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Power Controllability of A Three-Phase Converter With An Unbalanced Ac Source

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Abstract: Three-phase dc–ac power converters suffer from power oscillation and over current problems in case of the unbalanced ac source voltage that can be caused by grid/generator faults. Existing solutions to handle these problems are properly selecting and controlling the positive- and negative-sequence currents. In this paper, a new series of control strategies which utilize the zero sequence components are proposed to enhance the power control ability under this adverse condition. It is concluded that by introducing proper zero-sequence current controls and corresponding circuit configurations, the power converter can enable more flexible control targets, achieving better performances in the delivered power and the load current when suffering from the unbalanced ac voltage.

Keywords: GCPPP, Transmission System Operators (TSOs).

I. INTRODUCTION

In many important applications for power electronics such as renewable energy generation, motor drives, power quality, and micro grid, etc., the three-phase dc–ac converters are critical components as the power flow interface of dc and ac electrical systems . As shown in Fig1, a dc–ac voltage source converter with a corresponding filter is typically used to convert the energy between the dc bus and the three-phase ac sources, which could be the power grid, generation units, or the electric machines depending on the applications and controls Since the power electronics are getting so widely used and becoming essential in the energy conversion technology, the failures or shutting down of these backbone dc–ac converters may result in serious problems and cost. It is becoming a need in many applications that the power converters should be reliable to withstand some faults or disturbances in order to ensure certain availability of the energy supply . A good example can be seen in the wind power application, where both the total installed capacity and individual capacity of the power conversion system are relatively high. The sudden disconnection of the power converter may cause significant impacts on the grid stability and also on the high cost for maintenance/repair. As a result, transmission system operators (TSOs) in different countries have been issuing strict requirements for the wind turbine behavior under grid faults. As shown in Fig. 2, the wind power converter should be connected (or even keep generating power) under various grid voltage dips for certain time according to the dip severity, and in someuncritical conditions (e.g.,90% voltage dip), the power converter may need long-time operation.

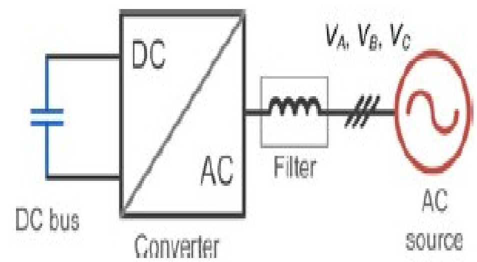

Fig.1. Typical dc–ac power converter application.

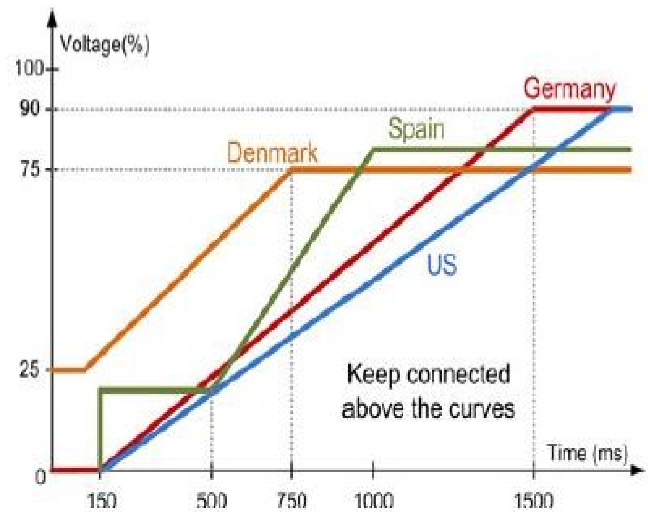

Fig2. Grid codes of wind turbines under the grid voltage dip by different countries.

When the ac source shown in Fig1 becomes distorted under faults or disturbances, the unbalanced ac voltages have been proven to be one of the greatest challenges for the control of the dc–ac converter in order to keep them normally operating and connected to the ac source. Special control methods which can regulate both the positive- and negative sequence currents have been introduced to handle these problems. However, the resulting performances by these control methods seem to be still not satisfactory: either distorted load currents or power oscillations will be presented, and thereby not only the ac source but also the power converter will be further stressed accompanying with the costly design considerations.

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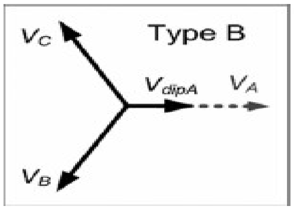
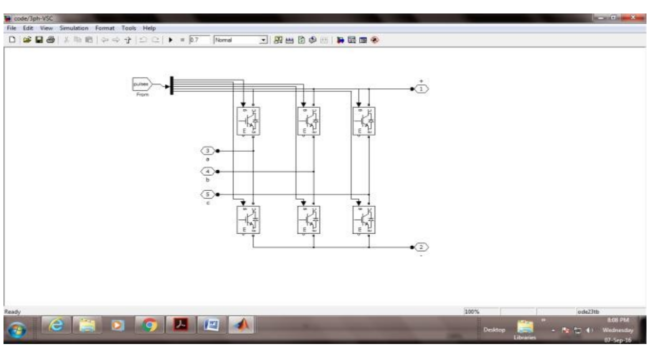


Fig.3. Phasor diagram definitions for the voltage dips in the ac source of Fig. 1. *VA* , *VB* , and *VC* means the voltage of three phases in the ac source.

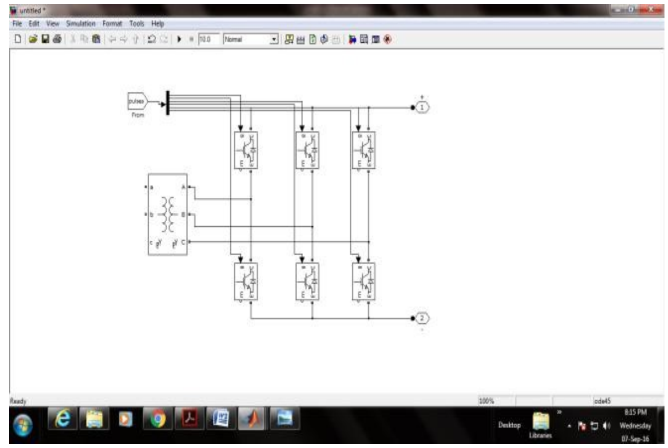
This paper targets to understand and improve the power control limits of a typical three-phase dc–ac converter system under the unbalanced ac source. A new series of control strategieswhich utilizes the zero-sequence components are then proposed to enhance the power control ability under this adverse condition. Besides the grid integration, the proposed control methods have the potential to be applied under other applications like the motor/generator connections or micro grids, where the unbalanced ac voltage is likely to be presented; therefore, the basic principle and feasibility are mainlyfocused

II. CONVERTER SYSTEM WITH THEZERO-SEQUENCE CURRENTPATH

As can be concluded, in the typical three-phase three-wire converter structure, four control freedoms for the load current seem to be not enough to achieve satisfactory performances under the unbalanced ac source. (No matter what combinations of control targets are used, either significant power oscillation or overloaded/distorted current will be presented.) Therefore, more current control freedoms are needed in order to improve the control performance under the unbalanced ac source conditions. Another series of the converter structure are shown as indicated as the four-wire system in Fig. 9(a) and the six-wire system in Fig. 9(b). Compared to the three-wire converter structure, these types of converters introduce the zero-sequence current path, which may enable extra current control freedoms to achieve better power control performances. It is noted that in the grid-connected application, the zero-sequence current is not injected into the grid but trapped in the typically used *d-Y* transformer.



(a)



(b)

Fig.4. Converter structure with the zero-sequence current path. (a) Four-wire system. (b) Six-wire system.

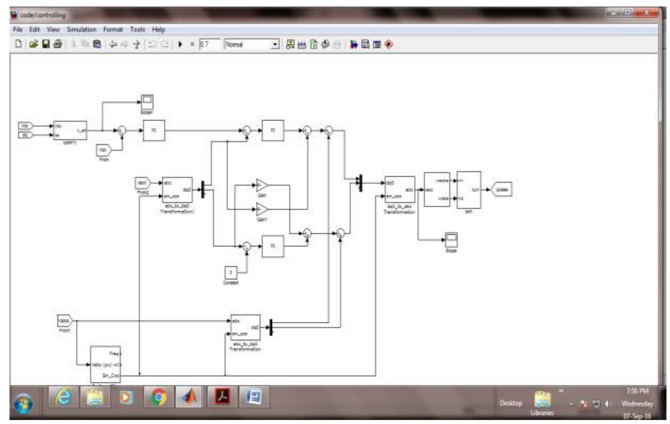


Fig.5. Control structure for the converter system with the zero-sequence current.

A potential control structure is proposed in Fig. 10, in which an extra control loop is introduced to enable the controllability of the zero-sequence current. After introducing the regulated zero-sequence current, the three-phase current generated by the converter can be written as

$$\mathbf{I_C} = \mathbf{I}^{+} + \mathbf{I}^{-} + \mathbf{I}^{0}. \quad (1)$$

By operating the voltage of the ac source (1) and the current controlled by the power converter(2), the instantaneous generated real power p, the imaginary power q in the $\alpha\beta$ coordinate, and the real power $p0$ in the zero coordinate can be calculatedas

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \\ v_\alpha \cdot i_\beta - v_\alpha \cdot i_\beta \\ v_0 \cdot i_0 \end{bmatrix}$$

$$= \begin{bmatrix} \overline{P} + P_{c2} \cdot \cos(2\omega t) + P_{s2} \cdot \sin(2\omega t) \\ \overline{Q} + Q_{c2} \cdot \cos(2\omega t) + Q_{s2} \cdot \sin(2\omega t) \\ \overline{P_0} + P_{0c2} \cdot \cos(2\omega t) + P_{0s2} \cdot \sin(2\omega t) \end{bmatrix} \quad (2)$$

Then, the instantaneous three-phase real power $p3\Phi$ and the imaginary power $q3\Phi$ of the converter can be written as

$$\begin{bmatrix} p_{3\phi} \\ q_{3\phi} \end{bmatrix} = \begin{bmatrix} p + p_0 \\ q \end{bmatrix} = \begin{bmatrix} \overline{P} + \overline{P_0} \\ \overline{Q} \end{bmatrix} + \begin{bmatrix} P_{c2} + P_{0c2} \\ Q_{c2} \end{bmatrix} \cos(2\omega t) + \begin{bmatrix} P_{s2} + P_{0s2} \\ Q_{s2} \end{bmatrix} \sin(2\omega t). \quad 2)$$

It is noted that the voltage and the current in zero sequence only contribute to the real power $p3\Phi$ of the converter. Each part of (2) can be calculated as

$$\overline{P} = \frac{3}{2}(v_d^+ \cdot i_d^+ + v_q^+ \cdot i_q^+ + v_d^- \cdot i_d^- + v_q^- \cdot i_q^-)$$

$$P_{c2} = \frac{3}{2}(v_d^- \cdot i_d^+ + v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^+ \cdot i_q^-)$$

$$P_{s2} = \frac{3}{2}(v_q^- \cdot i_d^+ - v_d^- \cdot i_q^+ - v_q^+ \cdot i_d^- + v_d^+ \cdot i_q^-)$$

$$\overline{Q} = \frac{3}{2}(v_q^+ \cdot i_d^+ - v_d^+ \cdot i_q^+ + v_q^- \cdot i_d^- - v_d^- \cdot i_q^-)$$

$$Q_{c2} = \frac{3}{2}(v_q^- \cdot i_d^+ - v_d^- \cdot i_q^+ + v_q^+ \cdot i_d^- - v_d^+ \cdot i_q^-)$$

$$Q_{s2} = \frac{3}{2}(-v_d^- \cdot i_d^+ - v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^+ \cdot i_q^-)$$

$$\overline{P_0} = \frac{3}{2}(v_{\mathrm{Re}}^0 \cdot i_{\mathrm{Re}}^0 + v_{\mathrm{Im}}^0 \cdot i_{\mathrm{Im}}^0)$$

$$P_{0c2} = \frac{3}{2}(v_{\mathrm{Re}}^0 \cdot i_{\mathrm{Re}}^0 - v_{\mathrm{Im}}^0 \cdot i_{\mathrm{Im}}^0)$$

$$P_{0s2} = \frac{3}{2}(-v_{\mathrm{Im}}^0 \cdot i_{\mathrm{Re}}^0 - v_{\mathrm{Re}}^0 \cdot i_{\mathrm{Im}}^0).$$

Then, matrix equation as

$$\begin{bmatrix} \overline{P} + \overline{P_0} \\ P_{c2} + P_{0c2} \\ P_{s2} + P_{0s2} \\ \overline{Q} \\ Q_{c2} \\ Q_{s2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d^+ & v_q^+ & v_d^- & v_q^- & v_{\mathrm{Re}}^0 & v_{\mathrm{Im}}^0 \\ v_d^- & v_q^- & v_d^+ & v_q^+ & v_{\mathrm{Re}}^0 & -v_{\mathrm{Im}}^0 \\ v_q^- & -v_d^- & -v_q^+ & v_d^+ & -v_{\mathrm{Im}}^0 & -v_{\mathrm{Re}}^0 \\ v_q^+ & -v_d^+ & v_q^- & -v_d^- & 0 & 0 \\ v_q^- & -v_d^- & v_q^+ & -v_d^+ & 0 & 0 \\ -v_d^- & -v_q^- & v_d^+ & v_q^+ & 0 & 0 \end{bmatrix} \begin{bmatrix} i_d^+ \\ i_q^+ \\ i_d^- \\ i_q^- \\ i_{\mathrm{Re}}^0 \\ i_{\mathrm{Im}}^0 \end{bmatrix} \quad (3)$$

It is noted that unlike the traditional approach in which the zero sequence components are normally minimized, the zero sequence voltage and the current here look like single-phase AC components running at the same fundamental frequency. As a result, the zero-sequence voltage/current can be represented by vectors in a synchronous reference frame in the zero sequenceas

$$\mathbf{V_0} = v_{\mathrm{Re}}^0 + v_{\mathrm{Im}}^0 j \quad (4)$$

$$\mathbf{I_0} = i_{\mathrm{Re}}^0 + i_{\mathrm{Im}}^0 j \quad (5)$$

where the real part and imaginary part can be represented as follows:

$$v_{\mathrm{Re}}^0 = V^0 \cos(\varphi^0) \quad (6)$$

It can be seen that if the three-phase ac source voltage is decided, then the converter has six controllable freedoms ($i+ d$, $i+q$,$i- d$, $i- q$, i0 Re, and $i0$ Im) to regulate the current flowing in the ac source. That means: six control targets/functions can be established by the converter having the zero-sequence current path. Similarly, the three-phase average active and reactive power delivered by the converter are two basic requirements for a given application, then, two control functions need to be first settled as So, for the converter system with the zero-sequence current path, there are four control freedoms left to achieve two more control targets than the traditional three-wire system, this alsomeans extended controllability and better performance under the unbalanced acsource.

III. ELIMINATION OF BOTH THE ACTIVEAND REACTIVE POWEROSCILLATION.

Because of more current control freedoms, the power converter with the zero-sequence current path can not only eliminate the oscillation in the active power, but also cancel the oscillation in the reactive power at the same time. This control targets can be written as

$Qs2 = 0.$

$$P_{3\phi c2} = P_{c2} + P_{0c2} = 0$$

$$P_{3\phi s2} = P_{s2} + P_{0s2} = 0$$

The power oscillation caused by the zero-sequence current $P0c2$ and $P0s2$ are used to compensate the power oscillation caused by the positive- and negative-sequence currents $Pc2$ and $Ps2$.

$$\begin{bmatrix} i_d^+ \\ i_q^+ \\ i_d^- \\ i_q^- \\ i_{\mathrm{Re}}^0 \\ i_{\mathrm{Im}}^0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_d^+ & v_q^+ & v_d^- & v_q^- & v_{\mathrm{Re}}^0 & v_{\mathrm{Im}}^0 \\ v_d^- & v_q^- & v_d^+ & v_q^+ & v_{\mathrm{Re}}^0 & -v_{\mathrm{Im}}^0 \\ v_q^- & -v_d^- & -v_q^+ & v_d^+ & -v_{\mathrm{Im}}^0 & -v_{\mathrm{Re}}^0 \\ v_q^+ & -v_d^+ & v_q^- & -v_d^- & 0 & 0 \\ v_q^- & -v_d^- & v_q^+ & -v_d^+ & 0 & 0 \\ -v_d^- & -v_q^- & v_d^+ & v_q^+ & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} P_{\mathrm{ref}} \\ 0 \\ 0 \\ Q_{\mathrm{ref}} \\ 0 \\ 0 \end{bmatrix}.$$

In order to facilitate the analytical solution, assuming that he d-axis or the real axis in the synchronous reference frame s allied with the voltage vectors in each of the sequence positive, negative, and zero), then all of the controllable current components with the zero-sequence current path can be solved by

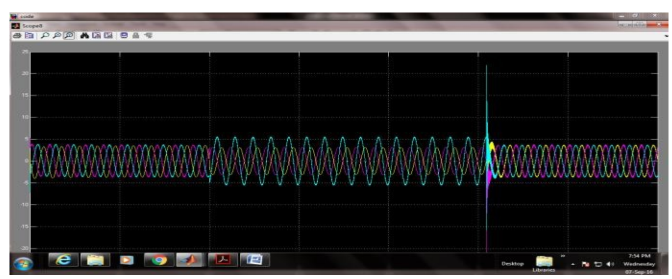


Fig.6. Simulation of converter control with no active and reactive power oscillation (three-phase converter with the zero-sequence path, *P*ref = 1 p.u., *Q*ref = 0 p.u., *Ps*2 = 0 p.u., *Pc* 2 = 0 p.u., *Qs*2 = 0 p.u., *Qc*2 = 0 p.u., *VA* = 0 p.u.).

A. Elimination of the Active Power Oscillation and the Negative-Sequence Current

Another promising control strategy for the converter using the zero-sequence current path is to eliminate the active power oscillation, and meanwhile cancel the negative-sequence current. The extra two control targets besides can be written

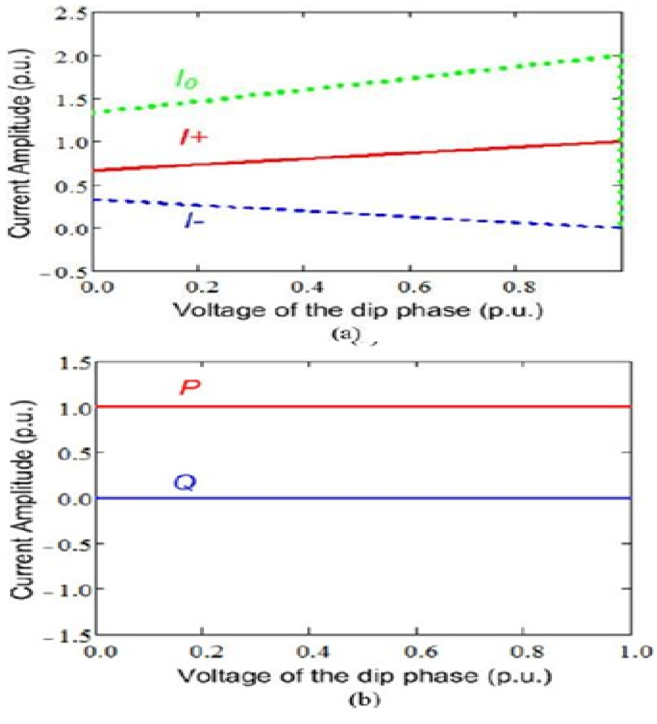


Fig.7. Profile of converter control with no active and reactive power oscillation (three-phase converter with the zero sequence path, *P*ref = 1 p.u., *Q*ref = 0 p.u., *Ps*2 = 0 p.u., *Pc* 2 = 0 p.u., *Qs*2 = 0 p.u., *Qc*2 = 0 p.u.). (a) Sequence current amplitude versus *VA* . (*I*+, *I*−, and *I*0 means the amplitude of the current in the positive, negative, and zero sequences, respectively). (b) *P* and *Q* ranges versus *VA*.

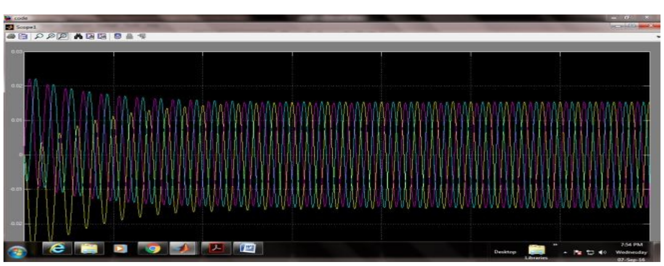


Fig.8.Simulation of converter control with no active power oscillation and no negative sequence (three-phase converter with the zero-sequence current path, *P*ref = 1 p.u., *Q*ref = 0 p.u., *Ps*2 = 0 p.u., *Pc*2=0p.u.,*id*− =0 p.u., *iq*− = 0 p.u., *VA* = 0 p.u. *I*+, *I*-, and *I*0 means the amplitude of the current in the positive, negative, and zero sequences, respectively).

And each of the current components can be calculated as

$$\begin{bmatrix} i_d^+ \\ i_q^+ \\ i_{\mathrm{Re}}^0 \\ i_{\mathrm{Im}}^0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_d^+ & v_q^+ & v_{\mathrm{Re}}^0 & v_{\mathrm{Im}}^0 \\ v_d^- & v_q^- & v_{\mathrm{Re}}^0 & -v_{\mathrm{Im}}^0 \\ v_q^- & -v_d^- & -v_{\mathrm{Im}}^0 & -v_{\mathrm{Re}}^0 \\ v_q^+ & -v_d^+ & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} P_{\mathrm{ref}} \\ 0 \\ 0 \\ Q_{\mathrm{ref}} \end{bmatrix}$$

In order to facilitate the analytical solution, assuming that the *d*-axis or the real axis in the synchronous reference frame is allied with the voltage vectors in each of the sequence, then all of the controllable current components with the zero-sequence current path can be solved as

$$i_d^+ \approx \frac{2}{3} \cdot \frac{P_{\mathrm{ref}}}{(v_d^+ - v_d^-)}$$

$$i_q^+ \approx \frac{2}{3} \cdot \frac{Q_{\mathrm{ref}}}{-v_d^+}$$

$$i_d^- = 0$$

$$i_q^- = 0$$

$$i_{\mathrm{Re}}^0 \approx \frac{-v_d^- \cdot i_d^+}{v_{\mathrm{Re}}^0}$$

$$i_{\mathrm{Im}}^0 \approx 0.$$

The current amplitude in the different sequences, as well as the delivered active/reactive power with relation to the voltage on the dipping phase are shown in Fig9(a) and (b), respectively.

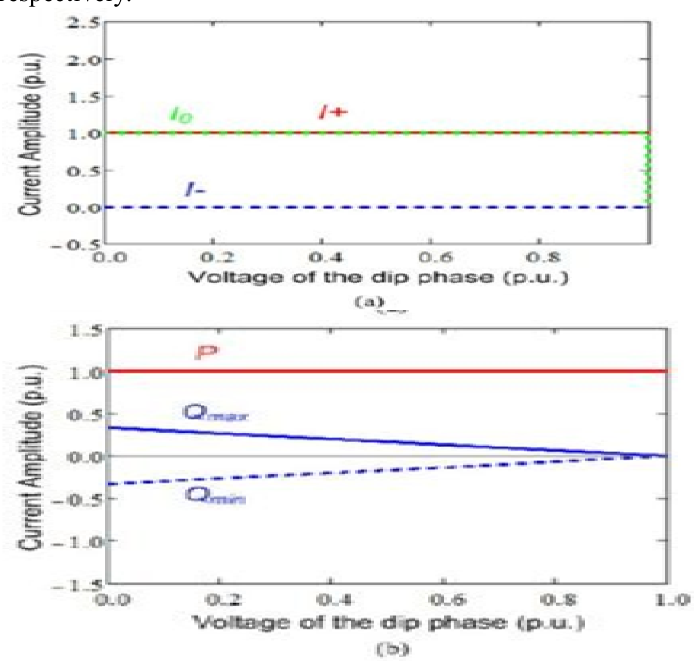


Fig.9. Profile of converter control with no active power oscillation and no negative sequence (three-phase converter with the zero-sequence current path, *P*ref = 1 p.u., *Q*ref = 0 p.u., *Ps*2 = 0 p.u., *Pc* 2 = 0 p.u., *id*− = 0 p.u., *iq*− = 0 p.u.). (a) Sequence current amplitude versus *VA* . (b) *P* and *Q* ranges versus *VA* .

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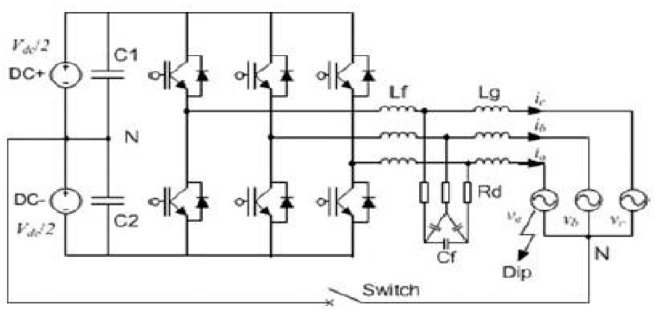
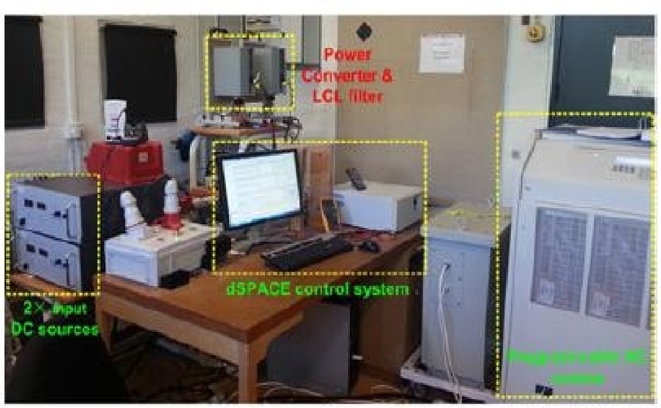
It is noted that the converter has to deliver constant positive- and zero-sequence currents in order to achieve this control strategy under different dips of the source voltage. The oscillation of the reactive power is maintained in amuch smaller range (up to 0.3 p.u.) compared to that in the three-wire system (up to 1.3 p.u.) in Fig9(b). The zero-sequence current is controlled as zero when the voltage dip is at 1.0p.u.

III.EXPERIMENTALRESULTS

The control results by different converter structures and control strategies are validated on a downscale dc–ac converter. As shown in Fig. 15, the circuit configurations and setup photo are both illustrated. A three-phase two-level converter with corresponding *LCL* filter is used to interconnect two dc voltage sources and a programmable three-phase ac voltage source. The detail parameters of the experimental setup are shown in Table III. It is noted that the converter is controlled to operate at the inverter mode, where the active power is flowing from the dc source to the ac source. By opening and closing a switch shown in Fig10(a), the converter can be shifted between the typical three-wire system and four-wire system with the zero-sequence current path. The amplitude of the phase A voltage in the programmable ac source is adjusted to 0.1 p.u. (22 *V*rms) in order to establish an adverse unbalancedcondition.



(a)



(b)

Fig.10. Configurations of the experimental setup. (a) Circuit topology (b) Setup photo.

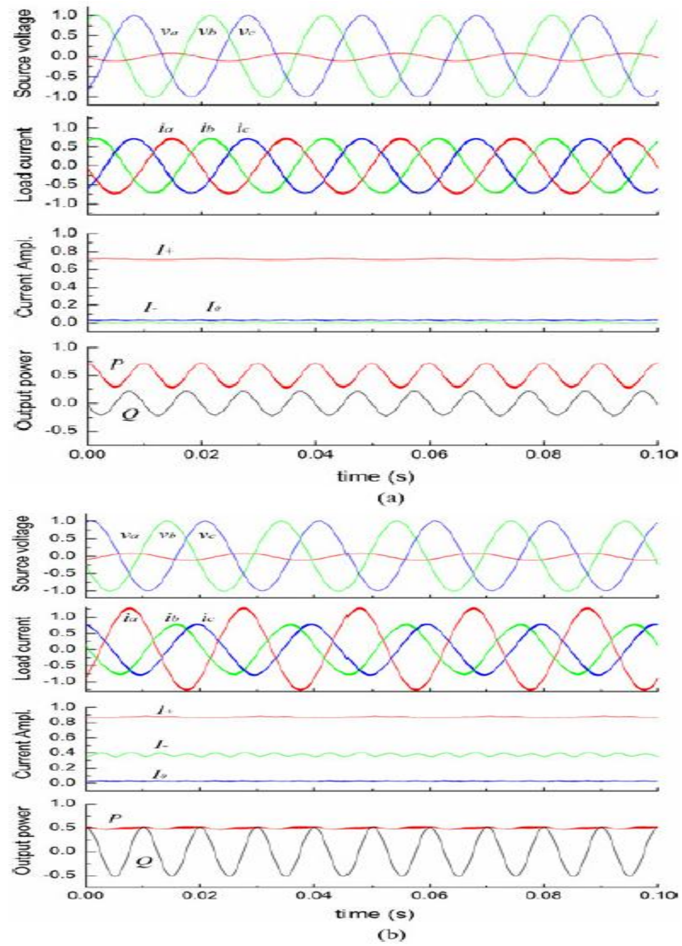
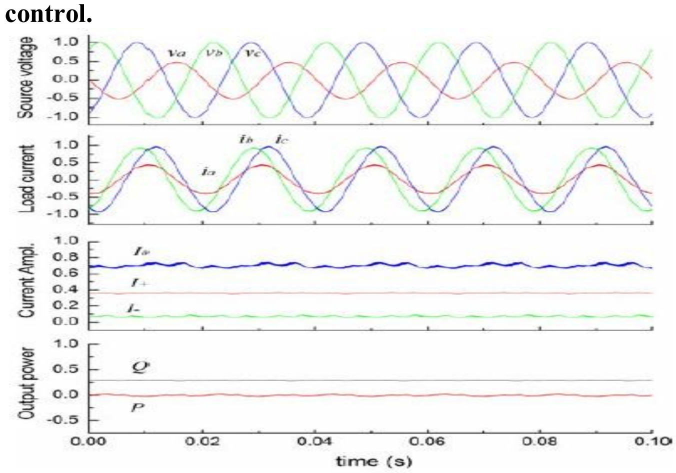


Fig.11. Experimental control performance of the converter in Fig. 15(a) with only three wires (units are nominalized by parameters in Table III, reference given: *P*ref = 0.5 p.u., *Q*ref = 0 p.u., ac source condition: amplitude of the phase voltage *VA* = 0.1 p.u., *VB* =*VC* = 1 p.u.). (a) No negative-sequence current control (b) No P oscillation control.



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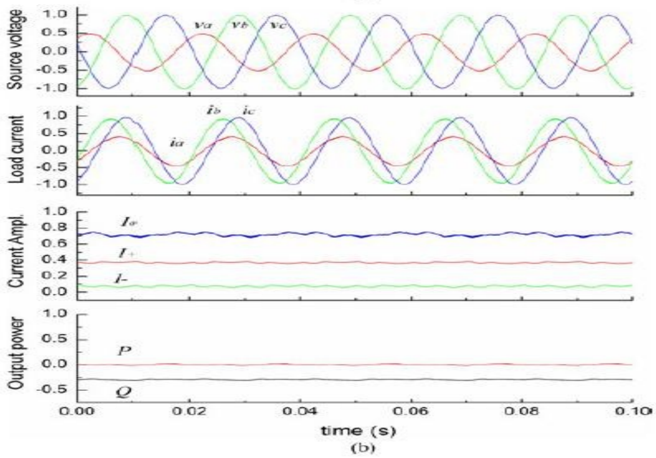

Fig.12. Experimental results of the converter's reactive power capability when using no P & no Q oscillation control in Fig. 17(a). (units are nominalized by parameters in Table III, reference given: *P*ref = 0 p.u., *Q*ref≈• }0.25 p.u. when the maximum load current achieves 1 p.u., the amplitude of the phase voltage *VA* = 0.5 p.u., *VB* =*VC* = 1 p.u.). (a) Deliver inductive reactive power (*Q*+). (b) Deliver capacitive reactive power (*Q*−).

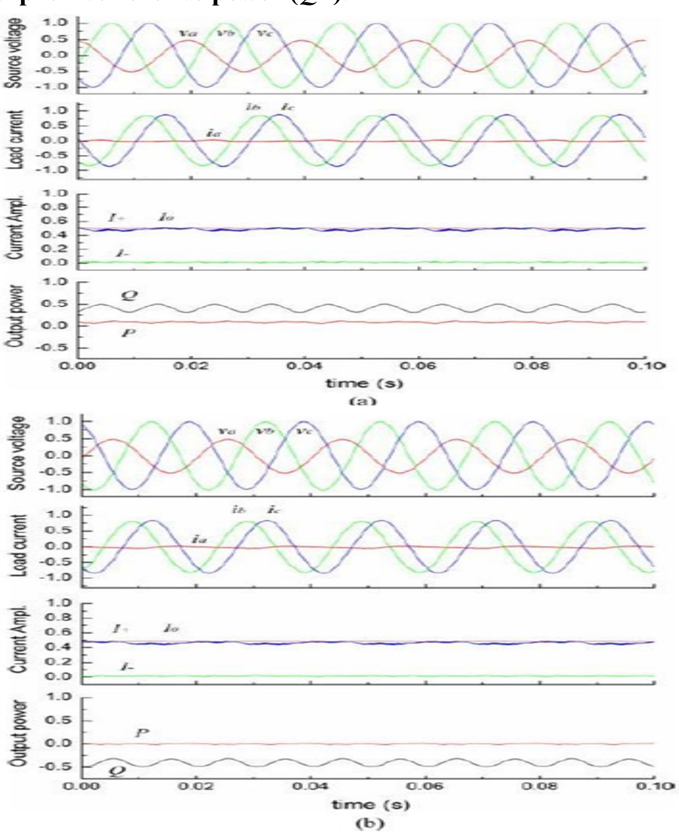

Fig.13. Experimental results of the converter's reactive power capability.

IV.CONCLUSION

In a typical three-phase three-wire converter structure, there are four current control freedoms, and it may be not enough to achieve satisfactory performances under the unbalanced ac source, because either significantly the oscillated power or the overloaded current will be presented. In the three-phase converter structure with the zero sequence current path, there are six current control freedoms. The extra two control freedoms coming from the zero sequence current can be utilized to extend the controllability of the converter and improve the control performance under the unbalanced ac source. By the proposed control strategies, it is possible to totally cancel the oscillation in both the active and the reactive power, or reduced the oscillation amplitude in the reactive power. Meanwhile, the current amplitude of the faulty phase is significantly relieved without further increasing the current amplitude in the normal phases. The advantage and features of the proposed controls can be still maintained under various conditions when delivering the reactive power. The analysis and proposed control methods are well agreed by experimentalvalidations.

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