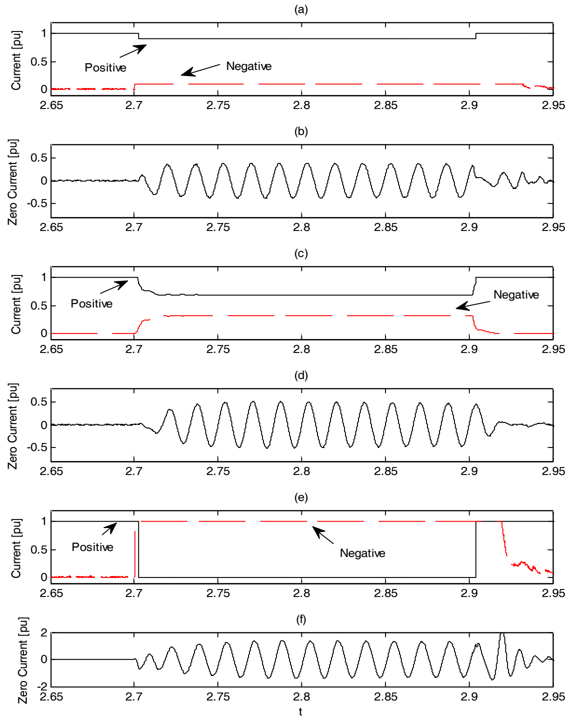

Fig. 10. Simulation result: (a) supplying symmetric currents (positive =0.9 pu, negative=1.0 pu), (b) measured zero sequence current of (a), (c) positive =0.68pu, negative=0.32pu current, (d) zero sequence current of (c), (e) positive =0.0 pu, negative=1.0 pu), (f) measured zero sequence current of (e)

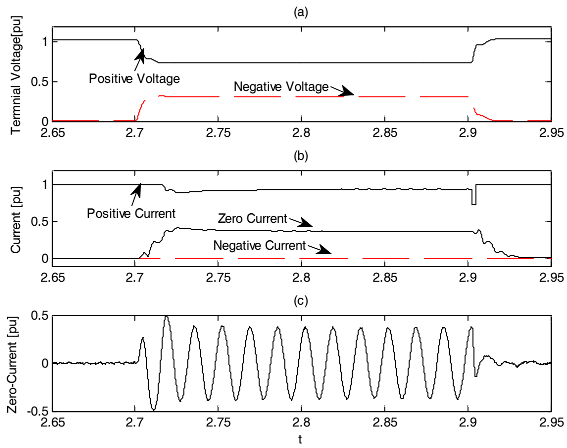

Fig. 11. Positive sequence current limit simulation I: (a) symmetric component of terminal voltage, (b) symmetric component of cluster current, (c) zero sequence current

The ratio of positive to negative sequence current is 0.9 and 0.75, the peak zero sequence current value is 0.38 pu, and 0.50 pu respectively. Only negative sequence current is used for compensating the voltage, the additional current to cluster is 1.18 pu. The most efficient way to use the switching device current ability is to set a limit the negative sequence current when grid voltage drop happens. That is, the current characteristics of delta-connected H-bridge STATCOM should be only positive sequence component even in the unbalanced voltage drop at Fig. 4.

In practical, the physical current through the switching device has a limit value. If the physical current limit is 1.3 pu, the positive sequence current is limited depending on the zero sequence current as shown in (10). In that case, the negative sequence current is limited in zero value. When a single phase ground fault occurs according to a different fault resistance, limitation of positive sequence current is shown in Figs. 11 and 12.

The voltage distortion is 40%, and the zero sequence current of 0.37 pu is required to balance the cluster. Therefore, the positive sequence current has to lower reference value, 0.93 pu, as shown in Fig. 11. When the voltage distortion is 50%, the positive sequence does not

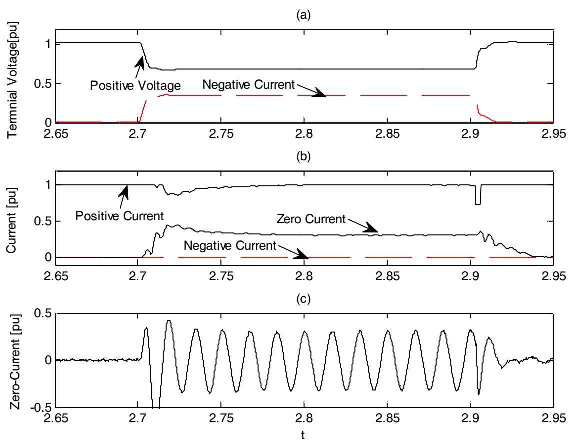

Fig. 12. Positive sequence current limit simulation II: (a) symmetric component of terminal voltage, (b) symmetric component of cluster current, (c) zero sequence current

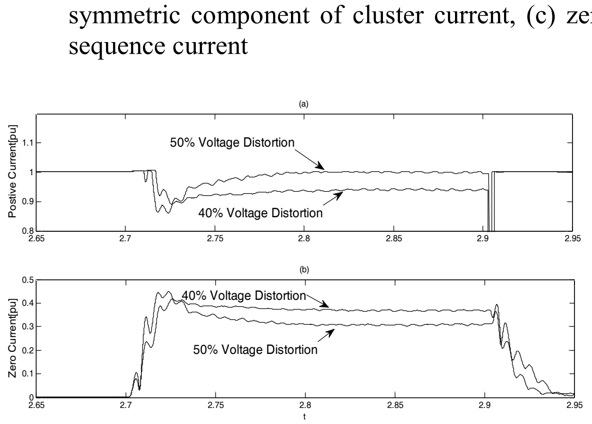

Fig. 13. (Zoomed-in) Simulation results, I and II: (a) Positive sequence current, (b) zero sequence current

constrained since only zero sequence current is 0.3 pu, as shown in Fig. 12. In order to clearly compare the results, the positive and zero sequence current waveform is zoomed in depending on the voltage distortion as shown in Fig. 13. From the simulation result, it is identified that the zero sequence has nonlinear characteristics in response to the voltage distortion degree as Section 4.2. According to the different fault event, even the positive sequence current can be limited in order to protect the switching device from thermal destruction.

6. Conclusions

In general, the STATCOM operates as a voltage controller to support voltage sagging effectively. This paper proposed the current limit strategy of delta-connected H-bridge STATCOM under the unbalanced fault event. The current strategy is to supply maximum positive sequence component current and to restrict the negative sequence component current even if the unbalanced voltage sagging occurs. It might be simple and obvious, no one has ever considered the strategy in terms of feasibility and efficiency by using the delta-connected H-bridge STATCOM. From the result, only positive sequence component must be considered with the V-I characteristics for the unbalanced fault.

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