An Artificial Neural Network Based Power Converter for the Control of Positive and Negative Sequence Currents in Unbalance Ac Source

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Abstract:

The switching strategy for a AC/DC or DC/AC converter by Neural Networks is proposed, with this application the power controllability can be easily controlled by selecting proper positive and negative sequence currents. With the advert of utilising zero sequence components the enhancement of power control by quick switching response, easy structure and better regulated output. This proposed system is designed to avoid over current problems in unbalanced ac sources caused by generator/grid faults. Additionally it avoids the required extra power loop or hysteresis controller which simplifies the control algorithm. The validity of the developed control system is investigated via computer simulations using MATLAB/Simulink.

I.INTRODUCTION

In many important applications for power electronics such as renewable energy generation, motor drives, power quality, and microgrid, etc., the three-phase dc–ac converters are critical components as the power flow interface of dc and ac electrical systems. As shown in Fig. 1, 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.
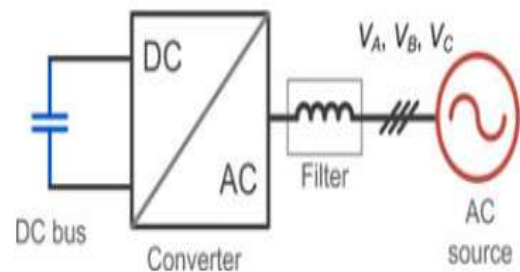

Fig. 1.Typical dc–ac power converter application.

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 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.

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. 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. 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.
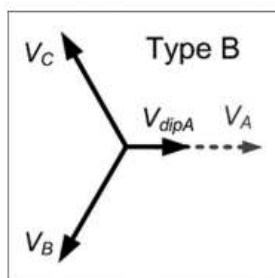

Fig. 2. Phasor diagram definitions for the voltage dips in the ac source of Fig. 1. *VA , VB* , and *VC* means the voltage of three phases in the ac source.

Besides the grid integration, the proposed control methods have the potential be applied under other applications like the motor/generator connections or microgrid, where the unbalanced ac voltage is likely to be presented; therefore, the basic principle and feasibility are mainly focused.

II.MODELING OF PROPOSED THEORY

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, severe unbalanced ac voltage is first defined as a case study in this paper. As shown in Fig. 3, the phasor diagram of the three phase distorted ac voltage are indicated, it is assumed that the type B fault happens with the significant voltage dip on phase A of the ac source. Also, there are many other types of voltage faults which have been defined as type A–F. According to [2] , any distorted three-phase voltage can be expressed by the sum of components in the positive sequence, negative sequence, and zero sequence. For simplicity of analysis, only the components with the fundamental frequency are considered in this paper, however, it is also possible to extend the analysis to higher order harmonics. The distorted three-phase ac source voltage in Fig. 4 can be represented by

$$\mathbf{V_S} = \mathbf{V^+} + \mathbf{V^-} + \mathbf{V^0}$$

$$= \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = V^+ \begin{bmatrix} \sin(\omega t + \varphi^+) \\ \sin(\omega t - 120° + \varphi^+) \\ \sin(\omega t + 120° + \varphi^+) \end{bmatrix}$$

$$+ V^- \begin{bmatrix} \sin(\omega t + \varphi^-) \\ \sin(\omega t + 120° + \varphi^-) \\ \sin(\omega t - 120° + \varphi^-) \end{bmatrix} + V^0 \begin{bmatrix} \sin(\omega t + \varphi \\ \sin(\omega t + \varphi \\ \sin(\omega t + \varphi \end{bmatrix}$$

(1)

Where $V+, V-$, and $V0$ are the voltage amplitude in the positive, negative, and zero sequence, respectively. And $\phi+$, $\phi-$, and $\phi 0$ 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] 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.
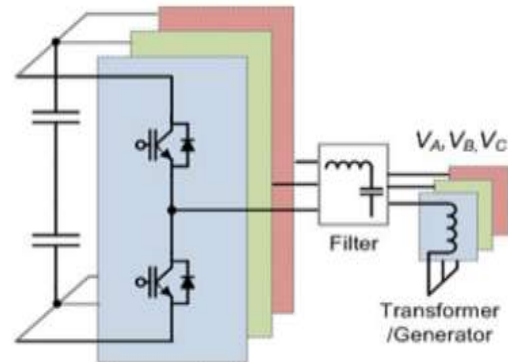

Fig.3. Typical three-phase three-wire 2L-voltage source converter

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.

As a result, the three-phase load current controlled by the converter can be written as

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

(2)

With the voltage of the ac source in (1) and the current controlled by the converter in (2), the instantaneous real power p and the imaginary power q in $\alpha\beta$ coordinate, as well as the real power $p0$ in the zero coordinate can be calculated as

$$\begin{bmatrix} p \\ q \\ p_0 \end{bmatrix} = \begin{bmatrix} v_\alpha \cdot i_\alpha + v_\beta \cdot i_\beta \\ v_\alpha \cdot i_\beta - v_\alpha \cdot i_\beta \\ v_0 \cdot 0 \end{bmatrix}$$

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

$$(3)$$

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

$$\begin{bmatrix} p_{3\phi} \\ q_{3\phi} \end{bmatrix} = \begin{bmatrix} p + p_0 \\ q \end{bmatrix}$$

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

$$(4)$$

Where P and Q are the average parts of the real and imaginary power, $Pc2, Ps2$ and $Qc2, Qs2$ are the oscillation parts, which can be calculated as

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

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

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

$$(5)$$

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

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

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

$$(6)$$

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

$$v_d^+ = V^+ \cos(\varphi^+)$$
$$v_q^+ = V^+ \sin(\varphi^+)$$
$$v_d^- = V^- \cos(\varphi^-)$$
$$v_q^- = -V^- \sin(\varphi^-)$$

$$(7)$$

$$i_d^+ = I^+ \cos(\delta^+)$$
$$i_q^+ = I^+ \sin(\delta^+)$$
$$i_d^- = I^- \cos(\delta^-)$$
$$i_q^- = -I^- \sin(\delta^-).$$

$$(8)$$

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

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

$$(9)$$

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 also means: four control targets/functions can be established. Normally, the three-phase average active and reactive powers delivered by the converter are two basic requirements for a given application, then, two control targets have to be first settled as

$$\overline{P_{3\phi}} = \overline{P} = P_{\text{ref}}$$
$$\overline{Q_{3\phi}} = \overline{Q} = Q_{\text{ref}}.$$

$$(10)$$

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

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reference Pref injected to the grid is normally set as positive, meanwhile the large amount of the reactive power Qref may be needed in order to help to support the grid voltage [12], [13]. As for the electric machine application, the Pref is set as negative for the generator mode and positive for the motor mode, there may be no or just a few reactive power Qref requirements for magnetizing of the electric machine. While in most power quality applications, e.g., STACOM, Pref is normally set to be very small to provide the converter loss, and a large amount of Qref 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

$$i_d^- = 0$$
$$i_q^- = 0. \tag{11}$$

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

$$i_d^+ = \frac{2}{3} \cdot \frac{v_d^+ \cdot P_{\text{ref}} + v_q^+ \cdot Q_{\text{ref}}}{(v_d^+)^2 - (v_d^-)^2}$$

$$i_q^+ = \frac{2}{3} \cdot \frac{P_{\text{ref}}}{v_d^+} - \frac{v_d^+}{v_q^+} \cdot i_d^+ \tag{12}$$

$$i_d^- = 0$$
$$i_q^- = 0. \tag{13}$$

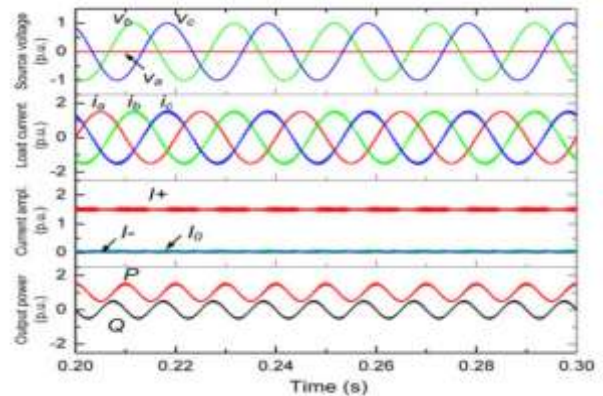Fig. 5. Simulation of the converter with no negative-sequence current control(three-phase three-wire converter, Pref = 1 p.u., Qref = 0 p.u., $Id- = 0$ p.u.,$Iq- = 0$ p.u., $VA = 0$ p.u., $I+$, $I-$, and $I0$ means the amplitude of the curren tin the positive, negative, and zero sequences, respectively).

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

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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 *VA*. Fig. 5. Simulation of the converter with no negative-sequence current control(three-phase three-wire converter, *P*ref = 1 p.u., *Q*ref = 0 p.u., $Id- = 0$ p.u.,

$Iq- = 0$ p.u., *VA* = 0 p.u., *I*+, *I*−, and *I*0 means the amplitude of the currentin the positive, negative, and zero sequences, respectively).

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

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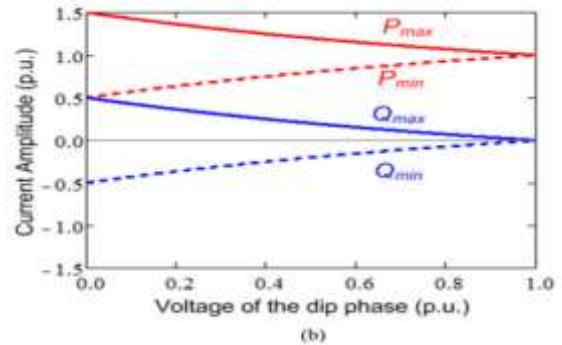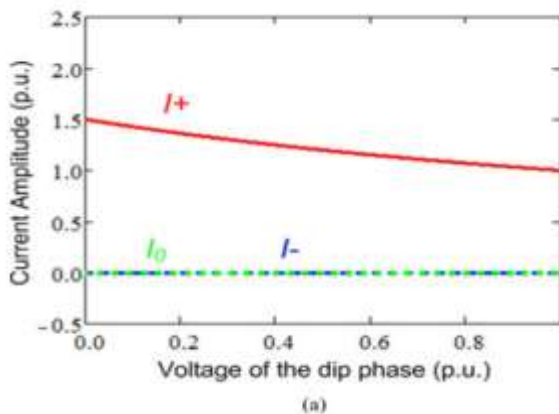$$P_{3\phi s2} = P_{s2} = 0.$$

(14)

(a)

(b)

Fig. 6. Profile of converter control with no negative-sequence current (three phase three-wire converter, *P*ref = 1 p.u., *Q*ref = 0 p.u., $Id- = 0$ p.u.,$Iq- = 0$ p.u.). (a) Sequence current amplitude versus *VA* (*I*+, *I*−, and *I*0means the amplitude of the current in the positive, negative, and zero sequences, respectively). (b) *P* and *Q* oscillation range versus *VA*

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

(15)

Where

$$M = (v_d^+)^2 + (v_q^+)^2 - (v_d^-)^2 - (v_q^-)^2.$$

(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
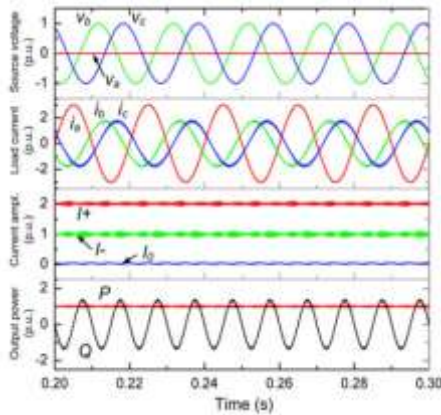
Fig. 7. Simulation of the converter control with no active power oscillation(three-phase three-wire converter, Pref = 1 p.u., Qref = 0 p.u., P_{s2} = 0 p.u.,P_{c2} = 0 p.u., VA = 0 p.u. $I+$, $I-$, and $I0$ means the amplitude of the currentin the positive, negative, and zero sequences, respectively.

positive- and negative-sequence current to achieve this control strategy, and up to ± 1.3 p.u. oscillation in the reactive power is generated when VA dips to zero. Another three possible control strategies which can eliminate the oscillation of the reactive power as shown in (17) or reduce the oscillations of both active and reactive power as shown in(18) and (19), are also possible for the three-phase three-wire converter under the unbalanced ac source
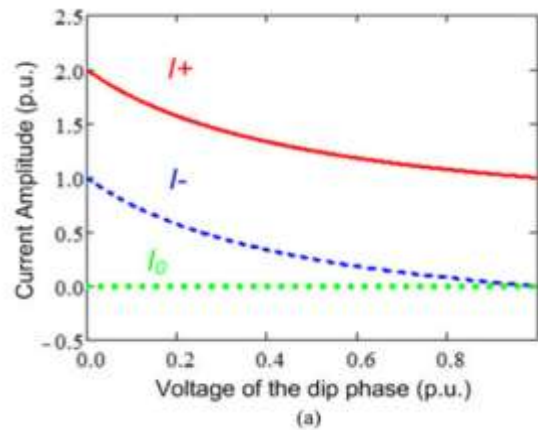
$$Q_{c2} = 0$$

$$Q_{s2} = 0 \quad (17)$$

$$P_{c2} = 0$$

$$Q_{s2} = 0 \quad (18)$$
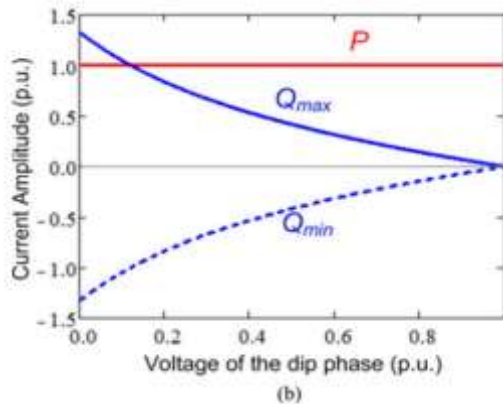
$$P_{s2} = 0$$

$$Q_{c2} = 0. \quad (19)$$

It can be seen that the active power oscillation at twice of the fundamental frequency can be eliminated. However, the disadvantage of this control strategy is also significant: first, the converter has to deliver up to 3 p.u. load current in the faulty phase which is much larger than the currents in other two normal phases—this large current may cause overloading of the system and result in failures. Moreover, significant fluctuation of the reactive power will be presented compared to the control strategy in Fig. 5. In case of the grid-connected application, this significant reactive power oscillation may cause grid voltage fluctuation, which is un preferred especially with weak grid and grid faults.

The current amplitude in the different sequences, as well as the delivered active/reactive power with relation to the voltage amplitude on the dipping phase is shown in Fig.8(a) and (b),respectively. It is noted that the converter has to deliver both the

Fig. 8. Profile of converter control with no active power oscillation (three phase three-wire converter, Pref = 1 p.u., Qref = 0 p.u., $Ps2$ = 0 p.u., $Pc2$ =0 p.u.). (a) Sequence current amplitude versus VA . ($I+$, $I-$, and $I0$ means the amplitude of the current in the positive, negative, and zero sequences, respectively).(b) P and Q range versus VA .

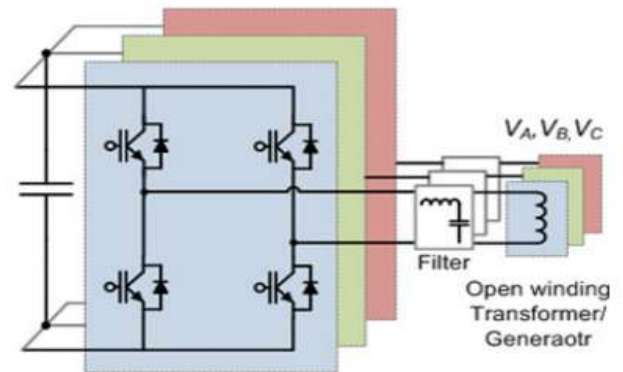## CONVERTER SYSTEM WITH THE ZERO-SEQUENCECURRENT PATH

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 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 freedoms to achieve better power control performances. It is

notedthat in the grid-connected application, the zero-sequence currentis not injected into the grid but trapped in the typically used d-Ytransformer.
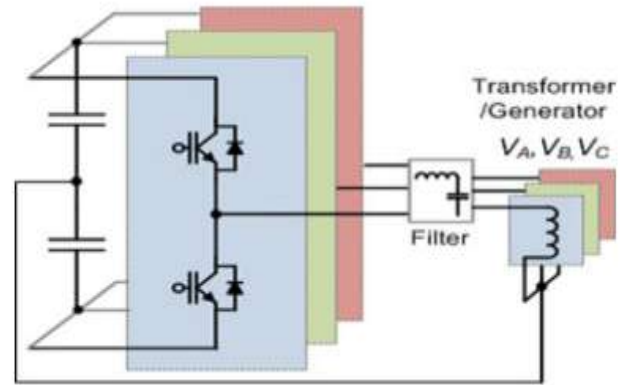
(a)

(b)

Fig. 9.Converter structure with the zero-sequence current path. (a) Four-wire system. (b) Six-wire system.

A.   Elimination of Both the Active and Reactive Power Oscillation.

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

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

$$P_{3\phi s2} = P_{s2} + P_{0s2} = 0 \qquad (30)$$

$$Q_{c2} = 0$$

$$Q_{s2} = 0. \qquad (31)$$

The power oscillation caused by the zero-sequence currentP_{0c2} and P_{0s2} are used to compensate the power oscillation caused by the positive- and negative-sequence currents P_{c2} andP_{s2}. When combing (26), (30), and (31), each of the current components controlled by converter can be calculated as

$$
\begin{bmatrix} i_d^+ \\ i_q^+ \\ i_d^- \\ i_q^- \\ i_{Re}^0 \\ i_{Im}^0 \end{bmatrix} = \frac{2}{3}
\begin{bmatrix}
v_d^+ & v_q^+ & v_d^- & v_q^- & v_{Re}^0 & v_{Im}^0 \\
v_q^+ & -v_d^+ & v_q^- & -v_d^- & v_{Re}^0 & -v_{Im}^0 \\
v_q^- & -v_d^- & -v_q^+ & v_d^+ & -v_{Im}^0 & -v_{Re}^0 \\
v_d^- & -v_q^- & v_d^+ & -v_q^+ & 0 & 0 \\
v_q^- & -v_d^- & v_q^+ & -v_d^+ & 0 & 0 \\
-v_d^- & -v_q^- & v_d^+ & v_q^+ & 0 & 0
\end{bmatrix}^{-1}
\begin{bmatrix} P_{ref} \\ 0 \\ 0 \\ Q_{ref} \\ 0 \\ 0 \end{bmatrix} \qquad (32)
$$

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 (positive, negative, and zero), then all of the controllable current components with the zero-sequence current path can be solved by

$$i_d^+ \approx \frac{2}{3} \cdot \frac{P_{ref}}{(v_d^+ - v_d^-) \cdot (1 - v_d^-/v_d^+)}$$

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

$$(33)$$

$$i_d^- \approx \frac{v_d^-}{v_d^+} \cdot i_d^+$$

$$i_q^- \approx -\frac{v_d^-}{v_d^+} \cdot i_q^+ \qquad (34)$$
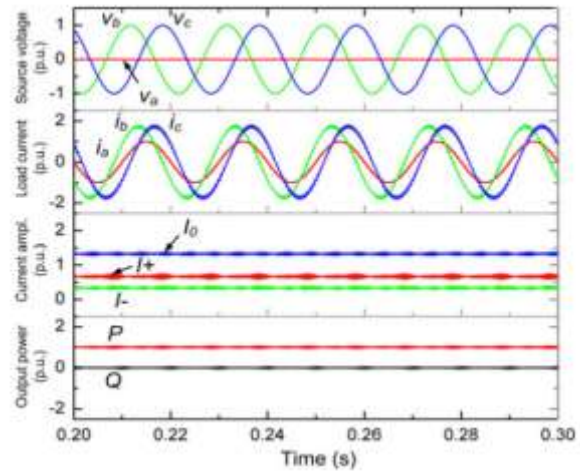

Fig.11. Simulation of converter control with no active and reactive power oscillation (three-phase converter with the zero-sequence path, Pref = 1 p.u.,Qref = 0 p.u., $Ps2$ = 0 p.u., $Pc2$ = 0 p.u., $Qs2$ = 0 p.u., $Qc2$ = 0 p.u., VA =0 p.u.).

$$i_{Re}^0 \approx \frac{2}{3} \cdot \frac{P_{ref} - \overline{P}}{v_{Re}^0}$$

$$i_{Im}^0 \approx \frac{v_d^+ \cdot i_q^- - v_d^- \cdot i_q^+}{v_{Re}^0}. \qquad (35)$$

When applying the current references in (33)–(35), the corresponding ac source voltage, load current, sequence current, and the instantaneous power delivered by the converter are

shown in Fig. 11. It can be seen that by this control strategy, the oscillation of both the active and reactive power at twice of the fundamental frequency can be eliminated. Moreover, compared to the control strategies for the three-wire system, the amplitude of the load current in each phase is not further increased, and the current in the faulty phase is smaller than the other two normal phases—this is a significant improvement. The current amplitude in different sequences, as well as the delivered active/reactive power with relation to the voltage amplitude on the dipping phase is

shown in Fig. 12(a) and (b), respectively. It is noted that the converter has to deliver positive-, negative-, and zero-sequence currents to achieve this control strategy. And the zero sequence current is controlled as zero when the voltage dip is at 1.0 p.u.

B. 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 (26) can be written

in the positive, negative, and zero sequences, respectively). (b) P and Q ranges versus VA. As

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

$$P_{3\phi s2} = P_{s2} + P_{0s2} = 0 \tag{36}$$

$$i_d^- = 0$$

$$i_q^- = 0. \tag{37}$$

Combing (26), (36), and (37), the matrix equation of (26) can be degraded as

$$
\begin{bmatrix} \overline{P} + \overline{P_0} \\ P_{c2} + P_{0c2} \\ P_{s2} + P_{0s2} \\ \overline{Q} \end{bmatrix} = \frac{3}{2} \begin{bmatrix} v_d^+ & v_q^+ & v_{Re}^0 & v_{Im}^0 \\ v_d^- & v_q^- & v_{Re}^0 & -v_{Im}^0 \\ v_q^- & -v_d^- & -v_{Im}^0 & -v_{Re}^0 \\ v_q^+ & -v_d^+ & 0 & 0 \end{bmatrix} \begin{bmatrix} i_d^+ \\ i_q^+ \\ i_{Re}^0 \\ i_{Im}^0 \end{bmatrix} \tag{38}
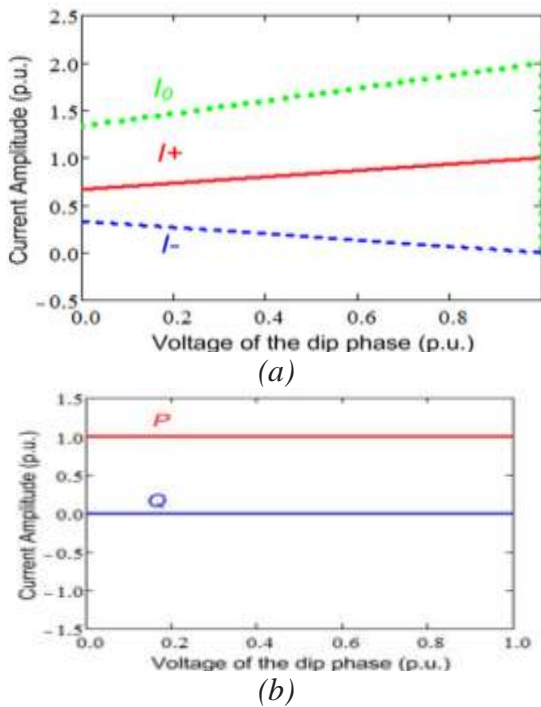$$

(a)

(b)

Fig. 12. Profile of converter control with no active and reactive power oscillation (three-phase converter with the zero sequence path, $Pref = 1$ p.u., $Qref = 0$ p.u., $Ps2 = 0$ p.u., $Pc2 = 0$ p.u., $Qs2 = 0$ p.u., $Qc2 = 0$ p.u.). (a) Sequence current amplitude versus VA. ($I+$, $I-$, and $I0$ means the amplitude of the current
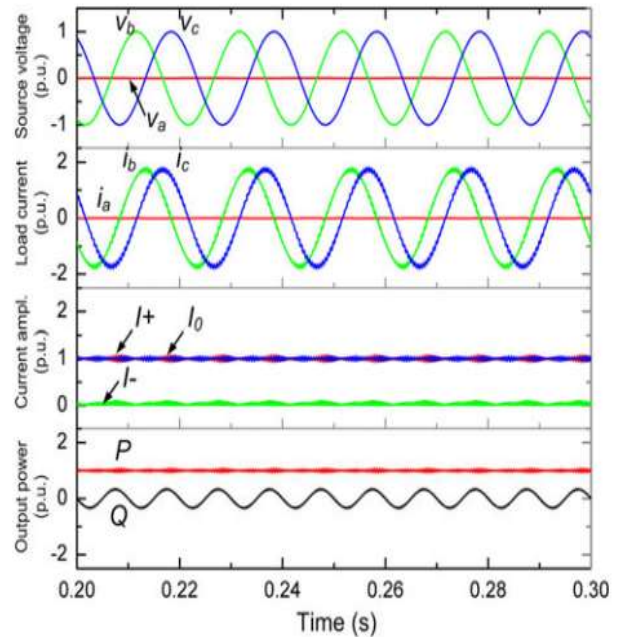

Fig. 13. Simulation of converter control with no active power oscillation and no negative sequence (three-phase converter with the zero-sequence current path, $Pref = 1$ p.u., $Qref = 0$ p.u., $Ps2 = 0$ p.u., $Pc2 = 0$ p.u., $id - = 0$ p.u.,$iq - = 0$ p.u., $VA = 0$ p.u. $I+$, $I-$, and $I0$ means the amplitude of the current in the positive, negative, and zero sequences, respectively).

And each of the current components can be calculated as

$$
\begin{bmatrix} i_d^+ \\ i_q^+ \\ i_{Re}^0 \\ i_{Im}^0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} v_d^+ & v_q^+ & v_{Re}^0 & v_{Im}^0 \\ v_d^- & v_q^- & v_{Re}^0 & -v_{Im}^0 \\ v_q^- & -v_d^- & -v_{Im}^0 & -v_{Re}^0 \\ v_q^+ & -v_d^+ & 0 & 0 \end{bmatrix}^{-1} \begin{bmatrix} P_{re} \\ 0 \\ 0 \\ Q_{re} \end{bmatrix}
$$
(39)

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

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

$$ i_q^+ \approx \frac{2}{3} \cdot \frac{Q_{\text{ref}}}{-v_d^+} $$
(40)

$$ i_d^- = 0 $$

$$ i_q^- = 0 $$
(41)

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

$$ i_{Im}^0 \approx 0. $$
(42)

When applying the current references in (40)–(42), the corresponding source voltage, lodad current, sequence current, andthe instantaneous power delivered by converter are shown in Fig. 13. It can be seen that by this control strategy, the oscillation of the active power at twice of the fundamental frequencycan be eliminated, and the load current in the faulty phase is reduced to zero.The current amplitude in the different sequences, as well asthe delivered

active/reactive power with relation to the voltage on the dipping phase are shown in Fig. 14(a) and (b), respectively.

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 a much smaller range (up to ±0.3 p.u.) compared to that in the three-wire system (up to ±1.3 p.u.) in Fig. 8(b). The zero-sequence current is controlled as zero when the voltage dip is at 1.0 p.u. Finally, the converter stresses for the active/reactive power oscillations and the current amplitude in the faulty/normal phases are compared in Table II, where different control strategies and converter structures are indicated, respectively.
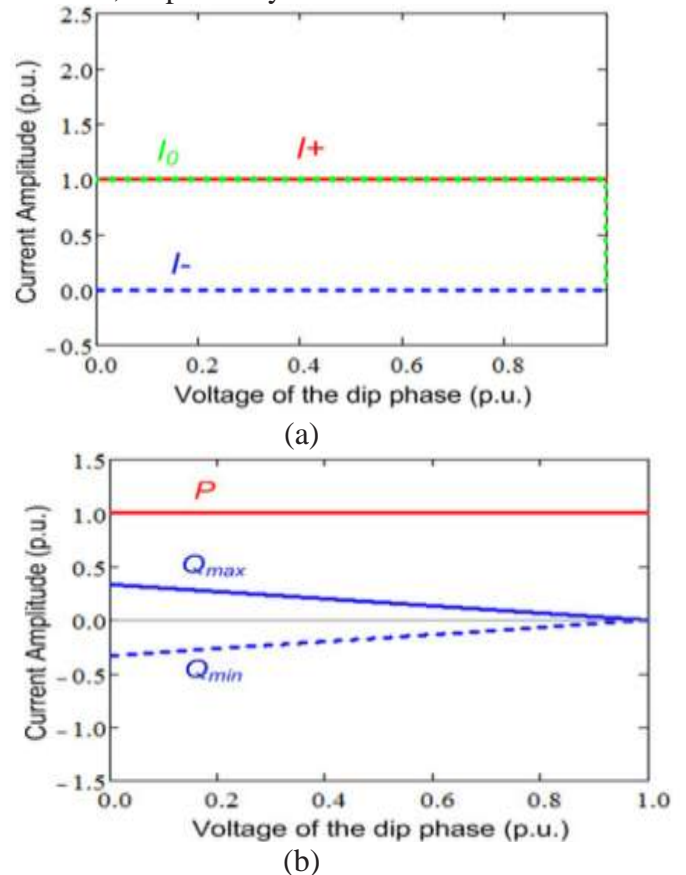

(a)

(b)

Fig. 14. Profile of converter control with no active power oscillation and nonegative

sequence (three-phase converter with the zero-sequence current path,Pref $= 1$ p.u., Qref $= 0$ p.u., $Ps2 = 0$ p.u., $Pc2 = 0$ p.u., $id- = 0$ p.u., $iq- =0$ p.u.). (a) Sequence current amplitude versus VA . (b) P and Q ranges versus VA .

It can be seen that by introducing the converter structures with the zero sequence current path and corresponding controls, the power oscillations under the unbalanced ac source are significantly reduced; meanwhile, the current amplitude in the normal phases is not further stressed, and the current stress in the faulty phases is significantly relieved. It is worth to mention that when enabling the proposed control methods, the zero-sequence current is flowing in/out of the midpoint of the dc bus at the fundamental frequency, thereby a larger dc capacitance or a rectifier with controllability of the midpoint potential is preferred for the four-wire converter structure shown in Fig. 9(a).

TABLE II
CONVERTER STRESS COMPARISON BY
DIFFERENT CONTROL STRATEGIES
(VALUES ARE REPRESENTED IN p.u., Pref $= 1$ p.u.,
Qref $= 0$ p.u.,AND $VA = 0$ p.u.)

Converter stress	Typical 3-wire		Zero-sequence	
	Control A	Control B	Control A	Control B
Active power osc. P_{osc}	0.5	0	0	0
Reactive power osc. Q_{osc}	0.5	1.3	0	0.3
Current in faulty phase I_{faulty}	1.5	3	1	0
Current in normal phase I_{norm}	1.5	2	2	2

Typical three-wire converter.
Control A: no negative-sequence current.
Control B: no active power oscillation.
Converter with the zero-sequence current path.
Control A: no active and reactive power oscillations.
Control B: no active power oscillation and no negative-sequence current

However, there is no such problem in the six-wire converter structure shown in Fig. 9(b).Moreover, according to (35) and (42), the reference current for the zero sequence is inverse proportional with the zero sequence

voltage $v0$. The effectiveness of the proposed control methods should rely on the amount of $v0$ in the unbalanced ac source. Insome cases of two-phase or three-phase faults with no or very small $v0$, the performance of the proposed control strategies will be different, and new control methods which do not utilizethe power from the zero sequence are needed. It is also noted that the dynamical performance and the sequence-extractingalgorithm are also critical considerations for the control methods under the unbalanced ac source, either for the transient condition(e.g., LVRT) or the stability during the steady-state operation, however, they are out of the scope of this paper.

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 experimental validations.

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