ANALYSIS OF DOUBLY-FED INDUCTION GENERATOR BASED WIND TURBINE SYSTEM UNDER VARIOUS TYPE OF FAULT CONDITIONS

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Abstract: The doubly-fed induction generator (DFIG) is a variable speed induction machine and is widely used as modern large wind turbine generators. It is a wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through an AC/DC/AC PWM converter. This paper describes the modeling aspects of doubly-fed induction generator during steady state and faulty conditions. Vector decoupling controls strategy has been adopted to establish the mathematical model of DFIG based wind generator. In this paper, 1.5 MW DFIG is modeled in MATLAB/Simulink and, voltage and current waveforms are presented and discussed for symmetrical and unsymmetrical faults located at various locations of grid connected wind power system in Myanmar.

Keywords: Doubly-fed induction generator, Faulty conditions, Mathematical model, Vector control.

I. INTRODUCTION

With the increase in penetration of wind in power generation, the dynamic behavior of the power system will change because of various technologies used for wind and conventional generators. The doubly-fed induction generator (DFIG) is the most widely used device for wind power generation. DFIG is a popular wind turbine (WT) system due to advantages like it can operate in generator and motor mode for both sub and super-synchronous speed mode, also speed variation of ±30% around synchronous speed can be obtained, and the size of the converter is related to the selected speed range. Recently, the number of small size wind farm based on DFIG located within the distribution system is increasing at a very fast rate. As the penetration of wind power continually increases, more wind turbines are required to stay grid connected during a grid fault to maintain the reliability during and after a short-term fault [1]. The capability of WT to stay connected to the grid during voltage dips is called as the low-voltage ride-through (LVRT) capability. In order to fulfill the LVRT conditions for DFIG based WTs, there are two important conditions to be considered during a fault condition. The first is the over-current that can occur in rotor and stator circuits, and then the second is over voltage in the DC-link, both leads to the unbalanced energy that cannot be transmitted into the grid [2].

This paper is organized into the following sections: after briefly introducing the modeling of the DFIG based wind turbine in Section 2. Next, Section 3 presents the implementation of the case studies for various type of fault conditions. Finally, conclusions are drawn in Section 4.

II. MODELING OF DFIG BASED WIND TURBINE

The DFIG based Wind Turbines (WTs) are mechanically coupled to the blades via the gearbox, and electrically coupled to the constant frequency three-phase grid network via the stator windings. The rotor windings are also connected to the grid through the partially rated back-to-back variable frequency power converters (VFC).

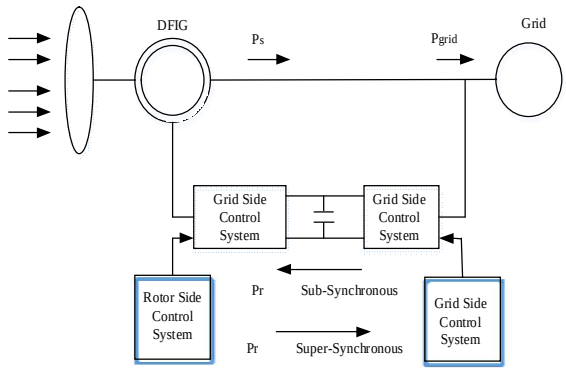


Fig.1. Schematic diagram of a grid-connected DFIG based WT system [3]

The grid-connected DFIG based WT is depicted in Fig.1 which the variable speed operation is achieved through the rotor side power converter controller [3,4]. Depending on the available wind speed, the generated power is delivered to the point of common connection (PCC) through the stator and rotor circuits during which the rotor speed is greater than the synchronous speed (i.e., $\omega_r > \omega_s$). If ω_r is less than ω_s, then only the stator circuit injects the generated power to the PCC via the stator circuit, while the

rotor circuit absorbs the active power form the PCC via the back-to-back converters.

2.1. Drive Train Model

The mechanical part of the wind turbine consistsof a yaw system, a pitch system, rotor blades, a tower and a gearbox. These parts are responsible for extracting and transmitting the power from the wind to the generator. The extracted power can be expressed as

$$P_m = \frac{1}{2}\rho A V_{wind}^3 C_p(\lambda,\beta) \quad (1)$$

$$\lambda = R_T \times \omega_T / V_{wind} \quad (2)$$

where P_m is the mechanical output power of the wind turbine (Watt), ρ is the air density (Kg/m^3), A is the swept area (m^2), C_p is the power coefficient of the wind turbine and V_{wind} is the wind speed (m/s), λ is a function of the tip speed ratio, ω_T is the rotational speed (rad/s) and R_T is the radius of blade (m).

The torque output (T) by the wind turbine can be expressed as

$$T = \rho\pi R^3 C_p(\lambda,\beta) V_{wind}^2 / 2\lambda \quad (3)$$

Therefore, the rotor speed can be regulated to maintain λ at its optimum value λ_{opt} and C_p at its maximum designed value C_{popt}. In this case, the maximum mechanical power captured by the wind turbine is given by:

$$P_{max} = \rho\pi R^5 C_{popt}\omega_{opt}^3 / 2\lambda_{opt}^3 = k_{opt}\omega_{opt}^3 \quad (4)$$

And the maximum torque is

$$T_{max} = \rho\pi R^5 C_{popt}\omega_{opt}^2 / 2\lambda_{opt}^3 = k_{opt}\omega_{opt}^2 \quad (5)$$

wherek_{opt} is the constant which is determined by the wind characteristics. The power coefficient $C_p$can be approximated using the wind turbine characteristics:

$$C_p(\lambda,\beta) = k_1\left(\frac{k_2}{\lambda_i} - k_3\beta - k_4\right)e^{((-k_5)/\lambda_i)} + k_6\lambda$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (6)$$

where the coefficients k_1 to k_6 depend on the design characteristics of the wind turbine which are given by k_1=0.5176, k_2=116, k_3=0.4, k_5=21 and k_6=0.0068.

2.2. Modeling of the DFIG and Converters

For a doubly-fed induction machine, the Park transformation's application to the traditional a,b,c model allows to write a dynamic model in a d-q reference frame as follows:

$$V_{ds} = R_s I_{ds} + \frac{d}{dt}\psi_{ds} - \omega_s\psi_{qs}$$

$$V_{qs} = R_s I_{qs} + \frac{d}{dt}\psi_{qs} + \omega_s\psi_{ds}$$

$$V_{dr} = R_r I_{dr} + \frac{d}{dt}\psi_{dr} - \omega_r\psi_{qr}$$

$$V_{qr} = R_r I_{qr} + \frac{d}{dt}\psi_{qr} + \omega_r\psi_{dr} \quad (7)$$

whereV is the voltage, I is the current, R is the resistance, Ψ is the magnetic flux and ω is the rotor frequency, The subscripts s and r indicates stator and rotor quantities.

The stator and rotor fluxes can be expressed:

$$\psi_{ds} = L_s I_{ds} + L_m I_{dr}$$

$$\psi_{qs} = L_s I_{qs} + L_m I_{qr}$$

$$\psi_{dr} = L_r I_{dr} + L_m I_{ds}$$

$$\psi_{qr} = L_r I_{qr} + L_m I_{qs} \quad (8)$$

In this case,

$L_s = L_{\sigma s} L_m / (L_{\sigma s} + L_m)$ and $L_r = L_{\sigma r} L_m / (L_{\sigma r} + L_m)$

whereL_s and L_r is the stator and rotor self-inductances respectively. L_m is the magnetizing inductance.

The rotor-side power converter (RSPC) can be modeled in terms of rotor voltage dynamics expressed as a function of the rotor currents as follows:

$$V_{rdq} = E_{dq} + \frac{L_r}{\omega_b}\frac{dI_{rdq}}{dt} + j\omega_r L_r I_{rdq} + R_r I_{rdq} \quad (9)$$

In this case, E_{dq} stands for the back-EMF induced in the rotor windings which is a function of the stator fluxes and voltages [5,6]. This means that E_{dq} is given by:

$$E_{dq} = \frac{L_m}{L_s}\left(V_{sdq} - j\omega_r\psi_{sdq} - \frac{R_s}{L_s}\psi_{sdq}\right) \quad (10)$$

In a wind turbine, the stator is directly connected to the grid. That means that the stator voltage V_s is imposed by the grid. The rotor voltage V_r is controlled by a converter and is used to perform the machine control. In addition, using the electrical equivalent circuit in Fig.2, the grid-side power converter (GSPC) and dc-link dynamics can be represented by the following dynamic equations:

$$V_{sdq} = V_{gdq} + L_f\frac{dI_{gdq}}{dt} + j\omega_s L_f I_{gdq} + R_f I_{gdq} \quad (11)$$

The dc-link model can be deduced from the balance of the active power at the dc-link node as:

$$V_{dc}(t)\,I_{dc}(t) = P_g(t) - P_r(t) - P_{loss}(t) \quad (12)$$

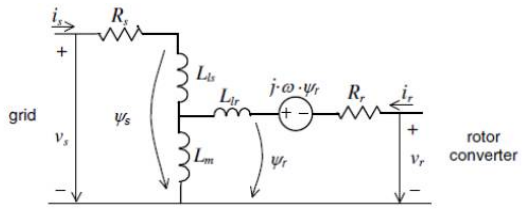


Fig.2. Equivalent circuit diagram of the DFIG

However, for high power converters, the power loss is usually less than 1% of the total power generated, and the effect of $P_{loss}(t)$ in (12) can be neglected. Also assuming the dc-link capacitor C_{dc} is constant in time and substituting $I_{dc}(t)=C_{dc}(dV_{dc}(t))/(dt)$ in (12), the dc-link dynamic model can be presumed as follows:

$$C_{dc}\frac{dV_{dc}}{dt} = \frac{P_g}{V_{dc}} - \frac{P_r}{V_{dc}}$$

$$P_r = \frac{3}{2}\left(V_{qr}I_{qr} + V_{dr}I_{dr}\right)$$

$$P_g = \frac{3}{2}\left(V_{qg}I_{qg} + V_{dg}I_{dg}\right) \quad (13)$$

Then, when the total power losses in the power converters are neglected, the total active and reactive powers injected into the grid via the point of common coupling (PCC) by the DFIG wind turbine are the sum of the stator and rotor powers as:

$$P_T = P_s + P_g \text{ and}$$

$$Q_T = Q_g + Q_s \quad (14)$$

Thus, the reactive powers from the stator terminals, rotor terminals and GSPC ac-side are defined by:

$$Q_s = \frac{3}{2}\left(V_{qs}I_{ds} - V_{ds}I_{qs}\right)$$

$$Q_r = \frac{3}{2}\left(V_{qr}I_{dr} - V_{dr}I_{qr}\right)$$

$$Q_g = \frac{3}{2}\left(V_{qg}I_{dg} - V_{dg}I_{qg}\right) \quad (15)$$

III. CASE STUDIES

The wind turbine consist of 1.5MW connected to a 33kV distribution system exporting power to a 132kV grid through a 20km, 33kV feeder and a 500kW load is connected on the 400V bus of the wind turbine. The single line diagram of this system is illustrated in Fig.3.

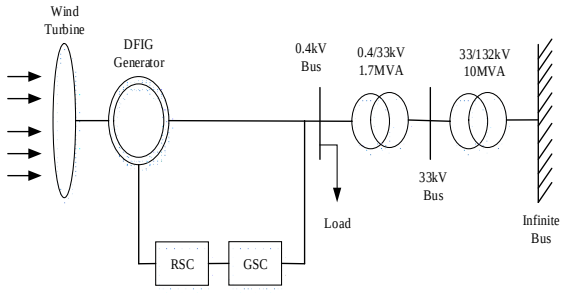


Fig.3. Single line diagram of the DFIG wind turbine connected to a distribution system

The purpose of this study is to understand the behavior of a DFIG, under different faulty conditions. Various symmetrical and unsymmetrical faults have been created at the B400 line and at the B33 line. Time domain voltage and current waveforms at the B400 bus and at the B33 bus are observed for 0.1 seconds. Simulations start at t=0 sec and faults are created at t=0.4sec. Faults are cleared after 0.1 sec at t=0.5 sec. Fault resistance has been kept constant at 0.001Ω. Simulink model of a 1.5MW DFIG wind turbine is shown in Fig.4.

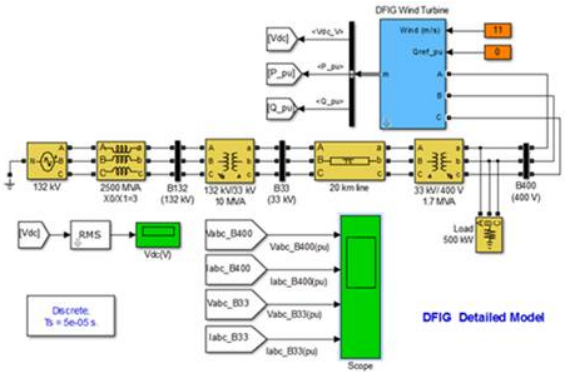


Fig.4. Simulink model of a 1.5MW DFIG wind turbine

3.1. Three Phase Fault

A three phase fault is a symmetrical fault that affects each of the three phases equally. The three phase fault is created at the B400 line and B33 line.

3.1.1. At B400 Line

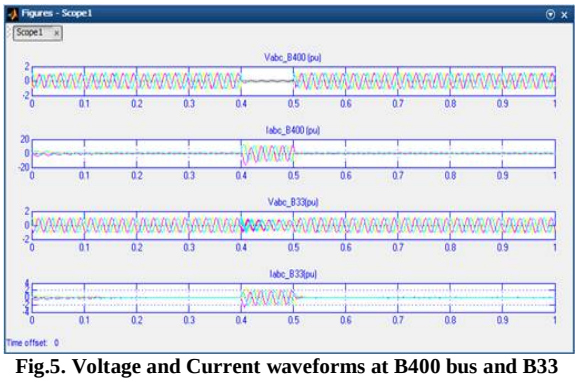


Fig.5. Voltage and Current waveforms at B400 bus and B33 bus

A three phase fault is created at the B400 line att=0.4s and cleared at t=0.5s. The voltage and current waveforms at the B400 bus and the B33 bus are shown in Fig.5. During the fault, voltages of all three phases reach very low values and currents will suddenly increase at the instant of fault initiation. The value of DC-link voltage increases to 1700V that exceeds the capacitor rating which is not acceptable in Fig.6.

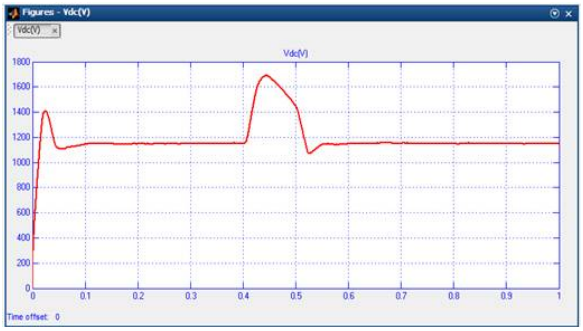


Fig.6. DC-link voltage

3.1.2. At B33 Line

A three phase fault is created at the B33 line at t=0.4s and cleared at t=0.5s. The voltage and current waveforms at the B400 bus and B33 bus are shown in Fig.7. Results are similar to a three phase fault at the B400 line.

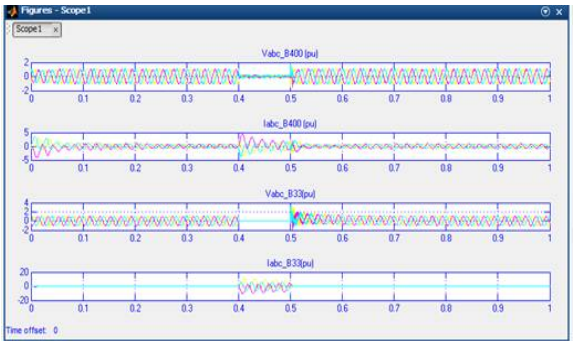


Fig.7. Voltage and Current waveforms at B400 bus and B33 bus

3.2. Phase to Phase Fault

A phase to phase fault is an unsymmetrical fault that does not affect each of the three phases equally. The phase to phase (phase 'a' to phase 'b') fault is created at the B400 line and B33 line.

3.2.1. At B400 Line

A phase to phase (phase 'a' to phase 'b') fault is created at the B400 line at 0.4s and cleared at 0.5s. Current going through phase 'a' should return through phase 'b' during the fault condition. After the fault initiation, this can be seen as Ia=−Ib, phase 'a' current and phase 'b' current going in opposite directions as shown in Fig.8. Ideally, phase 'c' current should decay to zero. Initially, there is a marginal drop of phase 'c' current and afterwards a transient condition results. This is due to the feeding from other wind generators and from the power system. The value of DC-link voltage increases about 7% of its nominal value that is illustrated in Fig.9.

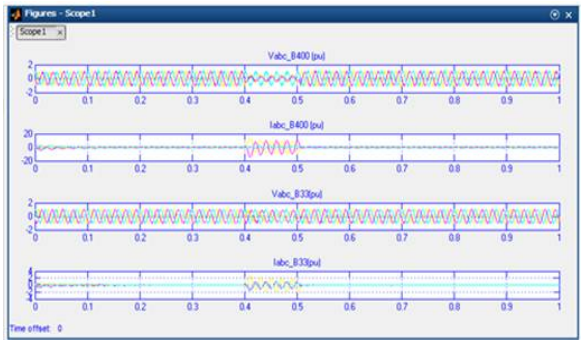


Fig.8. Voltage and Current waveforms at B400 bus and B33 bus

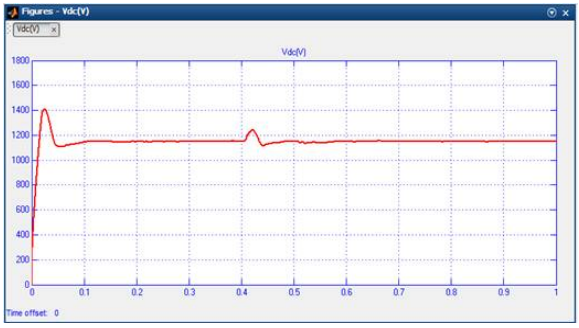


Fig.9. DC-link voltage

3.2.2. At B33 Line

A phase to phase (phase 'a' to phase 'b') fault is created at the B33 line at 0.4s and cleared at 0.5s. The voltage and current waveforms at B400 bus and B33 bus are shown in Fig.10.

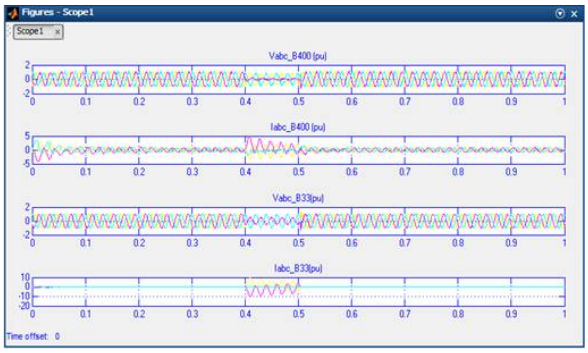


Fig.10. Voltage and Current waveforms at B400 bus and B33 bus

3.3. Phase to Ground Fault

A phase to ground fault is also an unsymmetrical fault. The phase to ground fault is created at B400 line and B33 line.

3.3.1. At B400 Line

A phase to ground fault is created at B400 line at t=0.4s and cleared at t=0.5s. The voltage and current waveforms at B400 bus and B33 bus are shown in Fig.11. Ideally, phase 'b' (red color) and phase 'c'

(green color) currents should drop to zero, and phase 'a' (yellow color) should experience an over current. A marginal increase in phase 'a' (yellow color) is observed and a reduction in phase 'b' and 'c' voltages can be seen in Fig.11. The effect of phase to ground fault on DC-link voltage is less during grid fault as shown in Fig.12.

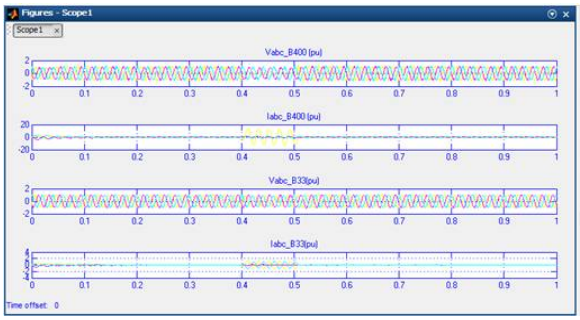


Fig.11. Voltage and Current waveforms at B400 bus and B33 bus

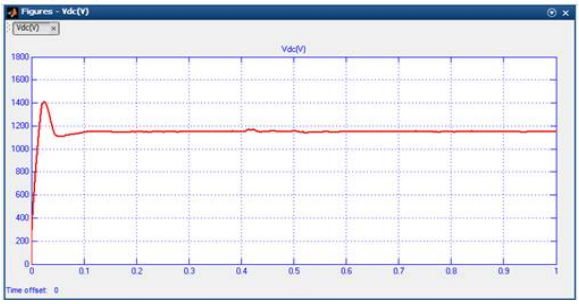


Fig.12. DC-link voltage

3.3.2. At B33 Line

A phase to ground fault is created at B33 line at t=0.4s and cleared at t=0.5s. Voltage and current waveforms are obtained at the B400 bus and B33 bus as shown in Fig.13.

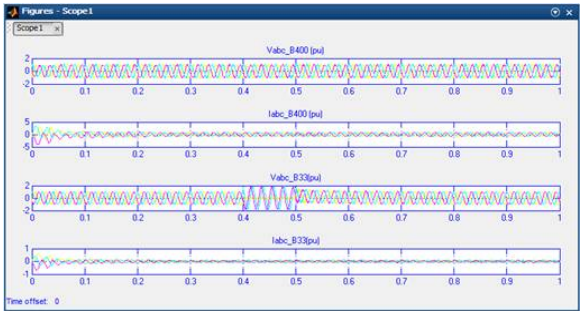


Fig.13. Voltage and Current waveforms at B400 bus and B33 bus

CONCLUSIONS

In this paper, the 1.5 MW wind turbine is modeled and simulated for symmetrical and unsymmetrical faults located at various locations of grid connected wind power system in Myanmar. The effect of three phase fault on grid voltage is most severe during different grid fault. Fluctuations with regard to grid voltage and dc link voltage is maximum for three phase fault followed by phase to phase fault and then phase to ground fault. In conclusion, understanding fault current behavior will help in selecting proper instrument transformers, switchgear and control gear, and in designing effective protection systems.

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