Unbalanced-Grid-Fault Ride-Through Control for a Doubly Fed

Induction Generator Wind Turbine with Series Grid-Side Converter

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Abstract: - The grid codes now require doubly fed induction generator (DFIG) wind turbines having the "low voltage ride-through (LVRT)" capability. However, a traditional DFIG with a partially rated back-to-back converter has inherent difficulties to ride through the grid faults, especially for the unbalanced grid faults. Modifications to the traditional DFIG configuration for ride-through have become necessary. A DFIG system with series grid-side converter (SGSC) has an excellent potential for voltage dips tolerance. This paper analyzes the reasons of a DFIG system with SGSC for ride-through and presents a control scheme for operation under unbalanced grid faults conditions. During grid faults, the each component of the generator's stator flux is effectively controlled through the SGSC. Also, the stator and rotor currents are further restricted by controlling the rotor-side converter (RSC) to reduce the absorbing energy from wind turbine. Then, successful ride-through of a DFIG system with SGSC under all types of severe unbalanced grid faults at the point of common coupling (PCC) are achieved with reduced electromagnetic torque oscillation. The proposed control scheme is validated by means of simulations.

Key-Words: - Doubly fed induction generator (DFIG), series grid-side Converter (SGSC), unbalanced grid fault, wind turbine, low voltage ride-through (LVRT), wind power generation, voltage dips, voltage sags

1 Introduction

Wind power has become one of the most important and promising sources of renewable energy that can partially solve the energy crisis and environmental dilemma we are confronting today [1]. With the increased penetration of wind power into power grids, its impact on a power grid cannot be neglected as before. Grid codes now usually require wind turbines to remain connected to the grid even during extreme voltage dips such as a short-term low or even a zero voltage event at the point of common coupling (PCC). This is the so-called "low voltage ridethrough (LVRT)" requirement adopted by most European countries [2-3].

The majority of wind turbines above 1MW are

Doubly Fed Induction Generators (DFIGs) with a partially rated back-to-back converter used between the rotor circuit and the grid [4-8]. While a saving is made on the size of the power electronic converter, it is well known that a DFIG system with this configuration is very sensitive to grid disturbances, especially to voltage dips. During a fault, the transient current on the stator is reflected on the rotor windings. The resulting rotor current may exceed the rotor-side converter (RSC) current rating and destroy the converter if no protection elements are included.

The mainstream scheme adopted by manufacturers to ride through grid faults is the so-called "crowbar protection" [9-10]. When the crowbar is in operation, the high fault current will flow through the crowbar instead of the converter. Thus, the RSC is well preserved during the fault. However, under such a scenario, the DFIG behaves as a squirrel-cage induction machine and consumes lots of reactive power from the grid for magnetization, which may further exacerbate the stability of the connected grid. Also, the operation of a crowbar is associated with large transient electromagnetic torques which will increase the fatigues on the mechanical components of the wind turbine generator system (WTGS), especially on the gearbox. Another LVRT technology is the rotor flux control technique [11], which controls the RSC to counteract the undesired components in the stator flux. However, the active and reactive power control over the machine is lost during the fault and the DFIG system also consumes reactive power during the grid recovery. Furthermore, this method is unable to ride through the severe grid faults such as the voltage dips down to zero at PCC which means it is not suitable for the new grid codes.

In order to fulfill the new grid codes which require wind turbines to ride through a short-term low or even a zero voltage event at PCC, modifications to the traditional DFIG configuration for ride-through have become necessary. Petersson [12] has proposed a new configuration with a grid-side converter in series with the stator windings of the DFIG and has revealed that DFIG system with this configuration has an excellent potential for voltage dips tolerance, but this scheme is not efficient in the power processing capability. Then in [13-15], a modified configuration by employing a parallel grid-side rectifier in addition to the series grid-side converter (SGSC) is further presented to improve power processing capabilities and successful ride-through of severe balanced voltage dips at PCC are demonstrated. However, in reality, unbalanced faults occur more frequently than balanced faults in transmission system. And compared to the balanced faults, due to the negative-sequence component injected by the unbalanced grid faults, a more severe current and torque oscillation will appear when unbalanced voltage dips occur [16]. Therefore, it is necessary to study the behavior of DFIG with this

new configuration under unbalanced grid faults.

This paper proposes an unbalanced-grid-fault ridethrough control scheme for a DFIG wind turbine with the configuration explored in [14-15, 17]. The paper has been organized as follows. Section 2 reviews the configuration of the DFIG wind turbine with SGSC. The behaviors of DFIG system with SGSC under unbalanced grid faults are analyzed in Section 3. The proposed control scheme is designed in Section 4 and validated by means of simulations in Section 5. Discussion is provided in Section 6 and finally Section 7 draws the conclusions.

2 DFIG Configuration with Series Grid-Side Converter

The configuration of the DFIG system with SGSC is shown in Fig. 1. In contrast to the traditional configuration of wind turbines based on the DFIG, a series grid-side converter and a three phase injection transformer are added in this configuration. Also, a RL filter is connected between the SGSC and the transformer to limit harmonic losses of the injection transformer [14-15, 17]. The SGSC, which shares the common dc link voltage with the rotor-side converter and the parallel grid-side converter (PGSC), is connected via a three phase injection transformer in series with the main stator windings of the DFIG system. The stator terminal voltage of DFIG becomes the sum of the grid voltage and series injected voltage of SGSC. Thus the transition of DFIG system during grid faults can be changed by controlling the output voltage of the SGSC. But whether the DFIG system demonstrates a good LVRT performance depends on the control scheme of SGSC.



Fig.1. Configuration of DFIG system with SGSC

3 Behaviors of DFIG System with SGSC under Unbalanced Grid Faults

3.1 Dynamic Response of Traditional DFIG System under Unbalanced Grid Faults

In the traditional DFIG configuration, the stator is directly connected to the grid. An abrupt drop of the grid voltage will directly transmit to the stator terminals of DFIG. According to the law of constant flux, additional negative-sequence and transient DC flux components in the stator flux will appear to guarantee the total stator flux constancy. Therefore, under unbalanced grid faults, the generator stator flux will contain positive-sequence, negativesequence and transient DC flux components. The relationship of each component between stator flux and stator voltage can be expressed as

$$\psi_{s} = \psi_{sDC} + \psi_{s1} + \psi_{s2}$$
$$= \left(\frac{U_{s}}{j\omega_{0}} - \frac{U'_{s1}}{j\omega_{0}} - \frac{U'_{s2}}{-j\omega_{0}}\right)e^{-t/\tau_{s}} + \frac{u'_{s1}}{j\omega_{0}} + \frac{u'_{s2}}{-j\omega_{0}}$$
(1)

where subscripts 1, 2, DC denote positive-, negativeand zero- (DC) sequence components in the flux or voltage vectors, respectively. Ψ_s , ω_0 and τ_s are the stator flux vector, synchronous angular speed and stator time constant, respectively. U_s and U'_s are the stator voltage vectors just before and after the grid fault. u'_s represents the stator voltage vector after the grid fault.

Each component of the stator flux as shown in (1) will induce a voltage in the rotor according to its amplitude and its relative speed with respect to the rotor. The induced rotor voltages can be expressed in the stationary reference frame as [18]

$$\boldsymbol{u}_{\mathrm{r}} = \frac{L_{\mathrm{m}}}{L_{\mathrm{s}}} \left(\frac{d}{dt} - j\omega_{\mathrm{r}} \right) \boldsymbol{\psi}_{\mathrm{s}}$$
$$= \frac{L_{\mathrm{m}}}{L_{\mathrm{s}}} \left(\frac{d}{dt} - j\omega_{\mathrm{r}} \right) \left(\boldsymbol{\psi}_{\mathrm{s1}} + \boldsymbol{\psi}_{\mathrm{s2}} + \boldsymbol{\psi}_{\mathrm{sDC}} \right)$$
(2)

where $L_{\rm m}$, $L_{\rm s}$, $\boldsymbol{u}_{\rm r}$ and $\omega_{\rm r}$ are the mutual inductance, stator self inductance, rotor voltage vector and rotor speed, respectively.

Substituting (1) into (2), the induced rotor voltages can be expressed in the rotor reference frame as

Table 1 Amplitudes of stator flux components andtheir induced voltages in the rotor side under

	Amplitudes of stator flux components	Induced voltages in the rotor side
ψ_{s1}	1 <i>-p</i> /2	(1- <i>p</i> /2)× <i>s</i>
ψ_{s2}	<i>p</i> /2	p/2×(2-s)
$\psi_{\rm sDC}$	0~ <i>p</i>	$(0 \sim p) \times (1 - s)$

$$\boldsymbol{u}_{r}^{r} = \boldsymbol{u}_{r1}^{r} + \boldsymbol{u}_{r2}^{r} + \boldsymbol{u}_{rDC}^{r}$$

$$\approx |\boldsymbol{u}_{s1}'| \cdot \frac{L_{m}}{L_{s}} \cdot s \cdot e^{js\omega_{0}t}$$

$$+ |\boldsymbol{u}_{s2}'| \cdot \frac{L_{m}}{L_{s}} \cdot (2-s) \cdot e^{-j(2-s)\omega_{0}t}$$

$$-j\omega_{r} \frac{L_{m}}{L_{s}} \cdot \left(\frac{\boldsymbol{U}_{s}}{j\omega_{0}} - \frac{\boldsymbol{U}_{s1}'}{j\omega_{0}} - \frac{\boldsymbol{U}_{s2}'}{-j\omega_{0}}\right) \cdot e^{-t/\tau_{s}} \cdot e^{-j\omega_{r}t}$$
(3)

where *s* is the slip and superscript r denotes the rotor reference frame.

Table 1 shows the approximate amplitudes of each stator flux component and their induced voltages in the rotor side under phase-to-phase grid fault. The symbol p denotes the depth of the grid fault. As can be seen in Table 1 and (3), relative large voltages are induced in the rotor side. For the worst case (s=-0.3and p=1), the maximum voltage amplitudes induced by the negative-sequence and the transient DC flux components can reach 1.15pu and 1.3pu, respectively. Considering that the rotor resistance and the transient inductance are usually very small, if the RSC cannot generate a voltage equal to the sum of the three voltages induced by the stator flux components, the RSC will lose current control transitorily and rotor over-current will appear. Fig. 2 shows the simulation results of a 2MW traditional DFIG detailed in the Appendix under phase-to-phase grid fault at PCC. The machine initially operates with full load and is at 30% super-synchronous speed. The control scheme implemented in the simulation model is the vector

control algorithm to achieve the decoupling control of stator active and reactive powers and to keep the common dc link voltage constant [4]. No additional action or control limit is included to constrain the fault current. As shown in Fig. 2, due to the RSC cannot generate a voltage to counteract the induced voltage by the stator flux components, high rotor over-current appears and further causes severe oscillation of the electromagnetic torque.

Thus, to avoid the appearance of rotor over-current and guarantee the DFIG system to ride through the grid faults, the stator flux each component should be effectively restricted, especially for the negativesequence and the transient DC flux components due to the relative speeds of which with respect to the rotor windings are rather high. Besides, the severe torque oscillation, which will increase the fatigues on the mechanical components of WTGS, should also be considered.



Fig.2. Simulation results of a 2MW traditional DFIG under phase-to-phase grid fault at PCC

3.2 Principle for Suppressing the Rotor Over-Current

As shown in Fig. 1, a SGSC is introduced between the grid and the stator terminals of DFIG. The generator's stator terminal voltage u_s becomes the sum of the grid voltage vector u_i and SGSC series injected voltage vector u_g which can be expressed in the stationary reference frame as

$$\boldsymbol{u}_{s} = \boldsymbol{u}_{i} + \boldsymbol{u}_{g} \tag{4}$$

Equation (4) indicates that the generator's stator terminal voltage can be changed due to the existence of the SGSC. Also, the transition of the generator stator flux imposed by the stator terminal voltage during the grid faults can be changed through the output voltage of SGSC. As analyzed in Section 3.1, under unbalanced grid faults, the negative-sequence and the transient DC flux components will induce relative large voltages in the rotor side. If the SGSC can generate a voltage to counteract the negativesequence and the transient DC flux components in the stator side, the rotor over-current caused by these two components can be eliminated.

On the other hand, if the DFIG equivalent mechanical output power P_{mec} imported from the rotor shaft is still large, an abrupt drop of the grid voltage positive-sequence component will cause the increase of the positive-sequence current which also maybe cause the rotor over-current. So the positive-sequence current should also be restricted.

Neglecting the impedance of the series transformer, the electromagnetic power of DFIG can be written as

$$P_{\rm em} = -\frac{R_{\rm r}}{s} i_{\rm r}^2 + {\rm Re} \left[\frac{\boldsymbol{u}_{\rm r}}{s} \cdot \hat{\boldsymbol{i}}_{\rm r} \right]$$
(5)

Splitting the terms R_r/s and u_r/s into $R_r+(1-s)R_r/s$ and $u_r/s+(1-s)u_r/s$, (5) can be rewritten as

1

$$P_{\rm em} = -R_{\rm r} i_{\rm r}^{2} - \frac{(1-s)R_{\rm r}}{s} i_{\rm r}^{2} + {\rm Re} \left[\boldsymbol{u}_{\rm r} \cdot \hat{\boldsymbol{i}}_{\rm r} \right] + {\rm Re} \left[\frac{(1-s)\boldsymbol{u}_{\rm r}}{s} \cdot \hat{\boldsymbol{i}}_{\rm r} \right]$$
⁽⁶⁾

In (6), the first term is the power loss in the rotor windings. The third term is the power input from the excitation power supply to the rotor side. The remaining terms are the DFIG equivalent mechanical output power P_{mec} imported from the rotor shaft, which can be expressed as

$$P_{\rm mec} = -\frac{(1-s)R_{\rm r}}{s}\dot{i_{\rm r}}^2 + {\rm Re}\left[\frac{(1-s)\boldsymbol{u}_{\rm r}}{s}\cdot\hat{\boldsymbol{i}}_{\rm r}\right] \quad (7)$$

Fig. 3 shows the equivalent circuit of DFIG with $R_{\rm s}$, $X_{\rm ls}$, $R_{\rm r}$, $X_{\rm lr}$, $i_{\rm m}$ and $X_{\rm m}$ the stator resistance and

leakage reactance, rotor resistance and leakage reactance, magnetizing current and reactance based on (5)-(7). All the quantities in Fig. 3 are referred to the stator side.





Neglecting the power loss in the DFIG, the stator active power output P_s is approximately equal to the electromagnetic power P_{em} . If P_s is controlled to zero, P_{em} is also approximately equal to zero. So do both the rotor active power output P_r and the DFIG equivalent mechanical output power P_{mec} imported from the rotor shaft according to (5) and (7). Also, if P_{em} is zero, the relative positive-sequence stator and rotor currents can also be restricted according to (5), which can increase the possibility of the DFIG system to ride through the grid faults.

It is also important to note that the rest power will be stored in the mechanical inertia of the wind power generation system, causing the speedup of the DFIG.

If P_{mec} is reduced to zero in the super-synchronous speed operation, the energy absorbed by the turbine rotor for a 2MW wind turbine system with a grid fault is approximately equal to

$$\Delta E = (1 - s)P_{\rm em} \times \Delta t \approx (1 - s)P_{\rm s} \times \Delta t \qquad (8)$$

where Δt is the duration of the grid fault.

The relationship between the energy and generator speed can be expressed as [19]

$$\Delta E = \frac{1}{2} J \left(\omega_2^2 - \omega_1^2 \right) \tag{9}$$

where J is the moment of inertia, and ω_1 and ω_2 are the speed of generator before the grid faults instant and after the recovery voltage instant, respectively.

Also, the relationship between the moment of inertia J and the inertia constant H is

$$H = \frac{\frac{1}{2}J\omega_0^2}{P_{\text{nom}}}$$
(10)

where P_{nom} is the rated power of generator.

Assuming the speed of generator before the grid fault is 1.3pu. According to (8)-(10), and with the parameters provided in the appendix, the calculated speedup of the generator with a 150ms grid fault is approximately 31r/min, which is about 1.5% of the generator speed. Thus, the speedup of generator is quite small, and the scheme of controlling the DFIG active power output P_s to zero is feasible during a short-time grid fault. However, for a longer time grid fault, the emergency pitch angle regulation scheme should be used to reduce the incoming torque. Otherwise, over-speed will occur and the over-speed protection will trip the turbine.

3.3 Active Power Flow of DFIG System with SGSC under Grid Faults

Fig. 4 shows the active power flow of the DFIG system with SGSC under grid faults during supersynchronous speed operation. As shown in Fig. 4, if the output power is still large enough during the grid faults, the surplus active power will flow into the common dc link. Meanwhile, the active power from the RSC to the common dc link is also quite large. Considering the limitation of the PGSC rating, these active powers cannot be delivered to the grid through the PGSC. The common dc link voltage will rise sufficiently and exceed its safe limitation. Therefore, during the grid faults, the active power output of DFIG should be scaled with the remaining voltage or reduced to an even lower value to protect the dc link capacitor. Otherwise, an additional dc link crowbar is needed. Thus, the reduction of DFIG active power output not only increases the possibility of the DFIG system to ride through the grid faults, but also can effectively protect the dc link capacitance.

Note that when the DFIG system operates in the sub-synchronous speed, the surplus active power through the SGSC to the common dc link can be partially or completely consumed by DFIG through RSC. Therefore the regulation stress of the PGSC in the sub-synchronous speed is smaller than the one in the super-synchronous speed. Similarly, when DFIG system operates in the synchronous speed, although the active power from the SGSC cannot be consumed by DFIG through RSC anymore, the active power from the RSC to the common dc link is zero. So the regulation stress of the PGSC in the synchronous speed is also smaller than the one in the supersynchronous speed. So the super-synchronous speed operation condition is the worst case scenario for the PGSC to keep the common dc link voltage constant. And for this reason, we only show the simulations of DFIG in the super-synchronous speed operation for the sake of brevity in Section 5.



Fig.4. Active power flow of DFIG system with SGSC under grid faults during super-synchronous speed operation

4 Proposed Control Scheme for Grid Unbalanced Faults Ride-through

During normal grid condition, the RSC and PGSC are controlled in conventional manners to achieve the decoupling control of stator active and reactive powers and to keep the common dc link voltage constant, respectively [4]. And for the SGSC, it is maintained in a zero voltage vector switch state to eliminate harmonic losses as shown in [14, 17].

During the severe unbalanced grid faults, Flannery and Venkataramanan [17] proposed that the negativesequence component of the stator flux is kept at zero to reject the undesirable effect to the rotor side while the positive-sequence component of the stator flux is to scale in proportion to the positive-sequence component of the remaining grid flux to eliminate the transient DC flux component and to restrain the surplus active power flowing into the common dc link. As a result, in order to avoid the appearance of the transient DC flux component and provide the required system response, the positive-sequence stator flux controller must be carefully tuned. On the other hand, since the transient DC flux component is not considered as the control target to be restricted, once the transient DC flux component appears, it will only be damped with the stator time constant τ_s . However, τ_s is relatively big (about a few seconds) for a MW-class DFIG, thus the attenuation speed of the transient DC flux component is rather slow.

Therefore, in order to overcome the problems highlighted above, we propose that the transient DC component is controlled in the negative-sequence stator flux controller to suppress the adverse effect on the rotor side and accelerate its attenuation and the positive-sequence stator flux controller is only used to control the generator stator positive-sequence flux component to match the remaining grid voltage.

A detailed description of the proposed control scheme of DFIG system with SGSC for the grid unbalanced faults ride-through is given as follows:

For RSC and PGSC, the control schemes are still the same as the normal grid conditions. But for the RSC, the active power output command of DFIG is set to zero to increase the possibility of the DFIG system to ride through the grid faults and effectively protects the dc link capacitance as mentioned in Section 3. For the PGSC, an area of concern with unbalanced grid faults is the stabilization of the common dc link voltage. This was checked in simulation and it was found that the grid-side converter could be controlled to avoid over-current during the unbalanced grid faults [11, 20]. Also, with other improved control scheme of PGSC such as the one mentioned in [21] the common dc link voltage can be more readily stabilized. We have focused our investigations on the control scheme of SGSC, and the control scheme of PGSC isn't discussed too much for the sake of brevity. The SGSC is activated to control the each component of stator flux as shown in Fig. 5 when a grid fault is detected.

Fig. 5 shows the proposed controller of SGSC including three parts: 1) DFIG stator flux estimation and decomposition; 2) Generation of stator positive-sequence flux component command and the setting of stator negative-sequence and transient DC flux components command; 3) Implementation of SGSC output series voltage control.

The generator's total stator flux can be calculated as follows using the measured stator terminal voltage and current in the stationary reference frame

$$\boldsymbol{\psi}_{\rm s} = \int (\boldsymbol{u}_{\rm s} - \boldsymbol{R}_{\rm s} \boldsymbol{i}_{\rm s}) dt \tag{11}$$

Based on the analysis in Section 3.1, Ψ_s contains Ψ_{s1} , Ψ_{s2} and Ψ_{sDC} . In the positive reference frame (PRF) rotating at the speed of ω_0 , Ψ_{s1} will be changed to a dc component while Ψ_{s2} and Ψ_{sDC} will be changed to ac components at the frequencies of $2\omega_0$ and ω_0 , respectively. Similarly, in the negative reference frame (NRF) rotating at the speed of $-\omega_0$, Ψ_{s2} will be changed to a dc component while Ψ_{s1} and Ψ_{sDC} will be changed to a dc component at the frequencies of $-\omega_0$, Ψ_{s2} will be changed to a dc component while Ψ_{s1} and Ψ_{sDC} will be changed to ac components at the frequencies of $2\omega_0$ and ω_0 , respectively. Thus, Ψ_s in the PRF and NRF can be expressed as

$$\boldsymbol{\psi}_{s} e^{-j\omega_{0}t} = \boldsymbol{\psi}_{s1}^{+} + \boldsymbol{\psi}_{s2}^{-} e^{-j2\omega_{0}t} + \boldsymbol{\psi}_{sDC} e^{-j\omega_{0}t} \quad (12)$$

$$\psi_{\rm s} e^{j\omega_0 t} = \psi_{\rm s1}^+ e^{j2\omega_0 t} + \psi_{\rm s2}^- + \psi_{\rm sDC} e^{j\omega_0 t} \qquad (13)$$

Applying two notch-filters [16] at $2\omega_0$ and ω_0 to remove the negative-sequence and transient DC flux components, the positive-sequence flux component in the PRF can be obtained. Analogously, applying a notch-filter at $2\omega_0$ to remove the positive-sequence flux component in the NRF, the negative-sequence and the transient DC flux components can be obtained. Thus, after filtering, the flux components in the PRF and NRF reduce to

$$\boldsymbol{\psi}_{\mathrm{sf}}^{+} = \boldsymbol{\psi}_{\mathrm{s1}}^{+} \tag{14}$$

$$\boldsymbol{\psi}_{\mathrm{sf}}^{-} = \boldsymbol{\psi}_{\mathrm{s2}}^{-} + \boldsymbol{\psi}_{\mathrm{sDC}} \boldsymbol{e}^{j\boldsymbol{a}_{0}t} \tag{15}$$

In addition, during unbalanced grid faults, the grid flux Ψ_{g} (including stator ohmic drop) can be expressed in the PRF as

$$\boldsymbol{\psi}_{g} = \frac{\boldsymbol{u}_{g} - R_{s}\boldsymbol{i}_{s}}{j\omega_{0}} \tag{16}$$

Equation (16) indicates Ψ_g also contains positivesequence, negative-sequence and transient DC flux component, which can be expressed in the PRF as

$$\psi_{g}e^{-j\omega_{0}t} = \psi_{g1}^{+} + \psi_{g2}^{-}e^{-j2\omega_{0}t} + \psi_{gDC}e^{-j\omega_{0}t} \quad (17)$$

Similarly, applying two notch-filters at $2\omega_0$ and ω_0 to remove the negative-sequence and transient DC flux components, the positive-sequence component of the grid flux can be obtained. This is the command for the positive-sequence stator flux component controller, viz.:

$$\boldsymbol{\psi}_{s1}^{+*} = \boldsymbol{\psi}_{g1}^{+} \tag{18}$$

For the negative-sequence and transient DC flux components, they are undesirable components in the stator flux. Thus the command for these two flux components is zero, viz.:

$$\psi_{s2,DC}^{-*} = 0$$
 (19)

The proportional regulators are driven by the error between the command and their respective estimated stator flux components expressed in (14) and (15).

Note that the command for the positive-sequence stator flux component controller has some important characteristics which are summarized as follows:

1) Equation (18) also can indicate the grid flux during normal operation. Thus when the grid fault is cleared, this command can bring the stator flux back to the normal value.

2) A reduction of the stator positive-sequence flux component also causes a reduction of corresponding induced rotor voltage. This means that there is more rotor voltage margin to generate a voltage to control the stator active power output of DFIG to zero and to counteract the remaining negative-sequence and transient DC flux components which cannot be rejected completely by SGSC due to the proportional regulator.

5 Simulation Results

In order to evaluate the ride-through capability of the proposed control scheme, the system has been simulated on a 2MW DFIG wind turbine with SGSC. The simulated DFIG system parameters are given in the Appendix.



Fig.5. Block diagram of SGSC during grid faults



Fig.6. Configuration of a simulated 2MW DFIG system

Fig. 6 shows a hypothetic network configuration of the DFIG system used in this study [11, 21]. The over-modulation PWM technology for the RSC is used and the maximal rotor voltage is assumed to be a high value (1.35 times as much as half of the common dc link voltage). The SGSC rating in this paper is approximately 0.43pu [13-14, 16].

The grid fault occurs at 3s at PCC as shown in Fig. 6, and removed at 3.15s. Before the grid fault, the DFIG system with SGSC operates at a normal speed of 1950r/min (the maximal slip: -0.3). The reactive and active power outputs of the generator are zero and 2MW (rated power), respectively. The fault occurrence is detected from a sudden change of the grid voltage, activating the fault ride-through control of SGSC as shown in Fig. 5. And the output power of the generator is set to zero to restrict the stator and rotor currents and avoid the rise of the common de

link voltage during the grid fault. When the generator stator flux (or stator voltage) is detected back to its normal value, the SGSC is dormant (zero voltage vector), and the DFIG returns to its normal operation.

Fig. 7 shows the simulation results of the DFIG system with SGSC for all types of unbalanced grid faults such as single phase-to-ground fault, double phase-to-ground fault and phase-to-phase fault. As analyzed in [22], the propagation of voltage dips through different types of transformer connections results in a different performance of voltage dips on the secondary side of the transformers. The different voltage dips types through a Δ /Yg transformer seen at the DFIG stator terminal compared to all types of unbalanced grid faults at PCC are shown in Table 2.

As shown in Fig. 7 (e), during unbalanced grid faults, with the injected series voltages of SGSC (Fig. 7 (d)), the negative-sequence and the transient DC flux components are effectively restricted. So the adverse effects of these two components on the rotor side are well-limited and the RSC can generate a voltage (Fig. 7 (c)) to equilibrate the induced voltage. Thus, the rotor over-current is avoided as can be seen clearly in Fig. 7 (b). It is worth noting that the rotor currents still have some second order harmonic

components. This fact is due to the small steady-state error of the proportional regulator and the negativesequence flux component cannot be completely rejected. Fig. 7 (g) and (h) show the active and reactive power outputs of the DFIG. As can be seen, with the effective control of RSC, the active power output of DFIG rapidly drops to zero and the DFIG system hardly absorbs reactive power from the grid. Also, due to the reduction of the active power output, the common dc link voltage, shown in Fig. 7 (j), is well-limited without the help of dc link crowbar. In Fig. 7 (f), the generator stator positive-sequence flux component scales in proportion to the remaining grid positive-sequence flux component during faults and returns to normal value when the faults are cleared, which thanks to the command of the stator positivesequence flux component controller. Besides, as shown in Fig. 7 (i), due to the electromagnetic torque is controllable during all kinds of severe unbalanced grid fault, its fluctuation is quite small which means that the electromagnetic transient shock to the grid and the mechanical stresses in the wind turbine are relatively small. The speed of the DFIG during the grid faults is from 1.3pu to 1.315pu (about 23r/min) which is in closed agreement with the calculated using the analytical equations derived in Section 3.2.



Fig.7 Simulation results of a 2MW DFIG system with SGSC for all types of unbalanced grid faults at PCC (a) Grid voltage through a Δ /Yg transformer U_g (pu), (b) Rotor current i_r (pu), (c) Rotor voltage U_r (V), (d) Series injected voltage of SGSC in the SGSC side U_{sgsc} (V), (e) Amplitude of stator negative-sequence and transient

DC flux components in the NRF $\Psi_{s_{2,DC}}$ (pu), (f) Amplitude of stator positive-sequence flux component in the PRF Ψ_{s1}^{*} (pu), (g) Active power P_{s} (pu), (h) Reactive power Q_{s} (pu), (i) Electromagnetic torque T_{e} (pu), (j) Common dc link voltage V_{dc} (V), (k) Rotor speed ω_{r} (pu).

Tab	le 2	Propagati	ion of vo	ltage d	lips th	irough	$a \Delta/Yg$
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Voltage Dip Caused by	Single phase- to-Ground Fault	Double phase-to- Ground Fault	Phase-to-phase Fault	
Voltage Dip at PCC	$\begin{array}{c} \begin{array}{c} \begin{array}{c} \\ \\ \end{array} \\ \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ A \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ \end{array} \\ \end{array} \\ \end{array} \\ \begin{array}{c} \\ \end{array} \\ $		0.5 1 A,B C	
After Propagation through a Yg-Δ Transformer	$ \begin{array}{c} $	0.58 120° 0.58 60° a	0.87 0.87 a c	

transformer

Similar tests for different rotor speeds and fault occurrence times have also been carried out and the system performance are found to be similar to those shown in Fig. 7. Besides, the proposed control scheme also can make the DFIG system with SGSC ride through balanced grid faults with the undesirable transient DC flux component being restricted in the negative-sequence and transient DC flux components controller. Due to space limitation, they are not shown here.

It is worth noting that with the increased penetration of wind power into the power grid, the new grid codes now require the WTGS not only can ride through grid faults, but also must inject reactive current in order to assist the grid on recovering its rated voltage. As can be seen from Fig. 7, the RSC is controllable throughout grid faults and also has a current margin, which means the DFIG system with SGSC can provide reactive power to the grid during grid faults. Fig. 8 shows the simulation results of a 2MW DFIG system with SGSC under double phaseto-ground grid fault at PCC with reactive power injected to the grid. The pre-fault condition is the same as that given earlier. Fig. 8 (h) shows clearly the reactive power support capability of the system under severe unbalanced grid fault. Also, the rotor over-current and common dc link over-voltage is avoided as can be seen clearly in Fig. 8 (b) and (j).



Fig.8. Simulation results of a 2MW DFIG system with SGSC under double phase-to-ground grid fault at PCC with reactive power output

In order to fulfill the new grid codes, it has become

necessary to increase the DFIG system cost. Among these solutions, the "crowbar protection" technology maybe a relatively low-cost means. However, as analyzed in Section 3, during severe unbalanced grid faults, due to the high rotor voltage induced by the high negative-sequence flux component in the stator, the RSC is impossible to control the rotor current with the available dc-link voltage. Thus, the Crowbar needs to be active throughout the whole dip for the most severe unbalanced grid faults [23]. Under such a condition, the machine is no longer DFIG but a conventional induction machine which loses the control over the active and reactive power and starts to absorb lots of reactive power from the grid for magnetization, which means the wind turbines do not fulfill the reactive requirement of latest grid codes during the activation of a crowbar. Recently, some manufacturers have proposed to install big STATCOMs in addition to the crowbar in the wind farm to fulfill the new grid codes [24], which means a relative large increase of the system operation cost.

On the other hand, from a mechanical perspective, the operation of a crowbar is problematic because severe electromagnetic torque oscillation will appear during severe unbalanced grid faults. If the severe torque oscillation cannot be sufficiently damped, it will lead to failure of the gearbox and rotor shaft. In a recent survey, the gearbox is found to be the most critical component, since its downtime per failure is high in comparison to other components in a WTGS [25]. Also, considering that the wind farms are usually in remote and rural areas and the gearbox is in high erection, once the gearbox is damaged, it is difficulty to maintenance. Hence, the "crowbar protection" technology will also cause an additional cost on system maintenance and lost of profits.

Although the introduction of the SGSC and three phase injection transformer will increase the cost of the system, it also provides excellent capability for voltage dips tolerance. The DFIG system with SGSC can effectively suppress the rotor over-current and inject reactive current to assist the grid on recovering its rated voltage even during severe grid faults. Most importantly, compared to the "crowbar protection" technology, due to the fact that the electromagnetic torque is controllable throughout the grid faults, the electromagnetic transient shock to power grids and the mechanical stresses in WTGS are relatively small which assures a longer life of the gearbox and other mechanical components of the WTGS.



Fig.9. Comparison of electromagnetic torque response under phase-to-phase grid fault at PCC

Fig. 9 shows the electromagnetic torque response between the proposed control scheme with SGSC and the Crowbar protection under phase-to-phase grid fault at PCC. The value of the Crowbar resistor is 0.21Ω determined according to the criterion that the maximum rotor line voltage does not exceed the common dc link voltage in order to avoid the common dc link over-voltage [9]. Also, under such a severe unbalanced grid fault, the Crowbar is active throughout the whole dip. It is clear from Fig. 9 that the oscillation of electromagnetic torque with Crowbar is more severe than the proposed control scheme with SGSC.

7 Conclusions

This paper has presented an unbalanced grid-fault ride-through control scheme for the DFIG system with series grid-side converter to ride through all types of unbalanced grid faults at PCC. During the grid fault, the positive-sequence flux component in the stator flux is controlled to match the remaining grid positive-sequence flux component and the negative-sequence as well as the transient DC components in the stator flux is controlled to zero. Also, the active power output of DFIG is controlled to zero through the RSC to maintain the common de link voltage in its safe limitation and to further reduce the corresponding stator and rotor currents. Simulation results confirmed the effectiveness of the proposed control scheme with successful ridethrough under all types of unbalanced grid faults at PCC and reduced electromagnetic torque oscillation during the grid faults.

Appendix

Simulation system parameters:

- Machine parameters Ratings: $S_n=2MW$, $f_n=50Hz$, $U_n=690V$ (Line voltage rms);
- Pole pairs: 2, Winding connection (stator/rotor): *Y/Y*;

Stator resistance: 0.00488pu;

Stator leakage inductance: 0.1386pu;

Rotor resistance: 0.00549pu;

Rotor leakage inductance: 0.1493pu;

Magnetizing inductance: 3.9527pu;

 $N_{\rm s}/N_{\rm r}$: 0.45;

Inertia constant H: 3.5s.

• Step-up transformer and transmission network parameters

Ratings: $S_n=2.5$ MW, $f_n=50$ Hz;

Primary windings: 20kV-Yg;

Secondary windings: $690V-\Delta$;

Short circuit impedance: $Z_1=0.0098+j0.09241$ pu; Transmission line impedance: $Z_1=0.01+j0.1$ pu.

- Grid-side converter parameters Reactor: L_s=0.6mH, R_s=6mΩ;
 DC-link capacitor: 38000µF;
 DC-link voltage reference value: 1200V;
 SPWM and unity power factor control.
- Series transformer parameters Ratings: $S_n=2MW$, $f_n=50Hz$; Stator to SGSC side transformer turns ratio: 0.5; Sum of transformer and choke resistance: 0.01pu; Sum of transformer and choke inductance: 0.05pu.
- The gains in the proportional regulators of SGSC controller

 $K_{P1}^{+}=4, K_{P2,DC}^{-}=12.$

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