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A Control Strategy of DFIG under Unbalanced Grid Voltage

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***Abstract*—Under an unbalanced power grid voltage conditions, the DFIG's stator side active power, reactive power, and electromagnetic torque will generate twice-multiplied frequency pulse quantities. In this paper, a double SRF (synchronous rotating coordinate system) control strategy was advanced. This strategy will produce a corresponding rotor voltage and current when controlling the DFIG's rotor voltage and current, and then control them to eliminate the effects of an unbalanced grid voltage. The simulation model was set up using the software EMTP-RV, and the DFIG's stator side active power, reactive power, and electromagnetic torque were analysed using both the DFIG conventional stator voltage oriented vector control strategy and the double SRF DFIG control strategy under unbalanced power grid voltage conditions. It is verified that the double SRF control strategy can effectively eliminated twice-multiplied frequency pulse quantity of the electromagnetic torque, reactive power and total mechanical power under unbalanced power grid voltage conditions. It has great significance to the DFIG stability working by using the double SRF control strategy in the DFIG control system.**

***Index Terms*—Double-fed induction generator, unbalanced grid voltage, double synchronization rotate frame, simulation, control strategy.**

I. INTRODUCTION

Due to the distribution characteristics of wind resources, most of the wind power turbine system is located in remote areas, where longer power transmission lines are usually needed for electrical energy transmission. On the one hand, it makes the grid relatively weak at the junction of the wind farm access to the power grid; on the other hand, the unbalanced phenomenon could be aroused at the junction of wind generators access to the power grid because of the asymmetry of grid impedance, line breakage, insulation aging etc. [1], [2].The unbalanced grid voltages have the negative effects on the motor's normal operation, such as power energy loss increasing, device heat increasing, torque rippling and which in turn cause reactive power fluctuations and the fatigue loss of the gear box and mechanical transmission shaft, etc. Corresponding control measures must be taken, otherwise the unbalanced effects will deteriorate the grid voltages further [3], [4]. Therefore, as for the alternators, the wind generators would be cut out from power grid when the grid voltage's unbalance degree reaches a certain value (such as 6 %) [5]. In fact, most wind generators' access to distributed power system has been away from the power grid when the grid voltage's unbalance degree is higher than 2 % [6]. The grid voltage's unbalance degree has direct effects on the DFIG operation states for its stators were directly connected to the grid.

But how the DFIGs' operation states are controlled under unbalanced power voltage? At present, three research methods could eliminate the impacts of unbalanced grid voltage: firstly, by feeding a series converter into in the DFIG's stator loop [7], [8]; secondly, by controlling power grid side converter to have the STATCOM features for compensating stator voltage [9]; thirdly, by controlling rotor side current or voltage of the DFIG [10]. This paper focuses on the third unbalanced control strategy of DFIG, that is the double synchronization rotate frame (SRF) control strategy.

II. DFIG RUNNING STATE UNDER UNBALANCED GRID VOLTAGES

A. Definition unbalance

For an unbalanced three-phase power system, the unbalance degree of three-phase voltage is usually expressed by the percentage of the specific value of negative and positive sequence components, as represented by the following

$$\varepsilon = \frac{u}{u} \times 100\%. \tag{1}$$

As it isn't convenient to in on-site measurement and calculation, this paper adopts the simplified scalar Unbalance definition as follows

$$\varepsilon_u = \frac{82\sqrt{\left(\left|U_{AB}\right| - u_{Lavg}\right)^2 + \left(\left|U_{BC}\right| - u_{Lavg}\right)^2 + \left(\left|U_{CA}\right| - u_{Lavg}\right)^2}}{u_{Lavg}}, \tag{2}$$

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where $|U_{AB}|$, $|U_{BC}|$, $|U_{CA}|$ respectively represent AB, BC, CA three-phase line voltage phase; $u_{Lavg}=(|U_{AB}|+|U_{BC}|+|U_{CA}|)/3$ is the average line voltage phasor.

B. DFIG operating status analysis

Under an unbalanced grid voltage conditions, using symmetrical component method we analyse the DFIG's operating status. Positive sequence voltage of the stator coil will initiate positive sequence current and which in turn cause the rotating magnetic field of the same rotating direction as rotor; negative sequence voltage of the stator coil will initiate negative sequence current and which in turn cause rotating magnetic field of the opposite rotating direction as rotor. Normally, the DFIG has no neutral line, so the effects of zero sequence components needn't be taken into account in the analysis.

Using the symmetric component method, the DFIG's circuit can be equivalent to the sum of positive and negative sequence circuits, and every circuit maintains a three-phase balanced status. Similar to the analysis under a balanced power grid, under an unbalanced power grid, the DFIG's mathematical model in positive and negative sequence SRF can be respectively obtained by DFIG operating status analysis in the positive SRF (d^p q^p) and negative SRF (d^n q^n). U^p_{rdq} and U^n_{rdq} represent respectively the rotor voltage's positive and negative sequence components in SRF; $I_{sdq}{}^p$ and $I_{sdq}{}^n$ represent respectively the stator current's positive and negative sequence components in SRF; $I_{rdq}{}^p$ and $I_{rdq}{}^n$ represent respectively the rotor current's positive and negative sequence components in SRF; Ψ^p_{sdq} and Ψ^n_{sdq} represent respectively the stator flux linkage's positive and negative sequence components in SRF; Ψ^p_{rdq} and Ψ^n_{rdq} represent respectively the rotor flux linkage's positive and negative sequence components in SRF.

In positive sequence SRF, DFIG's mathematical model can be expressed as follows：

$$\begin{cases}\psi^p_{sdq}=L_S I^p_{sdq}+L_m I^p_{rdq},\\ \psi^p_{rdq}=L_m I^p_{sdq}+L_r I^p_{rdq},\\ U^p_{sdq}=R_s I^p_{sdq}+\dfrac{d}{dt}\psi^p_{sdq}+j\omega_{s0}\psi^p_{sdq},\\ U^p_{rdq}=R_s I^p_{rdq}+\dfrac{d}{dt}\psi^p_{rdq}+j\left(\omega_{s0}-\omega_r\right)\psi^p_{rdq}.\end{cases} \tag{3}$$

In negative sequence SRF, DFIG's mathematical model can be expressed as follows：

$$\begin{cases}\psi^n_{sdq}=L_s I^n_{sdq}+L_m I^n_{rdq},\\ \psi^n_{rdq}=L_m I^n_{sdq}+L_r I^n_{rdq},\\ U^n_{sdq}=R_s I^n_{sdq}+\dfrac{d}{dt}\psi^n_{sdq}-j\omega_{s0}\psi^n_{sdq},\\ U^n_{rdq}=R_s I^n_{rdq}+\dfrac{d}{dt}\psi^n_{rdq}-j\left(\omega_{s0}+\omega_r\right)\psi^n_{rdq}.\end{cases} \tag{4}$$

According to the relationship between positive and negative sequence SRF and the stationary coordinate system ABC, the positive and negative sequence voltage vector of the stationary coordinate system can be expressed respectively as follows

$$U^p=e^{j\left(\omega_{s0}t+\varphi^p\right)}U^p_{dq},\ \ U^n=e^{-j\left(\omega_{s0}t+\varphi^n\right)}U^n_{dq}. \tag{5}$$

In the above expression, U^p and U^n represent respectively the positive and negative sequence voltage vector of the static coordinate system ABC.

Therefore, the stator voltage vector U^s under an unbalanced power grid can be expressed as follows

$$U_s=U^p_s+U^n_s=e^{j\left(\omega_{s0}t+\varphi^P\right)}U^p_{sdq}+e^{-j\left(\omega_{s0}t+\varphi^n\right)}U^n_{sdq}. \tag{6}$$

Similarly, the stator current vector I_s can be expressed as follows

$$I_s=I^p_s+I^n_s=e^{j\left(\omega_{so}t+\varphi^P\right)}I^p_{sdq}+e^{-j\left(\omega_{s0}t+\varphi^n\right)}I^n_{sdq}. \tag{7}$$

Using the coordinate's equivalent transformation method, the DFIG's stator side complex power in an unbalanced power grid can be expressed as follows

$$\overline{S_S}=\frac{3}{2}U_S I^*_S. \tag{8}$$

Taking expression (6) and (7) into expression (8) will yield the following expression:

$$\begin{cases}P_s(t)=\dfrac{3}{2}[P_{s0}+P_{sc2}\cos(2\omega_{s0}t+\varphi^P+\varphi^n)+P_{ss2}\sin(2\omega_{s0}t+\varphi^P+\varphi^n),\\ Q_s(t)=\dfrac{3}{2}[Q_{s0}+Q_{sc2}\cos(2\omega_{s0}t+\varphi^P+\varphi^n)+Q_{ss2}\sin(2\omega_{s0}t+\varphi^P+\varphi^n).\end{cases} \tag{9}$$

In the above expression, P_{s0} and Q_{s0} represent respectively the average of stator side active power and reactive power; P_{sc2}, P_{ss2}, Q_{sc2} and Q_{ss2} represent respectively the amplitude of twice-multiplied frequency pulse quantity of the DFIG's stator side active power and reactive power, and the frequency of which is $2\omega_{S0}$.

Expression (9) shows that stator side active power and reactive power emerge apparently twice-multiplied frequency pulse quantity when the DFIG is working under an unbalanced power grid and the relationships between P_{s0}, P_{sc2}, P_{ss2}, Q_{s0}, Q_{sc2}, Q_{ss2}, and stator voltage and current can be expressed as follows：

$$\begin{bmatrix}P_{s0}\\P_{sc2}\\P_{ss2}\\Q_{s0}\\Q_{sc2}\\Q_{ss2}\end{bmatrix}=\begin{bmatrix}u^p_{sq}&u^p_{sd}&u^n_{sq}&u^n_{sd}\\u^n_{sq}&u^n_{sd}&u^p_{sq}&u^p_{sd}\\-u^n_{sd}&u^n_{sq}&u^p_{sd}&-u^p_{sq}\\-u^p_{sd}&u^p_{sq}&-u^n_{sd}&u^n_{sq}\\-u^n_{sd}&u^n_{sq}&-u^p_{sd}&u^p_{sq}\\-u^n_{sq}&-u^n_{sd}&u^p_{sq}&u^p_{sd}\end{bmatrix}\begin{bmatrix}i^p_{sq}\\i^p_{sd}\\i^n_{sq}\\i^n_{sd}\end{bmatrix}. \tag{10}$$

The above expression shows that, in order to eliminate twice-multiplied frequency pulse quantity of active power and reactive power, the expression $\left[\mathrm{P_{SC2}}\ \mathrm{P_{SS2}}\ \mathrm{Q_{SC2}}\ \mathrm{Q_{SS2}}\right]^{\mathrm{T}}=0$ must be workable, and DFIG's stator current matrix $\left[\mathrm{i}_{\mathrm{sq}}^{\mathrm{P}}\ \mathrm{i}_{\mathrm{sd}}^{\mathrm{P}}\ \mathrm{i}_{\mathrm{sq}}^{\mathrm{N}}\ \mathrm{i}_{\mathrm{sd}}^{\mathrm{N}}\right]^{\mathrm{T}}$ must have zero solution. In other words, when DFIG working in an unbalanced power grid, there will be only one group of stator currents that can eliminate active power or reactive power pulse quantity as the stator side active power and reactive power is a fixed value, but active power and reactive power cannot be eliminated at the same time.

As coupling occurs between the stator magnetic field and the rotor-magnetic field, the DFIG's rotor voltage and rotor current have a harmonic wave which has a frequency equal to $\omega_{S0}+\omega_{r}$. Similar to the analysis of the stator, rotor side active power and reactive power can be obtained as follows:

$$\begin{cases} P_r(t)=\dfrac{3}{2}[P_{r0}+P_{rc2}\cos(2\omega_{s0}t+\varphi^{rp}+\varphi^{rn})+P_{rs2}\sin(2\omega_{s0}t+\varphi^{rp}+\varphi^{rn})], \\ Q_r(t)=\dfrac{3}{2}[Q_{r0}+Q_{rc2}\cos(2\omega_{s0}t+\varphi^{rp}+\varphi^{rn})+Q_{rs2}\sin(2\omega_{s0}t+\varphi^{rp}+\varphi^{rn}). \end{cases} \tag{11}$$

In the above expression, P_{r0}, Q_{r0} represent respectively the average of rotor side active power and reactive power; P_{rc2}, P_{rs2}, Q_{rc2}, and Q_{rs2} represent respectively the twice-multiplied frequency pulse amplitudes of the DFIG's rotor side active power and reactive power, the frequency is $2\omega_{s0}$. The above also shows that the rotor side power emerge twice-multiplied frequency pulse quantity of 100 Hz when the DFIG is working in an unbalanced power grid.

Neglecting loss, DFIG electromagnetic torque can be expressed as follows

$$\begin{aligned} T_e=\frac{1}{\omega_r}(P_s+P_r)= \\ =\frac{3}{2\omega}\Big[\left(P_{s0}+P_{r0}\right)+P_{sc2}\cos(2\omega_{s0}t+\varphi^{p}+\varphi^{n})+ \\ +P_{ss2}\sin(2\omega_{s0}t+\varphi^{p}+\varphi^{n})+ \\ +P_{rc2}\cos(2\omega_{s0}t+\varphi^{rp}+\varphi^{rn})+ \\ +P_{rs2}\sin(2\omega_{s0}t+\varphi^{rp}+\varphi^{rn})\Big]. \end{aligned} \tag{12}$$

Clearly, the twice-multiplied frequency pulse quantity of DFIG electromagnetic torque can be reduced or even eliminated by controlling the amplitude and phase position of the DFIG's rotor side power twice-multiplied frequency pulse.

From the above analysis, if no unbalanced control strategies are taken, twice-multiplied frequency pulse quantity will emerge both in stator and rotor side active power and reactive power, and electromagnetic torque, and even in the total output power of the power system when DFIG is working in an unbalanced power grid. Additionally, the twice-multiplied frequency pulse quantity is almost directly proportion to the increase in power grid Unbalance. And from the above analysis, it can be seen that twice-multiplied frequency pulse quantity of electromagnetic torque is consistent with twice-multiplied frequency pulse quantity of reactive power when the DFIG is working in an unbalanced power grid, and those two pulse quantities can be eliminated if some control measures are taken. Due to the DFIG's larger time constant of mechanical inertia, the speed of twice-multiplied frequency pulse quantity is very small. The twice-multiplied frequency pulse quantity of mechanical input power will be weakened when twice-multiplied frequency pulse quantity of the electromagnetic torque is eliminated, thus, even if the DFIG's stator side still has a larger amount of active power twice-multiplied frequency pulse quantity, twice-multiplied frequency pulse quantity of the entire wind power generation system caused by the unbalanced grid will be improved.

III. DOUBLE SRF CONTROL SYSTEM DESIGN

Due to the existence of the grid voltage negative's sequence components, the stator's active power, reactive power, and electromagnetic torque will generate twice-multiplied frequency pulse quantities. And producing appropriate rotor voltage and current by the control of the rotor side voltage and current is the key to enhancing DFIG unbalanced operation capacity, thus the control goal can be succeeded.

The double SRF control strategy is based on the symmetrical component method, where the rotor's positive and negative sequence currents in the positive and negative SRF are controlled respectively based on the DFIG's mathematical model in positive and negative SRF. The rotor's positive sequence current reference set is based on the controlling function of the DFIG's average active power (average torque) and average reactive power, and the rotor's negative sequence current set is based on the corresponding unbalanced control target.

The positive and negative sequence vector orientation of stator voltage is used respectively in the positive synchronous rotating coordinate system (d^p q^p) and the negative synchronous rotating coordinate system (d^n q^n), expressed as follows:

$$\begin{cases} u_{sq}^{p}=u_{s}^{p}, \\ u_{sd}^{p}=0, \end{cases} \text{ and } \begin{cases} u_{sq}^{n}=u_{s}^{n}, \\ u_{sd}^{n}=0. \end{cases} \tag{13}$$

From the DFIG flux linkage model type in the positive and negative SRF, I_{sqd}^{p} and I_{sqd}^{n} can be given as follows:

$$\begin{cases} I_{sdq}^{p}=\dfrac{1}{L_s}\psi_{sdq}^{p}-\dfrac{L_m}{L_s}I_{rdq}^{p}, \\ I_{sdq}^{n}=\dfrac{1}{L_s}\psi_{sdq}^{n}-\dfrac{L_m}{L_s}I_{rdq}^{n}. \end{cases} \tag{14}$$

Taking (13) and (14) into (10), the amplitude of stator reactive power twice-multiplied frequency pulse quantity can be given as follows:

$$\begin{cases} Q_{sc2}=\dfrac{1}{L_s}(u_s^p\psi_{sd}^n+u_s^n\psi_{sd}^p)-\dfrac{L_m}{L_s}(u_s^p i_{rd}^n+u_s^n i_{rd}^p), \\ Q_{ss2}=\dfrac{1}{L_s}(u_s^p\psi_{sq}^n-u_s^n\psi_{sq}^p)-\dfrac{L_m}{L_s}(u_s^p i_{rq}^n-u_s^n i_{rq}^p). \end{cases} \tag{15}$$

Making $Q_{sc2}=0, Q_{ss2}=0$, the following expression can be obtained:

$$\begin{cases} i_d^n = -\varepsilon_u i_d^p, \\ i_q^n = -\varepsilon_u i_q^p. \end{cases} \tag{16}$$

Taking (16) into the rotor current vector, when the control target of $Q_{sc2}=0, Q_{ss2}=0$ is achieved, the maximum amplitude of the needed rotor current should be

$$\left|I_r^r\right| = \left|I_r^{rp}\right| + \left|I_r^{rn}\right| = (1+\varepsilon_u)\sqrt{(i_{dr}^p)^2 + (i_{qr}^p)^2}. \tag{17}$$

The above expression shows that, in the certain case of i_{rd}^p and i_{rq}^p, the amplitude of rotor side current is increased with the increase of grid voltage unbalance degree ε_μ, which means when unbalance attains a certain value (beyond the design capacity of DFIG's rotor converter), the DFIG have to work with load shedding, or even be off the power grid.

The control of the coordinate system (d^p q^p) can be designed based on the DFIG voltage (3) in positive sequence SRF. If using a PI adjuster, the PI adjuster's output can be used to control the rotor current's dynamic items in (3), the controlling equation of rotor voltage in coordinate system (d^p q^p) can be obtained:

$$\begin{cases} u_{rq}^{p^*} = (K_{irP} + \dfrac{K_{irI}}{s})(i_{rq}^{p^*} - i_{rq}^p) + u_{rqc}^p, \\ u_{rd}^{p^*} = (K_{irP} + \dfrac{K_{irI}}{s})(i_{rd}^{p^*} - i_{rd}^p) + u_{rdc}^p. \end{cases} \tag{18}$$

In the above expression:

$$\begin{cases} u_{rqc}^p = \dfrac{L_m}{L_s}u_s^p - \dfrac{L_m}{L_s}(\dfrac{R_s}{L_s}\psi_{sq}^p + \omega_r\omega_{sd}^p) - (\omega_{s0}+\omega_r)(L_r - \dfrac{L_m^2}{L_s})i_{rd}^p, \\ u_{rdc}^p = \dfrac{L_m}{L_s}(\dfrac{R_s}{L_s}\psi_{sd}^p + \omega_r\omega_{sq}^p) - (\omega_{s0}+\omega_r)(L_r - \dfrac{L_m^2}{L_s})i_{rq}^p. \end{cases} \tag{19}$$

Similarly, the controlling of the coordinate system (d^p q^p) can be designed based on the rotor voltage in (4) in negative sequence SRF, and the controlling equation of rotor voltage in coordinate system (d^p q^p) can be obtained:

$$\begin{cases} u_{rq}^{n^*} = (K_{irP} + \dfrac{K_{irI}}{s})(i_{rq}^{n^*} - i_{rq}^n) + u_{rqc}^n, \\ u_{rd}^{n^*} = (K_{irP} + \dfrac{K_{irI}}{s})(i_{rd}^{n^*} - i_{rd}^n) + u_{rdc}^n. \end{cases} \tag{20}$$

In the above expression:

$$\begin{cases} u_{rqc}^n = \dfrac{L_m}{L_s}u_s^n - \dfrac{L_m}{L_s}(\dfrac{R_s}{L_s}\psi_{sq}^n + \omega_r\omega_{sd}^n) - (\omega_{s0}+\omega_r)(L_r - \dfrac{L_m^2}{L_s})i_{rd}^n, \\ u_{rdc}^n = \dfrac{L_m}{L_s}(\dfrac{R_s}{L_s}\psi_{sd}^n + \omega_r\omega_{sq}^n) - (\omega_{s0}+\omega_r)(L_r - \dfrac{L_m^2}{L_s})i_{rq}^n. \end{cases} \tag{21}$$

Accordingly, the DFIG's double SRF control structure in unbalanced grid voltage can be shown in Fig. 1.

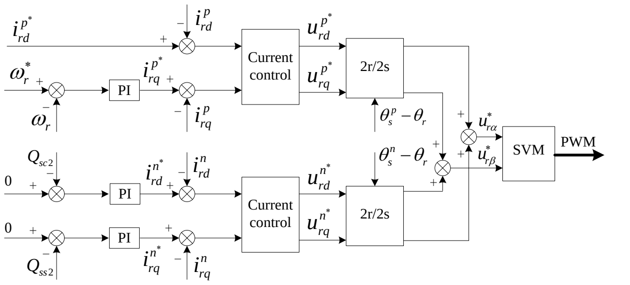

Fig. 1. DFIG's double SRF control structure under unbalanced grid voltage.

IV. SYSTEM SIMULATION

In order to validate the DFIG's double SRF control performance in unbalanced grid voltage, the model and simulation of the designed control system were researched using the software EMTP-RV and used the real wind farm data. The wind farm consisted of 17 sets of 1.5 MW double-fed wind power generators, which are divided into three groups: 5 platforms, 7 platforms and 5 platforms. Its outlet end public generatrixes access the system through a 690/35 kV step-up transformer. A 110 kV power system first connects with a 121 kV/35 kV step-down transformer before connecting to a 35 kV step-up transformer at the wind farm 35 kV output port. Lines use LGJ-300, and their impedance is $R+jX=1.972+j7.777\Omega$. The 110 kV system BUS minimum short-circuit capacity is 1351 MVA, and the system impedance is 8.96 Ω. The degree of the grid voltage unbalance is 10 % in the simulation. The wind power system wiring diagram is shown in Fig. 2.

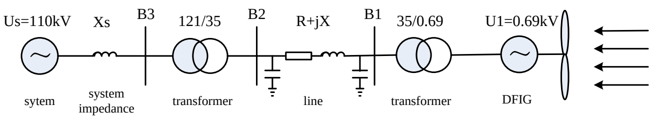

Fig. 2. DFIG wind power systems wiring diagram.

In the simulation, grid voltage was set to only have positive sequence fundamental voltage and negative sequence fundamental voltage and the degree of the power grid three-phase voltage unbalance is 10 %. The simulation time was set to 10 s, step length was 50 μs. In analysed simulation, the results of the stator side reactive power, electromagnetic torque, and total mechanical power waveform of the conventional vector control strategy were obtained and shown respectively in Fig. 3(a), Fig. 3(b) and Fig. 3(c). The results of the stator side reactive power, electromagnetic torque, and total mechanical power waveform of double SRF control strategies are shown respectively in Fig. 3(d), Fig. 3(e), and Fig. 3(f). Comparing the simulation waves of conventional vector control strategy and double SRF control strategy, it is easy to find that, for realizing the target of eliminating stator side reactive power pulsating quantity Q_{sc2} and Q_{ss2}, the twice-multiplied frequency pulse quantities of stator side reactive power Q_s, electromagnetic torque T_e, and total mechanical power P_m have improved inhibition when the double SRF control strategy is adopted.

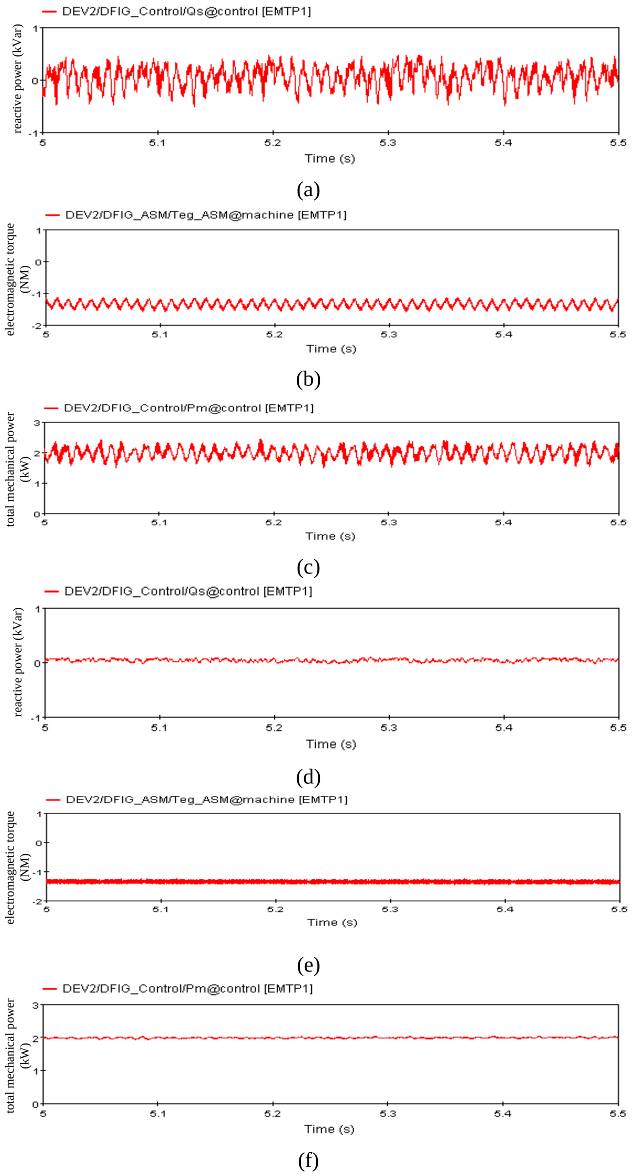

Fig. 3. Contrast between control strategies of double SRF and normal vector control under unbalanced grid voltage conditions: (a) the reactive power under conventional vector controlling, (b) the total mechanical power under conventional vector controlling, (c) the total mechanical power under conventional vector controlling, (d) the reactive power under double SRF controlling, (e) the total mechanical power under double SRF controlling, (f) the total mechanical power under double SRF controlling.

Under unbalanced grid voltage conditions, the stator side reactive power, electromagnetic torque, and total mechanical power waveform FFT harmonic analysis can be obtained under the DFIG conventional control strategy, and the spectrum diagram is shown in Fig. 4, where diagrams in Fig. 4(a), Fig. 4(b) and Fig. 4(c) are respectively the DFIG's stator side reactive power, electromagnetic torque, and total mechanical power spectrum under the conventional vector control strategy. Fig. 4(d), Fig. 4(e), and Fig. 4(f) are respectively the DFIG's stator side reactive power, electromagnetic torque, and total mechanical power spectrum under the double SRF control strategy.

In Fig.4 (a), Fig. 4(b), and Fig. 4(c), it is shown that, under an unbalanced grid voltage, in addition to the DC components, the generator's stator side reactive power contain 100 Hz , 200 Hz and 300 Hz ect., the total mechanical power and electromagnetic torque contain 100 Hz components with DFIG conventional vector control strategy. That is to say,under an unbalanced grid voltage, twice-multiplied frequency components will be generated when adopt a conventional vector control strategy.

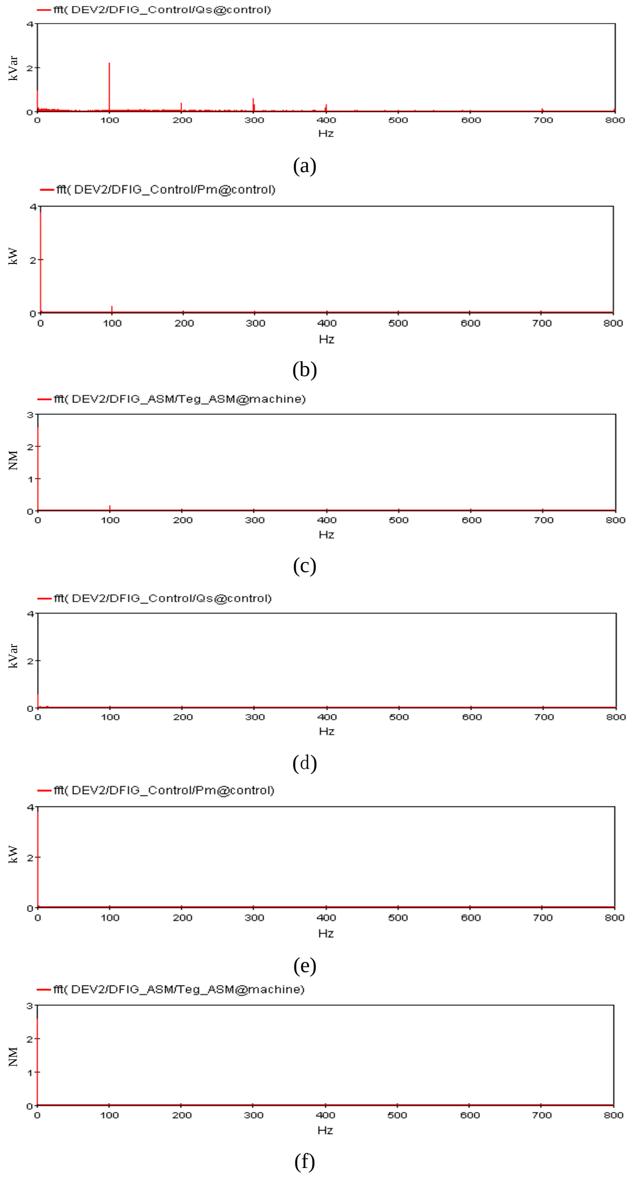

Fig. 4. FFT contrast between control strategies in double SRF and normal vector control unbalanced grid voltage: (a)The reactive power FFT analysis under conventional vector controlling, (b)The total mechanical power FFT harmonic analysis under conventional vector controlling, (c) Electromagnetic torque under conventional vector controlling, (d) The reactive power FFT harmonic analysis under double SRF controlling, (e)The total mechanical power FFT harmonic analysis under double SRF controlling, (f) Electromagnetic torque FFT analysis under double SRF controlling.

Fig.4 (d), Fig. 4(e), and Fig. 4(f) show that, under an unbalanced grid voltage conditions, the generator's stator side reactive power, the general mechanical power, and electromagnetic torque only contain DC components when adopt the DFIG double SRF control strategy, that is to say, two times frequency components are eliminated.

V. Conclusions

Due to the wind energy resources usually being located in remote areas, the electric grid is relatively weak and the

DFIG is often working under unbalanced grid voltage conditions. If appropriate unbalanced control strategy is not taken, the electromagnetic torque, the stator power, and reactive power will generate twice-multiplied frequency pulses resulting from the negative sequence components of grid voltage. It not only threatens wind power generators' safe operation, but also reduces the power quality of the wind power generation system.

This paper theoretically analyses the DFIG's operation characteristic under unbalanced grid voltage conditions; and studies DFIG unbalanced control strategies, advancing the double SRF control strategy. The analysis and simulation show that the proposed the DFIG double SRF control strategy in this paper can effectively suppress twice-multiplied frequency pulses of the electromagnetic torque, reactive power, and the total mechanical power under the unbalanced grid voltage conditions, and can realize the working stability of the double-fed wind turbine.

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