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CONTROLLABILITY OF A THREE-PHASE CONVERTER WITH AN UNBALANCED AC SOURCE

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Abstract— Three-stage dc–ac power converters experience the ill effects of force wavering and overcurrent issues if there should arise an occurrence of the unbalancedac source voltage that can be brought on by lattice/generator faults.Existing answers for handle these issues are and controlling the positive-and negative-arrangement streams. In this paper, another arrangement of control systems which use the zerosequencecomponents are proposed to upgrade the force controlability under this unfriendly condition. It is reasoned that by introducingproper zero-succession current controls and relating circuit setups, the force converter can empower more adaptable control targets, accomplishing better exhibitions in the deliveredpower and the heap current when experiencing the unequal air conditioning voltage.

I. INTRODUCTION

In numerous imperative applications for force gadgets suchas renewable vitality era, engine drives, power quality,and microgrid, and so forth., the three-stage dc–ac converters are basic parts as the force stream interface of dc and air conditioning electrical frameworks [1], [2]. As appeared in Fig. 1, a dc–ac voltage sourceconverter with a relating channel is normally used to convertthe vitality between the dc transport and the three-stage air conditioning sources,which could be the force matrix, era units, or the electricmachines relying upon the applications and controls [3]–[5].Since the force hardware are getting so generally utilized andbecoming fundamental as a part of the vitality transformation innovation, the disappointments or closing down of these spine dc–ac convertersmay result in significant issues and cost. It is turning into a need in numerous applications that the force converters ought to be reliableto withstand a few shortcomings or aggravations keeping in mind the end goal to ensurecertain accessibility of the vitality supply [6]–[13]. A decent case can be found in the wind power application, where boththe absolute introduced limit and individual limit of the powerconversion framework are moderately high. The sudden disengagement

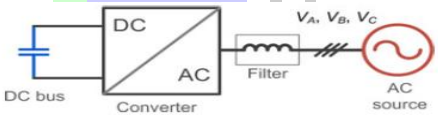

Fig. 1. Typical dc–ac power converter application.

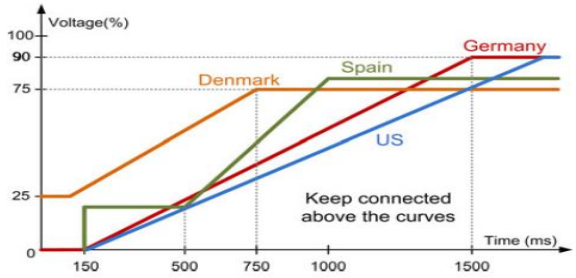

Fig. 2. Grid codes of wind turbines under the grid voltage dip by different countries.

of the power converter may cause significant impacts on the grid stability and also on the high cost for maintenance/repair [1]. 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 some uncritical conditions (e.g., 90% voltage dip), the power converter may need long-time operation [1], [2], [12], [13].

When the ac source shown in Fig. 1 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 [2], [14], [15]. Special control methods which can regulate both the positive- and negative-sequence currents have been introduced to handle these problems [2], [16]–[21]. 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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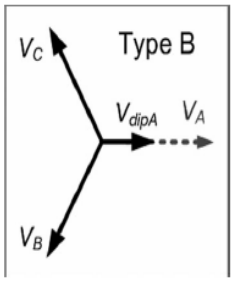

Fig. 3. Phasor diagram definitions for the voltage dips in the ac source Fig. 1. V_A, V_B, and V_C means the voltage of three phases in the ac source.

$$\mathbf{V_S} = \mathbf{V}^+ + \mathbf{V}^- + \mathbf{V}^0 = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V^+ \begin{bmatrix} \sin(\omega t + \varphi^+) \\ \sin(\omega t - 120^\circ + \varphi^+) \\ \sin(\omega t + 120^\circ + \varphi^+) \end{bmatrix} + V^- \begin{bmatrix} \sin(\omega t + \varphi^-) \\ \sin(\omega t + 120^\circ + \varphi^-) \\ \sin(\omega t - 120^\circ + \varphi^-) \end{bmatrix} + V^0 \begin{bmatrix} \sin(\omega t + \varphi^0) \\ \sin(\omega t + \varphi^0) \\ \sin(\omega t + \varphi^0) \end{bmatrix} \quad (1)$$

where V^+, V^-, and V^0 are the voltage amplitude in the positive, negative, and zero sequence, respectively. And φ^+, φ^-, and φ^0 represent the initial phase angles in the positive sequence, negative sequence, and zero sequence, respectively. The predefined voltage dip as indicated in Fig. 3 should contain voltage components in all the three sequences [2], [11].

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 strategies which 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 microgrids, where the unbalanced ac voltage is likely to be presented; therefore, the basic principle and feasibility are mainly focused.

II. LIMITS OF A TYPICAL THREE-WIRE CONVERTER SYSTEM

In order to analyze the controllability and the performance of

the power electronics converter under an adverse ac source, asevere unbalanced ac voltage is first defined as a case study inthis paper. As shown in Fig. 3, the phasordiagram of the threephasedistorted ac voltage are indicated, it is assumed that thetype B fault happens with the significant voltage dip on phaseA of the ac source. Also, there are many other types of voltagefaults which have been defined as type A–F in [22].According to [2] and [19], any distorted three-phase voltagecan be expressed by the sum of components in the positive sequence,negative sequence, and zero sequence. For simplicity ofanalysis, only the components with the fundamentalfrequencyare considered in this paper, however, it is also possible to extendthe analysis to higher order harmonics. The distorted three-phaseac source voltage in Fig. 3 can be represented by

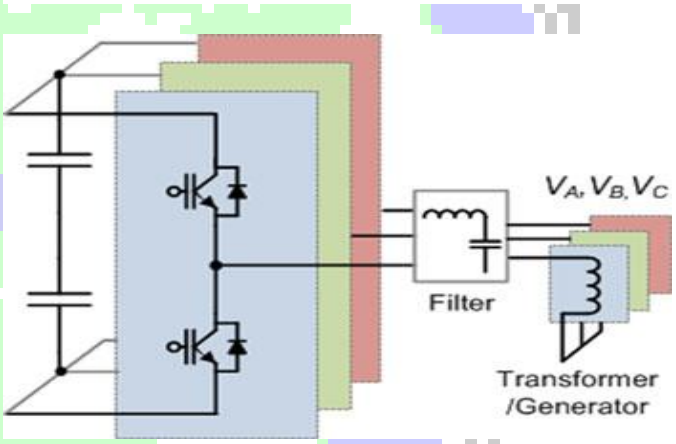

Fig. 4. Typical three-phase three-wire 2L-voltage source converter.

TABLE I
CONVERTER PARAMETERS FOR THE CASE STUDY

Rated output active power P_o	10 MW
DC bus voltage V_{dc}	5.6 kV DC
*Rated primary side voltage V_p	3.3 kV rms
Rated line-to-line grid voltage V_g	20 kV rms
Rated load current I_{load}	1.75 kA rms
Carrier frequency f_c	750 Hz
Filter inductance L_f	1.1 mH (0.25 p.u.)

*Line-to-line voltage in the primary windings of transformer.

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A typically used three-phase three-wire two-level voltage source dc–ac converter is chosen and basically designed, as shown in Fig. 4 and Table I, where the converter configuration and the parameters are indicated, respectively. It is noted that the three-phase ac source is represented here by three windings with a common neutral point, which can be the windings of an electric machine or a transformer.

Because there are only three wires and a common neutral point in the windings of the ac source, the currents flowing in the three phases do not contain zero-sequence components. As a result, the three-phase load current controlled by the converter can be written as

$$\mathbf{I_C} = \mathbf{I}^{+} + \mathbf{I}^{-}. \tag{2}$$

With the voltage of the ac source in (1) and the current controlledby the converter in (2), the instantaneous real power *p*and the imaginary power *q* in $\alpha\beta$ coordinate, as well as the realpower *p*0 in the zero coordinate can be calculated as

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \\ v_\alpha \cdot i_\beta - v_\alpha \cdot i_\beta \\ v_0 \cdot 0 \end{bmatrix} = \begin{bmatrix} \overline{P} + P_{c2} \cdot \cos(2\omega t) + P_{s2} \cdot \sin(2\omega t) \\ \overline{Q} + Q_{c2} \cdot \cos(2\omega t) + Q_{s2} \cdot \sin(2\omega t) \\ 0 \end{bmatrix}. \tag{3}$$

Then, the instantaneous three-phase real power $p_{3\Phi}$ and the imaginary power $q_{3\Phi}$ of the ac source/converter can be written

$$\begin{bmatrix} p_{3\phi} \\ q_{3\phi} \end{bmatrix} = \begin{bmatrix} p + p_0 \\ q \end{bmatrix} = \begin{bmatrix} \overline{P} \\ \overline{Q} \end{bmatrix} + \begin{bmatrix} P_{c2} \\ Q_{c2} \end{bmatrix} \cos(2\omega t) + \begin{bmatrix} P_{s2} \\ Q_{s2} \end{bmatrix} \sin(2\omega t) \tag{4}$$

where $\overline{P}$ and $\overline{Q}$ are the average parts of the real and imaginary power, P_{c2}, P_{s2} and Q_{c2}, Q_{s2} are the oscillation parts, which can be calculated as

$$\begin{aligned} \overline{P} &= \frac{3}{2}\left(v_d^+ \cdot i_d^+ + v_q^+ \cdot i_q^+ + v_d^- \cdot i_d^- + v_q^- \cdot i_q^-\right) \\ P_{c2} &= \frac{3}{2}\left(v_d^- \cdot i_d^+ + v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^+ \cdot i_q^-\right) \\ P_{s2} &= \frac{3}{2}\left(v_q^- \cdot i_d^+ - v_d^- \cdot i_q^+ - v_q^+ \cdot i_d^- + v_d^+ \cdot i_q^-\right) \end{aligned} \tag{5}$$

$$\begin{aligned} \overline{Q} &= \frac{3}{2}\left(v_q^+ \cdot i_d^+ - v_d^+ \cdot i_q^+ + v_q^- \cdot i_d^- - v_d^- \cdot i_q^-\right) \\ Q_{c2} &= \frac{3}{2}\left(v_q^- \cdot i_d^+ - v_d^- \cdot i_q^+ + v_q^+ \cdot i_d^- - v_d^+ \cdot i_q^-\right) \\ Q_{s2} &= \frac{3}{2}\left(-v_d^- \cdot i_d^+ - v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^+ \cdot i_q^-\right) \end{aligned} \tag{6}$$

where a positive *dq* synchronous reference frame and a negative *dq* synchronous reference frame are applied, respectively, to the positive- and negative-sequence voltage/current. Each of the components on the corresponding positive- and negative-*dq* axis can be written as

$$\begin{aligned} v_d^+ &= V^+ \cos(\varphi^+) \\ v_q^+ &= V^+ \sin(\varphi^+) \\ v_d^- &= V^- \cos(\varphi^-) \\ v_q^- &= -V^- \sin(\varphi^-) \end{aligned} \tag{7}$$

$$\begin{aligned} i_d^+ &= I^+ \cos(\delta^+) \\ i_q^+ &= I^+ \sin(\delta^+) \\ i_d^- &= I^- \cos(\delta^-) \\ i_q^- &= -I^- \sin(\delta^-). \end{aligned} \tag{8}$$

Then, (5) and (6) can be formulated as a matrix relation as

$$\begin{bmatrix} \overline{P} \\ \overline{Q} \\ P_{s2} \\ P_{c2} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d^+ & v_q^+ & v_d^- & v_q^- \\ v_q^+ & -v_d^+ & v_q^- & -v_d^- \\ v_q^- & -v_d^- & -v_q^+ & v_d^+ \\ v_d^- & v_q^- & v_d^+ & v_q^+ \end{bmatrix} \begin{bmatrix} i_d^+ \\ i_q^+ \\ i_d^- \\ i_q^- \end{bmatrix}. \tag{9}$$

It can be seen from (9) that if the ac source voltage is decided, then the converter has four controllable freedoms (i_d^+, i_q^+, i_d^-, and i_q^-) to regulate the current flowing in the ac source. That

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delivered by the converter are two basic requirements for a given application, then, two control targets have to be first settled as

$$\overline{P_{3\phi}} = \overline{P} = P_{\text{ref}}$$
$$\overline{Q_{3\phi}} = \overline{Q} = Q_{\text{ref}}. \quad (10)$$

It is noted that different applications may have different requirements for the control of the average power, e.g., in the power production application, the active power reference P_{ref} injected to the grid is normally set as positive, meanwhile the large amount of the reactive power Q_{ref} may be needed in order to help to support the grid voltage [12], [13]. As for the electric machine application, the P_{ref} is set as negative for the generator mode and positive for the motor mode, there may be no or just a few reactive power Q_{ref} requirements for magnetizing of the electric machine. While in most power quality applications, e.g., STACOM, P_{ref} is normally set to be very small to provide the converter loss, and a large amount of Q_{ref} is normally required.

Consequently, for the three-phase three-wire converter system, there are only two more current control freedoms left to achieve another two control targets besides (10). These two adding control targets may be utilized to further improve the performances of the converter under the unbalanced ac source, which have been generally investigated in [2] and [16]–[18]. However, this paper focuses more on the evaluation of control limits and the control possibilities under the whole voltage dipping range. In the following, two of the most mentioned control methods achieved by three-wire converter structure are investigated under the unbalanced ac source.

A. *Elimination of the Negative-Sequence Current*

In most of the grid integration applications, there are strict grid codes to regulate the behavior of the grid connected converters. The negative-sequence current which always results in the unbalanced load current may be unacceptable from the point view of a TSO [13]. Therefore, extra two control targets which aim to eliminate the negative-sequence current can be added as

$$i_d^- = 0$$
$$i_q^- = 0. \quad (11)$$

Translating the control targets in (10) and (11), all the controllable current components can be calculated as

$$i_d^+ = \frac{2}{3} \cdot \frac{v_d^+ \cdot P_{\text{ref}} + v_q^+ \cdot Q_{\text{ref}}}{(v_d^+)^2 - (v_d^-)^2}$$
$$i_q^+ = \frac{2}{3} \cdot \frac{P_{\text{ref}}}{v_d^+} - \frac{v_d^+}{v_q^+} \cdot i_d^+ \quad (12)$$
$$i_d^- = 0$$
$$i_q^- = 0. \quad (13)$$

When applying the current references in (12) and (13), the ac source voltage, load current, sequence current amplitude, and the instantaneous power delivered by the converter are shown in Fig. 5. The simulation is based on the parameters predefined in Fig. 4 and Table I. The ac source voltage is set with V_A

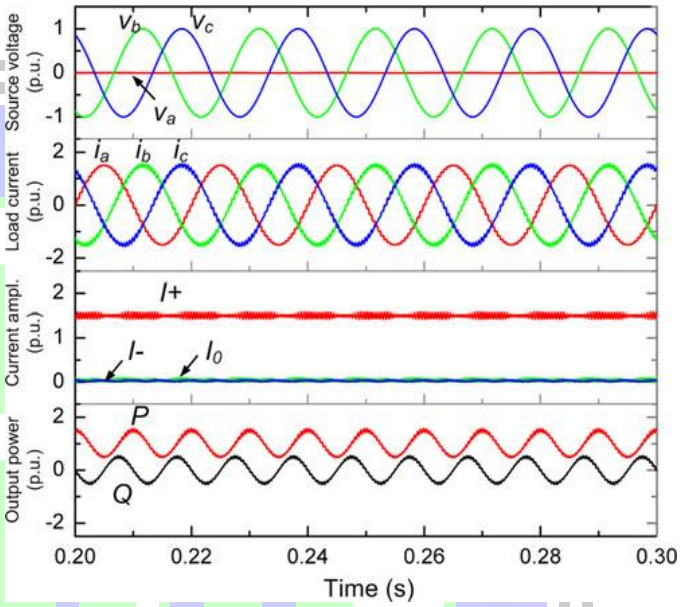

Fig. 5. Simulation of the converter with no negative-sequence current control (three-phase three-wire converter, $P_{\text{ref}} = 1$ p.u., $Q_{\text{ref}} = 0$ p.u., $I_d - = 0$ p.u., $I_q - = 0$ p.u., $V_A = 0$ p.u., $I+$, $I-$, and I_0 means the amplitude of the current in the positive, negative, and zero sequences, respectively).

dipping to zero. The average active power reference *P*ref for theconverter is set as 1 p.u. and the reactive power reference *Q*refis set as 0.It can be seen from Fig. 5 that with the extra control targetsin (11), there is no zero-sequence nor negative-sequence components

in the load current, i.e., the currents among the three

phases of converter are symmetrical under the given unbalancedac source condition.

The current amplitude in different sequences and the deliveredactive/reactive power with relation to the voltage amplitudeof the dipping phase *VA* are shown in Fig. 6(a) and (b), respectively.It is noted that only the positive-sequence current is generated

by the converter, and there is up to • *J*0.5 p.u. oscillationsboth in the active and reactive power when *VA* dips to zero.

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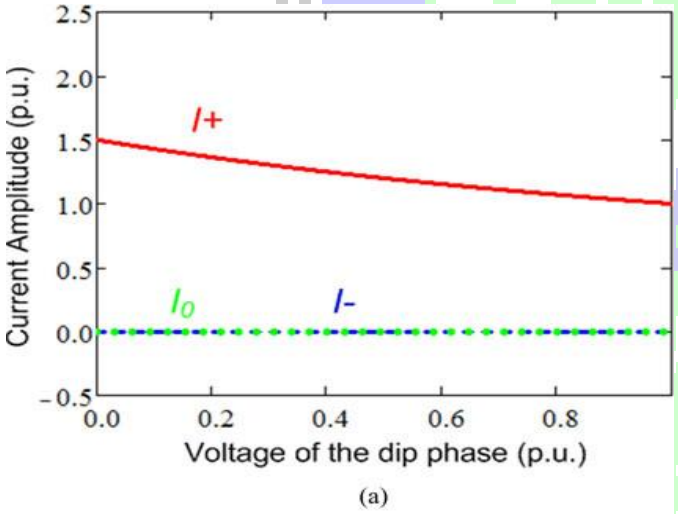
The significant fluctuation of the active power would result inthe voltage fluctuation of the dc bus [16]–[19], compromisingnot only the THD but also the reliability performances of theconverter according to [23].

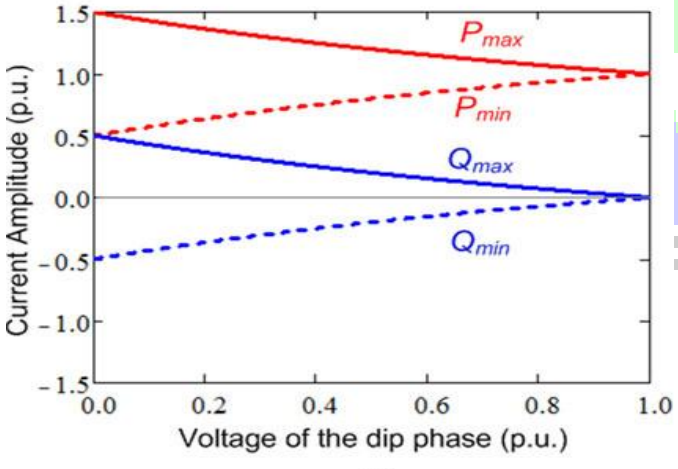
B. Elimination of the Active Power Oscillation

In order to overcome the disadvantage of the active power oscillation under the unbalanced ac source, another two extra control targets which aim to cancel the oscillation items in the instantaneous active power can be used to replace (11) as

$$P_{3\phi c2} = P_{c2} = 0$$
$$P_{3\phi s2} = P_{s2} = 0. \tag{14}$$



(a)



(b)

Fig. 6. Profile of converter control with no negative-sequence current (three-phase three-wire converter, $P_{\text{ref}} = 1$ p.u., $Q_{\text{ref}} = 0$ p.u., $I_d- = 0$ p.u., $I_q- = 0$ p.u.). (a) Sequence current amplitude versus V_A ($I+$, $I-$, and I_0 means the amplitude of the current in the positive, negative, and zero sequences, respectively). (b) P and Q oscillation range versus V_A.

Then, according to (9), each of the current components can be calculated as

$$\begin{bmatrix} i_d^+ \\ i_q^+ \\ i_d^- \\ i_q^- \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_d^+ & v_q^+ & v_d^- & v_q^- \\ v_q^+ & -v_d^+ & v_q^- & -v_d^- \\ v_q^- & -v_d^- & -v_q^+ & v_d^+ \\ v_d^- & v_q^- & v_d^+ & v_q^+ \end{bmatrix}^{-1} \begin{bmatrix} P_{\text{ref}} \\ 0 \\ 0 \\ 0 \end{bmatrix}$$
$$= \frac{2P_{\text{ref}}}{3M} \begin{bmatrix} v_d^+ \\ v_q^+ \\ -v_d^- \\ -v_q^- \end{bmatrix} \tag{15}$$

where

$$M = (v_d^+)^2 + (v_q^+)^2 - (v_d^-)^2 - (v_q^-)^2. \tag{16}$$

When applying the current references in (15), the corresponding source voltage, load current, sequence current, and the instantaneous power delivered by the converter are shown in Fig. 7.

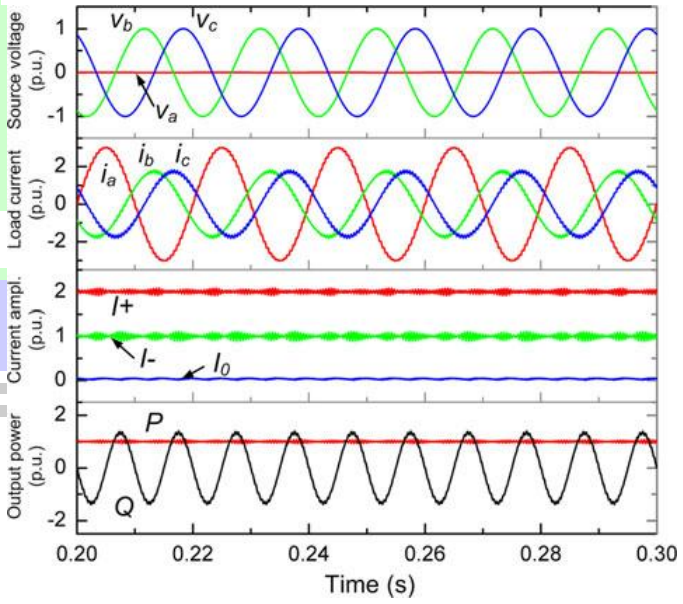


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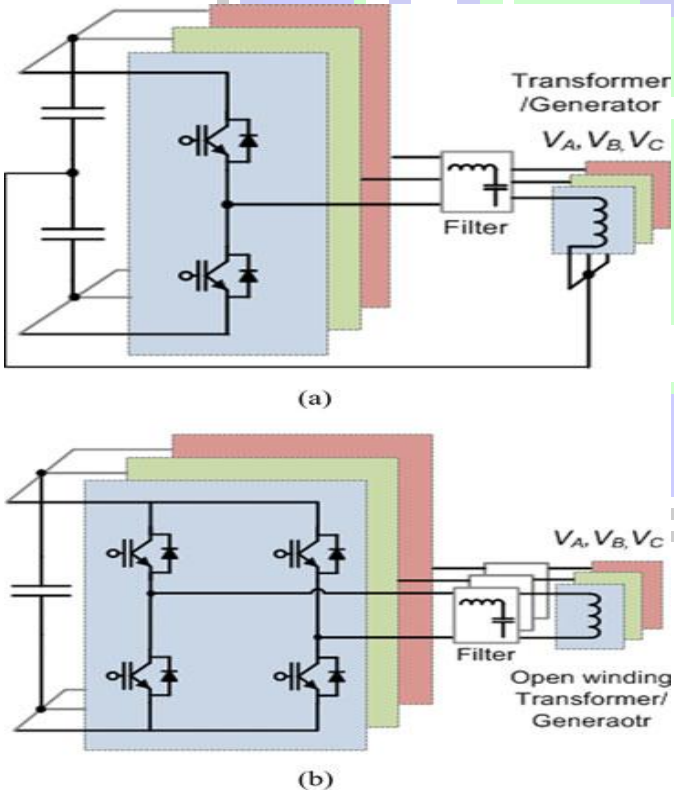
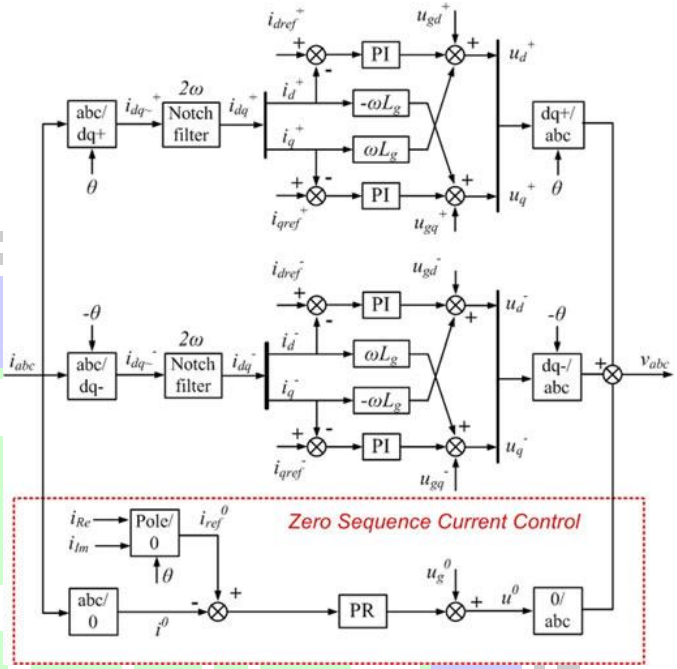
Fig. 7. Simulation of the converter control with no active power oscillation (three-phase three-wire converter, $P_{\text{ref}} = 1$ p.u., $Q_{\text{ref}} = 0$ p.u., $P_{s2} = 0$ p.u., $P_{c2} = 0$ p.u., $V_A = 0$ p.u. $I+$, $I-$, and I_0 means the amplitude of the current in the positive, negative, and zero sequences, respectively.

III. CONVERTER SYSTEM WITH THE ZERO-SEQUENCECURRENT PATH

As can be concluded, in the typical three-phase three-wireconverter structure, four control freedoms for the load currentseem to be not enough to achieve satisfactory performancesunder the unbalanced ac source. (No matter what combinationsof control targets are used, either significant power oscillationor overloaded/distorted current will be presented.) Therefore,more current control freedoms are needed in order to improve thecontrol performance under the unbalanced ac source conditions.Another series of the converter structure are shown as indicatedas the four-wire system in Fig. 9(a) and the six-wire systemin Fig. 9(b). Compared to the three-wire converter structure, these types of converters introduce the zero-sequence currentpath [24]–[26], which may enable extra current control freedomsto achieve better power control performances. It is notedthat in the grid-connected application, the zero-sequence currentis not injected intothegridb





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 [27]–[29]

$$\mathbf{I}_C = \mathbf{I}^+ + \mathbf{I}^- + \mathbf{I}^0. \tag{20}$$

By operating the voltage of the ac source (1) and the current controlled by the power converter (20), the instantaneous generated real power p, the imaginary power q in the $\alpha\beta$ coordinate, and the real power p_0 in the zero coordinate can be calculated as

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \\ v_\alpha \cdot i_\beta - v_\alpha \cdot i_\beta \\ v_0 \cdot i_0 \end{bmatrix} = \begin{bmatrix} \overline{P} + P_{c2} \cdot \cos(2\omega t) + P_{s2} \cdot \sin(2\omega t) \\ \overline{Q} + Q_{c2} \cdot \cos(2\omega t) + Q_{s2} \cdot \sin(2\omega t) \\ \overline{P_0} + P_{0c2} \cdot \cos(2\omega t) + P_{0s2} \cdot \sin(2\omega t) \end{bmatrix}. \tag{21}$$

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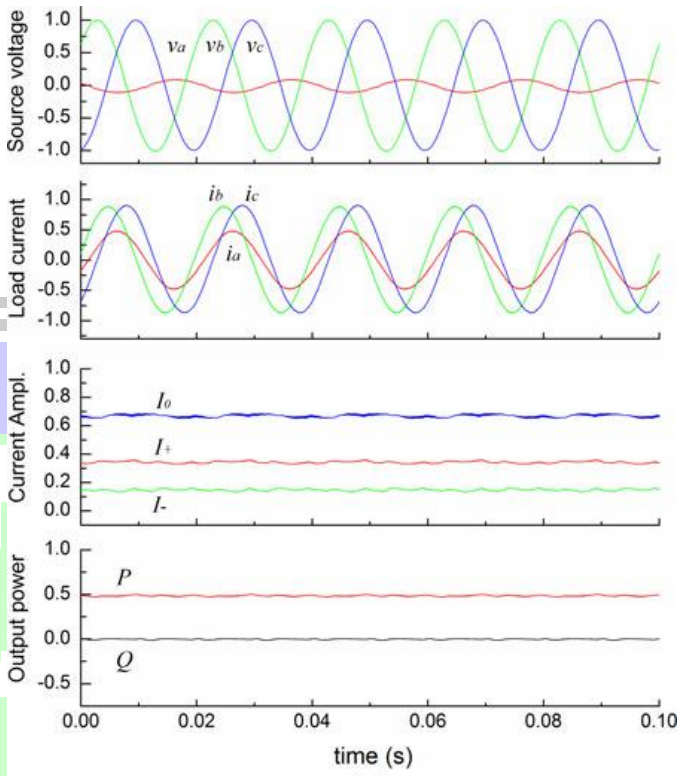
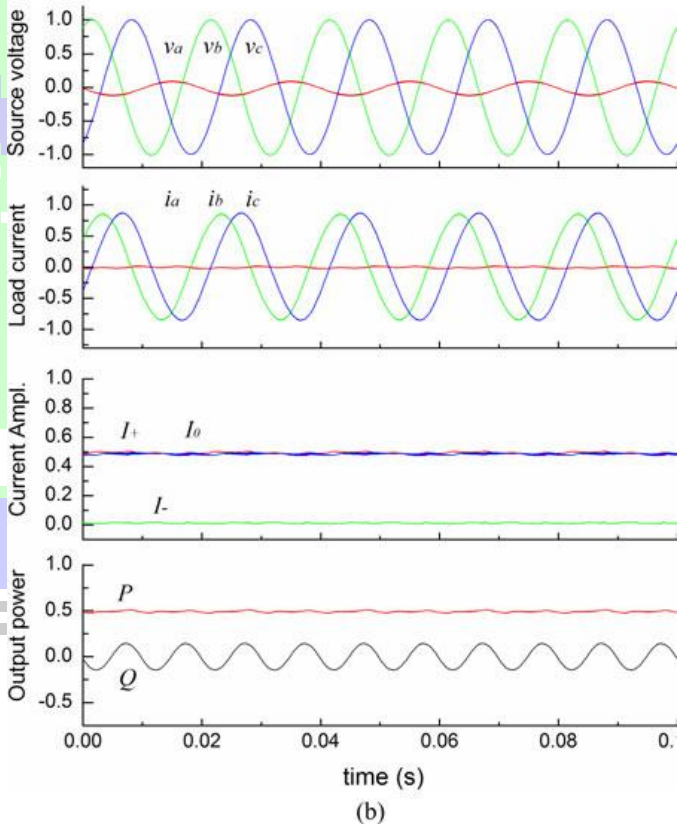
$$\begin{bmatrix} p_{3\phi} \\ q_{3\phi} \end{bmatrix} = \begin{bmatrix} p + p_0 \\ q \end{bmatrix} = \begin{bmatrix} \overline{P} + \overline{P_0} \\ \overline{Q} \end{bmatrix} + \begin{bmatrix} P_{c2} + P_{0c2} \\ Q_{c2} \end{bmatrix} \cos(2\omega t) + \begin{bmatrix} P_{s2} + P_{0s2} \\ Q_{s2} \end{bmatrix} \sin(2\omega t). \quad (22)$$

It is noted that the voltage and the current in zero sequence only contribute to the real power $p_{3\Phi}$ of the converter. Each part of (22) can be calculated as

$$\begin{aligned} \overline{P} &= \frac{3}{2}(v_d^+ \cdot i_d^+ + v_q^+ \cdot i_q^+ + v_d^- \cdot i_d^- + v_q^- \cdot i_q^-) \\ P_{c2} &= \frac{3}{2}(v_d^- \cdot i_d^+ + v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^+ \cdot i_q^-) \\ P_{s2} &= \frac{3}{2}(v_q^- \cdot i_d^+ - v_d^- \cdot i_q^+ - v_q^+ \cdot i_d^- + v_d^+ \cdot i_q^-) \quad (23) \\ \overline{Q} &= \frac{3}{2}(v_q^+ \cdot i_d^+ - v_d^+ \cdot i_q^+ + v_q^- \cdot i_d^- - v_d^- \cdot i_q^-) \\ Q_{c2} &= \frac{3}{2}(v_q^- \cdot i_d^+ - v_d^- \cdot i_q^+ + v_q^+ \cdot i_d^- - v_d^+ \cdot i_q^-) \\ Q_{s2} &= \frac{3}{2}(-v_d^- \cdot i_d^+ - v_q^- \cdot i_q^+ + v_d^+ \cdot i_d^- + v_q^+ \cdot i_q^-) \quad (24) \\ \overline{P_0} &= \frac{3}{2}(v_{\mathrm{Re}}^0 \cdot i_{\mathrm{Re}}^0 + v_{\mathrm{Im}}^0 \cdot i_{\mathrm{Im}}^0) \\ P_{0c2} &= \frac{3}{2}(v_{\mathrm{Re}}^0 \cdot i_{\mathrm{Re}}^0 - v_{\mathrm{Im}}^0 \cdot i_{\mathrm{Im}}^0) \\ P_{0s2} &= \frac{3}{2}(-v_{\mathrm{Im}}^0 \cdot i_{\mathrm{Re}}^0 - v_{\mathrm{Re}}^0 \cdot i_{\mathrm{Im}}^0). \quad (25) \end{aligned}$$



(a)



(b)

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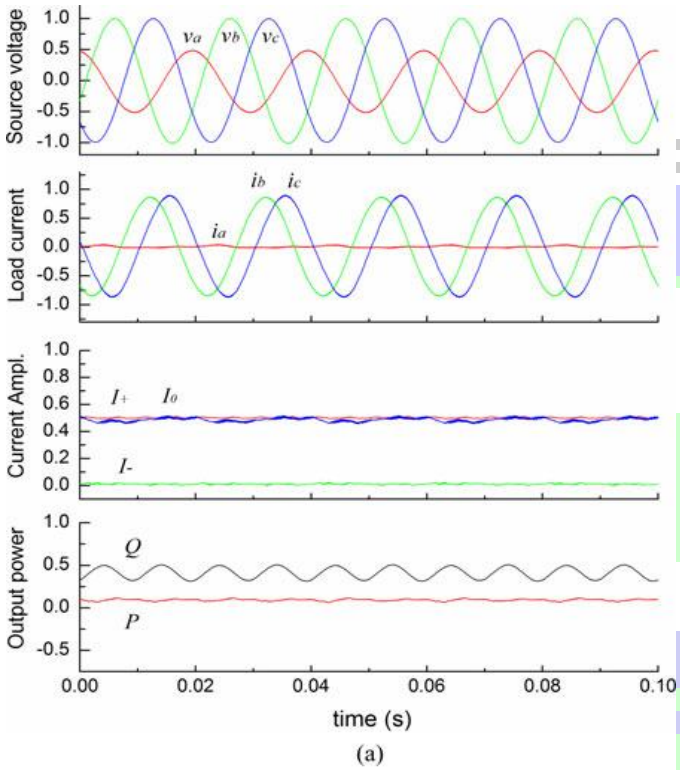
V. CONCLUSION

In a typical three-phase three-wire converter structure, thereare four current control freedoms, and it may be not enough



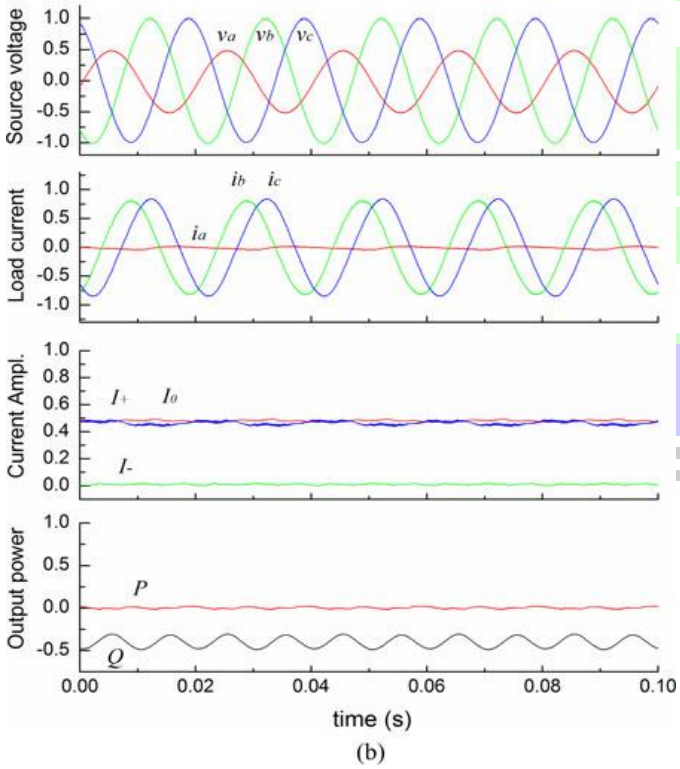


Fig. 19. Experimental results of the converter's reactive power capabilitywhen using no negative-sequence current and no P oscillation control shown inFig. 17(b). (units are nominalized by parameters in Table III, reference given:*P*ref = 0 p.u., *Q*ref≈ • }0.5 p.u. when the maximum load current achieves 1 p.u.,the amplitude of the phase voltage *VA* = 0.5 p.u., *VB* =*VC* = 1 p.u.). (a) Deliverinductive reactive power (*Q*+). (b) Deliver capacitive reactive power (*Q*−).to achieve satisfactory performances under the unbalanced acsource, because either significantly the oscillated power or theoverloaded current will be presented.In the three-phase converter structure with the zero sequencecurrent path, there are six current control freedoms. The extratwo control freedoms coming from the zero sequence current canbe utilized to extend the controllability of the converter and improvethe control performance under the unbalanced ac source.By the proposed control strategies, it is possible to totally cancelthe oscillation in both the active and the reactive power, orreduced the oscillation amplitude in the reactive power. Meanwhile,the current amplitude of the faulty phase is significantlyrelieved without further increasing the current amplitude in thenormal phases. The advantage and features of the proposedcontrols can be still maintained under various conditions whendelivering the reactive power. The analysis and proposed controlmethods are well agreed by experimental validations.

REFERENCES

[1] F. Blaabjerg, M. Liserre, and K. Ma, "Power electronics converters fowind turbine systems," *IEEE Trans. Ind. Appl.*, vol. 48, no. 2, pp. 708–719, Mar./Apr. 2012.

[2] R. Teodorescu, M. Liserre, and P. Rodriguez, *Grid Converters for Photovoltaicand Wind Power Systems*. New York, NY, USA: Wiley-IEEE,2011.

[3] J. Rocabert, G. M. S. Azevedo, A. Luna, J. M. Guerrero, J. I. Candela, andP. Rodriguez, "Intelligent connection agent for three-phase grid-connectedmicrogrids," *IEEE Trans. Power Electron*, vol. 26, no. 10, pp. 2993–3005,

Oct. 2011.

[4] J. W. Kolar and T. Friedli, "The essence of three-phase PFC rectifiersystems—Part I," *IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 176–198, Jan. 2013.

[5] J. Hu, L. Shang, Y. He, and Z. Z. Zhu, "Direct active and reactive powerregulation of grid-connected dc/ac converters using sliding mode controlpp. 210–222, Jan.2011.

[6] C. Wessels, F. Gebhardt, and F. W. Fuchs, "Fault ride-through of a DFIGwind turbine using a dynamic voltage restorer during symmetrical andasymmetrical grid faults," *IEEE Trans. Power Electron.*,vol. 26, no. 3,pp. 807–815, Mar. 2011.

[7] F. Aghili, "Fault-tolerant torque control of BLDC motors," *IEEE Trans.Power Electron.*, vol. 26, no. 2, pp. 355–363, Feb. 2011.

[8] Y. Xiangwu, G. Venkataramanan, W. Yang, D. Qing, and Z. Bo, "Gridfaulttolerant operation of a DFIG wind turbine generator using a passiveresistance network," *IEEE Trans. Power Electron.*, vol. 26, no. 10,pp. 2896–2905, Oct. 2011.

[9] B. A. Welchko, T. A. Lipo, T. M. Jahns, and S. E. Schulz, "Fault tolerantthree-phase AC motor drive topologies: A comparison of features, cost,and limitations," *IEEE Trans. Power Electron.*, vol. 19, no. 4, pp. 1108–1116, Jul. 2004.

[10] F. Blaabjerg, K. Ma, and D. Zhou, "Power electronics and reliability inrenewable energy systems," in *Proc. IEEE Int. Symp. Ind. Electron.*, May2012, pp. 19–30.

[11] Y. Song and B.Wang, "Survey on reliability of power electronic systems,"*IEEE Trans. Power Electron.*, vol. 28, no. 1, pp. 591–604, Jan. 2013.

[12] M. Altin, O. Goksu, R. Teodorescu, P. Rodriguez, B. Bak-Jensen, andL. Helle, "Overview of recent grid codes for wind power integration," in*Proc. 12th Int. Conf. Optim. Elect.Electron. Equip.*, 2010, pp. 1152–1160.

[13] *Grid Code. High and Extra High Voltage*, E.ON-netz, Bayreuth, Germany,Apr. 2006.reference frame grid synchronizationsystem for three-phase grid-connected power converters underadverse grid conditions," *IEEE Trans. Power Electron.*, vol. 27, no. 1,pp. 99–112, Jan. 2012.

[15] A. J. Roscoe, S. J. Finney, and G. M. Burt, "Tradeoffs between AC powerquality and DC bus ripple for 3-phase 3-wire inverter-connected deviceswithin microgrids," *IEEE Trans. Power Electron.*, vol. 26, no. 3, pp. 674–688, Mar. 2011.

[16] C. H. Ng, Li Ran, and J. Bumby, "Unbalanced-grid-fault ride-throughcontrol for a wind turbine inverter," *IEEE Trans. Ind. Appl.*, vol. 44, no. 3,. 845–856, May/Jun. 2008.

[17] P. Rodriguez, A. V. Timbus, R. Teodorescu, M. Liserre, and F. Blaabjerg,"Flexible active power control of distributed power generation systemsduring grid faults," *IEEE Trans. Ind. Electron.*, vol. 54, no. 5, pp. 2583–2592, Oct. 2007.

[18] H. Song and K. Nam, "Dual current control scheme for PWM converterunder unbalanced input voltage conditions," *IEEE Trans. Ind. Electron.*,vol. 46, no. 5, pp. 953–959, Oct. 1999.

[19] H. Akagi, Y. Kanazawa, and A. Nabae, "Instantaneous reactive powercompensators comprising switching devices without energy storage components,"*IEEE Trans. Ind. Appl.*, vol. IA-20, no. 3, pp. 625–630, May1984.

[20] J. Miret, M. Castilla, A. Camacho, L. Vicu˜na, and J. Matas, "Controlscheme for photovoltaic three-phase inverters to minimize peak currentsduring unbalanced grid-voltage sags," *IEEE Trans. Power Electron.*,vol. 27, no. 10, pp. 4262–4271, Oct. 2012.

[21] F. Gonz´alez-Esp´ın, G. Garcer´a, I. Patrao, and E. Figueres, "An adaptivecontrol system for three-phase photovoltaic inverters working in a pollutedand variable frequency electric grid," *IEEE Trans. Power Electron.*,vol. 27, no. 10, pp. 4248–4261, Oct. 2012.

[22] G. Saccomando, J. Svensson, and A. Sannino, "Improving voltage disturbancerejection for variable-speed wind turbines," *IEEE Trans. EnergyConvers.*, vol. 17, no. 3, pp. 422–428, Sep. 2002.

[23] N. Kaminski and A. Kopta, "Failure rates of HiPakModules due to cosmicrays," ABB Switzerland Ltd., Zurich, Switzerland, ABB Appl. note 5SYA2042-04, Mar. 2011.