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# Coordinated control strategy of doubly fed wind power generation system under unbalanced grid voltage

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Abstract. A coordinated control method for doubly fed wind power generation system under unbalanced grid voltage is presented in this paper, which can remove the negative effects of unbalanced voltage on the doubly fed induction generator (DFIG) such as the unbalance of stator and rotor current. And the method can suppress the double frequency oscillations of the output active and reactive power. To improve the operating performance, the operation mechanism of DFIG system with a series grid side converter (SGSC) under unbalanced grid voltage is described firstly, and the strategy for series grid side converter aiming at maintaining the stator three phase voltage balance is proposed, and then the stator and rotor currents will keep balanced. Meanwhile, the mathematical model of the parallel grid side converter (PGSC) is analysed under unbalanced grid voltage and the double frequency power control equation is established. According to the control equation, a control strategy based on a proportional resonance (PR) power compensator for the parallel grid side converter is put forward, then the control goal of suppressing the double frequency oscillations of the output active and reactive power of the whole system simultaneously is accomplished, which improves the output quality of the system and ensures the safe operation of the connected grid. The proposed coordinated control strategy in this paper verified by the simulations of a doubly fed wind power generation system model built in PSCAD/EMTDC.

## 1. Introduction

With the development and maturity of power electronics, a great deal of progress has been made in clean energy generation technologies represented by wind power generation. The variable-speed and constant-frequency double fed induction generator (DFIG) has been extensively used in the wind power generation system in virtue of the advantages of small converter capacity, decoupled control of active and reactive power, and great performance on operation [1,2]. However, many wind farms are at the end of the grid because of the particularity of the distribution of wind energy resources. Impedance asymmetry of the transmission line or unbalanced three-phase load may cause the unbalance of voltage at the grid connection point of the wind turbine. Unbalanced grid voltage will deteriorate the operating conditions of DFIG,

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which affects the stability of the whole system and reduces the quality of the output power. The focus of research on DFIG has shifted from improving the operating performance under normal grid voltage [3-5] to enhancing its operating capacity under unbalanced grid voltage for the past few years [6-12].

In many literatures, the control of DFIG under unbalanced grid voltage has been discussed. The research on operation and control of the DFIG power generation system under unbalanced grid voltage was performed deeply in [6-9], where the mathematical models including DFIG, the rotor side converter (RSC) and the grid side converter (GSC) are analyzed systematically, and the main-assisted, proportional-resonant (PR) and proportional-integral-resonant (PI-R) current regulators are designed respectively, then a series of alternative control methods are proposed, which realize the unified regulation and control of the positive and negative sequence current of the stator and rotor and suppress the negative effects of unbalanced grid voltage on DFIG. However, the design of these control strategies is too complex and the control objectives are limited by the number of control variables. A strategy which is on account of sliding-mode control for GSC is proposed to compensate the stator voltage in literature [10], but this method involves the GSC ignoring the effects of unbalanced grid voltage on DFIG. A series grid side converter (SGSC) is installed at the stator side for the unbalanced condition of the grid voltage in literature [11] and [12], then the adverse impact of grid voltage unbalance on the DFIG is overcame and the operating performance of the DFIG is improved. Finally, three alternative control target that include no negative sequence current injection into the grid, no double frequency oscillations in the active output power or no double frequency oscillations in the reactive output power are proposed for the parallel grid side converter (PGSC), However, the double frequency oscillations of active power and reactive power the entire system output will not be eliminated simultaneously with this strategy.

In this paper, the SGSC has been utilized in the stator side to compensate the stator voltage, and make the stator voltage be its rated value. Further, both the stator and rotor currents will maintain balanced in the circumstances so that the stability of DFIG will be improved under unbalanced voltage grid. Meanwhile, the mathematical model of PGSC is analyzed and the PGSC control equation for double frequency power is established when the grid voltage is unbalanced. On the basis of the control equation, a control strategy based on proportional resonance power compensator for PGSC is proposed, which can suppress the double frequency oscillations of the active and reactive power output simultaneously without affecting the normal operation of the DFIG. Finally, a simulation model with the above strategy is built in PSCAD/EMTDC, and the simulation verifies that the proposed coordinated control strategy can improve the output quality of the wind power generation system while ensuring the safe and stable operation of it.

#### 2. The model of DFIG system with a SGSC



Figure 1. The configuration of DFIG system with a SGSC.

The configuration of doubly fed wind power generation system with a SGSC is shown in figure 1, which is made up of a wind turbine, a gear box, a DFIG, RSC, a DC link capacitor, PGSC and the added SGSC.

The control system of DFIG with a SGSC includes the control of RSC, PGSC and SGSC. With the effective control of SGSC under unbalance grid voltage, the stator voltage becomes balanced and it is at the rated value, then the negative effects of unbalanced grid voltage on DFIG can be eliminate. Thus, the conventional vector control scheme for the RSC remains in full force under unbalanced grid voltage, which can realize the decoupling control of the active and reactive power and getting the maximum wind power by the wind turbine. It will focus on the research of the SGSC and PGSC control strategy in the following of this paper.

#### 3. Research on SGSC control strategy under unbalanced grid voltage

#### 3.1. Operation analysis of SGSC under unbalanced grid voltage

As windings of most grid step-up transformers are  $Y/\Delta$  type and DFIG generally operates in a three-phase, three-wire system, the zero sequence component is isolated when the grid voltage is unbalanced. The unbalance of system is mainly caused by the negative sequence grid voltage produced by unbalanced conditions. Therefore, positive and negative sequence grid voltages in the system are taken into account only in the process of analysis, then the unbalanced grid voltage can be described as equation (1).

$$U_{\rm g} = U_{\rm gp} + U_{\rm gn} \tag{1}$$

$$U_{\rm s} = U_{\rm g} + U_{\rm c} \tag{2}$$

Where  $U_g$ ,  $U_{gp}$  and  $U_{gn}$  are the grid voltage, the positive and negative sequence grid voltage. The role of the SGSC in the system is to compensate the stator voltage of the DFIG through one series transformer, and the stator voltage vector in the stationary coordinate system can be expressed [11,12] as equation (2), in which  $U_s$  are the stator voltage,  $U_c$  are the voltage that need to be compensated.

In order to achieve the goal that the stator voltage contain no negative sequence component, the SGSC should output a negative sequence voltage through the series transformer to offset the negative sequence component under the unbalanced grid voltage, when the grid voltage asymmetrically drops, the positive sequence component will also decline and deviate from its rated value. Therefore, the SGSC should also output a positive sequence voltage so that the positive sequence component of stator voltage is consistent with normal grid voltage. The control goal of the SGSC can be described as equation (3), where  $U_{sp}$  and  $U_{sn}$  are the positive and negative sequence components of stator voltage respectively, and  $U'_{gp}$  is the positive sequence grid voltage under normal grid voltage. The equation (1), (2) and (3) can be united to obtain the expressions of the positive and negative sequence voltage components that the SGSC should compensate under unbalanced grid voltage, which can be described as in equation (4).

$$\begin{cases} U_{\rm sp} = U'_{\rm gp} \\ U_{\rm sn} = 0 \end{cases}$$
(3)

$$\begin{cases} U_{\rm cp} = U'_{\rm gp} - U_{\rm gp} \\ U_{\rm cn} = -U_{\rm gn} \end{cases}$$

$$\tag{4}$$

Through the effective control of the SGSC, the stator voltage is consistent with the grid voltage under normal state. Further, the stator and rotor currents of the DFIG still maintain balance, and the current flowing through the SGSC will also remain balance. According to the

literature [13], transformed to the positive dq reference frame, the positive sequence component is converted into a constant component, while the negative sequence component is converted into a double frequency component. Then, the voltage compensated by the SGSC and the current flowing through the SGSC can be expressed in the positive dq reference frame as

$$\begin{cases} U_{cd}^{p} = U_{cd0}^{p} + U_{cd2}^{p} & i_{cd}^{p} = i_{cd0}^{p} \\ U_{cq}^{p} = U_{cq0}^{p} + U_{cq2}^{p} & i_{cq}^{p} = i_{cq0}^{p} \end{cases}$$
(5)

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Where  $U_{cd}$  and  $U_{cq}$  represent the d and q axis components of the compensation voltage output by the SGSC in the positive dq reference frame respectively;  $i_{cd}$  and  $i_{cq}$  represent the d and q axis components of the current flowing through the SGSC; The subscript 0 and 2 indicate the constant component and the double frequency component, respectively. The double frequency active and reactive power flowing through the SGSC can be expressed in the positive dq reference frame as (the d-axis is fixed on the stator voltage vector)

$$\begin{cases} P_{c2}^{p} = \frac{3}{2} \left( i_{cd0}^{p} U_{cd2}^{p} + i_{cq0}^{p} U_{cq2}^{p} \right) \\ Q_{c2}^{p} = \frac{3}{2} \left( i_{cd0}^{p} U_{cq2}^{p} - i_{cq0}^{p} U_{cd2}^{p} \right) \end{cases}$$
(6)

Where  $P_{c2}^{p}$  and  $Q_{c2}^{p}$  represent the double frequency active and reactive power flowing through the SGSC, respectively.

#### 3.2. Control strategy of SGSC under unbalanced grid voltage

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The positive and negative sequence voltage components that the SGSC is supposed to compensate are shown in equation (4), the compensation voltage can be obtained as

$$U_{\rm c} = U_{\rm cp} + U_{\rm cn} = (U'_{\rm gp} - U_{\rm gp}) - U_{\rm gn}$$
<sup>(7)</sup>

To satisfy the requirement of formula (7), it is necessary to separate the positive and negative sequence voltage components of the grid, and the 1/4 period delay method is used to perform the task in this paper. After getting the positive and negative voltage sequence components of the grid, the positive sequence component is converted to the positive dq reference frame, while the negative sequence component is converted to the negative dq reference frame. Then, the positive and negative sequence components of the output voltage of SGSC can be obtained through the formula (4). The positive and negative sequence components are converted to the stationary abc-axis, and added together. Finally, the method of hysteresis comparison is applied to realize the compensation of stator voltage.

#### 4. Research on control strategy for PGSC under unbalanced grid voltage

#### 4.1. Model analysis of PGSC under unbalanced grid voltage

The circuit diagram of PGSC is shown in figure 2, where  $E_{ga}$ ,  $E_{gb}$  and  $E_{gc}$  are three-phase AC voltages in PGSC, and  $i_{ga}$ ,  $i_{gb}$  and  $i_{gc}$  represent three-phase AC currents through the PGSC.  $U_{ga}$ ,  $U_{gb}$  and  $U_{gc}$  are the three-phase AC voltages of the grid.  $R_{g}$  indicates the connection resistance and  $L_{g}$  is the inductance of PGSC. C is the DC filter capacitor.  $i_{dc}$  is the current the inverter outputs, and  $U_{dc}$  is DC voltage;  $P_{g}$  and  $Q_{g}$  are the active power and reactive power injected into the grid by the PGSC, respectively.



Figure 2. The circuit diagram of PGSC.

The mathematical model of the PGSC under unbalanced grid voltage in the dq reference frame can be expressed as [13]

$$\begin{bmatrix} U_{gd} \\ U_{gq} \end{bmatrix} = R_g \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} + L_g p \begin{bmatrix} i_{gd} \\ i_{gq} \end{bmatrix} - \omega_g L_g \begin{bmatrix} i_{gq} \\ -i_{gd} \end{bmatrix} + \begin{bmatrix} E_{gd} \\ E_{gq} \end{bmatrix}$$
(8)

Among which  $U_{gd}$  and  $U_{gq}$  represent the d and q axis components of the three-phase grid voltage, respectively.  $i_{gd}$  is the d axis component of three-phase current through the PGSC and  $i_{gq}$  is the q axis component.  $E_{gd}$  and  $E_{gq}$  are the d and q axis components of the three-phase voltage that the inverter outputs.  $\omega_g$  is the angular frequency of grid voltage, and p represents the differential operator.

According to the literature [14], when the grid voltage becomes unbalanced, the voltages and currents flowing through the PGSC in the dq reference frame both contain double frequency components. Therefore, the voltage and current of the grid can be expressed in the dq reference frame as

$$\begin{cases} U_{gd}^{p} = U_{gd0}^{p} + U_{gd2}^{p} & i_{gd}^{p} = i_{gd0}^{p} + i_{gd2}^{p} \\ U_{gq}^{p} = U_{gq0}^{p} + U_{gq2}^{p} & i_{gq}^{p} = i_{gq0}^{p} + i_{gq2}^{p} \end{cases}$$
(9)

The subscript 0 and 2 indicate the constant component and the double-frequency component, respectively. The superscript p signifies the transformation to the positive dq reference frame. Then the double frequency active and reactive power which are outputted by PGSC can be expressed in the positive dq reference frame as (the d-axis is fixed in the stator voltage vector)

$$\begin{cases} P_{g2}^{p} = \frac{3}{2} \left( i_{gd0}^{p} U_{gd2}^{p} + i_{gq0}^{p} U_{gq2}^{p} + i_{gd2}^{p} U_{gd0}^{p} \right) \\ Q_{g2}^{p} = \frac{3}{2} \left( i_{gd0}^{p} U_{gq2}^{p} - i_{gq0}^{p} U_{gd2}^{p} - i_{gq2}^{p} U_{gd0}^{p} \right) \end{cases}$$
(10)

Where  $P_{c2}^{p}$  and  $Q_{c2}^{p}$  represent the active and reactive power that the PGSG outputs, respectively.

According to the direction of the power flows shown in figure 1, the output power of the whole system can be expressed as equation (11). Where  $P_t$  and  $Q_t$  represent the active and reactive power that the entire system outputs.  $P_s$  is the active power outputted by the stator and  $Q_s$  is the reactive power.  $P_g$  and  $Q_g$  are the active and reactive output power of the PGSC.  $P_c$  and  $Q_c$  are the

active and reactive power flowing through the SGSC. Under unbalanced grid voltage, the stator voltage and current of the generator will keep balanced by the effective control of the SGSC, and the power outputted by the stator will include no double frequency oscillations. However, according to the equation (6) and (10), it can be seen that the power through the SGSC and PGSC contain double frequency components. Therefore, the total output active and reactive power of the whole system contain double frequency components, which can be expressed as the equation (12), among which  $P_{t2}$  and  $Q_{t2}$  represent the double frequency components in the total output active and reactive power. The double frequency components contained in the output power will reduce the grid power quality. Therefore, in order to achieve the goal that the total output active and reactive power of the whole system contain no double frequency oscillations, it is necessary to take a suitable compensation measure for the PGSC to make the double frequency components in the output power of PGSC be equal to that through the SGSC. In this way, the output quality of the entire system under unbalanced grid voltage will be improved to meet the requirements of grid connection under different operating conditions.

$$\begin{cases} P_{t}=P_{s}+P_{g}-P_{c}\\ Q_{t}=Q_{s}+Q_{g}-Q_{c} \end{cases}$$
(11)

$$\begin{cases} P_{t2} = P_{g2}^{p} - P_{c2}^{p} \\ Q_{t2} = Q_{g2}^{p} - Q_{c2}^{p} \end{cases}$$
(12)

# 4.2. Control strategy of the PGSC under unbalanced grid voltage

The control objective of the PGSC is to make the DC capacitor voltage constant and adjust the power factor of the wind turbine access point. It is necessary to add a compensation controller which can have a large gain when the frequency is two times as much as the grid frequency without affecting normal operation of the system under unbalanced grid voltage. Proportional resonance controller which is widely used in converters and filters can realize no static error adjustment of sinusoidal quantity. And controlling of double frequency components in the power independently is achieved to compensate the output voltage of the PI controller so that the double frequency oscillation in the total active and reactive power of the DFIG system are suppressed simultaneously.

The transfer function of PR controller is

$$G_{PR}\left(s\right) = k_p + \frac{2k_R s}{s^2 + \omega^2} \tag{13}$$

Where  $\omega$  is the angular frequency of the grid, and it is set to two times as much as the angular frequency when the grid voltage is unbalanced.  $k_p$  is the proportional coefficient while  $k_R$  is the resonance coefficient. Bring  $s = j\omega$  into the equation (13) and the gain of PR controller at its fundamental frequency can be obtain as

$$G_{PR}(s) = k_p + \frac{2jk_R\omega}{(j\omega^2) + \omega^2} = \infty$$
(14)

According to the equation (14), it can be seen that the gain of PR controller at its fundamental frequency is infinite. But in the actual operation of power system, the frequency fluctuation of  $\pm 0.5$  Hz is allowed, however, PR controller has rapid attenuation of the gain at other frequencies. Therefore, in order to widen high-gain band of the PR controller, a cut-off frequency is usually introduced to constitute a quasi-PR (Q-PR) controller whose transfer function is expressed as

$$G_{QPR}(s) = k_p + \frac{2\omega_c k_R s}{s^2 + 2\omega_c s + \omega^2}$$
(15)

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Where  $\omega_c$  is the cut-off frequency. Bring  $s = j\omega$  into the equation (15) and the gain of quasi-PR controller at its fundamental frequency can be obtained as

$$G_{QPR}(s) = k_p + \frac{2j\omega_c k_R \omega}{(j\omega)^2 + 2j\omega_c \omega + \omega^2} = k_p + k_R$$
(16)

The gain of Q-PR controller at its fundamental frequency is  $k_p + k_R$ , which can be adjusted. And Q-PR controller avoid the problem that infinite gain leads to instability of the controller.



Figure 3. The Bode diagram of  $G_{QPR}(s)$ .

The Bode diagram of  $G_{QPR}(s)$  is shown in figure 3. For a Q-PR controller, the parameter  $k_R$  determines the amplitude gain at the fundamental frequency, the bigger  $k_R$  is, the greater amplitude gain is. The width of system band depends on  $\omega_c$ , the bigger  $\omega_c$  is, the wider the band is. And  $k_p$  affects the amplitude gain and phase margin at the low and high frequency, the smaller it is, the lower the gain at low and high frequency is, meanwhile, the time of dynamic response will also be reduced.

For the sake of controlling the double frequency components in the output power of PGSC, the derivative of equation (13) need to be obtained and it can be expressed as

$$\begin{cases} \frac{dP_{g2}^{p}}{dt} = \frac{3}{2} \left( i_{gd0}^{p} \frac{dU_{gd2}^{p}}{dt} + i_{gq0}^{p} \frac{dU_{gq2}^{p}}{dt} + U_{gd0}^{p} \frac{di_{gd2}^{p}}{dt} \right) \\ \frac{dQ_{g2}^{p}}{dt} = \frac{3}{2} \left( i_{gd0}^{p} \frac{dU_{gq2}^{p}}{dt} - i_{gq0}^{p} \frac{dU_{gd2}^{p}}{dt} - U_{gd0}^{p} \frac{di_{gq2}^{p}}{dt} \right) \end{cases}$$
(17)

In order to control double frequency components independently, the equations (8) and (9) should be combined, then the voltage equation of double frequency in PGSC can be expressed as

$$\begin{bmatrix} E_{gd2}^{p} \\ E_{gq2}^{p} \end{bmatrix} = -R_{g} \begin{bmatrix} i_{gd2}^{p} \\ i_{gq2}^{p} \end{bmatrix} - L_{g} p \begin{bmatrix} i_{gd2}^{p} \\ i_{gq2}^{p} \end{bmatrix} + \omega_{g} L_{g} \begin{bmatrix} i_{gq2}^{p} \\ -i_{gd2}^{p} \end{bmatrix} + \begin{bmatrix} U_{gd2}^{p} \\ U_{gq2}^{p} \end{bmatrix}$$
(18)

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The equations (17) and (18) are united, and the control equation of double frequency components in the power can be described as

$$\left| \frac{2L_{g}}{3U_{gd0}^{p}} \frac{dP_{g2}^{p}}{dt} = \frac{L_{g}i_{gd0}^{p}}{U_{gd0}^{p}} \frac{dU_{gd2}^{p}}{dt} + \frac{L_{g}i_{gq0}}{U_{gd0}^{p}} \frac{dU_{gq2}^{p}}{dt} + U_{gd2}^{p} - R_{g}i_{gd2}^{p} + \omega_{g}L_{g}i_{gq2}^{p} - E_{gd2}^{ref} \right| \\
\left| \frac{2L_{g}}{3U_{gd0}^{p}} \frac{dQ_{g2}^{p}}{dt} = -\frac{L_{g}i_{gd0}^{p}}{U_{gd0}^{p}} \frac{dU_{gd2}^{p}}{dt} + \frac{L_{g}i_{gd0}^{p}}{U_{gd0}^{p}} \frac{dU_{gq2}^{p}}{dt} - U_{gq2}^{p} + R_{g}i_{gq2}^{p} + \omega_{g}L_{g}i_{gd2}^{p} + E_{gq2}^{ref} \right| \\$$
(19)

Where  $E_{gd2}^{ref}$  and  $E_{gd2}^{ref}$  indicate the double frequency voltage commands in the positive dq reference frame.

According to the control principle of the Q-PR controller, the voltage command of power compensation controller can be designed as

$$E_{gd2}^{ref} = w_{gd2}^{p} - \frac{2L_{g}}{3U_{gd0}} \left( k_{p} + \frac{2\omega_{c}k_{R}s}{s^{2} + 2\omega_{c}s + (2\omega_{g})^{2}} \right) \left( P_{g2}^{ref} - P_{g2}^{p} \right)$$

$$E_{gq2}^{ref} = w_{gq2}^{p} + \frac{2L_{g}}{3U_{gd0}} \left( k_{p} + \frac{2\omega_{c}k_{R}s}{s^{2} + 2\omega_{c}s + (2\omega_{g})^{2}} \right) \left( Q_{g2}^{ref} - Q_{g2}^{p} \right)$$
(20)

Where  $P_{g_2}^{ref}$  and  $Q_{g_2}^{ref}$  represent reference values of the double frequency components in the active and reactive power outputted by the PGSC. And the block diagram of power compensation based on the Q-PR controller is shown in figure 4.



Figure 4. The block diagram of power compensation based on the Q-PR controller.

There is the configuration of the coordinated control system for the doubly fed wind power generation system with a SGSC in figure 5, and  $\theta_g$  is the angle of the grid voltage calculated by the phase locked loop (PLL).

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**Figure 5.** The configuration of the coordinated control strategy for the doubly fed wind power generation system with a SGSC.

#### 5. Simulation results

For verifying the validity and availability of the coordinated control strategy proposed in this paper, the DFIG system model shown in figure 1 has been conducted in PSCAD/EMTDC and the simulation analyses are performed. The main parameters of the simulation model are shown in table 1 (Several parameters refer to the literature [15]).

Table	<b>1.</b> The	parameters	of system	simulation	model.
		P			

Model parameters	Value
Rated frequency system/Hz	50
Rated power of DFIG/MW	0.9
Stator rated voltage of DFIG/kV	0.69
Voltage ratio step-up transformer /kV	0.69/20
Voltage ratio series transformer /kV	0.69/0.69
SGSC connected inductance/mH	0.12
DC capacitor/µF	7800
DC voltage/kV	0.8

The DFIG system operates under normal grid voltage between 0 and 5s. After 5s, the grid voltages of B and C phase fall 80% at the same time.  $5\sim7s$ , only the SGSC voltage compensation control strategy is adopted, and the coordinated control strategy of SGSC and PGSC is adopted after 7s.

Figure 6 shows the three-phase voltage simulation results of the system installed a SGSC when the grid voltage fails. According to figure 6(a), it can be seen that the asymmetric fault occurs in the grid after 5s, while the voltages of B and C phase simultaneously drop. And the stator voltage without a SGSC is shown in figure 6(b). After the transformation of step-up transformer, the grid voltage will not contain zero-sequence component, only the positive and

negative sequence components are included. Figure 6(c) shows the compensation voltage which the SGSC outputs. Figure 6(d) shows that the stator voltage with the SGSC. Through the effective control of the SGSC, the stator voltage of the DFIG is consistent with normal grid voltage after short transient process, and the SGSC has a great dynamic response characteristic.



**Figure 6.** Voltage simulation results of the DFIG system with a SGSC. (a) The grid voltage, (b) The stator voltage before compensating, (c) The voltage outputted by SGSC and (d) The stator voltage after compensating.



**Figure 7.** Steady state simulation waveforms with conventional control strategy. (a) The output active power of system, (b) The output reactive power of system, (c) The stator current and (d) The rotor current.

For highlighting the feasibility and superiority of the control strategy better, the case that DFIG system still adopts the conventional control strategy under unbalanced conditions is used as a comparative example. Figures 7(a) and 7(b) show the simulation waveforms of the total active power and reactive power which the DFIG system with the conventional control strategy

outputs, respectively. According to the simulation results, the total active power of the whole system under conventional control strategy includes double frequency components with the amplitude of 0.095 MW approximately during grid unbalance, and the total reactive power includes double frequency components with the amplitude of 0.133 Mvar approximately. The stator current is shown in figure 7(c), while the rotor current waveform is shown in figure 7(d). It can be seen that the stator current become unbalanced severely, and distortion of stator current appears.

Figures 8(a) and 8(b) show the simulation waveforms of the total active power and reactive power which the DFIG system only with a SGSC outputs respectively. The simulation results indicate that the total active power of the DFIG system with a SGSC only includes double frequency components with the amplitude of 0.055 MW approximately when the grid voltage is unbalanced, and the total reactive power includes double frequency components with the amplitude of 0.060Mvar approximately. Compared to the double frequency components under the conventional control strategy, they decrease by 42.1% and 54.9%, respectively. The stator and rotor currents of DFIG under SGSC voltage compensation strategy is shown in figure 8(c) and figure 8(d) respectively, it can be seen that the stator and rotor currents maintain balanced, for which the operating stability of the DFIG system with a SGSC is significantly enhanced.



**Figure 8.** Steady state simulation waveforms of the DFIG system with a SGSC. (a) The output active power of system, (b) The output reactive power of system, (c) The stator current and (d) The rotor current.

Figures 9(a) and 9(b) show the simulation results of the total active power and reactive power which the DFIG system with the coordinated control of SGSC and PGSC strategy outputs respectively, and it can be calculated from the simulation plots that the total active power of the DFIG system with coordinated control of SGSC and PGSC strategy includes double frequency components with the amplitude of 0.0062 MW approximately under the unbalanced grid condition, and the total reactive power includes double frequency components with the approximately. Compared to the active and reactive double frequency components that the DFIG system with the conventional control strategy outputs, they decrease by 93.5% and 95.2%, respectively. The simulation pictures of the total output active and reactive power double frequency components are shown in figures 9(c) and 9(d), and the transient process of the simulation waveforms states that the coordinated control strategy has a good dynamic response characteristic. The stator and rotor currents of the DFIG with coordinated control strategy are shown in figures 9(e) and 9(f), respectively. The stator and rotor currents

still remain balanced, which indicates that the coordinated control strategy can also realize the suppression of the power double frequency oscillations without affecting the normal operation of the system. Therefore, the case verifies the validity and feasibility of the proposed control strategy.



**Figure 9.** Steady state simulation waveforms with the coordinated control strategy. (a) The output active power of system, (b) The output reactive power of system, (c) Double frequency components, (d) Double frequency components of the total output active power of the total output reactive power, (e) The stator current and (f) The rotor current.

#### 6. Conclusion

Based on the unbalance of the stator and rotor currents of the DFIG and the double frequency oscillations of the output power under unbalanced grid voltage, the operating mechanism that the added SGSC maintain the stator voltage balance is analyzed, Through the reasonable control of the SGSC, it is ensured that the stator voltage of the DFIG is consistent with the three-phase voltage of normal grid, then the stator and rotor currents maintain balanced and the grid connected operation performance of the DFIG is improved under unbalanced grid voltage. Furthermore, the control strategy for RSC need not be changed under unbalanced grid voltage. On the basis of the DFIG system with a SGSC, the mathematical model of the PGSC is analyzed and the double frequency power control equation is established under unbalanced grid voltage. Combined with the double frequency oscillations generated by the SGSC, a control strategy based on a Q-PR power compensator for PGSC is proposed to suppress the double frequency oscillations of the active and reactive power output simultaneously. The coordinated control strategy of SGSC and PGSC improves the output quality of the doubly fed wind power generation system while ensuring the normal operation of the DFIG. Finally, the proposed coordinated control strategy has been verified by building a simulation model in

PSCAD/EMTDC. The simulation results indicate that the coordinated control strategy has dynamic characteristic, and the capacity of resisting disturbance of DFIG system is significantly improved under the fault of grid voltage.

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