Control of DFIG under Unsymmetrical Voltage Dip

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Abstract- **Today, doubly fed induction generator (DFIG) gains the dominant market power in the wind energy industry. It provides the benefits of variable speed operation cost-effectively, and can control its active and reactive power independently. Crowbar protection is often adopted to protect the rotor side voltage source converter (VSC) from transient over current during grid voltage dip. But under unsymmetrical voltage dip, the severe problems are not the transient over current, but the electric torque pulsation and DC voltage ripple in the back to back VSCs. This paper develops dynamic models in Matlab/Simulink, investigates the behavior of DFIG during an unsymmetrical voltage dip, and proposes new controllers in separated positive and negative sequence. Methods to separate positive and negative sequence components in real time are also developed, and their responses to unsymmetrical voltage dip are compared. Simulation results prove that the separated positive and negative sequence controller limit the torque pulsation and DC voltage ripple effectively.**

I. INTRODUCTION

The wind generation in Europe reached approximately 33,600 MW until the end of 2004. The demands of connecting large scale wind parks to the power grid are increasing. Nowadays, the large scale wind farms are required to be controllable both in active and reactive power, and to have the low voltage ride through capability when grid faults happen. Because of its ability to provide variable speed operation and independent active and reactive power control in a cost-effective way, the doubly fed induction generator (DFIG) has the largest world market share of wind turbine concepts since the year 2002 [1]. Many researches have studied the low voltage ride through (LVRT) capability of DFIG [3] [4] [5] [6] [7] , most of them are focused on the behaviors and protections of DFIG under symmetrical fault. Transient over current in the rotor is identified as the most severe LVRT problem of the DFIG, because the rotor side voltage source converter (VSC) is very sensitive to thermal overload. The active crowbar protection is designed to short circuit the rotor under such circumstance, both to protect the rotor side VSC and to damp out the oscillations faster. In reality, unsymmetrical fault happens much more frequently than symmetrical fault. Under unsymmetrical fault, the most severe problem is not the transient over current in the rotor, but the large electric torque pulsation which causes tear and wear of the gearbox, and large voltage ripple in the DC link of back to back VSC which may decrease the lifetime of the DC capacitance. Literatures [8] and [9] give new definitions of instantaneous active and reactive power. These definitions can be used to design and operate the grid connected VSC under unbalanced situations [10] [11]. Unlike the normal grid connected VSC which has a constant instantaneous active power input from the rectifier side in the above literatures, the rotor side VSC of DFIG can also send pulsating instantaneous active power to the DC link. Thus it is necessary to study the behavior of DFIG under unsymmetrical voltage dip, and design proper controllers to improve the behaviors of DFIG under unsymmetrical voltage dip.

II. DFIG SYSTEM DESCRIPTION

A. System Description

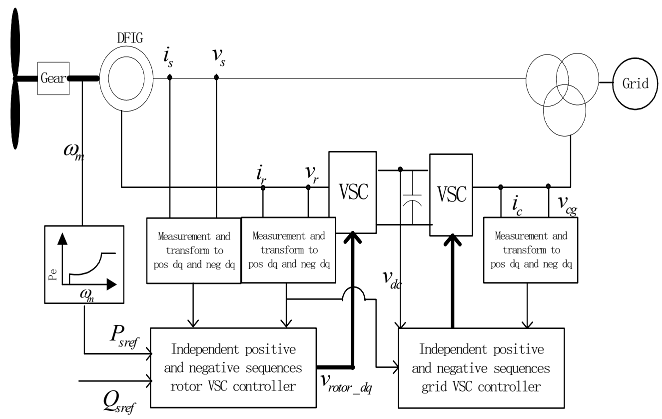

Figure 1 simplified diagram of DFIG system with proposed controllers

Figure 1 describes the DFIG system and the proposed controllers. The controllers of rotor VSC and grid VSC control stator currents and grid converter currents, both in independent positive and negative sequences. According to symmetrical components theory [2], during unbalanced voltage dip, the system can be decoupled into positive, negative and zero sequence. Positive and negative sequences are balanced three phase systems, they can be transferred to positive dq and negative dq system. Their voltages and currents are DC values and can be easily controlled by simple PI controller.

The positive and negative sequence has to be totally decoupled. Otherwise, when controlling the positive sequence, the negative sequence will be influenced, and vice versa. The coupling between positive and negative sequence will deteriorate the control performance.

In order to fully decouple positive and negative sequence, the following assumptions are made:

- DFIG's stator and rotor windings are assumed to be in symmetrical.

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- Grid VSC's three phase ac inductances and resistances are in symmetrical.

The reference stator currents and grid converter currents are calculated according to instantaneous reactive power theory. The instantaneous reactive power theory is given in [8] and [9]. When applying it on a three phase three line power system, the theory is simple and easy to understand. It becomes complex for three phase four line power system. In this paper, only three phase three line power system is studied, the zero sequence is omitted. This choice is justified by the following reasons:

- The transformer is often Y/Δ connected.
- The neutral point of stator winding of DFIG is not grounded.

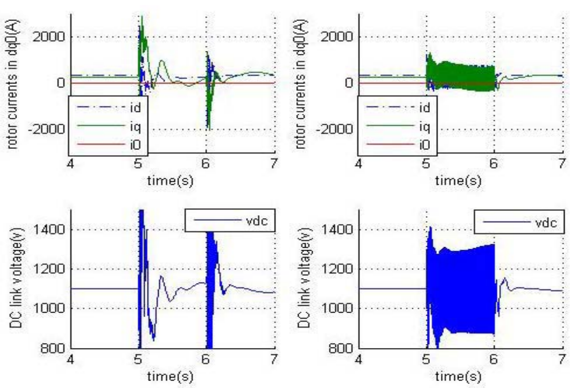
In the next sections, the simulation results of DFIG under symmetrical and unsymmetrical voltage dips will be presented first, then the instantaneous reactive power theory will be used to analyze this result.

B. *Symmetrical and Unsymmetrical Voltage Dip*

Distinctive differences between the behaviors of DFIG under symmetrical and unsymmetrical voltage dips can be identified as Figure 2.

Figure 2 (a) shows that under symmetrical voltage dip, the most severe problem is the transient over current in the rotor. This over current problem is generally protected by the so called "crowbar protection", which use thyristor controlled resistor bank to short circuit the rotor windings.

Figure 2 (a) shows that under unsymmetrical voltage dip, the maximum rotor currents are smaller, but have second order harmonics, and cause large DC voltage ripples in the DC link. A noticeable point is that the magnitude of rotor transient currents under unsymmetrical voltage dip also depends on the starting moment of the dip. The starting moment of the voltage dip determines the initial conditions of the stator currents, and thus determines the natural response of the stator currents. The natural response of stator currents has a large influence on the transient rotor currents.



(a) (b)

Figure 2simulation results of DFIG under (a) symmetrical and (b) unsymmetrical voltage dips. Graphs from top to bottom are rotor currents and DC voltage, respectively.

C. *Applying Instantaneous Reactive Power Theory on Separated Positive dq and Negative dq Sequence*

According to instantaneous reactive power theory [8], the instantaneous power p and q in stationary αβ reference frame are

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} v_\alpha i_\alpha + v_\beta i_\beta \\ v_\beta i_\alpha - v_\alpha i_\beta \end{bmatrix} \quad (1)$$

Eq. (1) is true for both balanced and unbalanced three phase three line system. The stationary αβ reference frame can be decoupled into positive and negative sequence as Eq.(2).

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \begin{bmatrix} v_\alpha^+(t) + v_\alpha^-(t) \\ v_\beta^+(t) + v_\beta^-(t) \end{bmatrix} \quad (2)$$

Using Eq. (1), Eq.(2) and Park's transformation, the instantaneous active and reactive power of positive and negative dq sequences can be derived as Eq. (3).

$$\begin{bmatrix} p \\ q \end{bmatrix} = \begin{bmatrix} \bar{p} + \tilde{p} \\ \bar{q} + \tilde{q} \end{bmatrix} = \begin{bmatrix} (v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^-) \\ (v_q^+ i_d^+ - v_d^+ i_q^+ + v_q^- i_d^- - v_d^- i_q^-) \end{bmatrix}$$
$$+ \sin(2\theta) \begin{bmatrix} (v_d^+ i_q^- - v_q^+ i_d^- + v_q^- i_d^+ - v_d^- i_q^+) \\ (v_d^+ i_d^- + v_q^+ i_q^- + v_d^- i_d^+ + v_q^- i_q^+) \end{bmatrix} \quad (3)$$
$$+ \cos(2\theta) \begin{bmatrix} v_d^+ i_d^- + v_q^+ i_q^- + v_d^- i_d^+ + v_q^- i_q^+ \\ v_d^+ i_q^- - v_q^+ i_d^- + v_q^- i_d^+ - v_d^- i_q^+ \end{bmatrix}$$

The terms of sin(2θ) and cos(2θ) in Eq. (3) are the oscillation parts of instantaneous power p and q. The oscillation parts of instantaneous active power p will cause DC voltage ripple and electric torque pulsation, such as shown in simulation results of DFIG in Figure 2.

In order to limit the DC voltage ripple or torque pulsation under unsymmetrical voltage dip, the terms of sin(2θ) and cos(2θ) of instantaneous active power p in Eq. (3) has to be controlled to zero. Rearranging Eq. (3), four independent equations can be used to determine the four reference currents $i_d^+, i_q^+, i_d^-, i_q^-$, and the currents can be controlled by voltages of VSC $v_d^+, v_q^+, v_d^-, v_q^-$ with simple PI controllers.

$$\begin{bmatrix} \bar{p} \\ \bar{q} \\ \tilde{p}_{\sin 2\theta} \\ \tilde{p}_{\cos 2\theta} \end{bmatrix} = \begin{bmatrix} P_{ref} \\ Q_{ref} \\ 0 \\ 0 \end{bmatrix} = \begin{bmatrix} v_d^+ i_d^+ + v_q^+ i_q^+ + v_d^- i_d^- + v_q^- i_q^- \\ v_q^+ i_d^+ - v_d^+ i_q^+ + v_q^- i_d^- - v_d^- i_q^- \\ v_d^+ i_q^- - v_q^+ i_d^- + v_q^- i_d^+ - v_d^- i_q^+ \\ v_d^+ i_d^- + v_q^+ i_q^- + v_d^- i_d^+ + v_q^- i_q^+ \end{bmatrix} \quad (4)$$

$\tilde{p}_{\sin 2\theta}$ and $\tilde{p}_{\cos 2\theta}$ are the two oscillation terms of instantaneous active power p. In order to control them to zero, instantaneous voltage and current has to be separated to positive and negative sequence in real time.

III. Real Time Separation of Positive and Negative Sequences

The proposed control method requires fast and accurate separation of positive and negative sequences. Two methods are often used [10].

The first method is based on the fact that the negative sequence component appears as second order harmonic in the synchronous rotating frame - positive dq, and the positive sequence component appears as second order harmonic in the negative synchronous rotating frame – negative dq. The low pass filter can be used to bypass the DC values and suppress the high frequency oscillations. Thus the positive and negative sequences are separated in real time. The description of this method is shown in Figure 3.

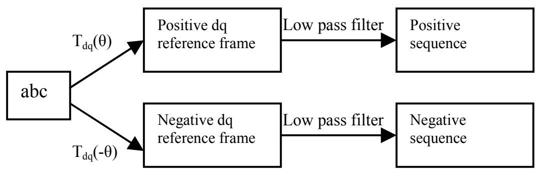


Figure 3 Separate positive and negative sequences by low pass filters

The second method is the so called "signal delay cancellation" method. The abc system is first transformed into stationary reference frame αβ coordinates using Clark's transformation, then it is delayed for T/4. The positive and negative sequence can be calculated by adding or subtracting the present real time signal with the delayed signal. It is explained mathematically in the following way.

The abc system can be transformed into stationary αβ reference frame using Clark's transformation, and can be expressed in positive and negative sequence as:

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \begin{bmatrix} v_\alpha^+(t) + v_\alpha^-(t) \\ v_\beta^+(t) + v_\beta^-(t) \end{bmatrix} = \begin{bmatrix} v^+\cos(\omega t + \phi^+) + v^-\cos(-\omega t + \phi^-) \\ v^+\sin(\omega t + \phi^+) + v^-\sin(-\omega t + \phi^-) \end{bmatrix} \quad (5)$$

Delay this signal for T/4:

$$\begin{bmatrix} v_\alpha(t - \frac{T}{4}) \\ v_\beta(t - \frac{T}{4}) \end{bmatrix} = \begin{bmatrix} v^+\sin(\omega t + \phi^+) - v^-\sin(\omega t + \phi^-) \\ -v^+\cos(\omega t + \phi^+) + v^-\cos(-\omega t + \phi^-) \end{bmatrix} \quad (6)$$

Comparing the above equations of αβ(t) Eq.(5) and αβ(t-T/4) Eq.(6), it is clear that the positive and negative sequence can be derived by adding or subtracting them.

$$\begin{bmatrix} v_\alpha^+(t) \\ v_\beta^+(t) \\ v_\alpha^-(t) \\ v_\beta^-(t) \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 0 & 0 & -1 \\ 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & -1 & 0 \end{bmatrix} \cdot \begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \\ v_\alpha(t - T/4) \\ v_\beta(t - T/4) \end{bmatrix} \quad (7)$$

The positive and negative sequence in αβ coordinates can be further transformed into positive dq and negative dq sequences using Eq.(8).

$$\begin{bmatrix} v_d^+(t) \\ v_q^+(t) \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \cdot \begin{bmatrix} v_\alpha^+(t) \\ v_\beta^+(t) \end{bmatrix}$$
$$\begin{bmatrix} v_d^-(t) \\ v_q^-(t) \end{bmatrix} = \begin{bmatrix} \cos(-\theta) & \sin(-\theta) \\ -\sin(-\theta) & \cos(-\theta) \end{bmatrix} \cdot \begin{bmatrix} v_\alpha^-(t) \\ v_\beta^-(t) \end{bmatrix} \quad (8)$$

At the moment of voltage dip and/or recovering, the "signal delay cancellation" method will have large transients and also a time delay of T/4. This method is summarized as following graph.

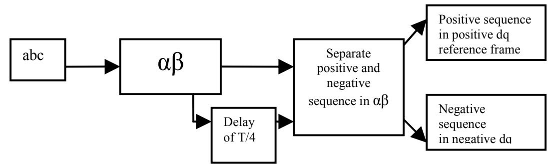
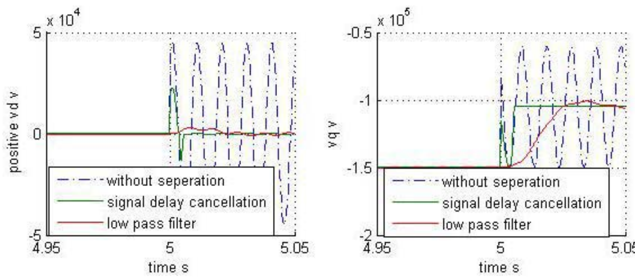


Figure 4 Separate positive and negative sequences by "signal delay cancellation" method

The unbalanced voltages in the positive dq reference frame with and without applying those two separation methods are shown in Figure 5.



(a) (b)

Figure 5 unbalanced voltages in positive dq reference frame with and without using the two separation methods (a) vd (b) vq

Without the two separation methods, the unbalanced three phase voltage or current has second order harmonics in the positive dq reference frame. Both separation methods have time delays before their outputs can reach to steady states. The "signal delay cancellation" is much faster than "low pass filter" method, but it has larger transients at the start and end period of voltage dip.

IV. SEPARATED POSITIVE AND NEGATIVE SEQUENCE CONTROLLERS OF DFIG

D. Control of Rotor VSC

Assuming the DFIG itself is in symmetric, the voltage equations of positive and negative dq sequence in generator convention are

$$\begin{bmatrix} v_{ds}^\pm \\ v_{qs}^\pm \\ v_{dr}^\pm \\ v_{qr}^\pm \end{bmatrix} = \begin{bmatrix} -R_s i_{ds}^\pm - (\pm\omega_s \psi_{qs}^\pm) + \frac{d\psi_{ds}^\pm}{dt} \\ -R_s i_{qs}^\pm + (\pm\omega_s \psi_{ds}^\pm) + \frac{d\psi_{qs}^\pm}{dt} \\ -R_r i_{dr}^\pm - (\pm\omega_s - \omega_r)\psi_{qr}^\pm + \frac{d\psi_{dr}^\pm}{dt} \\ -R_r i_{dr}^\pm + (\pm\omega_s - \omega_r)\psi_{dr}^\pm + \frac{d\psi_{qr}^\pm}{dt} \end{bmatrix} \quad (9)$$

In Eq.(9), ω_s is the stator electrical angular velocity, and ω_r is the rotational speed of rotor times the number of pole pairs $\omega_m \cdot p$.

The positive and negative sequences are completely decoupled as shown in Eq.(9), thus the DFIG can be controlled in positive and negative dq sequence independently. The controller of rotor VSC is designed from Eq.(9), which uses rotor voltages to control stator currents, and uses stator currents to control active and reactive power as shown in Figure 1. The controller is shown in Figure 6.

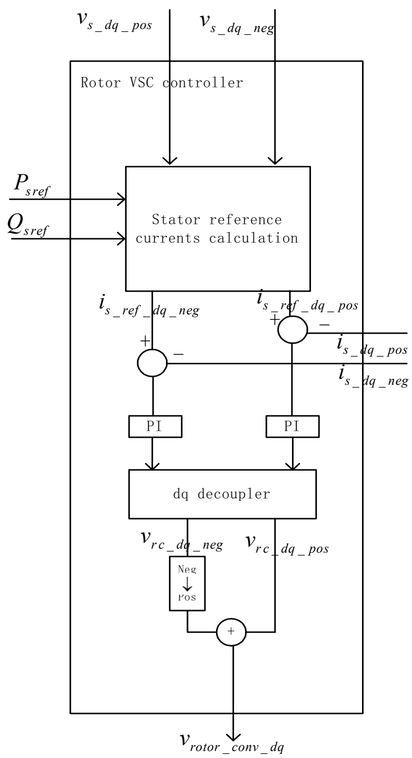


Figure 6 Separated positive and negative sequence controller of rotor VSC

In rotor VSC controller, the cross-coupling terms between d and q coordinates are $(\pm\omega_s-\omega_r)\psi_{qr}^{\pm}$ and $(\pm\omega_s-\omega_r)\psi_{dr}^{\pm}$. They are different in positive and negative sequence. In order to completely decouple d and q axis, these cross-coupling terms are feed forwarded and added with the outputs of PI controllers.

E. Control of Grid VSC

Assuming the smoothing ac inductance and resistance of grid VSC is balanced, the voltage equations of positive and negative dq sequence are

$$\begin{bmatrix} v_{dc}^{\pm} \\ v_{qc}^{\pm} \end{bmatrix} = \begin{bmatrix} v_{dg}^{\pm} + R_c i_{dc}^{\pm} + (\pm\omega_s L_c i_{qc}^{\pm}) + L_c \dfrac{di_{dc}^{\pm}}{dt} \\ v_{qg}^{\pm} + R_c i_{qc}^{\pm} - (\pm\omega_s L_c i_{dc}^{\pm}) + L_c \dfrac{di_{qc}^{\pm}}{dt} \end{bmatrix} \tag{10}$$

Unlike the works presented in [10] and [11], in this paper the DC voltage ripples are caused by both the rotor VSC and grid VSC. The instantaneous active power of grid VSC has to be controlled in coordination with the rotor VSC, in order to eliminate the DC voltage ripple.

The reference currents of grid VSC are calculated from dc link voltage vdc, grid ac voltage, rotor power, and reference reactive power Q_{ref}. The details of this controller can be seen in Figure 7.

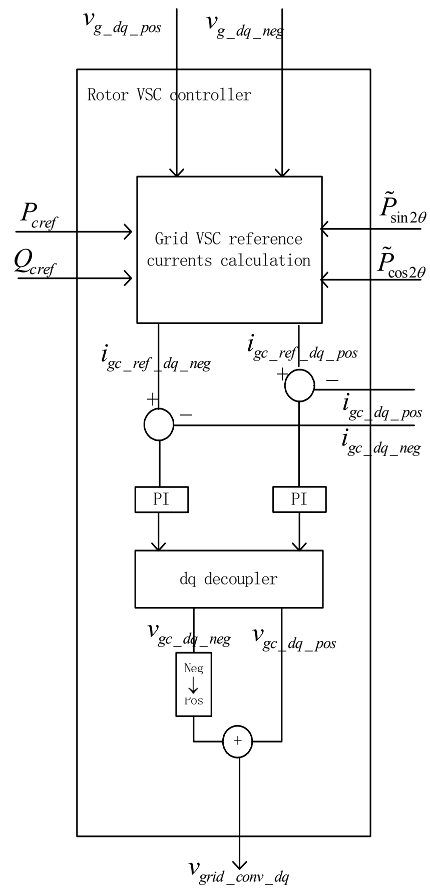


Figure 7 Separated positive and negative sequence controller of grid VSC

In grid VSC controller, the cross-coupling terms between d and q coordinates are $(\pm\omega_s L_c i_{qc}^{\pm})$ and $(\pm\omega_s L_c i_{dc}^{\pm})$. Same as in the rotor VSC controller, they are feed forwarded and added with outputs of PI controllers.

V. MODELING AND SIMULATION

A. Modeling DFIG System

The complete DFIG system with controllers is modeled in Matlab/Simulink [3]. These models are developed in the synchronous rotating reference frame in order to improve the simulation speed, because the balanced three phase voltage and current in the synchronous rotating reference frame are DC values at steady state. The simulink model of DFIG system is shown in following graph.

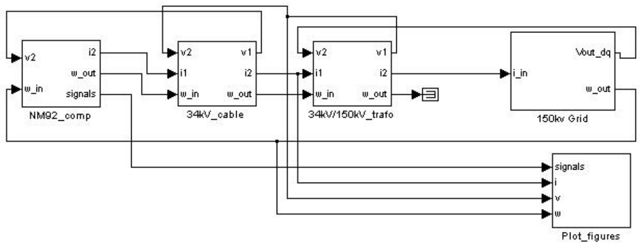


Figure 8 Simulink model of DFIG system

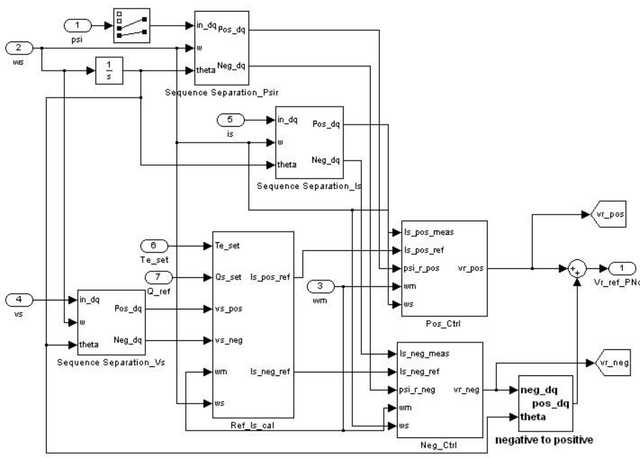


Figure 9 Simulink models of "separated positive and negative sequence controller" of rotor VSC

As shown in Figure 9, the stator voltages and currents are separated by "sequence separation" block, then fed into the "ref_Ir_cal" block with reference active and reactive power to calculate the reference stator currents. The stator currents are controlled through "pos_ctrl" and "neg_ctrl" blocks separately. Finally the required rotor voltages are calculated, which are assumed they can be perfectly produced by the rotor VSC.

The topology of the controller of grid VSC is quite similar as that of the rotor VSC. The main difference is that it has to be controlled in coordination with rotor VSC, in order to eliminate the effects caused by rotor power oscillations.

In order to improve simulation speed in Matlab/Simulink, the DC link is modified, based on the following equation.

$$v_{dc}(t) = \sqrt{\frac{2}{C}\left[\int_0^t (p_{rec}(t) - p_{inv}(t))dt + v_{dc}(0)^2\right]} \quad (11)$$

B. Separated Positive and Negative Controller of Rotor VSC

The effects of proposed controller on rotor VSC can be seen in Figure 10.

The separated positive and negative controller of rotor VSC drastically limits the torque pulsation to less than 20% of the original value. The stator power oscillation is limited, but the rotor power oscillation increases a little bit. As the stator power often dominates the total power of the generator, the total power oscillation is still limited a lot.

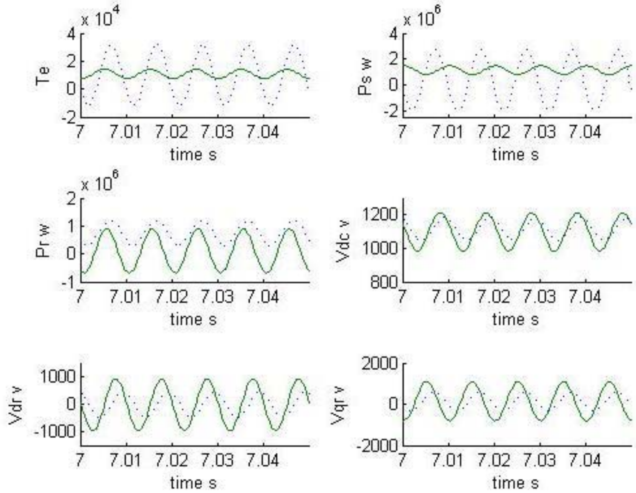


Figure 10 Compare the results of DFIG under unsymmetrical voltage dip with and without "separated positive and negative sequence controller". Dotted line – normal controller, solid line – "separated positive and negative sequence controller". Graphs from left to right and from top to bottom are electric torque Te, stator power Ps, rotor power Pr, DC voltage Vdc, rotor voltage Vdr, and rotor voltage Vqr, respectively.

The rotor reference voltages in positive and negative sequences from normal controller and new controller are shown in Figure 11.

During the unsymmetrical voltage dip, the normal controller also tries to counteract to the 100Hz oscillation in the electric torque Te. It outputs a certain degree of negative sequence voltage, but its output reference voltage is not correct comparing with the new controller as shown in Figure 11.

The normal controller can be tuned very fast to limit the torque pulsations during unsymmetrical voltage dip, but the stability margin will decrease.

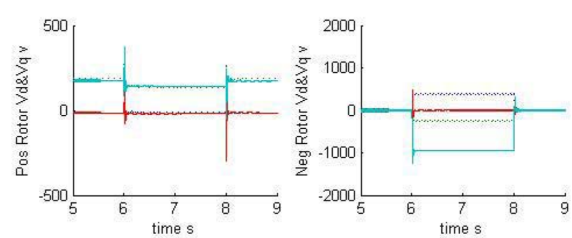


Figure 11 rotor voltages of positive dq and negative dq sequences. Dotted line – normal controller, solid line – "separated positive and negative sequence controller". Left graph is rotor voltage of positive sequence, and right graph is voltages of negative sequence.

C. Separated Positive and Negative Controller of Grid VSC

The effects of proposed controller on grid VSC can be seen in the following graph.

When the grid VSC is controlled separately in positive and negative sequence, and controlled in coordination with the rotor VSC, the DC voltage ripple is drastically limited to less than 10% of the original value. The instantaneous active power of grid VSC is intended to be controlled to have second order harmonic, in order to compensate the rotor power oscillation.

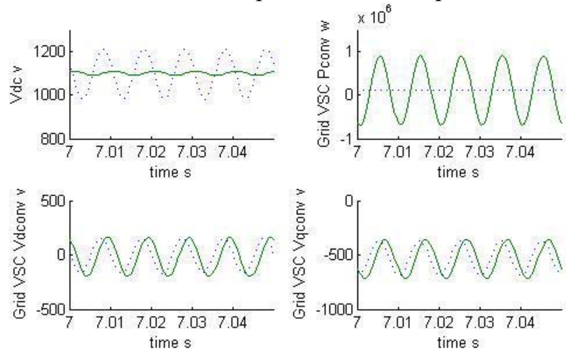


Figure 12 Compare the results of DC link of back to back VSCs under unsymmetrical voltage dip with and without "separated positive and negative sequence" controller. Dotted line – normal controller, solid line – "separated positive and negative sequence controller". Graphs from left to right and from top to bottom are DC voltage Vdc, grid VSC active power, rotor voltage Vdr, and rotor voltage Vqr, respectively.

Same as previously discussion of rotor VSC controller, the normal controller of grid VSC can be tuned very fast to counteract to the DC link voltage ripple, but its stability margin will decrease.

Figure 13 shows the positive dq and negative dq sequence voltages of grid VSC controlled by normal controller and new controller. The positive dq voltages are the same, but negative dq voltages are different.

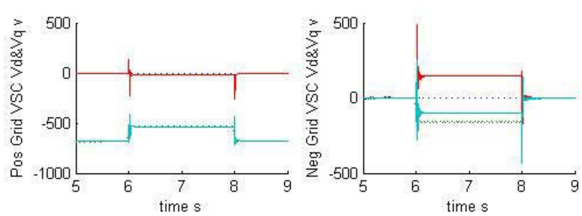


Figure 13grid VSC voltages of positive dq and negative dq sequences. Dotted line – normal controller, solid line – "separated positive and negative sequence controller". Left graph is grid VSC voltage of positive sequence, and right graph is voltages of negative sequence.

VI. CONCLUSIONS AND RECOMMENDATIONS

The LVRT capability of DFIG under symmetrical voltage dip has been thoroughly investigated in many researches, while DFIG's behavior under unsymmetrical voltage dip is seldom studied. Instead of the large transient rotor current which is caused by the symmetrical voltage dip, the large electric torque pulsation and DC voltage ripple in back to back VSCs are identified as the most severe problems of DFIG under unsymmetrical voltage dip. In this paper, the DFIG is proposed to be controlled in positive and negative sequence independently. In order to implement the separated positive and negative sequence controllers of DFIG, two methods to separate positive and negative sequence in real time are compared. The "signal delay cancellation" is much faster than the "low pass filter", and is chosen in this study. Equations of instantaneous active p and reactive power q, and voltage equations of DFIG and grid VSC in positive dq and negative dq sequence are derived. The complete DFIG system with proposed controller is modeled in Matlab/Simulink. The simulation results prove that the independent positive and negative sequence controllers of rotor VSC and grid VSC effectively limit the electric torque pulsation and DC voltage ripple.

In this paper, the control objective is focused on how to improve performance of DFIG itself under unsymmetrical voltage dip when it is connected to a strong power grid. In future, the control objective will be focused on how to use DFIG to improve grid performance when it is connected with a weak power grid, such as to limit the grid voltage unbalance and etc.

ACKNOWLEDGMENT

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