### 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

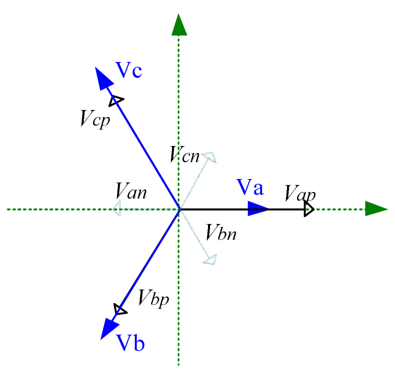


**Fig. 6.** Symmetric voltage component's phasor diagram when the one-phase fault occurs

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.

### 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.

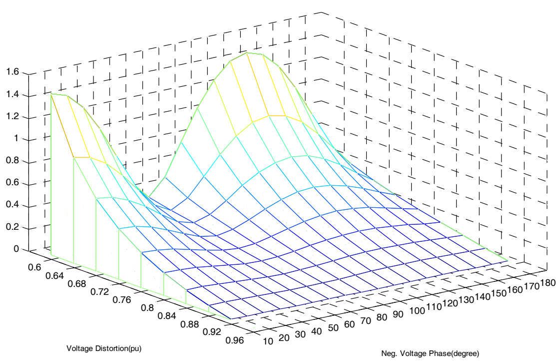


**Fig. 7.** Relationship between zero sequence current and distorted voltage (magnitude and phase displacement) under supplying only positive sequence current

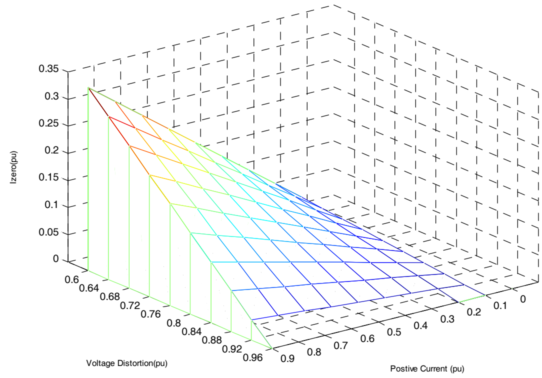


**Fig. 8.** Relationship between zero and positive sequence current under voltage distortion (Negative sequence voltage phase displacement is fixed as 180°)

**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-

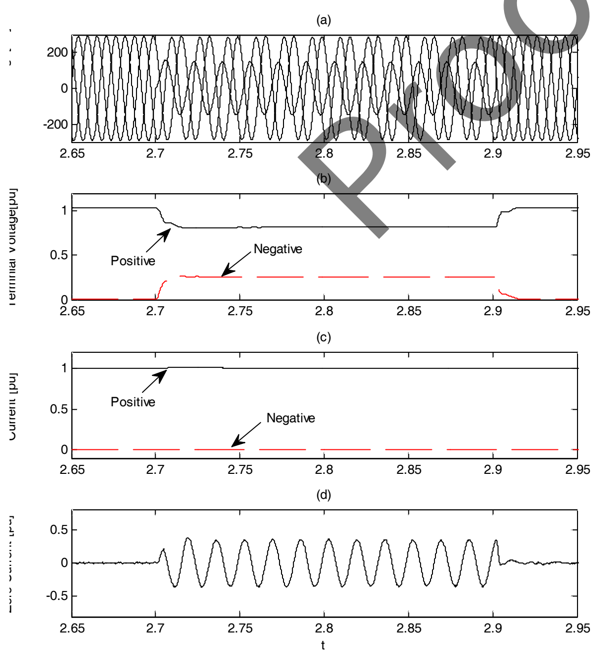


**Fig. 9.** Simulation result: (a) terminal voltage, (b) symmetric component of terminal voltage, (c) supplying symmetric currents (positive =1.0 pu, negative=0.0 pu), (d) measured zero sequence current of (c)

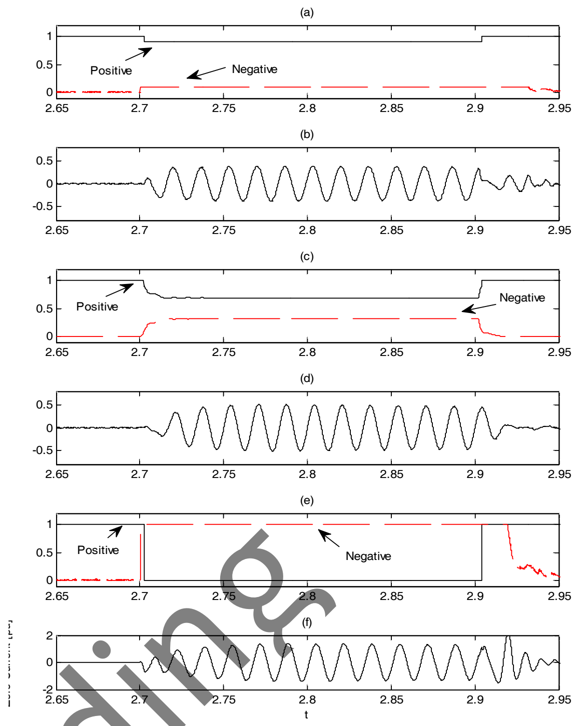


**Fig. 10.** Simulation result: (a) supplying symmetric currents (positive =0.9 pu, negative=1.0 pu), (b) measured zero sequence current of (a), (c) positive =0.68pu, negative=0.32pu current, (d) zero sequence current of (c), (e) positive =0.0 pu, negative=1.0 pu), (f) measured zero sequence current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

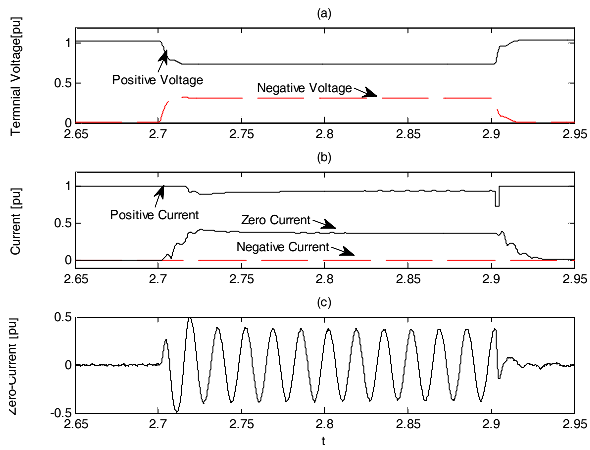


**Fig. 11.** Positive sequence current limit simulation I: (a) symmetric component of terminal voltage, (b) symmetric component of cluster current, (c) zero sequence current

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.

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

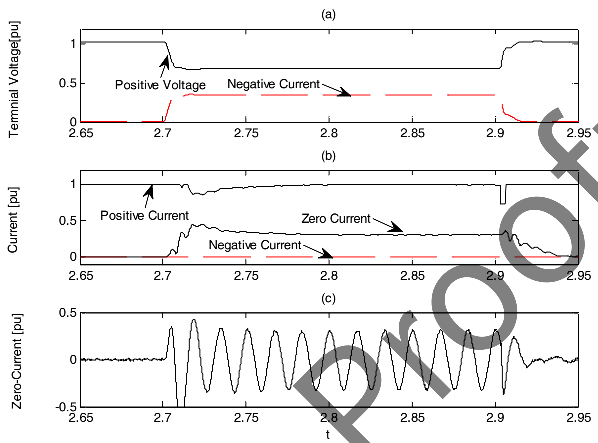


**Fig. 12.** Positive sequence current limit simulation II: (a) symmetric component of terminal voltage, (b) symmetric component of cluster current, (c) zero sequence current

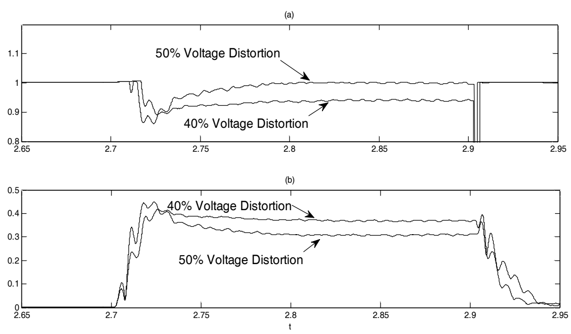


**Fig. 13.** (Zoomed-in) Simulation results, I and II: (a) Positive sequence current, (b) zero sequence current

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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