Grid-Synchronization Stability Improvement of Large Scale Wind Farm During Severe Grid Fault

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Abstract—Loss of synchronization between wind farm and power grid during severe grid faults would cause wind farm tripping. In this paper, the mechanism of grid-synchronization is uncovered, described as motion of an autonomous nonlinear differential equation with specific initial states. The revealed mechanism indicates that even though steady state working point exists, improper initial states and poor system dynamic properties could lead to synchronization instability. In order to keep wind farm synchronous with the power grid during severe grid faults, special requirements on system dynamic properties are stated. Moreover, to satisfy all the requirements, a current injecting method is proposed. By adjusting active and reactive output currents of the wind farm, the proposed method could ensure system synchronization stability during severe grid faults. Implementation of the proposed method on PMSG and DFIG based wind farm is illustrated. Simulation results validate the analysis and the control method.

Index Terms—Wind farm, grid-synchronization, severe grid fault, nonlinear system, power system stability.

I. INTRODUCTION

ENERGY issues have been discussed worldwide during last few decades. Replacing traditional fossil energy gradually is urgent nowadays. Wind power, as a kind of renewable energy, plays an important role in sustainable generation and will be developed further in the future. Variable speed wind generators are now the most prevalent wind power generators and have been widely adopted in wind farms [1].

The most prevalent control method utilized in variable speed wind generators is vector control. Although alternative control methods have been proposed, vector control is indispensable under certain situations such as ac-fault [2]. Phase-Locked-Loop(PLL), estimating frequency and angle of terminal voltage, is indispensable in vector control [3]. The situation that output frequency, which is determined by the PLL, is identical with the power grid frequency is regarded as grid-synchronization. However, it has been reported that

PLL based vector control has synchronization problems under weak connection [4], [5]. Main difference between strong connection and weak connection is short-circuit ratio(SCR) at the point of common connection(PCC) of wind farm. High line impedance or low grid voltage leads to low SCR, i.e. weakness. Consequently, the terminal voltage of wind farm is more vulnerable under weak connection [6]. Terminal voltage of wind farm is the input of PLL, while the dynamic of PLL determines the injected currents of wind farm, which will in turn affect the terminal voltage [7]. The weakness aggravates the interaction between wind farm and power grid, which significantly influences grid-synchronization. Hence, a lower grid voltage level and a larger grid impedance will result in a less stable situation of grid-synchronization [8].

It is important for variable speed wind generators to have capability of low voltage ride-through(LVRT) when ac-system short-circuit faults occur [9]–[11]. However, during severe short-circuit faults, connection between wind farm and power system is very weak because the low terminal voltage makes SCR at PCC of wind farm very low. Consequently, the synchronization issues between wind farm and power grid would arise during the faults. Hence, in addition to traditional LVRT techniques, special considerations on synchronization stability should be taken. Since the interaction between wind farm and power system under weak connection will cause the grid-synchronization problem, merely improving PLL tracking ability [12]–[15] is insufficient to ensure grid-synchronization. To solve this problem, the interaction should be taken into consideration. PLL and other relative parts, such as current injecting strategy and line impedance, should be analyzed as a whole system. It should be emphasized that grid-synchronization is a general issue associated with grid-tied power electronic equipments [16].

Boroyevich's team has been working on this problem for a long time and good progress has been made in understanding grid-synchronization [8], [17]–[19]. In [8], [19], a simplified large-signal system model is proposed to analyze grid-synchronization of voltage source converters. Based on the simplified model, a synchronization stability criterion is also proposed. In [5], loss of synchronization between full-scale converter based wind farm and power grid is identified under a severe grid fault. Based on the synchronization stability criterion proposed in [19], [5] also derived transfer limitation of wind farm active current and reactive current during severe ac faults. However, the synchronization stability criterion is established under steady state. Since dynamic behavior also affects system stability, the steady state criterion is not adequate, which would

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Fig. 1. System configuration.

be discussed further in later section.

As mentioned above, previous works have already pointed out that the coupling between PLL itself and line impedance may destabilize grid-synchronization. However, the dynamic process of synchronization between wind farm and power grid has not been fully investigated and understood. This paper uncovers the mechanism of grid-synchronization, indicating that the dynamic behavior may destabilize the system, even though the system is judged stable based on the steady state synchronization stability criterion. Hence, requirements on system dynamic behavior and additional methods are proposed to enhance grid-synchronization.

II. SYSTEM MODELING

A. Model of Grid-tied Wind Farm

The model system is a grid connected wind farm, as shown in Fig.1. The frequency deviation of the power system is omitted in this paper. Hence, the power grid is represented by its Thevenin equivalent circuit, where voltage source E is regarded as ideal with constant voltage and constant frequency. Wind generators in the wind farm are aggregated into one single machine [20], [21]. L_{line} and R_{line} represent the inductance and resistance of transmission line from the wind farm to the power grid, respectively.

This paper focuses on the synchronization between wind farm and power grid during fault. According to the grid code, wind generator should inject required reactive current during fault [22]. Generally, bandwidth of the current loops is much higher than the PLL. Hence, the wind generator can be regarded as an ideal controlled current source during fault steady state [5], [8], [23]. Electromagnetic behaviors of transmission line and grid impedance are also omitted.

The system could be represented as Fig.2(a). Resistance in dashed line is utilized to represent short-circuit resistance. Symbols in Fig.2(a) are defined in (1).

$$\begin{cases} \delta = \theta_{pll} - \theta_g \\ \theta_g = \int_0^t \omega_g dt = \int_0^t 2\pi f_n dt \\ \theta_{pll} = \int_0^t \omega_{pll} dt = \int_0^t 2\pi f_{pll} dt \\ \bar{I}_c^p = I_d^p + jI_q^p = |I_c^p| e^{j\phi_c} \\ \bar{E} = E_d + j0 = |E| \end{cases} \quad (1)$$

where ω_g and f_n are the electric angular velocity and frequency of power system, respectively. ω_{pll} and f_{pll} are the

Fig. 2. Simplified representation of the system.

Fig. 3. Relationship between the variables.

electric angular velocity and frequency of PLL, respectively. The initial value of θ_{pll} and θ_g are all assumed zero in (1). $\bar{I}_c^p$ represents the injected currents of wind farm and $\bar{E}$ is the grid voltage. Note that $\bar{I}_c^p$ is defined on the PLL frame while $\bar{E}$ is defined on the grid voltage frame. The angle difference between the two frame is δ . The two sources with different frequencies contribute to the terminal voltage V_T of wind farm. Based on the superposition principle, we can derive

$$V_T = Z_i(\omega_{pll}) |I_c^p| e^{j(\phi_c + \delta)} + K_v(\omega_g) E \quad (2)$$

When operating under normal condition, R_f in dashed line is omitted. Thus

$$\begin{cases} Z_i(\omega_{pll}) = (R_{line} + R_g) + j\omega_{pll}(L_{line} + L_g) \\ K_v(\omega_g) = 1 \end{cases} \quad (3)$$

When the short-circuit fault occurs, $Z_i(\omega_{pll})$ and $K_v(\omega_g)$ are expressed as

$$\begin{cases} Z_i(\omega_{pll}) = R_{line} + j\omega_{pll}L_{line} + \frac{(R_g + j\omega_{pll}L_g)R_f}{R_f + R_g + j\omega_{pll}L_g} \\ K_v(\omega_g) = \frac{R_f}{R_f + R_g + j\omega_g L_g} \end{cases} \quad (4)$$

The widely used synchronous reference frame PLL is illustrated in Fig.4. V_T is the input of PLL and θ_{pll} is the rotation angle of abc to dq transformation. The relationship between

Fig. 4. Block diagram of PLL.

the variables is shown in Fig.3. Assuming that three phase is balanced, $\hat{v}_q$ could be derived as (5) [8]

$$\hat{v}_q = |Z_i(\omega_{pll})I_c^p| \sin(\phi_c + \angle Z_i(\omega_{pll})) + |K_v(\omega_g)E| \sin(\angle K_v(\omega_g) - \delta) \quad (5)$$

where ω_g is constant. Hence, the first term of right side of (5), which is generated according to PLL angle, can be regarded as dc in PLL frame. We can further simplify expression (5) as

$$\hat{v}_q = a(\omega_{pll}) + b \sin(\phi_0 - \delta) \quad (6)$$

where

$$\begin{cases} a(\omega_{pll}) = |Z_i(\omega_{pll})I_c^p| \sin(\phi_c + \angle Z_i(\omega_{pll})) \\ b = |K_v(\omega_g)E| \\ \phi_0 = \angle K_v(\omega_g) \end{cases} \quad (7)$$

The system model could be deduced as a second-order non-linear differential equations, as shown in (8).

$$\begin{cases} \frac{d\lambda}{dt} = K_i \hat{v}_q \\ \frac{d\delta}{dt} = K_p \hat{v}_q + \lambda \\ \hat{v}_q = a(\omega_{pll}) + b \sin(\phi_0 - \delta) \end{cases} \quad (8)$$

where λ is the value of the integrator of PLL. K_p and K_i are the parameters of PI regulator of PLL, as shown in Fig.4. Note that the state variable of the second row of (8) is $\delta = \theta_{pll} - \theta_g$ instead of θ_{pll} . Relationship between angle δ and PLL input $\hat{v}_q$ reflects the interaction between wind farm and power grid.

B. System Weakness During Grid Faults

In (2), if we set

$$\begin{cases} \bar{E}' = E'_d + j0 = |E'| = |K_v(\omega_g)E| \\ \theta'_g = \angle K_v(\omega_g) \end{cases} \quad (9)$$

then Fig.2(a) is equivalent to Fig.2(b), in which the wind farm connects to another voltage source $\bar{E}'$ with grid impedance $Z_i(\omega_{pll})$. Based on $\bar{E}'$ and $Z_i(\omega_{pll})$, we can conveniently calculate short-circuit capacity at PCC of the wind farm.

When the grid fault occurs, the short-circuit capacity is

$$\begin{aligned} S_{sc}^f &= \frac{|E'|^2}{|Z_i(\omega_g)|} = \frac{|K_v(\omega_g)E|^2}{|Z_i(\omega_g)|} \\ &= \left| \frac{K_v(\omega_g)E^2}{\frac{R_{line} + j\omega_g L_{line}}{K_v(\omega_g)} + R_g + j\omega_g L_g} \right| \end{aligned} \quad (10)$$

Fig. 5. $\hat{v}_q$ curves under different conditions.

while in normal state, the short-circuit capacity is

$$S_{sc}^n = \frac{|E'|^2}{|Z_i(\omega_g)|} = \left| \frac{E^2}{R_{line} + j\omega_g L_{line} + R_g + j\omega_g L_g} \right| \quad (11)$$

Generally, a high grid impedance or a low grid voltage E lead to weak connection. However, from (4), we can obtain that $K_v(\omega_g) \ll 1$ when severe fault occurs. Hence, denominator of (10) is much larger than that of (11) and numerator of (10) is much smaller than that of (11). As a result, S_{sc}^f is much smaller than S_{sc}^n . That means even if the prefault power grid is strong(i.e. low grid impedance), the connection could also become weak under severe short-circuit faults where R_f is quite small. Consequently, no matter whether the prefault system is strong or not, the synchronization problem between wind farm and power grid should be taken into consideration.

III. ANALYSIS ON GRID-SYNCHRONIZATION

Steady state analysis method introduced in this section could be utilized to judge if there are operating points under given conditions. The analysis results are similar to the conclusion obtained via synchronization stability criterion proposed in [8]. Nevertheless, even if steady state working points exist, poor dynamic behavior of system would make these working points unavailable. To clearly understand the essence of this issue, mechanism of grid-synchronization is then revealed, offering a way to evaluate dynamic process of grid-synchronization.

A. Steady State Analysis

In steady state, PLL frequency ω_{pll} equals to power system frequency ω_g . From (8) we can obtain that when $\hat{v}_q = 0$ and $\lambda = 0$, the differential equations reach the equilibrium point. Thus, the zero-crossing points of curve $a(\omega_g) + b \sin(\phi_0 - \delta)$ could represent the steady state points. Along with the increasing amplitude of line impedance or output currents, amplitude of $|a(\omega_g)|$, the dc offset of the curve, will increase. When $|a(\omega_g)|$ is larger than b , $\hat{v}_q$ has no zero-crossing point and hence the system is impossible to be stable, as illustrated in Fig.5. On the other hand, if $b > |a(\omega_g)|$, steady state operating point exists. As shown in Fig.5, $b = |a(\omega_g)|$ is the critical point from the perspective of steady state. Note that either basic PLL or improved PLLs aim to regulate $\hat{v}_q$ to zero [12]–[15]. Hence, if $|a(\omega_g)|$ is larger than b , the system will lose grid-synchronization no matter how fast and sophisticated the PLL is.

Fig. 6. Illustrations on dynamic process of grid-synchronization.

In Fig.5, each curve has two zero-crossing points. Small-signal analysis method could be utilized to judge whether a zero-crossing point is stable or not. Assuming $a(\omega_g)$ is constant, the small-signal system matrix and its characteristic polynomial are shown in (12) and (13), respectively.

$$\mathbf{A} = \begin{bmatrix} 0 & -K_i b \cos(\delta_0 - \phi_0) \\ 1 & -K_p b \cos(\delta_0 - \phi_0) \end{bmatrix} \quad (12)$$

$$\begin{aligned} \rho_S(s) &= |s\mathbf{I} - \mathbf{A}| \\ &= s^2 + K_p b \cos(\delta_0 - \phi_0)s + K_i b \cos(\delta_0 - \phi_0) \end{aligned} \quad (13)$$

where $\delta_0 - \phi_0$ is the angle of the zero-crossing point. When $\delta_0 - \phi_0 < \frac{\pi}{2}$, equation $\rho_S(s) = 0$ has negative real-part solutions, indicating that the relative zero-crossing point is stable, otherwise unstable. The stable and unstable equilibrium points are shown in Fig.5.

B. Mechanism of Grid-Synchronization

To study the mechanism of grid-synchronization, extra simulations are demonstrated here. The simulated system is shown in Fig.1. Instead of short-circuit faults, steps of power grid voltage E are applied to mimic abnormal situations in this example for the reason that the obtained curves could have proper scales to be conveniently observed. As a result, expression in (3) rather than (4) should be used at abnormal situations and hence $\phi_0 = 0$ all the time because $K_v(\omega_g) = 1$ in (3). Moreover, $\bar{I}_c$ is set to 1 p.u. active current. Two cases with different power grid voltage variations are simulated in this example, as shown in Fig.6.

The blue sinusoidal curve(i.e. the normal curve) and the red sinusoidal curve(i.e. the abnormal curve) describe the value of $\hat{v}_q$ before and after voltage variation, respectively. Fig.6(a) shows that under normal situation, the system works at point A, a steady state working point where $\lambda = 0$ and $\delta - \phi_0 = \delta_0 - \phi_0$. After voltage E drops from 1 p.u. to 0.54 p.u. at $t = t_1$, the working point steps from A to B immediately. At point

B, $\lambda = 0$ and δ is the same as point A. However, point B is not an equilibrium point of the abnormal curve. Thus, B will move toward C(i.e. zero-crossing point of the abnormal curve) because $\hat{v}_q$ is positive at B, generating increasing trend of δ . After overshooting through point C, system enters the $v_q < 0$ region and the speed of δ (i.e. $\omega_{pll} - \omega_g$) decreases. $\omega_{pll} - \omega_g$ reaches zero in the $v_q < 0$ region and subsequently becomes negative. The system will finally settle at point C, a stable point during abnormal stage. The dynamic process can be described by (8) with initial states $\lambda_0 = 0$ and $\delta_0 - \phi_0$. When voltage E is recovered, the working point moves from point C to point A in a similar process. In Fig.6(b), voltage E drops from 1 p.u. to 0.46 p.u. at $t = t_1$. Point B on the red curve(i.e. abnormal curve) will move to its zero-crossing point C. Compared to Fig.6(a), the voltage drops deeper and hence the $v_q < 0$ region is smaller under abnormal situation in Fig.6(b). System reaches point D before $\omega_{pll} - \omega_g$ could decrease to zero. Hence, $\omega_{pll} - \omega_g$ still has a positive value at point D. As a result, δ finally goes into the positive part of the red curve after crossing point D. The system can never work at point C stably during abnormal stage in Fig.6(b), which means that synchronization stability of the system cannot be guaranteed. At the moment before the voltage recovers, the system works at point E. After the voltage is recovered, the working point steps from E to F. Finally, the system will work at point A again.

This example offers a basic sight of transient characteristics of grid-synchronization after large disturbance. Note that in this example, $\phi_0 = 0$ all the time. In fact, when a short-circuit fault occurs, expression in (4) should be used. Thus, angle ϕ_0 does not equal to zero during the fault. From the illustrations, we can obtain the following conclusion.

- Theoretically, dynamic process of synchronization between wind farm and power grid after large disturbance could be described as motion of autonomous nonlinear equation (8) with initial states $\lambda_0 = 0$ and $\delta_0 - \phi_0 \in [0, 2\pi]$.
- Overshoot may lead to instability even though steady state working point exists, especially when the dc offset is close to b (i.e. the zero-crossing point of $\hat{v}_q$ is close to its critical point), as the case in Fig.6(b).

In practice, the initial phase $\delta_0 - \phi_0$ could be any value in $[0, 2\pi]$. The reasons are listed below.

- The value of ϕ_0 in fault state, which is determined by impedance network, is uncertain and different from that in normal state.
- δ_0 is undetermined because of detection delay and protection. Take DFIG as a example, δ would vary randomly when crowbar of DFIG is activated. At the moment rotor-side converter is reconnected and output currents are controlled to their commands, which is regarded as the initial moment of (8), δ_0 could be any value in $[0, 2\pi]$.

The value of λ_0 is also undetermined at the initial moment because of detection delay and protection. However, since PLL is software based, we can manually reset λ to zero whenever needed. Consequently, the assumption that initial state $\lambda_0 = 0$ always holds.

IV. SYNCHRONIZATION STABILITY IMPROVEMENT DURING SEVERE SHORT-CIRCUIT FAULTS

A. Synchronization Stability Requirements

Loss of synchronization is usually regarded as an abnormal state and may lead to failure in power control and wind farm tripping. Hence, to maintain wind farm connected with power grid during grid fault, grid-synchronization should be ensured. Based on the steady state analysis and the mechanism of grid-synchronization mentioned in Section-III, special requirements on grid-synchronization for wind farm during severe short-circuit faults could be summarized as follow.

- Existence of working point should be ensured so that the wind farm can inject desired reactive current correctly during severe short-circuit faults.
- Dynamic process of grid-synchronization should be ensured stable. That means for every initial states $\lambda_0 = 0$ and $\forall \delta_0 \in [0, 2\pi]$, the trajectory of system equation (8), representing system behavior during faults, is supposed to converge to its steady state working point.

B. Adaptive Current Injecting Strategy

Previous works have investigated moderate fault situations where voltages are no lower than 0.1p.u. [9]–[11]. These works show no synchronization problems. However, loss of synchronization is identified at severe fault situation where voltages drop to less than 0.05p.u. [5]. Hence, in this part, severe grid fault situations are considered. An adaptive current injecting strategy is proposed to ensure synchronization stability when voltage drops to a very low value (e.g. below 0.1p.u.). The proposed method complies with all the special requirements.

The severe short-circuit fault could be represented by a quite small resistance R_f , as illustrated in Fig.2(a). Since R_f is much smaller than line impedance and grid impedance at severe fault situations, it can be deduced from (4) that

$$Z_i(\omega_{pll}) \approx R_{line} + j\omega_{pll}L_{line} \quad (14)$$

and

$$\angle K_v(\omega_g) \approx -\arctan\left(\frac{\omega_g L_g}{R_g}\right) \quad (15)$$

According to the PLL frequency, if we set output current commands of the wind farm adaptively, as shown in (16)

$$\begin{cases} \frac{I_q^p}{I_d^p} = -\tan \angle Z_i(\omega_{pll}) = -\frac{\omega_{pll}L_{line}}{R_{line}} \\ \sqrt{I_d^{p2} + I_q^{p2}} \leq 1\text{p.u.} \end{cases} \quad (16)$$

then

$$\phi_c + \angle Z_i(\omega_{pll}) = 0 \quad (17)$$

which means

$$a(\omega_{pll}) = 0 \quad (18)$$

Then (8) could be rewritten as

$$\begin{cases} \frac{d\lambda}{dt} = -K_i b \sin(\sigma) \\ \frac{d\sigma}{dt} = -K_p b \sin(\sigma) + \lambda \end{cases} \quad (19)$$

where $\sigma = \delta - \phi_0$.

The DC offset of $\hat{v}_q$ curve is zero under this control method. Hence, working point is bound to exist. To evaluate stability of (19), Lyapunov method is used [24], [25]. Consider the following Lyapunov function

$$V(\lambda, \sigma) = \frac{1}{2}\lambda^2 + K_i b(1 - \cos \sigma) \geq 0 \quad (20)$$

Hence,

$$\begin{aligned} \dot{V}(\lambda, \sigma) &= \lambda\dot{\lambda} + K_i b \sin \sigma \dot{\sigma} \\ &= -K_i b \lambda \sin \sigma - K_i K_p b^2 \sin^2 \sigma + K_i b \lambda \sin \sigma \\ &= -K_i K_p b \sin^2 \sigma \end{aligned} \quad (21)$$

It is true that $K_p > 0$ and $K_i > 0$. Then we can obtain

$$\dot{V}(\lambda, \sigma) \leq 0 \quad (22)$$

From Lyapunov stability criterion, system (19) is globally stable, indicating that the adaptive current injecting method could help the wind farm to maintain grid-synchronization.

The wind farm injects active power and reactive power to the grid, simultaneously. Since the terminal voltage of wind farm is very low during fault, the captured mechanical power cannot be dissipated via transmission line even the proposed current injection strategy injects active current. Note that utilizing the adaptive current injecting control, the reactive current cannot reach 1p.u. because the active current is supposed to be set non-zero. Consequently, this control method violates the grid code. However, this dilemma could be avoided by applying auxiliary SVG, which could inject extra reactive current to meet the grid code. If total active current and total reactive current injected by the wind farm and the SVG meet the adaptive current injecting strategy, and the total reactive current is no less than 1p.u., both the synchronization stability and the grid code could be guaranteed.

Under extreme situation where R_f equals to zero, the value of b is zero according to (7). Theoretically, utilizing the adaptive current injecting method, the value of $a(\omega_{pll})$ can be controlled to zero. Hence, according to Fig.4, the output frequency of wind farm is determined only by the integrator value λ of the PLL. If we manually reset λ to zero, the output frequency is f_n . However, the frequency of power grid may slightly drift from f_n during fault. For the cases where R_f is not zero, the value of b is not zero and the PLL can capture the frequency information of power grid hence output frequency of wind farm can track the power system frequency. However, if R_f is zero, wind farm can no more capture the information of power system frequency. Consequently, even though the proposed current injection method can stabilize the system under $R_f = 0$ situation, the output frequency of wind farm is not exactly the same as power grid.

Moreover, (19) could also utilized to explain why synchronization stability can be always guaranteed under strong power grid. If line impedance is small, the value of $|I_c^p Z_i(\omega_{pll})|$ is small compared to the amplitude of terminal voltage E . Hence, impact of term $a(\omega_{pll})$ is negligible under strong connection. Based on this assumption and former Lyapunov analysis, synchronization stability could be always ensured.

Fig. 7. Structure of PMSG.

Fig. 8. Current control block diagram of PMSG.

V. IMPLEMENTATION OF ADAPTIVE CURRENT INJECTING STRATEGY IN PMSG AND DFIG BASED WIND FARM

A. Implementation of Adaptive Current Injecting Strategy in PMSG Based Wind Farm

Full-scale converter is applied in PMSG wind farm. The advantage of this structure is the decoupling between grid-side converter and wind generator. It is possible for PMSG wind farm to control grid currents independently.

Structure of PMSG is shown as Fig.7. When working under normal state (i.e. no fault occurs), the grid-side converter regulates the dc voltage and the rotor-side converter controls electrical torque of the PMSG according to MPPT curve or upper level command. During short-circuit faults, the dc chopper could release surplus energy in the capacitor in case of over-voltage. Bang-bang control strategy is used to control the dc chopper. Pitch control of wind turbine is utilized to protect the drive train in case of over-speed.

Current control is shown in Fig.8. Under normal state, current commands are obtained by outer control loops. When severe faults occur, the proposed current strategy should be utilized.

B. Implementation of Adaptive Current Injecting Strategy in DFIG Based Wind Farm

Structure of DFIG is shown in Fig.9. Stator windings of the DFIG are directly connected to the power grid and the wound rotor connects to the power grid through a back-to-back converter. Consequently, the output currents are the combination of stator and grid-side converter currents, as shown in Fig.9.

Current control of DFIG under severe short-circuit faults is shown in Fig.10. Objective of the current control is to regulate

Fig. 9. Structure of DFIG.

Fig. 10. Current control block diagram of DFIG.

the d-axis and q-axis components of i_T in compliance with the adaptive current injecting strategy. DC voltage of the back-to-back converter is supposed to be controlled as constant by the grid-side converter. Thus, we can obtain

$$\begin{aligned} i_{sd}^* &= i_{Td}^* - i_{gd}^* \\ i_{sq}^* &= i_{Tq}^* - i_{gq}^* \end{aligned} \quad (23)$$

where i_{Td}^* and i_{Tq}^* are the target currents deduced by the adaptive current injecting strategy. i_{gd}^* is the grid-side converter d-axis current command generated by the dc voltage control loop. The reactive current i_{gq}^* of grid-side converter is often set to zero. Thus, i_{sd}^* and i_{sq}^* are the desired stator currents. However, only rotor currents of the DFIG is controllable. The relationships between rotor currents and stator currents of DFIG are shown as follow.

$$\begin{aligned} i_{rd}^* &= -\frac{L_s}{L_m} i_{sd}^* \\ i_{rq}^* &= \frac{1}{L_m} \Psi_s - \frac{L_s}{L_m} i_{sq}^* \end{aligned} \quad (24)$$

where $L_s = L_{ls} + L_m$. L_{ls} and L_m are stator leak inductance and mutual inductance, respectively. Stator flux Ψ_s could be obtained via flux observer, which has been widely studied in motor drive area. (25) shows a simple flux observer.

$$\Psi_s = \int (u_s + i_s R_s) dt \quad (25)$$

As a result, the desired currents of wind farm are converted to the rotor current commands of DFIG, which could be regulated by the rotor-side converter.

It should be mentioned that crowbar is utilized in DFIG to protect over-current when faults occur. When the faults occur, the crowbar is connected and the rotor-side converter is blocked. As a result, the DFIG works as an asynchronous machine and hence the currents of DFIG is uncontrollable during this stage. After several tens of milliseconds when crowbar is switched off and rotor-side converter is reconnected, output currents are again controllable and should be regulated according to Fig.10.

VI. SIMULATION VERIFICATION

Fig.1 is established using MATLAB/Simulink. Electromagnetical dynamic are considered to validate the effectiveness of the analysis and the proposed control methods. The converters are represented by average-value models. The parameters of test system are given in APPENDIX.

A. Steady State Working Point Validation

From (6) and the analysis in Section III-A, let $\hat{v}_q = 0$, then we can obtain two zero-crossing points. According to the small signal analysis in Section III-A, the $\delta_0 - \phi_0 < \frac{\pi}{2}$ zero-crossing point is the stable one. Consequently, we can get the steady state δ_0 under prefault and fault condition, respectively.

$$\begin{aligned} \delta_0 &= \phi_0 + \arcsin \frac{a(\omega_{pll})}{b} \\ &= \angle K_v(\omega_g) + \arcsin \frac{|Z_i(\omega_g)I_c^p| \sin(\phi_c + \angle Z_i(\omega_g))}{|K_v(\omega_g)E|} \end{aligned} \quad (26)$$

Particularly, when adaptive current injecting control law is applied, term $a(\omega_{pll}) = 0$. Hence

$$\delta_0 = \phi_0 = \angle K_v(\omega_g) \quad (27)$$

Fig.11(e) shows the δ curve. The steady state working points are also illustrated in Fig.11(e). Details of Fig.11 would be introduced in next part. With the parameters shown in APPENDIX, δ_0^{pr} and δ_0^{fa} are 0.4499rad and 4.4619rad, respectively. The simulation results match the calculated results exactly.

B. Effectiveness of Adaptive Current Injecting Strategy

This part illustrates feasibility of the adaptive current injecting strategy under a severe short-circuit fault. The short-circuit fault is simulated by connecting a small resistance R_f in parallel. PMSG and DFIG based wind farm are examined, respectively. The control strategies of PMSG and DFIG wind farm have been introduced in Section-V. PLL parameters in these two cases are set to $K_p = 200$ and $K_i = 50$. Note that the scale of $\hat{v}_q$ under fault state is much smaller compared to normal state. Hence, to ensure a similar bandwidth of PLL, here defines several voltage intervals. According to these voltage intervals, scheduled gain is applied to multiply $\hat{v}_q$. In the following simulation, voltage drops to lower than 0.1p.u. and the gain is 10 during the fault.

Fig. 11. Simulation results of PMSG.

1) *PMSG*: The short-circuit fault occurs in $t = 0.2s$. AC voltage drops to 0.02p.u., as shown in Fig.11(a). The generator-side converter controls electrical torque. At the same time, the dc chopper is activated in order to keep the dc bus below limitation, as shown in Fig.11(b). The grid-side converter could be treated as a current source injecting reactive and active currents in according to (16), as shown in Fig.11(c). In this case, electrical torque of the PMSG, controlled by the generator-side converter, is reduced when the fault occurs. Consequently, rotor speed will accelerate, activating pitch control, as shown in Fig.11(d) and Fig.11(f). By doing this, the input mechanical power is reduced and the burden on the dc chopper is then reduced. Fig.11(g) shows PLL frequency, which could converge to system frequency after transient process, validating the effectiveness of the adaptive current injecting strategy.

2) *DFIG*: This part validates the effectiveness of the proposed control strategy in DFIG wind farm. Two cases are established to show different characteristics under supersynchronous and subsynchronous conditions. Simulation results are shown as Fig.12 and Fig.13. In supersynchronous case, pitch control is activated to keep rotor speed below limitation. Desired currents obtained by adaptive current injecting strategy are the combination of stator currents and grid-side converter currents. Fig.12(d) and Fig.13(d) show that the rotor

Fig. 12. Simulation results of DFIG under hypersynchronous condition.

currents could track the current commands exactly during the fault, hence, in Fig.12(e) and Fig.13(e) the stator currents could be regulated to desired value, as well as the grid-side converter currents, as shown in Fig.12(c) and Fig.13(c). As a result, the output wind farm currents could track the adaptive current injecting law, keeping wind farm synchronous with power grid during the severe short-circuit fault, as shown in Fig.12(i) and Fig.13(i). It should be mentioned that when the crowbar is activated, there is a drastic transient process. In both cases examined here, the transient process is less than 30ms. After the crowbar is deactivated, the rotor-side converter reconnects and the value of PLL integrator is set to zero manually.

C. Robustness of Adaptive Current Injecting Strategy

The proposed current injecting method need to know parameters R_{line} and L_{line} of the transmission line. However, weather,

Fig. 13. Simulation results of DFIG under subsynchronous condition.

er, temperature, humidity and aging could lead to variation of the line parameters. Although the line parameters could be identified by measuring, precise parameters of the transmission line could not be obtained in practice. Hence, robustness of the proposed method is examined here to see whether the method can work with parameters mismatch caused by measuring error or other reasons.

Case studied here is the same as Fig.12. Parameters used in current injecting method is the normal value R_{line}^r and L_{line}^r shown in Table.I. The line parameters R_{line} and L_{line} are changed to examine the robustness, as shown in Fig.14. We can obtain that if the line parameters R_{line} and L_{line} locate in the blue line, L/R ratio keeps unchanged and hence stability will not be affected. However, if R_{line} increases(decreases) and L_{line} decreases(increases), system is possible to get into the unstable region where PLL frequency can no longer converge to system frequency. In this case, the system is stable until variation of the parameters is up to 21%, as the arrow in

Fig. 14. Examination on robustness of the proposed method.

Fig.14. The simulation result shows that the proposed method can work without knowing precise line parameters.

VII. CONCLUSION

Severe short-circuit faults make connection between wind farm and power grid weak, even though the connection of the pre-fault system is strong. Hence synchronization issues arise during the faults. In this paper, the dynamic process of grid-synchronization is described as motion of autonomous second-order nonlinear system with specific initial states. To ensure synchronization stability, special requirements for wind farm should be met. Moreover, the adaptive current injecting method is proposed, which can satisfy all the requirements. Simulations on both PMSG and DFIG based wind farm are then illustrated. Impact of detection delay and protection is considered in the simulations to better reflect a real-world scenario. Simulation results show that output currents of the wind farm could exactly track current commands generated by the adaptive current injecting method during the severe grid fault. Hence synchronization stability could be ensured and the method is verified. Robustness examination shows that the proposed method can work under a certain amount of parameters mismatch, which is 21% in the case examined in this paper.

Note that this paper uses an aggregated model to study the grid-synchronization issue. Actually, in wind farm, feeders and collection cables will lead to voltage difference between wind turbines, which is neglected in this paper. Hence, further work in detailed wind farm considering individual wind turbines and their connections should be elaborated. This would be the future work on the grid-synchronization issue.

APPENDIX

A. Parameters of wind farm

Rated frequency f_n : 50Hz
Power base S_{base} : 100MVA

Voltage base V_{base} : 575V
Rated power of wind farm P_n : 100MW
Rated voltage of E : 575V
Short-circuit ratio(SCR): 2
Resistance of transmission line R_{line} : 0.0369p.u.
Inductance of transmission line L_{line} : 0.1056p.u.
Resistance of grid impedance R_g : 0.0546p.u.
Inductance of grid impedance L_g : 0.382p.u.
Fault resistance R_f : 0.008p.u.

B. Parameters of PMSG

Resistance R_s : 0.006p.u.
Inductance in d-axis L_d : 1.305p.u.
Inductance in q-axis L_q : 0.296p.u.
Grid coupling inductance L_c : 0.3p.u.
Generator inertia constant: 0.62s
Turbine inertia constant: 4.32s
GSC voltage loop: $K_p = 15$, $K_i = 27.5$
GSC reactive power loop: 0.05, $K_i = 20$
GSC current loop: $K_p = 1.2$, $K_i = 1.25$
RSC speed loop: $K_p = 5$, $K_i = 1$
RSC current loop: $K_p = 0.025$, $K_i = 100$

C. Parameters of DFIG

Stator resistance R_s : 0.023p.u.
Stator inductance L_s : 0.18p.u.
Rotor resistance R_r : 0.016p.u.
Rotor inductance L_r : 0.16p.u.
Mutual inductance L_m : 2.9p.u.
Generator inertia constant: 0.685s
Turbine inertia constant: 4.32s
Grid coupling inductance L_c : 0.3p.u.
GSC voltage loop: $K_p = 6.4$, $K_i = 32$
GSC reactive power loop: 0.05, $K_i = 20$
GSC current loop: $K_p = 0.8$, $K_i = 2.5$
RSC speed loop: $K_p = 3$, $K_i = 0.06$
RSC current loop: $K_p = 2.4$, $K_i = 0.8$

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