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A New Technique to Control Active and Reactive Power for Wind Energy Conversion System under Unbalanced Grid Voltage

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Abstract: In this paper, an innovative control technique for wind power generation for smoothening the stator active or reactive power swell components under unbalanced grid voltage using doubly-fed induction generators (DFIG) is projected. The negative order component of the rotor current is used to diminish the active and reactive power waves, which is extracted by band pass filters. It is revealed that reducing the reactive power ripples can lead to results in the torque ripple reduction. Simulation results shows that the proposed control algorithm can reduce the active or reactive power ripple components as well as reducing the torque and speed ripples.

Keywords — Wind energy conversion, unbalanced gird voltage, DFIG, power control

I. INTRODUCTION

A doubly fed induction generator is most used in wind power generation. It is a wound rotor induction machine with slip rings attached at the rotor and fed by power converter. With DFIG, generation can be accomplished in variable speed ranging from sub- synchronous speed to super-synchronous speed. The power converters feeding the rotor winding is usually controlled in a current-regulated PWM type, thus the stator current can be adjusted in magnitude and phase angle. The rotor-side converter operates at the slip frequency and the power converter processes only the slip power. Thus if the DFIG is to be varied within 30% slip, the rating of the power converter is only about 30% of the rated power of the wind turbine. In this design the net power out of the machine is a summation of the power coming from the stator and the rotor.

The continuity of the power generation in the wind energy system can be affected by the existence of voltage unbalance in utility grid. Disconnecting the generator from the power system during unbalanced grid voltage reduces the utilization of the wind power. Thus, it is desirable to keep the generator connected to the grid as long as possible and to eliminate or reduce the effect of the unbalanced grid voltage [1],[2].

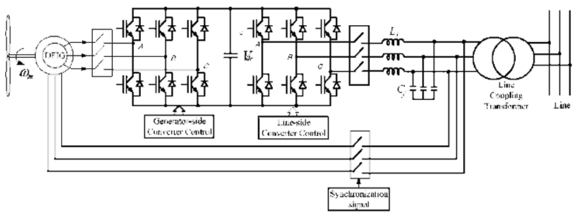

Fig. 1. Configuration of DFIG wind power system.

Due to the direct connection between the stator and the utility grid, the unbalanced grid voltage causes unbalanced stator currents which produce torque pulsations. The torque ripples can be a source of mechanical stress on the drive train and gearbox as well as a source of acoustic noise [3]. A DFIG control algorithm to reduce torque ripple for unbalanced grid voltage was reported in [4], where active and reactive power ripple components were not investigated. On the other hand, Nam et. al.

proposed an efficient dual current control algorithm using positive and negative sequence current components in ac/dc PWM converter systems [5].

In DFIG control, however, due to the variation of the rotor frequency the negative sequence component of the rotor current cannot be extracted by the symmetric component method.

In this paper, a novel control algorithm to eliminate the torque ripples of the DFIG in case of unbalanced grid voltage is presented. The presented control algorithmaims at eliminating either the double frequency active power or reactive power components to suppress the effect of the unbalanced grid voltage. Simulation results for 2[MW] DFIG system verified that the proposed algorithm is effective.

II. DFIG MODEL ANDCONTROL

Configuration of the overall wind generation system is shown in Fig. 1. The stator of DFIG is directly connected to the grid and the rotor is connected through back-to-back PWM converters.

The DFIG is controlled in a rotating d-q reference frame, with the d-axis aligned with the stator flux vector asshowninFig.2.The stator active and reactive powers of DFIG are controlled by regulating the current and voltage of the rotor. Therefore the current and voltage of the rotor needs to be decomposed into the components related to stator active and reactive power.

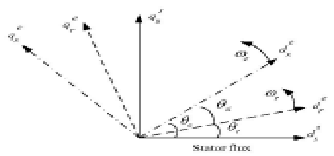

Fig. 2. Vector diagram for stator flux-oriented control.

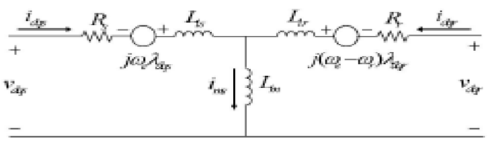

Fig. 3. Equivalent circuit of DFIG

A. DFIG model

Fig.3 shows the d-q equivalent circuit of DFIG. Under stator flux-oriented control, the fluxes, currents and voltages can be expressed as[6]

$$\lambda_{dqs} = L_s i_{dqs} + L_m i_{dqr} \quad (1)$$

$$\lambda_{dqr} = L_r i_{dqr} + L_m i_{dqs} \quad (2)$$

$$v_{dqs} = R_s i_{dqs} + \frac{d}{dt}\lambda_{dqs} + j\omega_e \lambda_{dqs} \quad (3)$$

$$v_{dqr} = R_r i_{dqr} + \frac{d}{dt}\lambda_{dqr} + j(\omega_e - \omega_r)\lambda_{dqr} \quad (4)$$

where

L_m : Magnetizing inductance;
L_s : Stator self-inductance;
L_r : Rotor self-inductance;
λ_{dqs} : Stator d-q axis flux linkage;
λ_{dqr} : Rotor d-q axis flux linkage;
i_{dqs}, i_{dqr} : Stator and rotor d-q axis currents.

The phase angle of the stator flux vector is calculated as follows;

$$\lambda_{dqs}^s = \int (v_{dqs}^s - R_s i_{dqs}^s)dt \quad (5)$$

$$\theta_e = \tan^{-1}\frac{\lambda_{qs}^s}{\lambda_{ds}^s} \quad (6)$$

where the superscript 's' indicates quantities in the stationary reference frame.

B. Power control

The stator flux vector is adjusted to be aligned with the d-axis. Adjustment of the q-axis component of the rotor current controls either the generator torque or the stator- side active power of the DFIG. On the other hand, regulating the rotor d-axis current component controls directly the stator-side reactive power. Using(1)-(6),the stator active and reactive power can be obtained as

$$P_s = -\frac{3}{2}\frac{L_m}{L_s} v_{qs} i_{qr} \qquad (7)$$

$$Q_s = \frac{3}{2}\frac{L_m}{L_s} v_{qs} (i_{ms} - i_{dr}) \qquad (8)$$

where $i_{ms}$is the magnetizing current.

It is noticeable that the stator active power component is proportional to the iq. and the stator reactive power component is proportional to idr,

III. DFIG CONTROL UNDER UNBALANCED GRID VOLTAGE

A. Generator-side converter control

The stator-side apparent power in unbalanced gridvoltage can be expressed in terms of the positive andnegative sequence components as [5]

$$S_s = 1.5(V_{dqs}^s I_{dqs}^{s*})$$

where

$$V_{dqs}^s = e^{j\omega_e t} V_{dqs}^p + e^{j(-\omega_e)t} V_{dqs}^n$$

$$I_{dqs}^s = e^{j\omega_e t} I_{dqs}^p + e^{j(-\omega_e)t} I_{dqs}^n .$$

Where w_e is the stator angular frequency and the superscripts 'p' and 'n' indicate the positive and negative sequence components, respectively. From (9), instantaneous active power p_s(t) and reactive power q_s(t)are obtained as

$$p_s(t) = P_{s0} + P_{sc2}\cos(2\omega_e t) + P_{ss2}\sin(2\omega_e t) \qquad (10)$$

$$q_s(t) = Q_{s0} + Q_{sc2}\cos(2\omega_e t) + Q_{ss2}\sin(2\omega_e t) \qquad (11)$$

where

$$P_{s0} = 1.5(V_{ds}^p I_{ds}^p + V_{qs}^p I_{qs}^p + V_{ds}^n I_{ds}^n + V_{qs}^n I_{qs}^n)$$
$$P_{sc2} = 1.5(V_{ds}^p I_{ds}^n + V_{qs}^p I_{qs}^n + V_{ds}^n I_{ds}^p + V_{qs}^n I_{qs}^p)$$
$$P_{ss2} = 1.5(V_{qs}^n I_{ds}^p - V_{ds}^n I_{qs}^p - V_{qs}^p I_{ds}^n + V_{ds}^p I_{qs}^n)$$
$$Q_{s0} = 1.5(V_{qs}^p I_{ds}^p - V_{ds}^p I_{qs}^p + V_{qs}^n I_{ds}^n - V_{ds}^n I_{qs}^n)$$
$$Q_{sc2} = 1.5(V_{qs}^p I_{ds}^n - V_{ds}^p I_{qs}^n + V_{qs}^n I_{ds}^p - V_{ds}^n I_{qs}^p)$$
$$Q_{ss2} = 1.5(V_{ds}^p I_{ds}^n + V_{qs}^p I_{qs}^n - V_{ds}^n I_{ds}^p - V_{qs}^n I_{qs}^p)$$

In stator flux-oriented control, the positive and negative sequence components of the stator d-axis voltage are zeros. Hence, the coefficients of the active and reactive power ripple components become

$$P_{sc2} = 1.5(V_{qs}^p I_{qs}^n + V_{qs}^n I_{qs}^p) \qquad (12)$$

$$P_{ss2} = 1.5(V_{qs}^n I_{ds}^p - V_{qs}^p I_{ds}^n) \quad (13)$$

$$Q_{sc2} = 1.5(V_{qs}^p I_{ds}^n + V_{qs}^n I_{ds}^p) \quad (14)$$

$$Q_{ss2} = 1.5(V_{qs}^p I_{qs}^n - V_{qs}^n I_{qs}^p) \quad (15)$$

and

$$P_{s2} = \sqrt{(A+B)^2 + (C-D)^2} \quad (16)$$

$$Q_{s2} = \sqrt{(A-B)^2 + (C+D)^2} \quad (17)$$

where

$$A = V_{qs}^p I_{qs}^n, B = V_{qs}^n I_{qs}^p, C = V_{qs}^n I_{ds}^p, and\ D = V_{qs}^p I_{ds}^n .$$

From P_{ss2} and P_{sc2}, it is obvious that the coefficient of the active power ripple P_{s2} is zero when A=-B and C=D. Similarly, the coefficient of the reactive power ripple $Q_{s2}$is zero when A=B and C=-D. It means that only either P_{s2}or Q_{s2} can be eliminated, not both.

The power ripple components can be expressed as a function of the rotor and stator currents as below.

$$\begin{aligned} P_{sc2} = 1.5\{ & 2(R_s + \frac{d}{dt}L_s) I_{qs}^p I_{qs}^n \\ & + \frac{d}{dt} L_m (I_{qs}^p I_{qr}^n + I_{qs}^n I_{qr}^p) \\ & - \omega_e L_m (I_{qs}^p I_{dr}^n - I_{qs}^n I_{dr}^p)\} \end{aligned} \quad (18)$$

$$\begin{aligned} P_{ss2} = 1.5\{ & \frac{d}{dt} L_m (I_{qs}^p I_{dr}^n - I_{qs}^n I_{dr}^p) \\ & - 2\omega_e L_s I_{qs}^p I_{qs}^n \\ & - \omega_e L_m (I_{qs}^p I_{qr}^n + I_{qs}^n I_{qr}^p)\} \end{aligned} \quad (19)$$

$$\begin{aligned} Q_{sc2} = -1.5\{ & \frac{d}{dt} L_m (I_{qs}^p I_{dr}^n + I_{qs}^n I_{dr}^p) \\ & + \omega_e L_m (I_{qs}^p I_{qr}^n - I_{qs}^n I_{qr}^p)\} \end{aligned} \quad (20)$$

$$\begin{aligned} Q_{ss2} = 1.5\{ & -\frac{d}{dt} L_m (I_{qs}^p I_{qr}^n - I_{qs}^n I_{qr}^p) \\ & + \omega_e L_m (I_{qs}^p I_{dr}^n + I_{qs}^n I_{dr}^p)\} \end{aligned} \quad (21)$$

The active power ripples of (18) and (19) cannot be eliminated completely due to the terms of

$$2(R_s + dL_s/dt) I_{qs}^p I_{qs}^n \text{ and } 2\omega_e L_s I_{qs}^p I_{qs}^n .$$

B. Generator torque

For unbalanced grid voltage, (1)-(4) are not sufficient to derive the generator torque equation. Equations (22)-(25)express the negative sequence components for the fluxes and voltages.

$$\lambda_{dqs}^n = L_s I_{dqs}^n + L_m I_{dqr}^n \quad (22)$$

$$\lambda_{dqr}^n = L_r I_{dqr}^n + L_m I_{dqs}^n \quad (23)$$

$$V_{dqs}^n = R_s I_{dqs}^n + \frac{d}{dt}\lambda_{dqs}^n + j(-\omega_e)\lambda_{dqs}^n \quad (24)$$

$$V_{dqr}^{n} = R_r I_{dqr}^{n} + \frac{d}{dt}\lambda_{dqr}^{n} + j(-\omega_e - \omega_r)\lambda_{dqr}^{n} \qquad (25)$$

The total apparent power of the generator can be expressed as

$$S_T = 1.5(V_{dqs}^{s} I_{dqs}^{s*} + V_{dqr}^{s} I_{dqr}^{s*}) \qquad (26)$$

where

$$V_{dqr}^{s} = e^{j(\omega_e - \omega_r)t} V_{dqr}^{p} + e^{j(-\omega_e - \omega_r)t} V_{dqr}^{n}$$

$$I_{dqr}^{s} = e^{j(\omega_e - \omega_r)t} I_{dqr}^{p} + e^{j(-\omega_e - \omega_r)t} I_{dqr}^{n}$$

where ω_r is the rotor speed.

Taking the real part of (26) and dividing it by the mechanical speed, the instantaneous torque is obtained as[7]

$$T_e(t) = T_{e0} + T_{ec2}\cos(2\omega_e t) + T_{es2}\sin(2\omega_e t) \qquad (27)$$

where

$$T_{e0} = 1.5L_m(I_{qs}^{p} I_{dr}^{p} + I_{qs}^{n} I_{dr}^{n})$$

$$T_{ec2} = 1.5L_m(I_{qs}^{p} I_{dr}^{n} + I_{qs}^{n} I_{dr}^{p})$$

$$T_{es2} = 1.5L_m(I_{qs}^{p} I_{qr}^{n} - I_{qs}^{n} I_{qr}^{p}).$$

It is noticeable from (18)-(21) and (27) that T_{ec2} and T_{es2} are related closely to the reactive power ripple component.

Due to the variation of the slip frequency, the negative sequence component of the rotor current cannot be calculated using the symmetric component method. A new method to extract the negative-sequence component is introduced in this paper as shown in Fig. 4. The three phase rotor currents are transformed into quantities in the synchronous reference frame. Using the band pass filters with a 120[Hz] cut-off frequency, the negative sequence components of the rotor d-q axis currents are extracted.

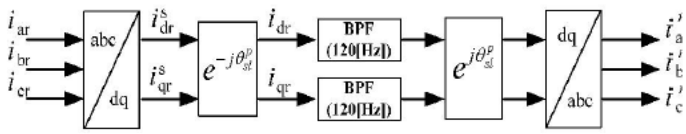

Fig. 4. Extraction process of rotor negative sequence current.

The negative sequence components are then transformed into the three-phase current. Negative sequence components of the rotor current are used to eliminate the stator active or reactive power ripples. The complete control block diagram employing two separate current controllers for the positive and negative sequence components is shown in Fig. 5.

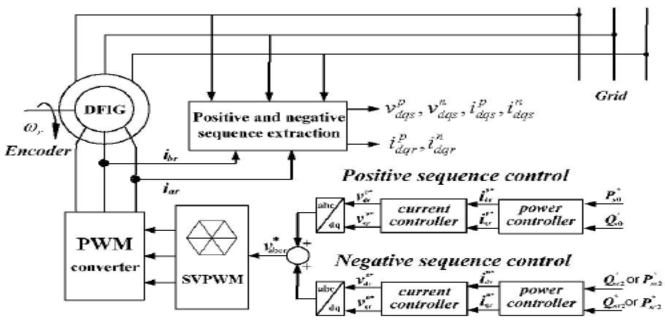

Fig. 5. Power control of DFIG system under unbalance grid voltage.

IV. SIMULATION RESULTS

To verify the feasibility of the proposed control scheme, computer simulations were performed. The DFIG used for simulation is rated at 2[MW] and the wind speed is constant at 10[m/s]. The grid voltage is 60[Hz] and 690[V]. For unbalance of the voltage, the magnitude of a-phase voltage is decreased by20%.

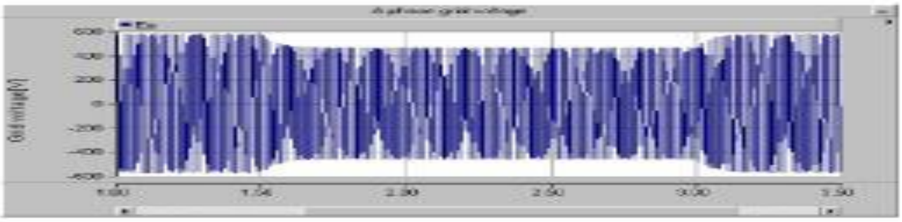

Fig. 6. A-phase gird voltage.

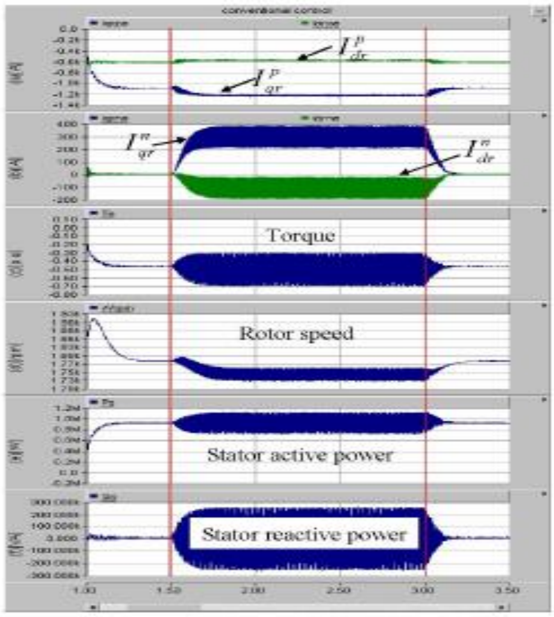

Fig. 7. Output performance under unbalanced grid voltage condition.

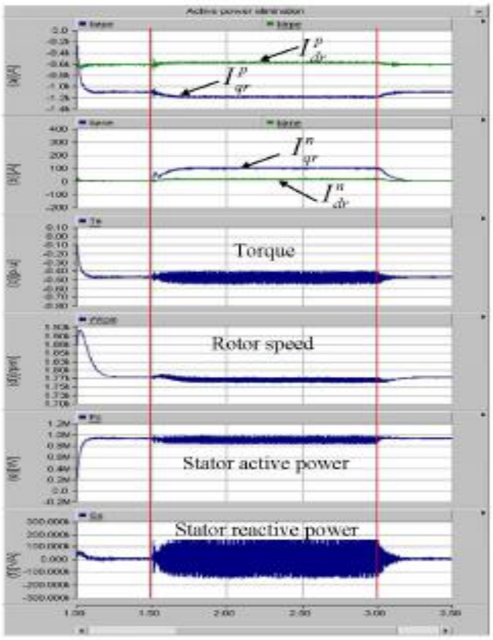

Fig. 8. Power control to eliminate the stator active power ripple.

Initially, the system runs under balanced grid voltage and then the grid voltage is disturbed after 1.5[s] and then the voltage balance is recovered after 3 [s].Without any compensation for the grid voltage condition shown in Fig. 6, there are significant ripple components in the rotor speed, torque, stator active and reactive power as shown in Fig.7. It is noticeable that the negative sequence components of the rotor d-q axis current contain high ripple components while the positive sequence components have no ripple component as shown in Fig. 7(a) and (b). Controlling the active power ripple component, the rotor d-q axis current ripples are eliminated as shown in Fig. 8 (b) and the active power ripples are reduced as shown in Fig. 8 (e). However, this control method cannot eliminate the torque and rotor speed ripples completely as shown in Fig. 8 (c) and (d).Torque and rotor speed ripples cause a serious mechanical stress on the generator shaft and gearbox as well as acoustic noise. To overcome the aforementioned limitation on the active power ripple control, the reactive power ripple control algorithm can be used. The negative sequence component ripple of the rotor d-q axis current, torque and speed ripples are successfully eliminated as shown in Fig. 9. On the other hand, the active power ripples cannot be eliminated. The proposed reactive power ripple control is as well efficient for variable wind speed. The control algorithm is able to reduce the effect of the high frequency components in the wind speed as shown in Fig. 10.

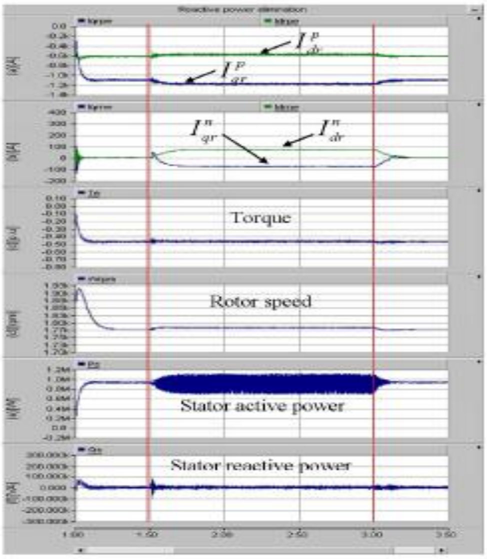

Fig. 9. Power control to eliminate the stator reactive power ripple.

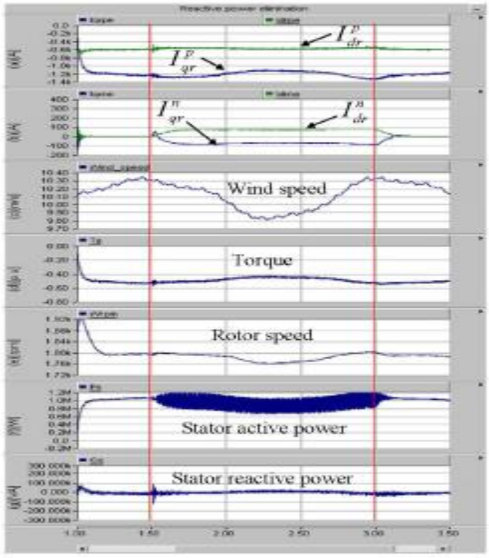

Fig. 10. Power control to eliminate the stator reactive power ripple according to the wind speed variation.

V. CONCLUSIONS

In this paper, a novel power control scheme of DFIG for wind power generation under unbalanced grid voltage has been proposed and simulated. The proposed control algorithm can reduce the active or reactive power ripples individually. The simulation results show that the reactive power ripple control is more efficient for eliminating the negative sequence component of the rotor current, speed and torque ripples. The proposed algorithm shows a good dynamic performance and ability to reduce the effect of the wind speed variation on the generator toque and speed. It helps the stable operation of the DFIG and power system at unbalanced voltage condition. It can reduce the fatigue of the rotating parts of the system including DFIG and turbine.

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