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Improved direct power control of a grid-connected voltage source converter during network unbalance*

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Abstract: This paper deals with an improved direct power control (DPC) strategy for the pulse width modulation (PWM) voltage source converter (VSC) under unbalanced grid voltage conditions. In order to provide enhanced control performance for the VSC, the resonant controllers tuned at the double grid frequency are applied in the DPC design to eliminate the power pulsations and dc link voltage ripples produced by the transient unbalanced grid faults. In this way, the output power and dc link voltage of the VSC can be directly regulated without positive and negative sequential decomposition. As a result, and as has been verified by experiment, the proposed method can provide fast dynamic response with easy implementation.

Key words: Voltage source converter, Direct power control, Unbalance, Resonant controller
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1 Introduction

The three-phase pulse width modulation (PWM) voltage source converter (VSC) has become increasingly popular in industrial applications due to its many advantages such as the bidirectional power flow, sinusoidal line current, and adjustable power factor and dc link voltage. These features, however, are less readily realized under unbalanced grid voltage conditions, a common occurrence in the remote, weak network due to the unbalanced load/transmission impedance or grid faults. With the rapid development of renewable energy and electric power systems, such as the wind and solar power conversion and high voltage dc (HVDC) transmission systems, the control and operation of the grid-connected VSC under unbalanced grid conditions has become a subject of intense research (Song and Nam, 1999; Xu *et al*., 2005; Suh and Lipo, 2006; Yin *et al*., 2008).

A variety of methods have been proposed to control the VSC under unbalanced grid conditions, the response and performance of a VSC during network unbalance being now well understood (Wu *et al*., 2008). Essentially, the most applicable methods have been based on the symmetrical component theory, which states that an unbalanced system can be viewed as a combination of positive and negative systems. Therefore, when these methods have been applied, the decomposition of the unbalanced three-phase quantities into the positive and negative sequences is essential and inevitable and, consequently, the stability and dynamic response of the overall control system are seriously affected. Moreover, the four controllable components of the VSC line current are not enough for regulating all of the six power components: the average, cosine, and sine terms of the VSC active and reactive power (Song and Nam, 1999; Yin *et al*., 2008). As a result, several control laws are derived according to the selection of power components as control targets, and then the current references could be calculated based on these different control laws. The reference current calculation, however, is extremely complicated and, often infeasible if the

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positive and negative sequence components of the grid voltage have the same magnitudes. In this case, the voltage matrix will become singular unless the instantaneous reactive power is redefined (Suh and Lipo, 2006; Hu and He, 2008). To solve these problems, new current controllers, such as the proportional-integral plus resonant (PIR) controller (Suh and Lipo, 2006) and the multi-frequency proportional-resonant controller (Hu and He, 2007), have been used to regulate the unbalanced current without involving sequential decomposition. In reality, only the decomposition of current could be avoided when these controllers are applied; the grid voltage and/or VSC output voltage still have/has to be decomposed for the current reference calculation. Another resonant scalar current control structure is designed to control the VSC without involving any sequential decomposition or reference frame transformation (Etxeberria-Otadui *et al.*, 2007), but the current reference calculation is still complicated and depends highly on the fundamental amplitude calculation and phase angle synchronization of the unbalanced grid voltage.

Among the extensive studies for the VSC, direct power control (DPC) has been developed (Noguchi *et al.*, 1998; Malinowski *et al.*, 2001; Escobar *et al.*, 2003) and demonstrated to have several advantages over the vector control strategy, e.g., simple implementation, fast dynamic response, and robustness to parameter variations and grid disturbances. The classical DPC scheme, however, will result in a changeable switching frequency, varying significantly with the operation condition due to switching patterns being directly selected from an optimal switching table. Consequently, the DPC with space vector modulation (DPC-SVM) (Malinowski *et al.*, 2004) and predictive control (P-DPC) (Larrinaga *et al.*, 2007) has been proposed to achieve a constant switching frequency. Recently, the application of DPC for the VSC under unbalanced grid voltage conditions has also been reported (Eloy-Garcia *et al.*, 2008), but sequential decomposition is still involved. In order to completely overcome this drawback, an improved DPC-SVM with resonant controllers applied is suggested in this paper, making it possible for the active and reactive input power of the VSC to be fully regulated without involving sequential decomposition.

2 Direct power control of the voltage source converter under normal grid condition

Detailed study on the DPC-SVM for a VSC has been provided by Zhi *et al.* (2009), and thus only a brief description is provided in this section.

Fig. 1 shows the power circuit of a three-phase boost-type grid-connected VSC, and Fig. 2 depicts its equivalent circuit in the positive d-q reference frame rotating at the synchronous speed of ω_s, in which the three-phase quantities have been transformed from the stationary a-b-c reference frame by the following transformation matrix:

$$\boldsymbol{V}^{+}=\begin{bmatrix}V_{\mathrm{d}}^{+}\\ V_{\mathrm{q}}^{+}\end{bmatrix}=\begin{bmatrix}\cos\theta_{\mathrm{s}} & \sin\theta_{\mathrm{s}}\\ -\sin\theta_{\mathrm{s}} & \cos\theta_{\mathrm{s}}\end{bmatrix}\begin{bmatrix}V_{\alpha}\\ V_{\beta}\end{bmatrix}$$

$$=\begin{bmatrix}\cos\theta_{\mathrm{s}} & \sin\theta_{\mathrm{s}}\\ -\sin\theta_{\mathrm{s}} & \cos\theta_{\mathrm{s}}\end{bmatrix}\times\frac{2}{3}\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix}\begin{bmatrix}V_{\mathrm{a}}\\ V_{\mathrm{b}}\\ V_{\mathrm{c}}\end{bmatrix}, \quad (1)$$

where the vector $\boldsymbol{V}$ represents a three-phase quantity, $\theta_s=\omega_s t$ is the phase angle of the grid voltage, and the superscript '+' denotes that the space vectors have been transformed into the positive synchronous reference frame.

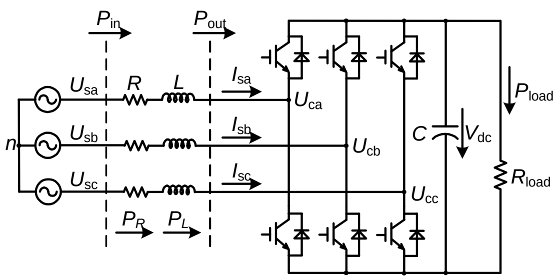

Fig. 1 Power circuit of the three-phase voltage source converter (VSC)

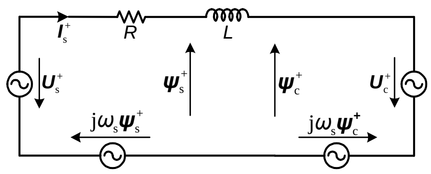

Fig. 2 Equivalent circuit of the voltage source converter (VSC)

Similar to the flux definition in an ac electrical machine operating at rated frequency, the source and converter flux linkages $\boldsymbol{\psi}_s$ and $\boldsymbol{\psi}_c$ can be defined as

$$\begin{cases} \boldsymbol{\psi}_s = \int \boldsymbol{U}_s \mathrm{d}t, \\ \boldsymbol{\psi}_c = \int \boldsymbol{U}_c \mathrm{d}t, \end{cases} \tag{2}$$

where the definition of each variable can be found in Figs. 1 and 2.

According to Fig. 2, the relationship between the grid voltage and VSC output voltage can be expressed as

$$\boldsymbol{U}_s^+ = R\boldsymbol{I}_s^+ + L\cdot\frac{\mathrm{d}\boldsymbol{I}_s^+}{\mathrm{d}t} + \mathrm{j}\omega_s(\boldsymbol{\psi}_s^+ - \boldsymbol{\psi}_c^+) + \boldsymbol{U}_c^+. \tag{3}$$

If the line resistance R is neglected, the voltage and flux in Eq. (3) can be given as

$$\begin{cases} \boldsymbol{U}_s^+ = \dfrac{\mathrm{d}\boldsymbol{\psi}_s^+}{\mathrm{d}t} + \mathrm{j}\omega_s\boldsymbol{\psi}_s^+, \\ \boldsymbol{U}_c^+ = \dfrac{\mathrm{d}\boldsymbol{\psi}_c^+}{\mathrm{d}t} + \mathrm{j}\omega_s\boldsymbol{\psi}_c^+. \end{cases} \tag{4}$$

Substituting Eq. (4) into Eq. (3), neglecting R and integrating Eq. (3) on both sides, yields

$$\boldsymbol{\psi}_s^+ = L\boldsymbol{I}_s^+ + \boldsymbol{\psi}_c^+. \tag{5}$$

Under normal grid voltage supply, the source flux $\boldsymbol{\psi}_s$ can be regarded as constant in the positive synchronous reference frame, which means that its differential equals zero. Taking into account Eq. (4), if the d-axis of the synchronous frame is aligned with the grid voltage vector, then the grid voltage can be simplified as

$$\boldsymbol{U}_s^+ = \mathrm{j}\omega_s\boldsymbol{\psi}_s^+ = -\omega_s\psi_{sq}^+ = U_{sd}^+ = U_s, \tag{6}$$

where U_s is the amplitude of grid voltage.

Based on Eq. (5), the input power from the grid into the VSC can be calculated as

$$P_{in} + \mathrm{j}Q_{in} = \frac{3}{2}\boldsymbol{U}_s^+ \times \hat{\boldsymbol{I}}_s^+ = \frac{3}{2}\boldsymbol{U}_s^+ \times \frac{1}{L}(\hat{\boldsymbol{\psi}}_s^+ - \hat{\boldsymbol{\psi}}_c^+), \tag{7}$$

where '^' means the conjugate complex of the space vectors.

Substituting Eq. (6) into Eq. (7), the active and reactive power inputs from the grid are expressed as

$$\begin{cases} P_{in} = -\dfrac{3}{2}\dfrac{U_s}{L}\psi_{cd}^+, \\ Q_{in} = \dfrac{3}{2}\dfrac{U_s}{L}\left(\psi_{cq}^+ + \dfrac{U_s}{\omega_s}\right). \end{cases} \tag{8}$$

Thus, the active and reactive power can be controlled independently by regulating the d- and q-axis converter flux linkages, respectively. Differentiating Eq. (8) results in

$$\begin{cases} \dfrac{\mathrm{d}\psi_{cd}^+}{\mathrm{d}t} = -\dfrac{2L}{3U_s}\dfrac{\mathrm{d}P_{in}}{\mathrm{d}t} = -\dfrac{2L}{3U_s}\dfrac{P_{in}^* - P_{in}}{T_s}, \\ \dfrac{\mathrm{d}\psi_{cq}^+}{\mathrm{d}t} = \dfrac{2L}{3U_s}\dfrac{\mathrm{d}Q_{in}}{\mathrm{d}t} = \dfrac{2L}{3U_s}\dfrac{Q_{in}^* - Q_{in}}{T_s}, \end{cases} \tag{9}$$

where T_s is the sampling time period, and P_{in}^* and Q_{in}^* are the input active and reactive power references, respectively.

Substituting Eqs. (8) and (9) into Eq. (4) results in the required d- and q-axis output control voltages of the VSC in the grid voltage vector oriented reference frame:

$$\begin{cases} U_{cd}^+ = -k_p(P_{in}^* - P_{in}) - \dfrac{2\omega_s L}{3U_s}Q_{in} + U_s, \\ U_{cq}^+ = k_p(Q_{in}^* - Q_{in}) - \dfrac{2\omega_s L}{3U_s}P_{in}, \end{cases} \tag{10}$$

where k_p is the gain of the proportional controller.

Eq. (10) indicates that the active and reactive power inputs can be fully controlled by directly regulating the converter voltage according to the power errors. Therefore, the inner current control loops in the conventional vector control schemes can be eliminated, which makes the DPC much simpler in implementation than the vector control.

3 Direct power control of the voltage source converter under unbalanced grid condition

If the grid voltage becomes unbalanced, even with a constant power input P_{in}, there will still be voltage ripples appearing on the dc link due to the nonzero instantaneous active power P_L crossing through the line inductance (Yin *et al*., 2008), which makes it hard to remove the ripples by just regulating $P_{\rm in}$. A straightforward way to eliminate the dc voltage ripples is by nullifying the instantaneous output power pulsations of $P_{\rm out}$ at the poles of the converter (Suh and Lipo, 2006; Yin *et al*., 2008; Hu and He, 2008), as shown in Fig. 1. However, if the vector control methods are applied, it is even more difficult to calculate the reference currents when $P_{\rm out}$ is selected as the control target, because the VSC output voltage $\boldsymbol{U}_{\rm c}$ is not smooth but includes large switching ripples, which makes it hard to be separated into the positive and negative sequences (Suh and Lipo, 2006).

To achieve a complete control of the instantaneous active and reactive power under an unbalanced condition, a novel DPC strategy for the VSC is investigated in this section. Unlike the previous control schemes, the dc voltage ripples can be eliminated by regulating the input power $P_{\rm in}$ instead of the output power $P_{\rm out}$, which makes the implementation of the proposed scheme much simpler compared with the output-power-control schemes.

With unbalanced voltage supply, the complex input power from power source can be given by

$$\begin{aligned} S_{\rm in} &= P_{\rm in} + {\rm j}Q_{\rm in} = \frac{3}{2}\boldsymbol{U}_{\rm s}\times\hat{\boldsymbol{I}}_{\rm s} \\ &= \frac{3}{2}\left(\boldsymbol{U}_{\rm s+}^{+}{\rm e}^{{\rm j}\omega_{\rm s}t}+\boldsymbol{U}_{\rm s-}^{-}{\rm e}^{-{\rm j}\omega_{\rm s}t}\right)\times\left(\hat{\boldsymbol{I}}_{\rm s+}^{+}{\rm e}^{-{\rm j}\omega_{\rm s}t}+\hat{\boldsymbol{I}}_{\rm s-}^{-}{\rm e}^{{\rm j}\omega_{\rm s}t}\right) \\ &= \left[P_{\rm in\,a}+P_{\rm in\,c2}\cos(2\omega_{\rm s}t)+P_{\rm in\,s2}\sin(2\omega_{\rm s}t)\right] \\ &\quad + {\rm j}\left[Q_{\rm in\,a}+Q_{\rm in\,c2}\cos(2\omega_{\rm s}t)+Q_{\rm in\,s2}\sin(2\omega_{\rm s}t)\right], \end{aligned} \tag{11}$$

where the superscript '−' denotes the negative synchronous reference frame rotating at the angular speed of $-\omega_{\rm s}$, while the subscripts '+' and '−' represent the positive and negative sequence components of the space vectors, respectively. $P_{\rm in\,a}$ and $Q_{\rm in\,a}$ are the average power outputs, while $P_{\rm in\,c2}$, $Q_{\rm in\,c2}$ and $P_{\rm in\,s2}$, $Q_{\rm in\,s2}$ are the cosine and sine power pulsations with double grid frequency (100 Hz), respectively.

Referring to Eqs. (10) and (11), if power pulsations are included, the power inputs $P_{\rm in}$ and $Q_{\rm in}$ cannot be fully regulated with only a proportional controller or a PI controller, because neither of the controllers can provide a gain high enough at the pulsation frequency. For regulating the power pulsations directly, a resonant controller tuned at the known pulsation frequency is applied together with the proportional controller in the DPC introduced previously. When the proportional plus resonant (PR) controller is adopted, the output control voltages of the VSC in Eq. (10) are gained as

$$\begin{cases} U_{\rm cd}^{+} = -\left[k_{\rm p}+\dfrac{k_{\rm r}s}{s^2+2\omega_{\rm c}s+(2\omega_{\rm s})^2}\right](P_{\rm in}^{*}-P_{\rm in}) \\ \qquad -\dfrac{2\omega_{\rm s}L}{3U_{\rm s}}Q_{\rm in}+U_{\rm s}, \\ U_{\rm cq}^{+} = \left[k_{\rm p}+\dfrac{k_{\rm r}s}{s^2+2\omega_{\rm c}s+(2\omega_{\rm s})^2}\right](Q_{\rm in}^{*}-Q_{\rm in}) \\ \qquad -\dfrac{2\omega_{\rm s}L}{3U_{\rm s}}P_{\rm in}. \end{cases} \tag{12}$$

Herein $k_{\rm p}$ is the gain of the proportional controller, which determines the dynamics of the system and can be tuned in the same way as for a conventional PI controller; $k_{\rm r}$ serves as the gain of a generalized AC integrator, which can be tuned to shift the vertical magnitude response at the resonant frequency; $\omega_{\rm c}$ is adopted to widen the frequency bandwidth of the resonant controller so as to make it more stable and less sensitive to the possible frequency variations (Teodorescu *et al*., 2006). Based on the above design rules, the parameters of the controllers are chosen as $k_{\rm p}$=3, $k_{\rm r}$=300, and $\omega_{\rm c}$=π for the following study.

Eq. (12) indicates that the active and reactive power errors can be regulated to zero even if there are double grid frequency pulsations existing in the reference and/or calculated input power. To avoid the positive and negative synchronous reference frame transformation and sequential decomposition, the input power can be calculated in the stationary α-β reference frame as

$$\begin{aligned} P_{\rm in} + {\rm j}Q_{\rm in} &= \frac{3}{2}\boldsymbol{U}_{{\rm s}\alpha\beta}\times\hat{\boldsymbol{I}}_{{\rm s}\alpha\beta} \\ &= \frac{3}{2}\left[(U_{{\rm s}\alpha}I_{{\rm s}\alpha}+U_{{\rm s}\beta}I_{{\rm s}\beta})+{\rm j}(U_{{\rm s}\beta}I_{{\rm s}\alpha}-U_{{\rm s}\alpha}I_{{\rm s}\beta})\right]. \end{aligned} \tag{13}$$

In previous control schemes, the active power reference of VSC is usually generated by a PI controller, which regulates the dc bus voltage $V_{\rm dc}$. However, if voltage ripples appear on the dc bus, the PI controller is unable to work properly owing to the lack of a gain high enough at the ripple frequency. Consequently, some low-pass filters are adopted to eliminate the voltage ripples from the control loop (Etxeberria-Otadui *et al*., 2007), but it is predictable that the dynamic response of the control system will be seriously affected. Following the idea of the unbalanced DPC, a resonant controller tuned at the double grid frequency can be incorporated into the dc voltage regulator as

$$P_{\text{in}}^{*}=\left[k_{\text{p}}+\frac{k_{\text{i}}}{s}+\frac{k_{\text{r}}s}{s^{2}+2\omega_{\text{c}}s+(2\omega_{\text{s}})^{2}}\right](V_{\text{dc}}^{*}-V_{\text{dc}}). \quad (14)$$

Thus, the error between the reference and measured dc link voltage can be minimized to zero by the PIR controller, whose control parameters are designed as k_{p}=0.5, k_{i}=30, k_{r}=200, and ω_{c}=π in the study.

Based on the proposed DPC described by Eqs. (12) and (14), the schematic diagram of the control system is depicted in Fig. 3. The power errors are regulated by a PR controller, and then the VSC output control voltage is calculated by Eq. (12) and passed to a voltage limiter, which can prevent the voltage references from exceeding the maximum output voltage of the VSC. An improved phase-locked loop (PLL), as shown in the dashed line block, is designed to track the amplitude, frequency, and phase angle of the positive sequence grid voltage. A resonant controller tuned at the double grid frequency is adopted to compensate for the angular error between θ_{s}' and θ_{s}, which is the phase angle of the unbalanced grid voltage and its positive sequence component, respectively. As a result, the effect of the negative sequence component on the PLL is greatly reduced and thus the frequency and phase angle of the positive sequence component can be tracked accurately without involving sequential decomposition.

4 Experimental validation

Experimental studies of the proposed DPC were carried out on a laboratory VSC test bench, which is rated at 5 kW, and its line inductance and dc link capacitance are designed as 6 mH and 500 μF, respectively. The improved DPC scheme was realized on a TI TMS320F2812 DSP, and the waveforms were acquired by a YOKOGAWA 16-channel DL750 scope. Fig. 4 shows the experimental results of the VSC

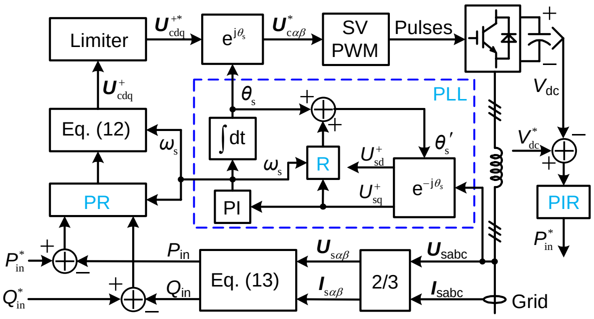

Fig. 3 Schematic diagram of the improved direct power control (DPC) for the voltage source converter (VSC)
R: resonant; PR: proportional plus resonant; PIR: proportional-integral plus resonant; SV: space vector; PWM: pulse width modulation; PLL: phase-locked loop

under unbalanced voltage supply with the proposed DPC applied, and the switching frequency was set at 5 kHz. The unbalanced grid voltage dip with phase-a voltage dropping to 80% of its normal value was generated by a three-phase PWM inverter rated at 20 kW.

In Fig. 4a, the DPC scheme described by Eq. (9) was applied, and a PI controller was adopted to obtain the active input power reference. As can be seen, the pulsation components were present obviously in both of the active and reactive power inputs during voltage unbalance, and voltage ripples were generated on the dc bus, the reason for which may be concluded as follows. Firstly, the PI controller fails to regulate V_{dc} and thereby an improper active power reference is engendered. Secondly, the power inputs P_{in} and Q_{in} cannot track their references accurately with only a proportional controller applied, as has been pointed out previously. Fig. 4b shows the dynamic response of VSC with the proposed DPC applied. It can be seen that the dc voltage ripples were eliminated immediately under the transient grid unbalance. The active power pulsations, however, were not completely removed, because they had to compensate for P_L to obtain a constant dc bus voltage.

As can be seen from Figs. 4a and 4b, when the DPC was applied, the line current was seriously distorted when the grid voltage became unbalanced. Eloy-Garcia *et al*. (2008) suggested using two compensating power pulsation terms to eliminate the current distortion, and designed a switch table to track the oscillating power references, which resulted in a changeable switching frequency. When the improved DPC is applied, the power compensating terms are

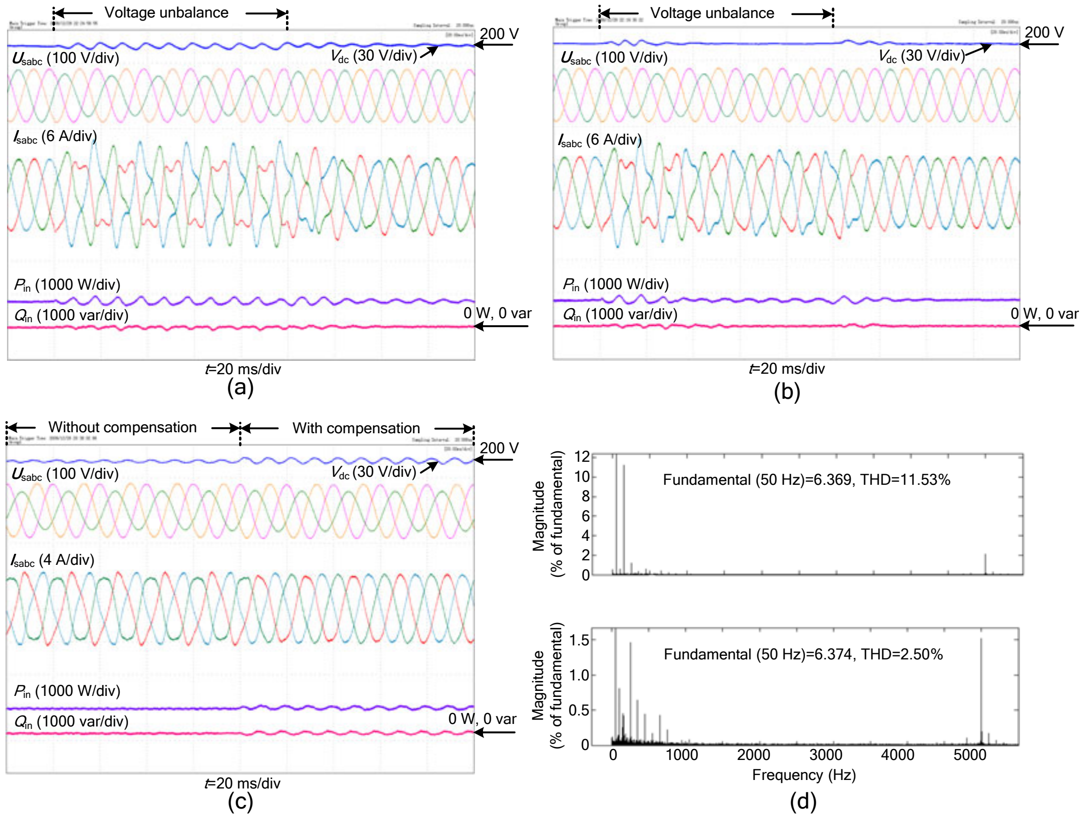

Fig. 4 Experimental results of the improved direct power control (DPC) under grid voltage unbalance
(a) Conventional DPC; (b) Proposed DPC during transient grid unbalance; (c) Proposed DPC with control target change from constant power inputs to sinusoidal-balanced line current; (d) Harmonic spectra of line current

easily regulated by the PR controller. If the negative sequence and current harmonics are eliminated, Eq. (11) can be given by

$$S_{\text{in}} = \frac{3}{2}\left(\boldsymbol{U}_{\text{s+}}^{+}\text{e}^{\text{j}\omega_{\text{s}}t} + \boldsymbol{U}_{\text{s-}}^{-}\text{e}^{-\text{j}\omega_{\text{s}}t}\right) \times \hat{\boldsymbol{I}}_{\text{s+}}^{+}\text{e}^{-\text{j}\omega_{\text{s}}t}. \quad (15)$$

As shown in Eq. (15), in addition to the average power, some 100 Hz pulsations generated by the negative sequence voltage and line current are also included in the complex input power. In other words, these pulsation terms should be added to the power references so as to obtain the sinusoidal-balanced line current. According to Eq. (15), the compensating power pulsations can be calculated in the positive synchronous reference frame as

$$\begin{aligned} S_{\text{com}} &= P_{\text{com}} + \text{j}Q_{\text{com}} \\ &= \frac{3}{2}\boldsymbol{U}_{\text{s-}}^{-}\text{e}^{-\text{j}\omega_{\text{s}}t} \times \hat{\boldsymbol{I}}_{\text{s}}^{+}\text{e}^{-\text{j}\omega_{\text{s}}t} = \frac{3}{2}\boldsymbol{U}_{\text{s-}}^{+} \times \hat{\boldsymbol{I}}_{\text{s}}^{+} \\ &= \frac{3}{2}\left[\left(U_{\text{sd-}}^{+}I_{\text{sd}}^{+} + U_{\text{sq-}}^{+}I_{\text{sq}}^{+}\right) + \text{j}\left(U_{\text{sq-}}^{+}I_{\text{sd}}^{+} - U_{\text{sd-}}^{+}I_{\text{sq}}^{+}\right)\right]. \end{aligned} \quad (16)$$

As shown in Fig. 4c, if the compensating terms are added to the power references, the current distortion is restrained and the sinusoidal-balanced line current is obtained. As can be seen in Fig. 4d, the total harmonic distortion (THD) detected by Matlab/Simulink was reduced from 11.53% to only 2.50%.

In previous unbalanced control schemes of VSC, the active and reactive power pulsations could not be eliminated simultaneously because there were not enough controllable current components to regulate the four active and reactive power pulsations (Song and Nam, 1999; Yin *et al.*, 2008), unless the instantaneous reactive power was redefined (Suh and Lipo, 2006). As a result, only a near-unity power factor can be realized, even if the reactive power reference is set to zero. With the proposed DPC applied, however, this problem can also be solved owing to the cancellation of the inner current control loops. As shown in Fig. 4c, both the active and reactive power pulsations can be eliminated so long as the constant power references are given.

From the experimental results shown above, it can be concluded that when the improved DPC is adopted, three selectable control targets can be achieved for different applications: (1) constant dc bus voltage, which is useful for the sensitive dc loads, (2) sinusoidal-balanced line current, which is practicable for improving the grid power quality, and (3) constant power inputs, which are helpful for the stability of the weak grid. For our present purposes, however, these control targets are exclusive and sinusoidal line current and constant dc voltage are not acquired simultaneously, in contrast to the conventional unbalanced vector control schemes. The combination of these control targets under much more severe unbalanced grid voltage dips will be reported in the future work.

5 Conclusions

We investigate an improved DPC with resonant controllers applied to regulate the power pulsations and dc bus voltage ripples of a VSC during network unbalance. The detailed design of the control system is presented and the effectiveness of the proposed scheme is confirmed by experimental studies. Compared with previous unbalanced control methods for VSC, the proposed method provides the following: (1) simple implementation without any reference current calculation or carefully tuned inner current control loops, (2) fast dynamic response owing to the cancellation of any sequential decomposition, (3) simultaneous elimination of the active and reactive power oscillations due to direct regulation of the power errors by the PR controllers, and (4) good elimination of the dc link voltage ripples based on input power control instead of output power control.

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