Impact of DFIG based Wind Energy Conversion System on Fault Studies and Power Swings

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Abstract—The integration of renewable energy sources into power systems changes the transient and fault current characteristics of the conventional grid. The variation in the system response during grid disturbance like sudden load changes or fault would cause the failure of traditional protection and control. Since the operating condition of DFIG depends on the characteristics of the grid and its control, the short circuit current in the system becomes more complex. This paper analyzes the short circuit characteristics of DFIG and develops an analytical expression for the three phase fault current. Depending on the severity of the fault in terms of voltage drop, the fault current responses are developed with and without crow bar resistance. The power swings that originates in the system when the fault is cleared are also analyzed in the paper. The transient simulation studies are performed in PSCAD/EMTDC by integrating DFIG to WSCC system. Case studies are performed to analyze the impact of location of fault to the power swing and fault current contribution.

Index Terms—Doubly fed induction generator (DFIG), fault, power oscillation, reactive power, rotor angle oscillation, short circuit.

I. INTRODUCTION

The rise in electrical power demand and environmental concerns are driving the power grid towards greener and renewable energy integration. Among the renewable energy integration, wind plants are growing fast in recent years [1]. With The DFIG based Wind Energy Conversion System (WECS) is the most common in wind power plants due to its variable speed operation [2]. With the increased penetration of DFIG, the fault studies becomes more complicated and power oscillations due to any disturbance in the system need to be analyzed in detail.

The capability of Low Voltage Ride Through (LVRT) [3] and four quadrant operation which makes possible to operate at any desired power factor, makes DFIG based WECS different from other renewable sources. The intermittent nature of wind energy can also be mitigated upto an extend by providing the battery storage in the DC link of DFIG [4]. DFIG based WECS consists of three parts as shown in Fig. 1: 1) Mechanical wind driven turbine which can operate at variable wind speeds, 2) Doubly Fed Induction Machine whose rotor terminals are externally available and 3) back to back voltage source converter (VSC) which ensures the bidirectional power flows during variable speeds. The stator terminal of the machine is normally directly connected to the grid and the rotor terminals are connected to the back to back converters. This converter is hitched back to the grid through a transformer to reduce the voltage rating of the converter. The back to back VSC converters are normally low rated (one third rating of the machine).

The integration of wind energy makes the short circuit studies more intrinsic. The 3 generator 9 bus, Western System Coordinating Council (WSCC) system is selected for detailed modeling for transient stability studies. The excitation control, governor control are modeled for analyzing the rotor angle oscillation of the synchronous generators. Sudden load disturbance, in the extreme case of faults, will disturbs the rotor torque and corresponds to rotor angle oscillation. These disturbance in the rotor angle will reflect as power oscillation in the entire system and in worst case, it can leads the system to collapse. The integration of low inertia renewable sources will make the system more weak [5].

The transient stability improvement with DFIG system is discussed in [5]. The change in dynamics and operational characteristics of the conventional grid due to the large penetration of DFIG is addressed. A decoupled FRT technique to enhance the system stability is discussed in [6]. The optimal crowbar resistance is found to improve the power transfer capability of the system. The detailed study on impact of the penetration of wind integration should be done before implementing the control schemes. This paper discusses the short circuit analysis and power angle oscillation with high penetration of wind integration with power system.

978-1-4799-5141-3/14/$31.00 ©2016 IEEE
II. Transient Modeling of DFIG

The basic circuit configuration of DFIG is as shown in Fig. 1. The stator terminal of wound rotor induction machine is connected directly to the grid and rotor terminals through a step up transformer to reduce the voltage rating of the converters. During different modes of operation like sub-synchronous and super-synchronous, the rotor circuit needs to supply power in both the directions. The back to back converters of IGBT switches with anti parallel diodes are employed as shown in Fig. 1 which allows the bidirectional power flow. The DFIG is modeled in synchronous reference frame (d-q) to get the independent control of active and reactive powers [7].

The electromagnetic torque developed in the machine can be expressed in terms of direct and quadrature axis currents and flux as follows,

$$T_{em} = \frac{3}{2} P \frac{L_m}{L_s} (\psi_{qs} i_{dr} - \psi_{ds} i_{qr})$$  \hspace{1cm} (1)

Where, $P$ is the no of poles, $L_m$ and $L_s$ are mutual and self inductances, $\psi_{ds}$ and $\psi_{qs}$ are the d axis and q axis stator flux, $i_{dr}$ and $i_{qr}$ are the d axis and q axis rotor currents. The synchronous rotating frame is selected such that d axis is aligned with the stator flux which results,

$$\psi_{ds} = \psi \quad and \quad \psi_{qs} = 0$$  \hspace{1cm} (2)

Then the torque equation reduces to

$$T_{em} = \frac{3}{2} P \frac{L_m}{L_s} (-\psi_{ds} i_{qr})$$  \hspace{1cm} (3)

Similarly,

$$i_{ms} = (1 + \sigma_s) i_{sd} + i_{dr}$$  \hspace{1cm} (4)

Where,

$m_{ms} :$ Magnetizing current

$\sigma_s :$ Stator Leakage factor, $\sigma_s = \frac{L_s}{L_m}$

$i_{sd}$ and $i_{sq} :$ d axis and q axis stator currents

Therefore the reactive power required to provide the magnetizing current can be fed either from stator side or rotor side. In this paper, all the magnetizing current is fed from rotor side to maintain unity power factor at the DFIG terminals.

The voltage balance equations at the grid side converter terminals can be written as,

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} v_{ag} \\ v_{bg} \\ v_{cg} \end{bmatrix}$$  \hspace{1cm} (5)

Where, $v_a$, $v_b$, $v_c$ and $v_{ag}$, $v_{bg}$, $v_{cg}$ are the converter terminal and grid voltages respectively. The three phase active and reactive power can be expressed in dq frame as,

$$p = v_d i_{ds} + v_q i_{qs}$$  \hspace{1cm} (6)

$$q = v_q i_{ds} - v_d i_{qs}$$  \hspace{1cm} (7)

For grid side converter, d axis is aligned with the stator voltage,

$$v_d = V \quad and \quad v_q = 0$$  \hspace{1cm} (8)

The active and reactive power expression can be reduced to

$$p = v_d i_{ds} \quad and \quad q = -v_d i_{qs}$$  \hspace{1cm} (9)

Therefore, $i_{ds}$ is proportional to active power flow and $i_{qs}$ is proportional to reactive power flow through the grid side converter.

The Rotor Side Converter (RSC) is employed to control the electromagnetic torque developed in the machine by regulating $i_{qr}$ as given in eqn 1 and thus to control the rotor speed. The part of magnetization current required by the machine can be supplied from the RSC by regulating $i_{dr}$ as shown in eqn 4. The crowbar resistance is employed to limit the RSC current during grid faults [8]. The crow bar is switched on once the stator voltage is dipped and provide a bypass for the rotor current thus preventing any damage to RSC due to over current. The detailed analysis of fault current is discussed in III.

The main objective of Grid Side Converter (GSC) to maintain the DC link voltage constant irrespective of power flow during super synchronous and sub synchronous operation of DFIG. The GSC can also control the amount of reactive power injected to the grid by regulating $i_{qs}$ as shown in eqn 9. Even if the RSC is disconnected during grid faults and crowbar bypasses the excess current from rotor, the GSC can maintain the DC link voltage constant [9]. This helps DFIG to stay connected to the grid and resume its operation soon after the removal of fault.

III. Short Circuit Characteristics of DFIG

The equivalent circuit of DFIG in stator reference frame is shown in Fig. 2. The stator and rotor equations can be written as

$$\begin{aligned}
V_s &= R_s i_s + (1 + \sigma_s) L_0 \frac{d}{dt} (i_s) + L_0 \frac{d}{dt} (i_r e^{j\omega t}) \\
V_r &= R_r i_r + \sigma_r L_0 \frac{d}{dt} i_r + L_0 \frac{d}{dt} (i_s e^{-j\omega t})
\end{aligned}$$  \hspace{1cm} (10)

The flux function equations corresponding to voltage balance eqn 10 can be expressed as

$$\begin{aligned}
\psi_s &= \sigma_s L_0 i_s + L_0 \psi_r \\
\psi_r &= \sigma_r L_0 i_r + L_0 \psi_r
\end{aligned}$$  \hspace{1cm} (11)

$$\begin{aligned}
\frac{d\psi_s}{dt} &= \psi_s + \frac{d}{dt} \left( \sigma_s L_0 i_s + L_0 \psi_r \right) \\
\frac{d\psi_r}{dt} &= \psi_r + \frac{d}{dt} \left( \sigma_r L_0 i_r + L_0 \psi_r \right)
\end{aligned}$$  \hspace{1cm} (12)
Where,

\( V_s \) and \( V_r \) : Stator and rotor voltage  
\( i_s \) and \( i_r \) : Stator and rotor currents  
\( R_s \) and \( R_r \) : Stator and rotor resistances  
\( L_0 \) : Magnetizing inductance  
\( \sigma_s \) and \( \sigma_r \) : Stator and rotor leakage factor  
\( \omega_{ms} \) : Synchronous speed  
\( \psi_s \) and \( \psi_r \) : Stator and rotor flux  
\( \epsilon \) : Angle between stator and rotor axis  
\( \omega_r \) : Electrical angular velocity

The rotor currents and the stator voltages are within the limits during the normal operation of DFIG. Assume a fault occurs at a time of \( t_0 \) at the grid which causes the stator voltage to drop to \( V_s' \). It affects the flux linkages at stator and rotor. The analytical expression for the fault current without crowbar is turned on, the RSC is disconnected from the rotor winding. Therefore, the rotor induced current will be provided from the stator is developed in this section. Once the crowbar is turned on, the RSC is disconnected from the rotor winding. Therefore, the rotor induced current will be only due to the stator flux. The stator flux equation in terms of stator voltage and stator parameters can written as,

\[
\frac{d}{dt} \psi_s + \frac{R_s}{\sigma_s L_0} \psi_s = V_s - \frac{R_s}{\sigma_s} i_r 
\]

As the current injected from RSC to rotor is in slip frequency, the rotor flux will have the same speed as that of stator flux, i.e., the rotor injected current, slip frequency + rotor speed = stator flux frequency. Therefore, the stator flux eqn 14 before and after fault can be written as,

\[
\psi_s(t \leq t_0) = \frac{\sigma_s L_0}{R_s + j\omega_s \sigma_s L_0} \left( V_s - I_r R_s \right) e^{j\omega_r t} \\
\psi_s(t \geq t_0) = \frac{\sigma_s L_0}{R_s + j\omega_s \sigma_s L_0} \left( V_s' - I_r R_s \right) e^{j\omega_r t + \psi_0 e^{-\frac{t}{\tau_s}}} 
\]

where,

\[
\psi_0 = \frac{\sigma_s L_0 (V_s - V_s')}{R_s + j\omega_s \sigma_s L_0} e^{j\omega_r t_0}
\]

Since the stator resistance is negligible compared to stator reactance, the eqn 15 can be reduced to,

\[
\psi_s(t \leq t_0) = \frac{V_s}{j\omega_s} e^{j\omega_r t} \\
\psi_s(t \geq t_0) = \frac{V_s'}{j\omega_s} e^{j\omega_r t} + \frac{V_s - V_s'}{j\omega_s} e^{-\frac{t}{\tau_s}}
\]

The stator current in terms of stator flux can written from eqn 12 as,

\[
i_s = \frac{\psi_s - L_0 i_r}{\sigma_s L_0}
\]

Substituting the value of stator flux from eqn 16 in eqn 17,

\[
i_s = \frac{V_s - V_s'}{j\omega_s \sigma_s L_0} e^{j\omega_r t} \left( 1 - \frac{t}{\tau_s} \right) + \frac{V_s'}{j\omega_s \sigma_s L_0} e^{j\omega_r t} - \frac{L_0 i_r}{\sigma_s L_0}
\]

(18)

where, \( \tau_s \) : Stator time constant = \( \frac{\sigma_s L_0}{R_s} \)

The DC transient term makes sure that the flux linkages are not changed due to abrupt dip in the stator voltage. The DC transient magnitude depends on the amount of voltage reduced due to the fault and the stator time constant. The steady state term depends on the stator voltage magnitude and the amount of excitation current required by the machine.

**B. With Crowbar resistance**

The crowbar resistances are usually employed to limit the rotor current to safe margin during the grid faults. Due to the limitation of RSC current, the rotor speed/electromagnetic torque cannot be controlled during low voltage at the terminals. Since the DFIG terminals experiences a low voltage at its terminals, due to the grid fault, it cannot deliver the electrical power to the grid, which will increase the rotor speed to a dangerous value. The crowbar can be turned on during the grid faults to dissipate the energy from the mechanical turbine to a limit. Different types of crowbar connections are discussed in [10], [11]. The analytical expression for the fault current provided from the stator is developed in this section. Once the crowbar is turned on, the RSC is disconnected from the rotor winding. Therefore, the rotor induced current will be only due to the stator flux. The stator flux equation in terms of stator voltage and stator parameters can written as,

\[
\frac{d}{dt} \psi_s + \frac{R_s}{\sigma_s L_0} \psi_s = V_s - \frac{R_s}{\sigma_s} i_r
\]

As discussed in III-A, the stator flux before and after fault can expressed as,

\[
\psi_s(t \leq t_0) = \frac{V_s}{j\omega_s} e^{j\omega_r t} \\
\psi_s(t \geq t_0) = \frac{V_s'}{j\omega_s} e^{j\omega_r t} + \frac{V_s - V_s'}{j\omega_s} e^{-\frac{t}{\tau_s}}
\]

(20)

Therefore, eqn 20 and eqn 12 can used to find the analytical expression for fault current contribution from DFIG,

\[
i_s = \frac{V_s - V_s'}{j\omega_s \sigma_s L_0} e^{j\omega_r t} \left( 1 - \frac{t}{\tau_s} \right) + \frac{V_s'}{j\omega_s \sigma_s L_0} e^{j\omega_r t}
\]

(21)

By analyzing the fault currents of DFIG with and without crowbar resistances, the DC transient term is present due to the constant flux linkage theorem. The transient term depends on the low voltage caused at the DFIG terminals due to the grid fault. More the voltage dip in the terminal, more the severity of the fault current. But the transient term may die out depending on the value of time constant of the stator.

When the crowbar is not connected in the rotor circuit, the term corresponding to the rotor current provided from the RSC will be present as shown in eqn 18. Since the RSC
is disconnected in the case of crowbar activation, the rotor current is negligibly small and is produced only due to the stator flux linkage which is very small due to the low voltage at the terminals. Therefore, as shown in eqn 21 the steady state term donot have the component corresponding to the rotor current.

IV. POWER SWING OF DFIG DURING GRID DISTURBANCE

The fault in the power system decreases the voltage of the system and the electromagnetic torque developed in synchronous machines. The location of fault and fault impedance affects the severity of voltage drop at the terminals of the generators. The reduction in electromagnetic torque compared to the mechanical torque input to the machine accelerates the rotor leading to a higher rotor angle position. Once the fault is cleared, depending on the change of network configuration due to the removal of fault, the rotor angle reaches to its new equilibrium point. The frequency of oscillation of the rotor angle depends on the amount of damping provided by the machine and synchronizing coefficient [12].

To analyze stability of the power system, rotor angle of the interconnected machines are investigated. The range of transient stability margin can be specified by Transient Stability Index (TSI) defined as [13]:

$$\eta = \frac{360^0 - \delta_{max}}{360^0 + \delta_{max}} \times 100, \quad -100 \leq \eta \leq 100$$  \hspace{1cm} (22)

where, $\delta_{max}$ is the the maximum rotor angle difference (in degrees) between two generators. The system is stable if the value of TSI is positive [13]. Even though the DFIG is not synchronously coupled with the grid, the power electronic converter may affect the amount of damping provided by DFIG system [14]. Section V describes the simulation validation of DFIG performance in terms of fault current and power oscillation during grid faults.

V. RESULTS AND DISCUSSION

The standard 9 bus 3 generator, Western System Coordinating Council (WSCC) system is selected for detailed modeling in PSCAD. The single line diagram of the system is given in Fig.3. The system consists of three synchronous generators, three loads and 6 transmission lines as shown in figure. All the generators are modeled with its excitation controls and turbine governor control. All the transmission lines are modeled as long Bergeron lines which can reflect the transient performance.

![Fig. 3. Single line diagram of WSCC System](image)

The bus 1 is considered as swing bus for voltage angle reference. The excitation system is modeled as IEEE standard ‘AC86’ model. The turbine governor system is modeled as [15] to maintain the speed at synchronous speed. To investigate the performance of DFIG in power oscillation damping, a 60 MW wind farm is connected at bus 5. The wind farm is represented by aggregated system of 60 MVA, which actually consists of thirty 2 MW DFIG system connected in parallel modeled as equivalent single DFIG driven by single wind turbine [16]. Different cases are simulated to analyze the fault current and power oscillations in the system.

A. Case 1 : Fault at Load Bus

A three phase fault is applied at a bus 6 at a simulation time of 4 second. The fault is cleared after 150 milli second and the system is resummed to the original network. The system response to the fault is shown in Fig. 4.

The bus voltage magnitude and phase angles are as shown in Fig. 4 (a) and (b). The bus 6 voltage is going to zero p.u. during the fault and the DFIG terminal voltage is around 0.6 p.u. Since the generator 2 is far from the fault, it experiences only a low voltage of 0.96 p.u. The power oscillation in the various lines are shown in Fig. 4 (c). The power oscillation is due to the generator dynamics which arises due to its advancement during the fault as shown in Fig. 4 (d).

Since the Power System Stabilizer is not modeled for the generators, the rotor angle oscillation and thus the power oscillation persists in the system for few seconds. The generator 3 is experiencing the maximum swing of $14^0$ with respect to the generator at bus 1. Therefore the TSI of the system for the three phase solid fault of 150 msec duration at Bus 6 is obtained as 92.513 which shows that the system is well stable. Moreover the generators have almost coherent nature.

![Fig. 4. System Response for Case 1 : Three phase fault applied at Bus 6. (a) Bus Voltages in p.u. (b) Bus voltage Phase angles in degrees (c) Power Flows in selected lines in MW (d) Generator rotor angle speed variations](image)
The fault current contribution from DFIG is shown in Fig. 7. The terminal voltage of DFIG is decreased to 0.6 p.u. causing the DC component in the stator. Once the fault is cleared, the terminal voltage is taking some time to reach back to 1 p.u. The fault current is contributed from DFIG at this time. The DC component transient term decay depends on the stator time constant of DFIG. Once the terminal voltage reaches at its nominal value of 1 p.u around 4.6 second, the DFIG resumes its normal operation.

B. Case 2: Fault at Generator Bus

A three phase slid fault is applied at bus 2 (generator bus) at a simulation time of 4 second. The fault is cleared in 150 millisecond resuming the prefault network. The bus voltage magnitude and phase angles are shown in Fig. 6 (a) and (b). Due to the advancement of generator rotor during fault, the voltage phase angles are disturbed. This in turn causes the power oscillations in the entire system. The power flows through selected lines are as shown in Fig. 6 (c). The generator rotor dynamics are shown in Fig. 6 (d).

The DFIG dynamics are shown in Fig. 7. The DFIG terminal voltage falls to 0.65 p.u. during the fault and it is resumed to its nominal value around 6.5 seconds. Since the fault at bus 2 is nearer to DFIG terminals compared to Case 1, it is taking more time to reach the steady state after clearing the fault. The fault current from ‘a’ phase reaches to a value of 170 A which is more than Case 1.

Since the fault is at the Generator 2 terminals, it experiences more fluctuations compared to other generators. Therefore generator 2 and generator 3 becomes incoherent and they swing differently. The maximum swing between two machines is around 21° between generator 2 and generator 3. The TSI for the system for the fault at bus 2 is found to be 88.9 which shows that the system is stable for the condition.

C. Case 3: Fault at the transmission line

The three phase solid fault occurs at the midpoint of transmission line connected between bus 5 and bus 7 at a simulation time of 4 second. The fault is cleared by opening the circuit breakers at both the end of the faulted line after 150 millisecond. Therefore, the system configuration is changed after clearing the fault. The system response to the line fault is shown in Fig. 8.

The bus voltage magnitude and phase angles are shown in Fig. 8 (a) and (b). Since the system configuration is changed after clearing the fault, the voltage phase angles are settled at a different value from the prefault condition. The power flows in the line are also changed and settles to a new operating points as shown in Fig. 8 (c). The power flowing through 7-8 and 4-5 are mostly affected due to the removal of the faulted line.

The DFIG dynamics during the fault are shown in Fig. 9. Since the fault is nearer to the DFIG compared to other cases, the fault current is maximum for Case 3. The DFIG terminal voltage settles down to the nominal value around 5.2 seconds and the current reaches its steady state at the time.
time constant depends the rate of decay of the DC transient term of the fault current supplied from DFIG. The rms fault current supplied from one of the phases is around 258 A which is much larger than the other two cases. The TSI of the system for line fault at 5-7 is found to be around 76. This shows the system is stable but not to the extend of other two cases. Once the fault is nearer to the DFIG terminals, which decreases the terminal voltage to a low value, causes a very high fault current to flow from DFIG.

VI. CONCLUSION

The transient performance of DFIG connected to a large system is discussed in the paper. An analytical expression for the fault current contributed from DFIG with and without crowbar resistance is developed. The fault current from DFIG consists of two terms viz, DC transient term which depends on the stator time constant (higher the value of resistance, higher the decay rate) and steady state term which depends on the amount of voltage dipped at the DFIG terminal. The power oscillations in the system due to the rotor dynamics after clearing the fault is studied by applying fault at different buses. It is shown from the simulation result that nearer the location of fault to the DFIG system, more the fault current contribution. The relays in the system must consider the DFIG dynamics and the transient fault current for its proper setting and coordination. This paper provides the study of the behavior of fault current contribution and power oscillations with the penetration of DFIG based wind generators.

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