

Coordination control of positive and negative sequence voltages of cascaded H-bridge STATCOM operating under imbalanced grid voltage

Liang Hao¹, Song Hanliang², Xiu Liancheng³ ✉, Liu Anling¹, Zhang Bin¹

¹State Grid Ankang Power Supply Company, Ankang, People's Republic of China

²School of Electric Power Engineering, Nanjing Institute of Technology, Nanjing, People's Republic of China

³School of Mechanical and Electrical Engineering, Sichuan Agricultural University, Chengdu, People's Republic of China

✉ E-mail: 649770915@qq.com

eISSN 2051-3305

Received on 28th August 2018

Accepted on 19th September 2018

E-First on 17th December 2018

doi: 10.1049/joe.2018.8692

www.ietdl.org

Abstract: When the grid voltage is imbalance, the current decoupling control strategy in d-q frame designed for the balanced system still let STATCOM output balanced voltage. In this case, the negative sequence component in the grid voltage may cause the device overcurrent. Here, the positive and negative sequence of grid voltage are separated first and that of the STATCOM output voltage is also controlled independently. However, how to determine and coordinate the positive and negative sequence voltage have not been effectively investigated yet. From the perspective of power balance, this paper gets the quantitative relationship between the phase shift angles of the positive and the negative sequence voltages. It also gets the quantitative relationship between the modulation ratios of the positive and the negative sequence voltages, and hence the effective coordination control strategy of positive and negative voltages of cascaded STATCOM operating under imbalanced grid voltage was developed. In addition, the phase of the positive and negative voltages, which is critical for the proposed coordination control strategy, can be obtained by the advanced open-loop phase synchronisation scheme. Finally, its detailed implementation was also provided. Simulation results show that the proposed method is correct and effective.

1 Introduction

The control of cascaded H-bridge STATCOM should quickly respond to the reactive power demand of the load, while ensuring the safe and stable operation of the device itself [1–3]. Especially when applied to the public power grid, the device must be able to withstand the impact of power system failures, keep stable operation in the process of grid recovery, and provide timely and effective dynamic reactive power support. If the STATCOM only carry out positive voltage control, the negative sequence voltage of the grid may cause the device overcurrent protection [3–5]. When a serious asymmetrical fault occurs in power grids, the system voltage drops rapidly, and without corresponding control, it will cause the output current of the STATCOM to exceed the withstanding current capacity of the device and threaten the safe operation of the device.

Most of the cascaded STATCOM control schemes, which are typical current decoupling control [1], model predictive control [6], decoupled P - Q control [7], non-linear control [8], and so on, are well-designed based on three-phase symmetric power system. However, various disturbances such as lightning, operation overvoltage, asymmetrical short-circuit fault, and asymmetric load will lead to an asymmetry of grid voltage, which will affect the normal operation of STATCOM [9, 10]. If there is no effective control for the asymmetric working conditions, the device will generate unbalanced and distorted currents, which will lead to the increase of the system loss and the decrease of the running performance [11]. Seriously, the device may fail to protect and quit operation, and even cause damage to the device directly. Yi *et al.* [12] adopted the switch function method to deeply analyse the adverse effects of grid voltage unbalance on cascaded STATCOM. However, during the unbalanced operation of the power grid, it is precisely the moment when the device plays a role of reactive power support. At this point, we should first consider the continuous safety and stability of the device itself, and the second is to make the device play a role and provide a stable and reliable reactive support for the system. When the grid voltage is

unbalanced, the common practice is to de-operate to protect the device and wait for the re-entry before the grid is normal. However, the grid-tied and high-power STATCOM is very complicated and frequent switching is not conducive to safe operation during a short time failure. Therefore, it is hoped that STATCOM can still work in grid connection mode when the grid voltage is unbalanced. Leon *et al.* [2] adopted a state observer (software sensor) to estimate AC voltages at the STATCOM connection point, and therefore the physical voltage sensors can be cancelled and the hardware gets simplified. However, the corresponding cost is heavy calculation burden and it cannot be implemented on the DSP-based control platform. Shi *et al.* [3] developed an individual phase current control method based on optimal zero-sequence current separation, which is adopted to get better adaptation to unbalanced grid conditions. However, it is applicative only for star-connected cascade STATCOMs. Xiong *et al.* [13] proposed a seamless self-healing scheme that can recover the STATCOM to its normal operation after the failed H-bridge units are bypassed, which can remarkably improve the continuous operation ability of the cascaded H-bridge STATCOM in case of failure. However, it did not analyse the system over-current around the asymmetric fault, which is the common grid fault. Additionally, during grid voltage imbalance, the frequently used synchronous reference frame (SRF) phase-locked loop (PLL) must compromise between steady-state accuracy and transient dynamics, failing to achieve the fast and accurate phase synchronisation [14]. Wang *et al.* [15] improved the PLL algorithm through a general delayed signal cancellation (DSC) operator, which can achieve the fast-transient response at high control bandwidth without suffering from the steady-state error caused by grid unbalance and harmonics. However, Dong *et al.* [16] pointed out that the above-mentioned PLL algorithm has the problem of stability in weak grid due to the converter interactions with grid impedance and power flow directions. In response to this problem, the open-loop phase synchronisation schemes are proposed [17–21], which fundamentally solved the stability problem. This article will learn

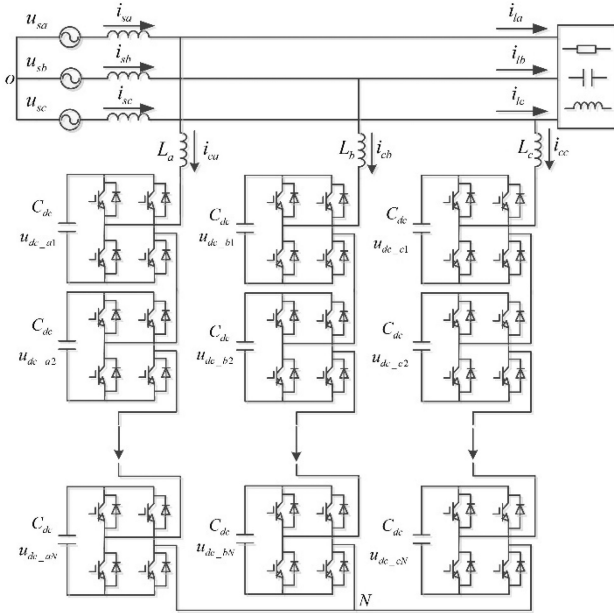


Fig. 1 Layout of cascaded H-bridge STATCOM

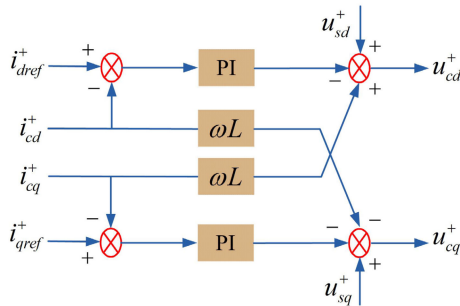


Fig. 2 Decoupling feedback control for the balanced system

from this method to achieve the accurate separation of positive and negative grid voltage.

This paper focuses on the control issues of cascaded H-bridge STATCOM operating under imbalanced grid voltage. Using the open-loop phase synchronisation scheme proposed in [18] to cope with the phase disturbance of the grid voltage, the sequence components of the STATCOM output voltages and the grid voltages can be separated. From the perspective of power balance, this paper gets the quantitative relationship between the phase shift angles of the positive and the negative voltages. It also gets the quantitative relationship between the modulation ratios of the positive and negative voltages, and hence the effective coordination control strategy of positive and negative voltages of STATCOM operating under imbalanced grid voltage was developed.

2 Configuration of cascaded STATCOM

The three-phase cascaded STATCOM comprise of cascaded multilevel inverter (CMI) in series with a linking inductor L_μ ($\mu = a, b, c$) [22–24], as illustrated in Fig. 1.

Several identical H-bridge inverters compose the CMI and the carrier phase shifted SPWM method is utilised. In each H-bridge, the DC-side capacitance is C_{dc} and the DC capacitor voltage is $u_{dc_ \mu k}$ ($k = 1, 2, \dots, N$). Ideally, the DC voltage of each power unit is equal. Besides, u_{sd} , i_{sd} , i_{ld} and i_{cd} represent the grid voltage, the grid-side current, the load current, and the output current of STATCOM. The typical current decoupling feedback control shown in Fig. 2, which is well designed for the three-phase balanced system [23–25], is selected as the basic control frame of the developed coordination control strategy here.

3 Mathematic analysis for the coordination control of positive and negative sequence

When the grid voltage is unbalanced, it can be decomposed into the positive sequence and the negative sequence components by adopting the symmetrical component method. According to the superposition principle, the positive and negative sequence voltages produce the positive and the negative sequence current, respectively. The unbalanced voltage can be rewritten as the sum of the positive and negative sequence voltages, that is

$$\begin{bmatrix} u_{sa} \\ u_{sb} \\ u_{sc} \end{bmatrix} = u_s^+ + u_s^- = U_s^+ \begin{bmatrix} \sin(\omega t) \\ \sin(\omega t - \frac{2\pi}{3}) \\ \sin(\omega t + \frac{2\pi}{3}) \end{bmatrix} + U_s^- \begin{bmatrix} \sin(\omega t + \beta) \\ \sin(\omega t + \beta + \frac{2\pi}{3}) \\ \sin(\omega t + \beta - \frac{2\pi}{3}) \end{bmatrix} \quad (1)$$

where U_s^+ and U_s^- are the amplitudes of the positive and negative sequence components, respectively. β is the phase difference between the negative and the positive sequence components.

For each phase of the inverter, the active power generated by the positive and negative sequence voltages flows into the DC capacitors of the corresponding phase and affects the DC capacitor voltages. Then, we analyse the power flow of the three-phase DC capacitors by assuming that the positive and negative sequence components are controlled separately.

Suppose the CMI output voltage is

$$\begin{bmatrix} u_{ca} \\ u_{cb} \\ u_{cc} \end{bmatrix} = U_c^+ \begin{bmatrix} \sin(\omega t + \delta^+) \\ \sin(\omega t - 2\pi/3 + \delta^+) \\ \sin(\omega t + 2\pi/3 + \delta^+) \end{bmatrix} + U_c^- \begin{bmatrix} \sin(\omega t + \beta + \delta^-) \\ \sin(\omega t + \beta + 2\pi/3 + \delta^-) \\ \sin(\omega t + \beta - 2\pi/3 + \delta^-) \end{bmatrix} \quad (2)$$

where u_{cu} is the instantaneous value of the CMI output voltage, and + and - in the superscript represent the positive and negative sequence components, respectively. δ^+ and δ^- are the phase shift angle of the CMI positive, negative sequence voltage ahead of the grid positive, negative sequence voltage, respectively.

Then, the instantaneous current i_{cu} of the STATCOM can also be expressed by the positive and negative sequence components, that is,

$$\begin{bmatrix} i_{ca} \\ i_{cb} \\ i_{cc} \end{bmatrix} = I_c^+ \begin{bmatrix} \sin(\omega t + \pi/2 + \delta^+) \\ \sin(\omega t + \pi/2 - 2\pi/3 + \delta^+) \\ \sin(\omega t + \pi/2 + 2\pi/3 + \delta^+) \end{bmatrix} + I_c^- \begin{bmatrix} \sin(\omega t + \pi/2 + \beta + \delta^-) \\ \sin(\omega t + \pi/2 + \beta + 2\pi/3 + \delta^-) \\ \sin(\omega t + \pi/2 + \beta - 2\pi/3 + \delta^-) \end{bmatrix} \quad (3)$$

Taking Phase *A* as an example, the power flowing through the Phase *A* of the inverter is

$$S_a = u_{ca} i_{ca} = (u_{ca}^+ + u_{ca}^-)(i_{ca}^+ + i_{ca}^-) \quad (4)$$

Taking (2) and (3) into (4), we have

$$2S_a = S_1 + S_2 + S_3 + S_4 \quad (5)$$

where

$$\begin{cases} S_1 = U_c^+ I_c^+ \sin(2\omega t + 2\delta^+) \\ S_2 = U_c^+ I_c^- [\sin(\delta^+ - \delta^- - \beta) + \sin(2\omega t + \beta + \delta^+ + \delta^-)] \\ S_3 = U_c^- I_c^+ [\sin(\beta - \delta^+ + \delta^-) + \sin(2\omega t + \beta + \delta^- + \delta^+)] \\ S_4 = U_c^- I_c^- \sin(2\omega t + 2\beta + 2\delta^-) \end{cases} \quad (6)$$

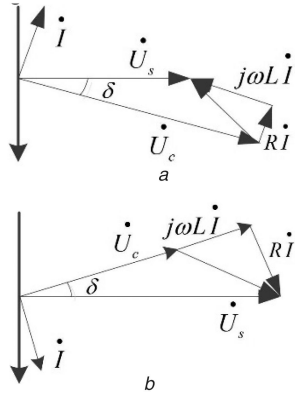


Fig. 3 Phasor diagram of a single-phase STATCOM
(a) Capacitive mode, (b) Inductive mode

Equation (6) shows that S_1 and S_4 are the double-frequency sinusoidal quantity. S_2 and S_3 contain the DC component, which is transmitted from the AC side of the H-bridge to the DC side, causing the instability of the DC capacitor voltage. Moreover, because of the DC component, the current in Phase A will increase, and the higher the negative sequence component is, the more the current increases, which may cause the over-current fault of the device.

The DC component can be expressed as

$$2\bar{p}_a = (U_c^+ I_c^- - U_c^- I_c^+) \sin(\delta^+ - \delta^- - \beta) \quad (7)$$

When the grid voltage contains the negative sequence component, the DC component power is the main factor that affects the stability of the DC capacitor voltage and leads to the device overcurrent fault. Therefore, to ensure the normal operation of STATCOM when the grid voltage is unbalanced, it is necessary to select the appropriate control amount to make this DC component power equal to 0, guaranteeing the stability of DC-side voltage.

Obviously, β in (7) is an uncertain quantity, which changes with the change of the phase difference between positive and negative sequence components in grid voltage and cannot be set up in advance. Therefore, to make the DC component power in (7) equal to 0, we have

$$U_c^+ I_c^- = U_c^- I_c^+ \quad (8)$$

Fig. 3 shows the vector diagram of a single-phase STATCOM. Based on the relationship among the CMI AC voltage U_L , the power grid voltage U_S and the linking inductor voltage U_L , we may have

$$\frac{U_L}{\sin \delta} = \frac{U_s}{\sin(\varphi + \pi/2)} = \frac{U_L}{\sin(\pi/2 - \varphi - \delta)} \quad (9)$$

where δ is the phase difference of U_L ahead of U_S , and φ is the impedance angle.

Based on (9), we may have

$$U_L = \frac{U_s \sin \delta}{\cos \varphi} \quad (10)$$

$$U_L = \frac{U_s \cos(\delta + \varphi)}{\cos \varphi} \quad (11)$$

From Fig. 3, we also have

$$I = \frac{U_s \sin \delta}{R} \quad (12)$$

where I and R are the output reactive current and the equivalent series resistance of STATCOM.

Considering the negative sequence components, (11) and (12) can be rewritten as

$$\begin{cases} U_c^+ = \frac{U_s^+ \cos(\varphi + \delta^+)}{\cos \varphi} \\ U_c^- = \frac{U_s^- \cos(\varphi + \delta^-)}{\cos \varphi} \\ I_c^+ = \frac{U_s^+ \sin \delta^+}{R} \\ I_c^- = \frac{U_s^- \sin \delta^-}{R} \end{cases} \quad (13)$$

Substituting (13) into (8) yields

$$\cos(\varphi + \delta^+) \sin \delta^- = \cos(\varphi + \delta^-) \sin \delta^+ \quad (14)$$

To meet (14), the phase shift angle of the positive sequence voltage must be equal to that of the negative sequence voltage, that is,

$$\delta^+ = \delta^- \quad (15)$$

Then, the DC component power is zero when the phase shift angle of the positive sequence voltage is equal to that of the negative sequence voltage. The same result is found for phases B and C.

When the grid voltage is unbalanced, (15) can ensure that there is no DC power injected into the capacitor, which is the limitation of the positive and negative sequence voltages from the phase shift angle of the inverter output voltage. In the case of grid voltage imbalance, the DC voltage level can be adjusted by the modulation ratio of positive and negative sequence CMI voltages. To keep the final DC voltage stable, the positive and negative sequence modulation ratios should be coordinated.

The amplitudes of the positive and negative voltages of the CMI is, respectively, as follows,

$$\begin{cases} U_c^+ = m^+ u_{dc} \\ U_c^- = m^- u_{dc} \end{cases} \quad (16)$$

Substituting (13) into (16) yields

$$u_{dc} = \frac{U_s^+ \cos(\varphi + \delta^+)}{m^+ \cos \varphi} = \frac{U_s^- \cos(\varphi + \delta^-)}{m^- \cos \varphi} \quad (17)$$

Considering (15), in this control conditions, the modulation ratio relationship between the positive and negative sequence components is:

$$\frac{m^+}{m^-} = \frac{U_s^+}{U_s^-} \quad (18)$$

The relationship described by (15) and (18) is the developed coordination control scheme of the positive and negative sequence components for cascaded H-bridge STATCOM under imbalanced grid voltage. Based on the power flow relationship between the power grid and the STATCOM device, this method coordinates the active power generated by the positive and negative sequence components, and avoids the device overcurrent during the grid failure, allowing the devices to operate steadily and continuously.

4 Implementation of coordination control of the positive and negative sequence components

In coordination control mode, the reference value of the positive and negative sequence current is not arbitrarily set, but to maintain the mathematical relationship of them. The STATCOM control system is divided into two parts, that is, the positive and the negative sequence components. The former is regulated by a current controller whose reference value can be set according to the required reactive power, as shown in Fig. 2. The latter does not

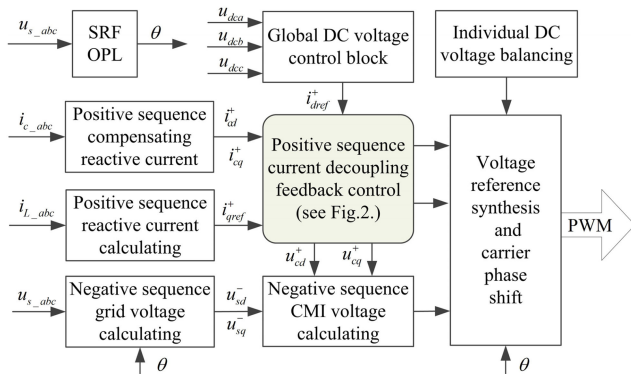


Fig. 4 Coordination control strategy of STATCOM

conduct current feedback control and it adopts the open-loop control. The output negative sequence voltage of the STATOM can be deduced as follows.

Park transformation matrix is given by

$$T_{\text{abc/dq}} = \frac{2}{3} \begin{bmatrix} \sin \omega t & \sin\left(\omega t - \frac{2\pi}{3}\right) & \sin\left(\omega t + \frac{2\pi}{3}\right) \\ \cos \omega t & \cos\left(\omega t - \frac{2\pi}{3}\right) & \cos\left(\omega t + \frac{2\pi}{3}\right) \end{bmatrix} \quad (19)$$

Therefore, the negative sequence components of grid voltage in d - q frame can be rewritten as

$$\begin{bmatrix} u_{sd}^- \\ u_{sq}^- \end{bmatrix} = \begin{bmatrix} U_s^- \cos \beta \\ U_s^- \sin \beta \end{bmatrix} \quad (20)$$

Similarly, the positive and negative sequence components of CMI voltage in $d-q$ frame can be rewritten as

$$\begin{bmatrix} u_{cd}^+ \\ u_{cd}^- \end{bmatrix} = \begin{bmatrix} U_c^+ \cos \delta^+ \\ U_c^+ \sin \delta^+ \end{bmatrix} \quad (21)$$

$$\begin{bmatrix} u_{\text{cd}}^- \\ u_{\text{ca}}^- \end{bmatrix} = \begin{bmatrix} U_c^- \cos(\beta + \delta^-) \\ U_c^- \sin(\beta + \delta^-) \end{bmatrix} \quad (22)$$

Considering (15), we have

$$\begin{bmatrix} \cos \delta^- \\ \sin \delta^- \end{bmatrix} = \begin{bmatrix} \cos \delta^+ \\ \sin \delta^+ \end{bmatrix} = \begin{bmatrix} \frac{u_{cd}^+}{U_c^+} \\ \frac{u_{cq}^+}{U_c^+} \end{bmatrix} \quad (23)$$

Rewrite (20) as

$$\begin{bmatrix} \cos \beta \\ \sin \beta \end{bmatrix} = \begin{bmatrix} \frac{u_{sd}^-}{U_s^-} \\ \frac{u_{sq}^-}{U_s^-} \end{bmatrix} \quad (24)$$

Combing (15), (18), (23), and (24), the output negative sequence voltage of the cascaded STATOM in $d-q$ frame can be deduced as

$$\begin{bmatrix} u_{cd}^- \\ u_{cq}^- \end{bmatrix} = \frac{1}{U_s^+} \begin{bmatrix} u_{sd}^- u_{cd}^+ + u_{sq}^- u_{cq}^+ \\ u_{sq}^- u_{cd}^+ - u_{sd}^- u_{cq}^+ \end{bmatrix} \quad (25)$$

Based on the above coordinated control algorithms of the positive and negative sequence components, the developed coordination control strategy of the positive and negative sequence for the cascaded H-bridge STATCOM can be described as shown in Fig. 4. The global DC voltage control block and the DC capacitor voltage balancing block in Fig. 4 can be referred in [3, 4, 26].

Table 1 Parameters of the simulation system

Parameters	Value
grid voltage	380 V
grid frequency	50 Hz
power unit quantity	2
switching frequency	5 kHz
capacitance of DC capacitor	7200 μ F
rated DC capacitor voltage	1 kV

In addition, when the phase of the grid voltage is disturbed, if the phase detection block cannot track the grid real-time phase, then the STATCOM cannot be accurately controlled and the above coordination control strategy also cannot be reached. The real-time phase of the grid voltage is obtained by the Synchronous Reference Frame based Open-loop Phase Locking (SRF-OPL) scheme proposed in [18, 21], which can effectively cope with the grid phase disturbances. The obvious advantages of this method are simple structure, easy implementation, and fast response.

5 Simulation verification

Matlab/simulink was adopted here to carry out the simulation verification. The main parameters of the *Y* type cascaded STATCOM simulation model are shown in Table 1 and the simulation results are shown in Fig. 5.

The grid voltage in the simulation is shown in Fig. 5a. The grid voltages suddenly increase 30% of the negative sequence component between 0.14 and 0.18 s. The phase difference between the positive and negative sequence components is 30° . The result shown in Fig. 5b is the device current without the negative sequence control. Fig. 5c is the device current waveform with the coordination control of the positive and negative sequence. Fig. 5d shows the imbalance degree of the current shown in Fig. 5c. Fig. 5e is the reactive component of the system current decomposed in the d - q frame at this moment. In the mode of the coordination control of the positive and negative sequence voltages, the negative sequence component of the CMI current can be effectively controlled, the CMI current imbalance degree is low enough, and the reactive component of the grid current is zero, realising the high-performance compensation of the positive sequence reactive power.

The simulation results show that the developed coordination control strategy of the positive and negative sequence component can well control the over-current problem caused by the negative sequence component of the grid voltage. So, the STATCOM can always operate stably, the imbalance degree of output current is low enough, the positive sequence reactive component of the system current basically remains at zero, and there is only fluctuation near the system voltage disturbance point, which shows STATCOM is still well done to compensate for reactive power load.

6 Conclusion

This paper proposes a separation and coordination control method of positive and negative sequence component for cascaded H-bridge STATCOM under unbalanced grid voltage, which decomposes the device into positive and negative sequence components. Through the analysis, we find that there is a relationship between the phase shift angle and the modulation ratio of positive and negative sequence components. Meanwhile, the control phase information can be obtained by the SRF-OPL phase-detection method to cope with the system voltage phase disturbances. Simulation results show that the method put forward here has a good ability to deal with system imbalance. In the system voltage asymmetry and phase disturbance conditions, the devices can operate stably and achieve the compensation of reactive power at the same time.

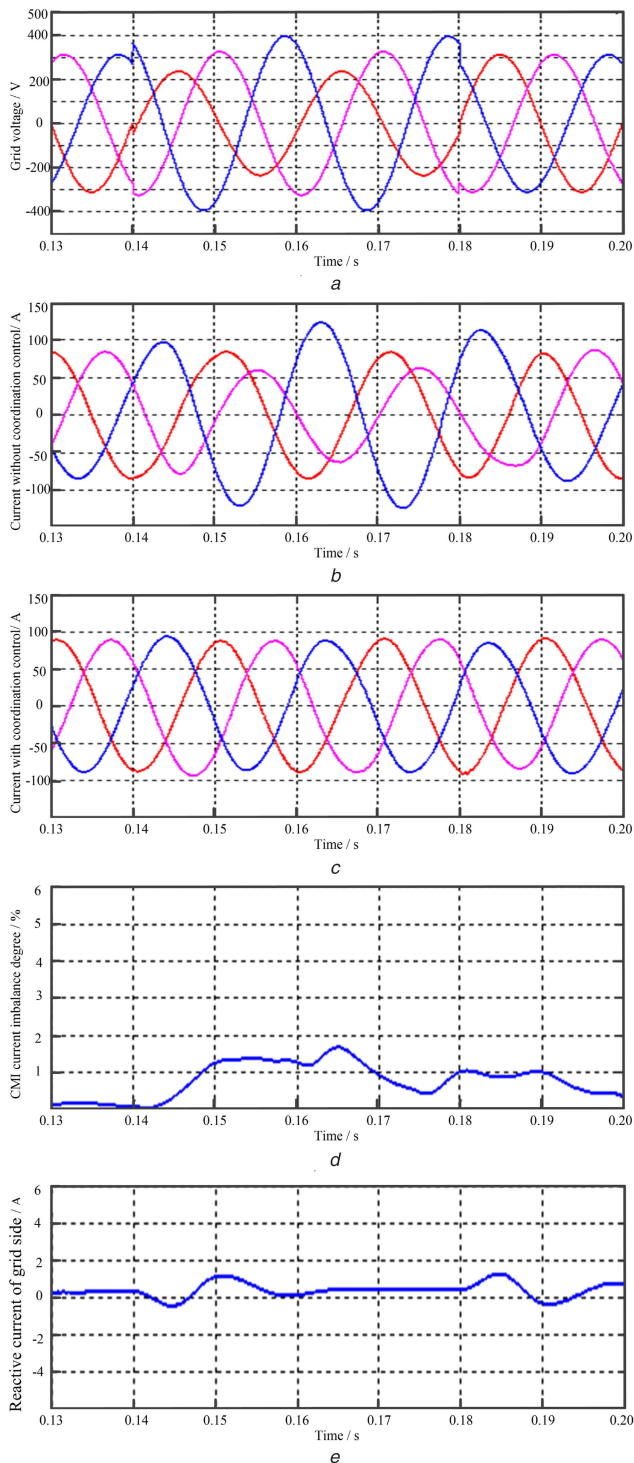


Fig. 5 Simulation results

(a) Grid voltage, (b) Current without coordination control, (c) Current with coordination control, (d) CMI current imbalance degree, (e) Reactive current of grid side

7 References

- [1] Xiong, L., Zhuo, F.: 'A novel DC voltage balancing method for cascaded STATCOM'. 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), Long Beach, CA, 2013, pp. 924–929
- [2] Leon, A.E., Mauricio, J.M., Solsona, J.A., *et al.*: 'Software sensor-based STATCOM control under unbalanced conditions', *IEEE Trans. Power Deliv.*, 2009, **24**, (3), pp. 1623–1632
- [3] Shi, Y., Liu, B., Shi, Y., *et al.*: 'Individual phase current control based on optimal zero-sequence current separation for a star-connected cascade STATCOM under unbalanced conditions', *IEEE Trans. Power Electron.*, 2016, **31**, (3), pp. 2099–2110
- [4] Sun, Y., Ma, L., Xiong, L.: 'A novel balancing method for DC voltage of cascaded multilevel STATCOM'. Proc. 2012 Asia-Pacific Power and Energy Engineering Conf., Shanghai, China, March 2012, pp. 1–5
- [5] Xiong, L., Zhuo, F., Zhu, M.: 'Study on the compound cascaded STATCOM and compensating for 3-phase unbalanced loads'. 2013 Twenty-Eighth Annual IEEE Applied Power Electronics Conf. and Exposition (APEC), Long Beach, CA, USA, 2013, pp. 3209–3215
- [6] Zhang, Y., Wu, X., Yuan, X.: 'A simplified branch and bound approach for model predictive control of multilevel cascaded H-bridge STATCOM', *IEEE Trans. Ind. Electron.*, 2017, **64**, (10), pp. 7634–7644
- [7] Fazeli, S.M., Ping, H.W., Abd Rahim, N.B., *et al.*: 'Individual-phase decoupled P-Q control of three-phase voltage source converter', *IET Gener. Transm. Distrib.*, 2013, **7**, (11), pp. 1219–1228
- [8] Yuan, Z., Song, Q., Liu, W., *et al.*: 'Nonlinear controller for cascade H-bridge inverter-based STATCOM'. 2005 IEEE/PES Transmission & Distribution Conf. & Exposition: Asia and Pacific, Dalian, 2005, pp. 1–5
- [9] Chen, H.C., Cheng, P.T.: 'A DC Bus voltage balancing technique for the cascaded H-bridge STATCOM With improved reliability under grid faults', *IEEE Trans. Ind. Appl.*, 2017, **53**, (2), pp. 1263–1270
- [10] Xiong, L., Zhuo, F.: 'Analysis on the asymmetrical operation ability of Y-connected CMLs'. 2013 IEEE ECCE Asia Downunder, Melbourne, VIC, 2013, pp. 924–929
- [11] Liu, T., Hao, X., Yang, X., *et al.*: 'A novel grid voltage feed forward control strategy for three-phase grid-connected VSI with LCCL filter'. 2012 IEEE Int. Symp. on Industrial Electronics, Hangzhou, 2012, pp. 86–91
- [12] Yi, G.P., Hu, R.J., Wei, J., *et al.*: 'Influence of grid voltage unbalance on STATCOM and the countermeasure', *Trans. China Electrotech. Soc.*, 2014, **29**, (6), pp. 238–247
- [13] Xiong, L., Ma, L., Zhuo, F., *et al.*: 'Seamless self-healing control strategy for cascaded multilevel STATCOM'. 2012 IEEE Int. Symp. on Industrial Electronics, Hangzhou, 2012, pp. 2003–2006
- [14] Golestan, S., Guerrero, J.M., Vasquez, J.C.: 'Three-phase PLLs: a review of recent advances', *IEEE Trans. Power Electron.*, 2017, **32**, (3), pp. 1894–1907
- [15] Wang, Y.F., Li, Y.W.: 'Grid synchronization PLL based on cascaded delayed signal cancellation', *IEEE Trans. Power Electron.*, 2011, **26**, (7), pp. 1987–1997
- [16] Dong, D., Wen, B., Boroyevich, D., *et al.*: 'Analysis of phase-locked loop Low-frequency stability in three-phase grid-connected power converters considering impedance interactions', *IEEE Trans. Ind. Electron.*, 2015, **62**, (1), pp. 310–321
- [17] Xiong, L., Zhuo, F., Wang, F., *et al.*: 'A fast orthogonal signal-generation algorithm characterized by noise immunity and high accuracy for single-phase grid', *IEEE Trans. Power Electron.*, 2016, **31**, (3), pp. 1847–1851
- [18] Xiong, L., Zhuo, F., Wang, F., *et al.*: 'A novel fast open-loop phase locking scheme based on synchronous reference frame for three-phase non-ideal power grids', *J. Power Electron.*, 2016, **16**, (4), pp. 1513–1525
- [19] Xiao, F., Dong, L., Li, L., *et al.*: 'A novel open-loop frequency estimation method for single-phase grid synchronization under distorted conditions', *IEEE J. Emerging Sel. Topics Power Electron.*, 2017, **5**, (3), pp. 1287–1297
- [20] Golestan, S., Guerrero, J.M., Vasquez, J.C.: 'Single-phase PLLs: a review of recent advances', *IEEE Trans. Power Electron.*, 2017, **32**, (12), pp. 9013–9030
- [21] Xiong, L., Zhuo, F., Liu, X., *et al.*: 'Research on fast open-loop phase locking scheme for three-phase unbalanced grid'. 2015 IEEE Applied Power Electronics Conf. and Exposition (APEC), Charlotte, NC, 2015, pp. 1672–1676
- [22] Xiong, L., Zhuo, F., Zhu, Y.: 'A novel control method for DC voltage of cascaded STATCOM'. Proc. of 7th Int. Power Electronics and Motion Control Conf., Harbin, China, 2012, pp. 2748–2753
- [23] Peng, F.Z., Lai, J.-S.: 'Dynamic performance and control of a static VAR generator using cascade multilevel inverters', *IEEE Trans. Ind. Appl.*, 1997, **33**, (3), pp. 748–755
- [24] Xiong, L.S., Zhuo, F.: 'Chopper controller based DC voltage control strategy for cascaded multilevel STATCOM', *J. Electr. Eng. Technol.*, 2014, **9**, (9), pp. 576–588
- [25] Maharjan, L., Inoue, S., Akagi, H.: 'A transformerless energy storage system based on a cascade multilevel PWM converter with star configuration', *IEEE Trans. Ind. Appl.*, 2008, **44**, (5), pp. 1621–1630
- [26] Liu, X., Xiong, L., Zhuo, F., *et al.*: 'A fast and accurate detection method of instantaneous reactive current in single-phase power system'. 2015 9th Int. Conf. on Power Electronics and ECCE Asia (ICPE-ECCE Asia), Seoul, 2015, pp. 1991–1996