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Control of DFIG-Based Wind Generation Systems under Unbalanced Network Supply

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Abstract- This paper develops a dynamic model and control scheme for DFIG systems to improve the performance and stability under unbalanced grid conditions. A dynamic DFIG model containing the positive and negative sequence components is presented using stator voltage orientation. The proposed model accurately illustrates the active power, reactive power and torque oscillations, and provides a basis for DFIG control system design during unbalanced network supply. Various control targets such as eliminating the oscillations of the torque, active/reactive power are discussed and the required rotor negative sequence current for fulfilling different control targets are described. Performance of a DFIG-based wind turbine under unbalanced condition using the proposed control method is evaluated by simulation studies using Matlab/Simulink. The proposed control scheme significantly attenuates the DFIG torque or active power oscillations during network unbalance whereas significant torque/power oscillations exist with the conventional control schemes.

I. INTRODUCTION

Nowadays, doubly-fed induction generators (DFIGs) are commonly used for large wind turbines operating at variable speed. For maintaining continuous operation of such wind turbines during power system disturbances, i.e., fault ride through capability, extensive studies have been carried out in the last few years. However, symmetrical voltages are considered in most cases [1-4]. In reality, asymmetric faults occur more frequently than symmetric faults in transmission system. The stator current of a DFIG could be highly unbalanced even with a small unbalanced grid voltage if no unbalance control were considered. The unbalanced voltage and current cause a number of problems such as overheating of stator windings, extra mechanical stresses due to torque pulsation, and output power pulsations.

Control and operation of DFIG systems during network unbalance were studied in [5-8]. However, in [5, 6], the focus was only on controlling the grid side converter to provide similar functions as a STATCOM. In [7, 8], control of DFIG for compensating torque pulsation under unbalanced supply voltage was investigated. However, since the required rotor compensating current oscillates at twice the line frequency, the controller needs to be carefully tuned to provide the required system response at double supply frequency. Furthermore, the impact of unbalanced stator voltage on the stator and rotor currents has not been fully defined and the relationships between the pulsations of the torque, the stator active/reactive power, and the rotor currents have not been fully established.

The aim of this paper is to develop a dynamic model and control scheme for DFIG systems to improve the performance and stability under unbalanced operation. A dynamic model of DFIG systems based on stator voltage orientation (SVO) under unbalanced condition is presented. The relationships between torque, output power, and unbalanced stator voltage supply and rotor current are fully established. Various control targets, such as no torque pulsation, or no power oscillation, are discussed. Based on the developed model, system control using two separate controllers, i.e., positive sequence controller and negative sequence controller are designed. The performance of a DFIG system operating under unbalanced conditions using the proposed control strategy is evaluated by simulations using Matlab/Simulink.

II. DFIG MODELING UNDER UNBALANCED CONDITIONS

The existing DFIG models are primarily developed on the basis of symmetric grid voltage. For unbalanced supply, both positive and negative sequence components of voltage and current need to be considered in order to accurately describe the system behavior. In order to obtain a decoupled control between torque/active power and reactive power, d-axis in the synchronous reference frame is generally oriented along the stator flux vector or the stator voltage vector. In this paper, stator voltage orientation is used.

A complex vector equivalent circuit of a DFIG in an arbitrary dq reference frame rotating at angular speed of ω_e is shown in Fig. 1 [9]. The flux and voltage equations in the synchronous reference frame are given as

$$\begin{aligned}\psi_s &= L_s I_s + L_m I_r \\ \psi_r &= L_r I_r + L_m I_s \\ V_s &= R_s I_s + \frac{d\psi_s}{dt} + j\omega_e \psi_s \\ V_r &= R_r I_r + \frac{d\psi_r}{dt} + j(\omega_e - \omega_r) \psi_r\end{aligned}\quad (1)$$

where ψ , V and I represent the flux, voltage and current. Subscripts s and r denote the stator and rotor quantities respectively. L_s and L_r are the stator and rotor self inductances, L_m is the mutual inductance, and ω_r is the rotor angular frequency.

According to (1), the rotor flux, stator current and rotor voltage can be given as

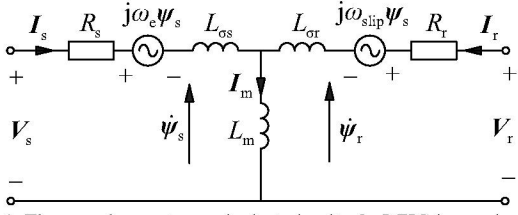


Fig. 1. The complex vector equivalent circuit of a DFIG in synchronous reference frame

$$\begin{aligned}
 \psi_r &= \frac{L_m}{L_s} \psi_s + \sigma L_r I_r \\
 I_s &= \frac{1}{L_s} (\psi_s - L_m I_r) \\
 V_r &= R_r I_r + \sigma L_r \frac{dI_r}{dt} + \frac{L_m}{L_s} \frac{d\psi_s}{dt} \\
 &\quad + j\omega_{slip} \left(\sigma L_r I_r + \frac{L_m}{L_s} \psi_s \right)
 \end{aligned} \tag{2}$$

where $\sigma = 1 - L_m^2 / L_r L_s$ is the leakage factor, and $\omega_{slip} = \omega_e - \omega_r$ is the slip frequency.

Assuming no zero sequence components, the vector F which represents three-phase quantities such as voltage, current and flux can be decomposed into positive and negative sequence components when the network is unbalanced, as [10]

$$\begin{aligned}
 F(t) &= F^p e^{j(\omega_e t + \phi^p)} + F^n e^{j(-\omega_e t + \phi^n)} \\
 &= (F_d^p + jF_q^p) e^{j\omega_e t} + (F_d^n + jF_q^n) e^{-j\omega_e t}
 \end{aligned} \tag{3}$$

where superscripts p and n denote the positive and negative components respectively, whereas subscripts d and q denote the d-axis and q-axis components respectively.

The positive and negative sequence components in the stationary reference frame are then transformed into (dq)+ and (dq)- reference frames rotating at angular speeds of ω_e and $-\omega_e$ respectively. The spatial relationship of these three reference frames is shown in Fig. 2, where d+ axis is oriented to the positive sequence stator voltage vector.

For a DFIG, its instantaneous stator power can be expressed in the (dq)+ reference frame as

$$\begin{aligned}
 p_s + jq_s &= -\frac{3}{2} V_s(t) I_s^*(t) \\
 &= -\frac{3}{2L_s} V_s(t) (\psi_s^*(t) - L_m I_r^*(t))
 \end{aligned} \tag{4}$$

According to (3), the stator voltage V_s , stator flux ψ_s and rotor current I_r can be expressed using their respective positive and negative sequence components. Thus, based on (4), the active and reactive power can then be expressed as

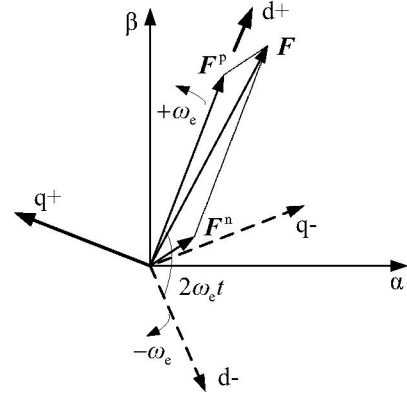


Fig. 2. Positive and negative sequence components and relationship between the different reference frames

$$\begin{aligned}
 p_s &= P_{s_av} + P_{s_sin2} \sin(2\omega_e t) + P_{s_cos2} \cos(2\omega_e t) \\
 q_s &= Q_{s_av} + Q_{s_sin2} \sin(2\omega_e t) + Q_{s_cos2} \cos(2\omega_e t)
 \end{aligned} \tag{5}$$

where $P_s, Q_s, P_{s_sin2}, P_{s_cos2}, Q_{s_sin2}$ and Q_{s_cos2} are given by

$$\begin{bmatrix} P_{s_av} \\ Q_{s_av} \\ P_{s_sin2} \\ P_{s_cos2} \\ Q_{s_sin2} \\ Q_{s_cos2} \end{bmatrix} = -\frac{3}{2L_s} \begin{bmatrix} V_{sd}^p & V_{sq}^p & V_{sd}^n & V_{sq}^n \\ V_{sd}^p & -V_{sq}^p & V_{sd}^n & -V_{sq}^n \\ V_{sd}^n & -V_{sq}^n & -V_{sd}^p & V_{sq}^p \\ V_{sd}^n & V_{sq}^n & V_{sd}^p & V_{sq}^p \\ -V_{sd}^n & -V_{sq}^n & V_{sd}^p & V_{sq}^p \\ V_{sd}^n & -V_{sq}^n & V_{sd}^p & -V_{sq}^p \end{bmatrix} \begin{bmatrix} \psi_{sd}^p \\ \psi_{sq}^p \\ \psi_{sd}^n \\ \psi_{sq}^n \end{bmatrix} - L_m \begin{bmatrix} I_{rd}^p \\ I_{rq}^p \\ I_{rd}^n \\ I_{rq}^n \end{bmatrix} \tag{6}$$

The electromagnetic torque T_e is given by

$$\begin{aligned}
 T_e &= \frac{3}{2} p_n \text{Im} [\psi_s(t) I_r^*(t)] \\
 &= \frac{3}{2} p_n \text{Im} \left[\frac{1}{L_s} \psi_s(t) (\psi_s^*(t) - L_m I_r^*(t)) \right] \\
 &= -\frac{3L_m}{2L_s} p_n \text{Im} [\psi_s(t) I_r^*(t)] \\
 &= T_{e_av} + T_{e_sin2} \sin(2\omega_e t) + T_{e_cos2} \cos(2\omega_e t)
 \end{aligned} \tag{7}$$

where T_{e_av}, T_{e_sin2} and T_{e_cos2} are given by

$$\begin{bmatrix} T_{e_av} \\ T_{e_sin2} \\ T_{e_cos2} \end{bmatrix} = -\frac{3p_n L_m}{2L_s} \begin{bmatrix} \psi_{sq}^p & -\psi_{sd}^p & \psi_{sq}^n & -\psi_{sd}^n \\ -\psi_{sd}^n & -\psi_{sq}^n & \psi_{sd}^p & \psi_{sq}^p \\ \psi_{sd}^n & -\psi_{sq}^n & \psi_{sd}^p & -\psi_{sq}^p \end{bmatrix} \begin{bmatrix} I_{rd}^p \\ I_{rq}^p \\ I_{rd}^n \\ I_{rq}^n \end{bmatrix} \tag{8}$$

According to (1) and neglecting the stator resistance, in the (dq)+ reference frame, the stator voltage is given by

$$\begin{aligned}
V_s(t) &= \frac{d(\psi_s^p + \psi_s^n e^{-j2\omega_e t})}{dt} + j\omega_e (\psi_s^p + \psi_s^n e^{-j2\omega_e t}) \\
&= j\omega_e \psi_s^p - j\omega_e \psi_s^n e^{-j2\omega_e t} \\
&= V_s^p + V_s^n e^{-j2\omega_e t}
\end{aligned} \quad (9)$$

Thus the relationship between stator voltage and stator flux is given as

$$\begin{aligned}
V_s^p &= j\omega_e \psi_s^p \\
V_s^n &= -j\omega_e \psi_s^n
\end{aligned} \quad (10)$$

Due to the fact that the d+ axis is oriented to the positive sequence stator voltage vector, its q+ axis component V_{sq}^p can be regarded as zero. Substituting (10) into (6) and (8) yields, then

$$\begin{aligned}
\begin{bmatrix} P_{s_av} \\ Q_{s_av} \\ P_{s_sin2} \\ P_{s_cos2} \\ Q_{s_sin2} \\ Q_{s_cos2} \end{bmatrix} &= -\frac{3}{2L_s \omega_e} \begin{bmatrix} 0 \\ (V_s^p)^2 - (V_s^n)^2 \\ 2V_{sd}^p V_{sd}^n \\ -2V_{sd}^p V_{sq}^n \\ 0 \\ 0 \end{bmatrix} + \\
&\frac{3L_m}{2L_s} \begin{bmatrix} V_{sd}^p & 0 & V_{sd}^n & V_{sq}^n \\ 0 & -V_{sd}^p & V_{sq}^n & -V_{sd}^n \\ V_{sq}^n & -V_{sd}^n & 0 & V_{sd}^p \\ V_{sd}^n & V_{sq}^p & V_{sd}^p & 0 \\ -V_{sd}^n & -V_{sq}^n & V_{sd}^p & 0 \\ V_{sq}^n & -V_{sd}^n & 0 & -V_{sd}^p \end{bmatrix} \begin{bmatrix} I_{rd}^p \\ I_{rq}^p \\ I_{rd}^n \\ I_{rq}^n \end{bmatrix} \quad (11) \\
\begin{bmatrix} T_{e_av} \\ T_{e_sin2} \\ T_{e_cos2} \end{bmatrix} &= -\frac{3p_n L_m}{2\omega_e L_s} \begin{bmatrix} -V_{sd}^p & 0 & V_{sd}^n & V_{sq}^n \\ V_{sq}^n & -V_{sd}^n & 0 & -V_{sd}^p \\ V_{sd}^n & V_{sq}^p & -V_{sd}^p & 0 \end{bmatrix} \begin{bmatrix} I_{rd}^p \\ I_{rq}^p \\ I_{rd}^n \\ I_{rq}^n \end{bmatrix} \quad (12)
\end{aligned}$$

According to (11) and (12), the following conclusions can be drawn:

(1) To minimize the stator active power fluctuation, i.e., $P_{s_sin2} = 0$ and $P_{s_cos2} = 0$, according to (11) the negative sequence rotor current needs to be controlled as

$$\begin{aligned}
I_{rd}^n &= -\frac{1}{V_s^p} (V_{sd}^n I_{rd}^p + V_{sq}^n I_{rq}^p) - \frac{2V_{sq}^n}{\omega_e L_m} \\
I_{rq}^n &= \frac{1}{V_s^p} (V_{sd}^n I_{rq}^p - V_{sq}^n I_{rd}^p) + \frac{2V_{sd}^n}{\omega_e L_m}
\end{aligned} \quad (13)$$

Under such condition, the average stator active and reactive power and the electromagnetic torque are given by

$$\begin{aligned}
P_{s_av} &= \frac{3L_m}{2L_s} \frac{(V_s^p)^2 - (V_s^n)^2}{V_s^p} I_{rd}^p \\
Q_{s_av} &= -\frac{3}{2L_s} \frac{(V_s^p)^2 + (V_s^n)^2}{V_s^p} \left(\frac{V_s^p}{\omega_e} + L_m I_{rq}^p \right) \\
T_{e_av} &= \frac{3p_n L_m}{2\omega_e L_s} \frac{(V_s^p)^2 + (V_s^n)^2}{V_s^p} I_{rd}^p
\end{aligned} \quad (14)$$

(2) To remove the oscillations of electromagnetic torque, i.e., $T_{e_sin2} = 0$ and $T_{e_cos2} = 0$, according to (12) the required negative sequence rotor current is given as

$$\begin{aligned}
I_{rd}^n &= \frac{1}{V_s^p} (V_{sd}^n I_{rd}^p + V_{sq}^n I_{rq}^p) \\
I_{rq}^n &= \frac{1}{V_s^p} (V_{sq}^n I_{rd}^p - V_{sd}^n I_{rq}^p)
\end{aligned} \quad (15)$$

Thus the average stator active and reactive power and the electromagnetic torque are given by

$$\begin{aligned}
P_{s_av} &= \frac{3L_m}{2L_s} \frac{(V_s^p)^2 + (V_s^n)^2}{V_s^p} I_{rd}^p \\
Q_{s_av} &= -\frac{3}{2L_s} \frac{(V_s^p)^2 - (V_s^n)^2}{V_s^p} \left(\frac{V_s^p}{\omega_e} + L_m I_{rq}^p \right) \\
T_{e_av} &= \frac{3p_n L_m}{2\omega_e L_s} \frac{(V_s^p)^2 - (V_s^n)^2}{V_s^p} I_{rd}^p
\end{aligned} \quad (16)$$

Equations (14) and (16) indicate that the average stator active power/torque and reactive power can be controlled by regulating I_{rd}^p and I_{rq}^p respectively. In the mean while, controlling I_{rd}^n and I_{rq}^n can eliminate the oscillations of either stator active power based on (13), or electromagnetic torque based on (15). Therefore, the average values of active power/torque and reactive power can be controlled independently using a positive sequence controller, and their oscillations can be eliminated using a negative sequence controller.

III. SYSTEM CONTROL

Fig. 3 shows the schematic diagram of a vector control system to provide precise control of the rotor positive and negative sequence currents.

A. Voltage phase-locked loop

For stator voltage orientation, the stator voltage frequency and angle can be measured by phase-locked loop (PLL). Various software PLL techniques have been proposed to obtain accurate phase information. Under unbalanced conditions, grid voltage contains positive and negative sequence components, and the PLL should lock the positive sequence voltage phase. A band-trap filter turned at twice the grid frequency can be

Finally PWM patterns for the rotor side converter are generated based on either space vector modulation or sinusoidal PWM method.

IV. SIMULATION STUDIES

In order to verify the proposed control scheme, simulations for a 2MW DFIG system shown in Fig. 4 were carried out using Matlab/Simulink. The DFIG system parameters are given in Table I.

Fig. 5 shows the enhanced performance with the proposed scheme compared with the conventional one without taking into account voltage unbalance. In the simulation, 5% grid voltage unbalance was applied at 0.1s. The high frequency switching harmonics have been filtered out from the waveforms for clarity. For the conventional control scheme, it can be seen from Fig. 5(A) that the stator current becomes highly unbalanced and the active/reactive power and torque all contain significant 100Hz oscillations. For the proposed control scheme, the controller was set to Target 1 during 0.1s-0.2s and switched to Target 2 during 0.2s-0.3s. As can be seen in Fig. 5(B), the oscillations of the active power and torque have been reduced significantly during 0.1s-0.2s and 0.2s-0.3s respectively.

Fig. 6 shows the DFIG dynamic behaviour when the mechanical torque step-changed between -0.4pu and -1pu with 5% voltage unbalance. Target 2 was selected for this case. As can be seen, the positive and negative sequence currents are well controlled, and the electromagnetic torque does not contain

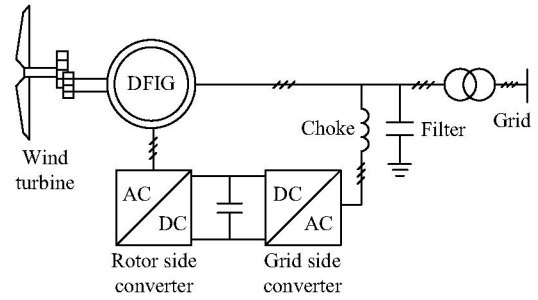


Fig. 4 Schematic diagram of the simulated system

TABLE I
PARAMETERS OF THE SIMULATED DFIG SYSTEM

DFIG	Rated power	2MW
	Stator voltage/Frequency	690V/50Hz
	R_s/R_r	0.0108pu / 0.012pu
	L_m	3.362pu
	L_{gs}/L_{gr}	0.102pu / 0.11pu
Lumped inertia constant	1.5s	
DC bus capacitor	C_{dc}	10000 μ F
Choke	L_g	0.25mH
Filter	R_f/C_f	0.06 Ω /1000 μ F

100Hz pulsation.

Fig. 7 shows the simulated results during a remote single-phase fault. The asymmetric fault occurred at 0.2s and resulted

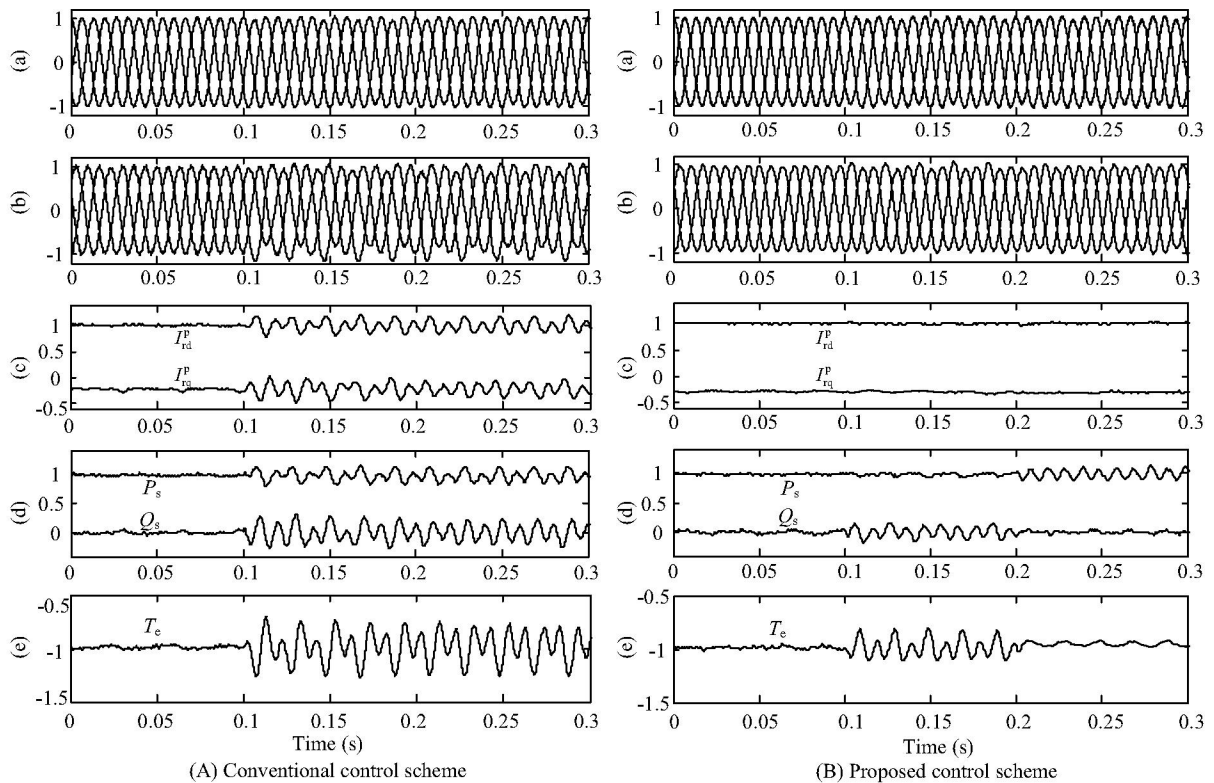


Fig. 5 Simulated results with 5% unbalanced voltages occurring at 0.1s, and applying Target 1 in 0.1-0.2s, Target 2 in 0.2-0.3s. (a) Stator voltages (pu); (b) Stator currents (pu); (c) Rotor currents in dq reference frame (pu); (d) Active and reactive power of stator side (pu); (e) Electromagnetic torque (pu)

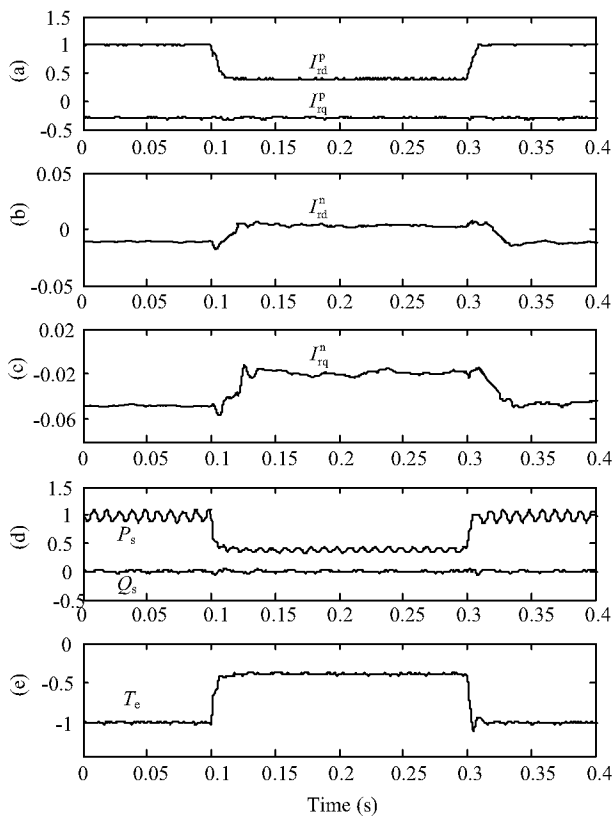


Fig. 6. Simulated results with the variation of input torque by Target 2. (a) Rotor positive sequence currents in dq frame (pu). (b) Rotor negative sequence d-axis current (pu). (c) Rotor negative sequence q-axis current (pu). (d) Active and reactive power (pu). (e) Electromagnetic torque (pu)

in a 10% negative-sequence voltage and a positive-sequence voltage dip of 7% on the DFIG terminal (see Fig. 7(a) and 7(b)). The electromagnetic torque behaviour of the proposed control scheme with the controller set Target 2 and that of the conventional control scheme are shown in Fig. 7(c) and 7(d) respectively. As can be seen, the torque ripple is significantly reduced by the proposed scheme.

V. CONCLUSIONS

To understand the system operation and to provide enhanced system control for DFIG systems under unbalanced conditions, a dynamic model based on SVO containing the positive and negative sequence components has been developed. Under unbalanced stator supply, torque and power oscillations have been fully defined and various control targets to enhance the system operation have been discussed. System control based on a positive sequence controller which controls average active and reactive power, and a negative sequence controller which minimizes torque or power oscillations is designed and validated by simulation. The proposed control strategy can significantly improve the performance and stability of DFIG systems during network unbalance.

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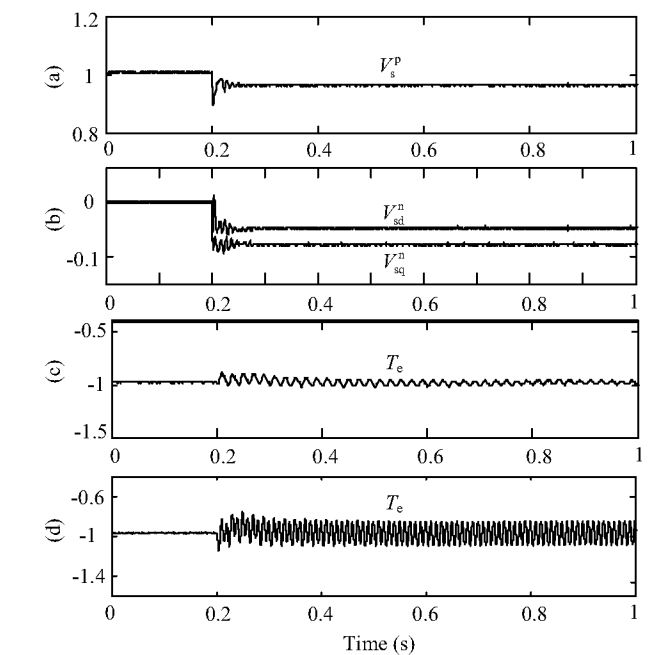


Fig. 7. Simulated results when asymmetric fault occurred at 0.2s by Target 2. (a) Stator positive voltage (pu). (b) Stator negative voltages (pu). (c) Electromagnetic torque (pu) by the proposed scheme. (d) Electromagnetic torque (pu) by conventional scheme

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