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Modelling of Doubly Fed Induction Generator in Wind Power Generation

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***Abstract*— This paper deals with the modelling and simulation of a double-fed induction generator (DFIG) based wind-power unit which is connected to the grid .A detailed model of a DFIG in the Stator flux reference frame, along with its controllers, is developed in this paper. This paper proposes a comprehensive set of differential equations for grid connection of DFIGs that takes into account the dynamics of the grid side line filter and transmission line. Time domain simulations are performed in Matlab/Simulink. Based on the model and simulation results, system stability is investigated for different wind Speed. This paper presents the steady-state model of a variable-speed wind power machine based on a 1.5MW doubly-fed induction generator (DFIG).**

***Keywords*— Double-fed induction generator (DFIG), grid side converter (GSC), rotor-side converter (RSC), sub synchronous resonance (SSR)**

I. INTRODUCTION

Wind power as a renewable source is currently preferred due to its abundant and clean nature. In the past several years, wind energy has been one of the fastest growing energy sources in the world. Wind turbine is a rotating machine which converts the kinetic energy of wind into mechanical energy. If the wind turbine is connected to a generator, which converts the mechanical power into electric power, the machine is then called a wind turbine generator. A group of wind turbines in the same location is called wind farm. With the development of wind power technology, the energy gain is not the only criteria to be considered when installing wind turbines; the impact on the environment, the power quality, and the maintaining of power grid stability are some of the important issues. More and more complicated control strategies have been implemented in wind system.

II. WIND TURBINE TECHNOLOGY

The kinetic energy of moving air molecules are converted into rotational energy by the rotor of wind turbine. This rotational energy in turn is converted into electrical energy by wind electric generator. The amount of power, which the wind transfers to the rotor, depends on the density of air, the rotor area, and the wind speed.The power contained by wind is given by,

$$P = 0.5 \times (air\ mass\ flow\ rate) \times (Wind\ Velocity)^2$$
$$= 0.5 \times (\delta \times A \times V) \times (V)^2$$
$$= 0.5 \times \rho \times A \times V^3$$

P = power contained in the wind (W)
ρ= air density (kg/m^3)
A = rotor area (m^2)
V=wind velocity before rotor interface (m/s)
The power coefficient (C_P) describes the efficiency of a turbine that converts the energy in the wind to rotational power.

$$Power\ Coeffiecent(C_P) = \frac{Electricity\ Produced\ by\ Wind\ Turbine}{Total\ Energy\ availabe\ in\ the\ wind}$$

Hence power output of the turbine is given by
$P_T = 0.5 \times \rho \times A \times V^3 \times C_P$
The tip speed ratio of the wind turbine is given as λ =ω*R/V
Where R = radius of the swept area in meters
ω= angular speed in radians per second. [1]

III. WIND TURBINE GENERATORS

1. Fixed Speed Wind Turbines (WT Type I)
   - Squirrel Cage Induction Generators (SCIG)
2. Partial Variable Speed Wind Turbine with Variable Rotor Resistance (WT Type II)
   - Wound rotor induction generator (WRIG)
3. Variable Speed Wind Turbine with Partial-Scale Power Converter (WT Type III)
   - Doubly-fed induction generator (DFIG)
4. Variable Speed Wind Turbine with Full-Scale Power Converter (WT Type IV)
   - Permanent magnet synchronous generator (PMSG)

Type I and Type II have very simple topology where the turbine is directly connected to the grid. Type I uses squirrel cage induction generator with its rotor shorted, while Type II connects its rotor to an adjustable resistor through an AC/DC rectifier. Both Type I and Type II wind turbine topology need reactive power compensator to maintain reliability during low wind speed or system fluctuation, since they have no reactive power control capability. Type III is doubly fed induction generator (DFIG)-based wind system. The stator of DFIG is directly connected to the grid at the Point of Common Coupling (P.C.C.) while the rotor is connected to the grid through back-to-back (AC/DC/AC) converters. Both grid side and rotor side converters are controlled by pulse-width modulation (PWM). Type IV uses synchronous or asynchronous machine connected to the grid using full rated AC/DC/AC power converter on its stator side and is pitch regulated. With the help of power converters in Type III and IV wind system topology, reactive power control is available.

The wind turbine topology modelled and simulated in this thesis is Type III DFIG wind power system, which is also the most widely used in the wind industry. One advantage of DFIG-based wind generation system is the reduced power level and thus cost of power converters. The converters used for this topology need to be rated at only 25% to 30% of overall machine rating, since they are connected in the rotor loop of the induction machine. Furthermore, vector control method can be easily implemented for decoupled control of real power and reactive power. In this case power factor control could also be implemented at a lower cost. [2]

IV. DOUBLY FED INDUCTION GENERATOR

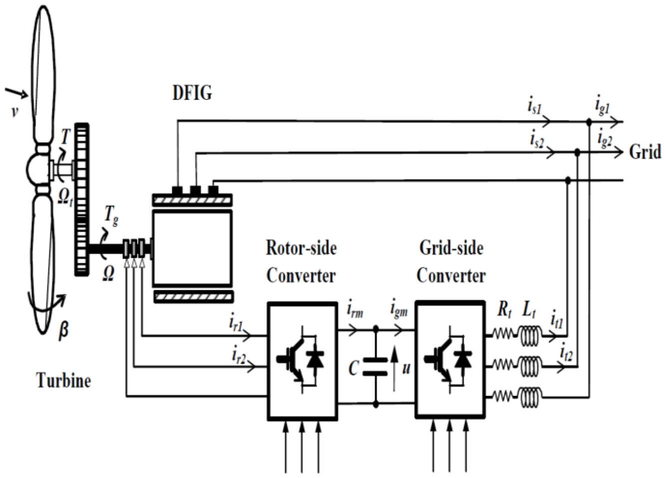


Figure 1 Doubly fed Induction Generator

Conventional wound-rotor induction machine in which the stator is directly connected to the grid through a transformer and the connection of the rotor to the stator (and grid) is via a back-to-back voltage source convertor. The rotor converter system consists of a grid side converter (GSC) and rotor side converter (RSC) connected via a DC link.

The generator is called DFIG because the power is fed from both stator and the rotor circuits to the grid. The rotor circuit handles typically about 25-30% of the generator rated power, this percentage allows the DFIG to have about 30 ± % operational speed range around the synchronous speed and reduces the rating and the cost of the rotor converter [3, 4].

The size of the converter is not related to the total generator power but to the selected speed range and, hence, to the ―slip‖ power, thus the cost of the converter increases when the speed range becomes wider. The selection of the speed range, therefore, is based on the economic optimization of investment costs and on increased efficiency. Since the DFIG is connected to the grid, the high transient currents due to the grid disturbances may destroy the power electronic devices of the rotor converter. A protection system called crowbar are being used in which the rotor winding can be short circuited during the fault period via a small resistance and released when the fault is cleared.

A. Power Flow/ Operating Modes OF DFIG

The DFIG stator is connected to the grid with fixed grid frequency (f_s) at fixed grid voltage (v_s) to generate constant frequency AC Power during all operating conditions and the rotor is connected to the frequency converter/VSC having a variable (slip/rotor) frequency ($f_r = sf_s$). At constant frequency f_s, the magnetic field produced in the stator rotates at constant angular velocity/speed ($\omega_s = 2\pi f_s \omega_s$), which is the synchronous speed of the machine. The stator rotating magnetic field will induce a voltage between the terminals of the rotor. This induced rotor voltage produces a rotor current (I_r), which in turn produces a rotor magnetic field that rotates at variable angular velocity/speed ($\omega_r = 2\pi f_r$). Usually the stator and rotor have the same number of poles (P) and the convention is that the stator magnetic field rotates clockwise. Therefore, the stator magnetic field rotates clockwise at a fixed constant speed of $\omega_s(rpm) = 120 f_s / P$. Since the rotor is connected to the variable frequency VSC, the rotor magnetic field also rotates at a speed of $\omega_r(rpm) = 120 f_r / P$. [5]

1. Sub-Synchronous Speed Mode

The rotor magnetic field rotates at a slower speed than the stator magnetic field. The mode, i.e., $\omega_m < \omega_s$,
if and only if its speed is exactly, $\omega_m = \omega_s - \omega_r > 0$, and both the phase sequences of the rotor and stator mmf's are the same and in the positive direction, as referred to as positive phase sequence ($\omega_r > 0$) .This condition takes place during slow wind speeds. In order to extract maximum power from the wind turbine, the following conditions should be satisfied:
The rotor side VSC shall provide low frequency AC current (negative V_r will apply) for the rotor winding.

The rotor power shall be supplied by the DC bus capacitor via the rotor side VSC, which tends to decrease the DC bus voltage. The grid side VSC increases/controls this DC voltage and tends to keep it constant. Power is absorbed from the grid via the grid side VSC and delivered to the rotor via the rotor side VSC. During this operating mode, the grid side VSC operates as a rectifier and rotor side VSC operates as an inverter. Hence power is delivered to the grid by the stator. The rotor power is capacitive.

2. Super synchronous Speed Mode

The super-synchronous speed mode is achieved by having the rotor magnetic field rotate counter clockwise. However, in order to represent the counter clockwise rotation of the rotor, which is analytically equivalent to inverting the direction of the rotor magnetic field. The machine is operated in the super-synchronous mode, i.e., $\omega_m > \omega_s$, if and only if its speed is exactly $\omega_m = \omega_s - (-\omega_r) = \omega_s + \omega_r > 0$, and the phase sequence in the rotor rotates in opposite direction to that of the stator, i.e., negative phase sequence ($\omega_r < 0$). This condition takes place during the condition of high wind speeds. The following conditions need to be satisfied in order to extract maximum power from the wind turbine and to reduce mechanical stress:

The rotor winding delivers AC power to the power grid through the VSCs. The rotor power is transmitted to DC bus capacitor, which tends to raise the DC voltage.

The grid side VSC reduces/controls this DC-link voltage and tends to keep it constant. Power is extracted from the rotor side VSC and delivered to the grid. During this operating mode, the rotor side VSC operates as a rectifier and the grid side VSC operates as an inverter. Hence power is delivered to the grid directly by the stator and via the VSCs by the rotor. The rotor power is inductive.

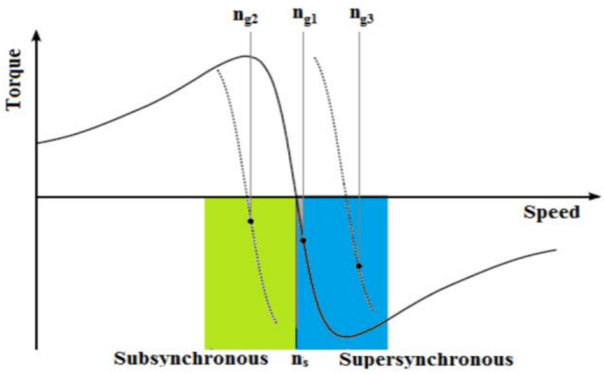


Figure 2 operating mode of DFIG

3. Synchronous Speed Mode

The machine is operated in the synchronous speed mode, i.e., $\omega_m = \omega_s$, if and only if its speed is exactly $\omega_m = \omega_s - 0 = \omega_s > 0$, and the phase sequence in the rotor is the same as that of the stator, but no rotor mmf is produced ($\omega_r = 0$).The following conditions are necessary in order to extract maximum power from the wind turbine under this condition: The rotor side converter shall provide DC excitation for the rotor, so that the generator operates as a synchronous machine. The rotor side VSC will not provide any kind of AC current/power for the rotor winding. Hence the rotor power is zero ($P_r = 0$). A substantial amount of reactive power can still be provided to the grid by the stator. As per the operating modes described above, at any wind speeds a wide range of variable speed operation can be direction during different rotor speed performed to achieve maximum wind power extraction.

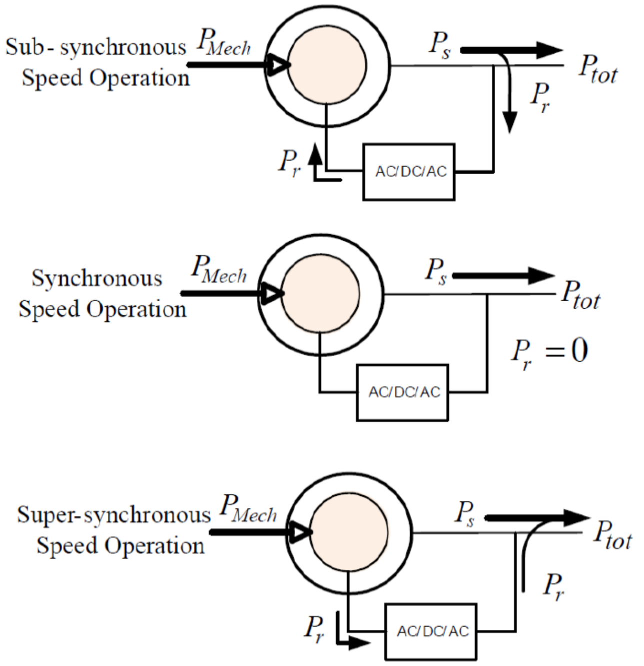


Figure3 DFIG stator and rotor active power flow

B. Vector-control scheme of grid-side PWM voltage source converter

Rotor-side converter is used to controlthe machine speed and the reactive power supplied throughthe machine stator, while the grid-side converter is used tomaintain the dc bus voltage constant. The reactive power ofthis converter can be controlled, and one strategy is tomaintain the power factor of this converter at unity. Thisminimizes the current flowing in the grid side converter.

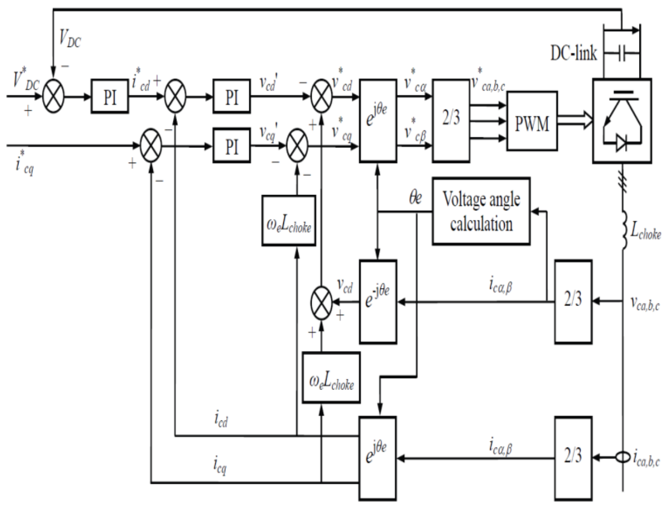


Figure 4 Grid-side converter control scheme

The grid-side converter aims to regulate the voltage of the dc bus capacitor. Moreover, it is allowed to generate or absorb reactive power for voltage support requirements. The function is realized with two control loops as well as outer regulation loop consisting of a dc voltage regulator. The output of the dc voltage regulator is the reference current i_{cdref} for the current regulator. The inner current regulation loop consists of a current regulator controlling the magnitude and phase of the voltage generated by converter from the i_{cdref} produced by the dc voltage regulator and specified q-axis i_{cqref} reference.

DC-link model

The dc-link model describes the dc-link capacitor voltage variations as a function of the input power to the dc-link .The energy stored in the dc capacitor is

$$W_{dc} = \int P_{dc}\, dt = \frac{1}{2} C V_{dc}^2$$

Where C is the capacitance, V_{dc} is the voltage, W_{dc} is the stored energy, and P_{dc} is the inputpower to the dc link. The voltage and energy derivatives are

$$\frac{dV_{dc}}{dt} = \frac{P_{dc}}{CV_{dc}}, \frac{dW_{dc}}{dt} = P_{dc}$$

The P_{dc} is calculated as $P_{dc} = P_{in} - P_c$. Where P_{in} is the input power from rotor-side converter and P_c is the grid-side converter output power. The dc-link voltage varies as P_{dc} and is a constant when $P_{dc} = 0$.

The grid-side converter controls the flow of real and reactive power to the grid, through the grid interfacing inductance. The objective of the grid-side converter is to keep the dc-link voltage constant regardless of the magnitude and direction of the rotor power. The vector control method is used as well, with a reference frame oriented along the stator voltage vector position, enabling independent control of the active and reactive power flowing between the grid and the converter. The PWM converter is current regulated, with the d-axis current used to regulate the dc-link voltage and the q-axis current component to regulate the reactive power. Fig.4 shows the schematic control structure of the grid-side converter.

A similar analysis for the control of the dqcurrents carried out for the grid-side converter can likewise be done for the control of the converter dqcurrents. The voltage equations in synchronously rotating dq-axis reference frame are:

$$V_{cd} = Ri_{cd} + L_{choke}\frac{di_{cd}}{dt} - \omega_e L_{choke} i_{cq} + V_{cd1}$$
$$V_{cq} = Ri_{cq} + L_{choke}\frac{di_{cq}}{dt} - \omega_e L_{choke} i_{cq} + V_{cq1}$$

The angular position of the grid voltage is calculated as

$$\theta_e = \int \omega_e dt = \tan^{-1}\left(\frac{v_{c\beta}}{v_{c\alpha}}\right)$$

Where $V_{c\alpha}$ and $V_{c\beta}$ are the converter grid-side voltage stationary frame components

The *d*-axis of the reference frame is aligned with the grid voltage angular positionθ_e. Sincethe amplitude of the grid voltage is constant, $V_{cq}$is zero and$V_{cd}$is constant. The active andreactive power will be proportional to i_{cd} and i_{cq} respectively.Assume the grid-side transformer connection is star, the converter active and reactive powerflow is

$$P_c = 3\left(V_{cd} i_{cd} + V_{cq} i_{cq}\right) = 3V_{cd} i_{cd}$$
$$Q_c = 3\left(V_{cd} i_{cq} + V_{cq} i_{cd}\right) = 3V_{cd} i_{cq}$$

Which demonstrates that the real and active powers from the grid-side converter are controlled by the $i_{cd}$and i_{cq}components of current respectively. To realise decoupled control, similar compensations are introduced likewise in equation:

$$V_{cd}^* = -v'_{Cd} + (\omega_e L_{choke} i_{cq} + V_d)$$
$$V_{cq}^* = -v'_{Cq} - (\omega_e L_{choke} i_{cd})$$

The reference voltage V_{cd}^* and V_{cq}^* are then transformed by inverse-Park transformation to give 3-phase voltage $V_{abc}^*$for the final PWM signal generation for the converter IGBT switching.

C. Vector-control scheme of rotor-side PWM voltage source converter

The purpose of the rotor inverter is to control the generator speed to achieve maximum power from the wind over a range of wind velocities. The rotor side inverter control scheme is based on a multitier structure that comprises a speed, active power, reactive power and current control loop.

The main objective of the RSC controller is to control the stator active and reactive power of the DFIG independently by controlling the rotor current component ($i_{dr}$and i_{qr}). The RSCcontrol scheme consists of two cascaded control loops. The inner current control loops regulate independently the *d*-axis and *q*-axis rotor current components, $i_{dr}$and i_{qr}, according to somesynchronously rotating reference frame [7]. The stator flux oriented reference frame is most popular. In this study, a new rotor flux-oriented vector control approach is proposed andcompared with the commonly used stator flux-oriented vector control.

During a fault, the transient currents on the stator are reflected on the rotor windings. The resulting rotor currents may exceed the rotor converter current rating. The transients can also result in a rise in the dc bus voltage during the fault, due to the power being generated. Voltage variations also occur during the voltage recovery period. The rotor-side converter must be designed to either withstand these conditions, or protection circuits must be used on the dc bus.

The wound rotor induction generator is controlled using a synchronously rotating reference frame, with the direct axis oriented along the stator flux vector position. In this manner, a decoupled control between the stator side active and reactive power can be achieved, which will be explained later-on in this section. In this system simulation, the generator-side PWM converter control scheme requires the measurements of the stator and rotor currents, stator voltages and the rotor position. To describe the control scheme, the general Park's model of an induction machine is introduced. Using the motor convention in a static stator-oriented reference frame, without saturation, the voltage vector equations are

$$\vec{V}_S = R_s\vec{\iota}_s + \frac{d\overrightarrow{\psi_s}}{dt}$$
$$\vec{V}_r = R_r\vec{\iota}_s + \frac{d\overrightarrow{\psi_r}}{dt} - j\omega\overrightarrow{\psi_r}$$

The flux vector equations are

$$\vec{\psi}_s = L_s\vec{\iota}_s + L_m\vec{\iota}_r$$
$$\vec{\psi}_r = L_m\vec{\iota}_s + L_r\vec{\iota}_r$$

Where $L_s$and L_r are the stator and rotor self-inductances

$$L_s = L_m + L_{ls}, L_r = L_m + L_{lr}$$

The stator flux equations are

$$\psi_{sd} = L_s i_{sd} + L_m i_{rd} = \psi_s = L_m i_{ms}$$
$$\psi_{sd} = 0$$

Defining leakage factor$\sigma = 1 = \frac{L_m^2}{L_s L_r}$equivalent inductance as $L_0 = \frac{L_m^2}{L_s}$The rotor voltage and flux equations

$$V_{ed} = R_r i_{rd} + \sigma L_r\frac{di_{rd}}{dt} - \omega_{slip}\sigma L_r i_{rd}$$
$$V_{ed} = R_r i_{rd} + \sigma L_r\frac{di_{rd}}{dt} - \omega_{slip}(L_0 i_{rd} + \sigma L_r i_{rd})$$
$$\psi_{rd} = \frac{L_m^2}{L_s} i_{ms} + \sigma L_r i_{rd}$$
$$\psi_{rq} = \sigma L_{rq}$$

Where the slip angular speed is$\omega_{Slip} = \omega_s - \omega_r$

The stator flux angle is calculated from

$$\psi_{s\alpha} = \int (V_{s\alpha} - R_s i_{s\alpha})dt$$
$$\psi_{s\beta} = \int (V_{s\beta} - R_s i_{s\beta})dt$$
$$\theta_s = \tan^{-1}\left(\frac{v_{s\beta}}{v_{s\alpha}}\right)$$

Where $\theta_s$is the stator-flux vector position.The control scheme of the rotor-side converter is organised in a generic way with two seriesof two PI-controllers. Fig. 5 shows a schematic block diagram for the rotor-side convertercontrol. The reference *q*-axis rotor current i_{rq}^*can be obtained either from an outer speed control loop or from a reference torque imposed on the machine. These two options may betermed a speed-control mode or torque-control mode for the generator, instead of regulatingthe active power directly. For speed-control mode, one outer PI controller is to control thespeed error signal in terms of maximum power point tracking. Furthermore, another PIcontroller is added to produce the reference signal of the *d*-axis rotor current component tocontrol the reactive power required from the generator. Assuming that all reactive power tothe machine is supplied by the stator, the reference value i_{rd}^*may set to zero.[8] The switchingdynamics of the IGBT-switches of the rotor converter are neglected and it is assumed thatthe rotor converter is able to follow demand values at any time.The control system requires the measurement of the stator and rotor currents, stator voltageand the mechanical rotor position. There is no need to know the rotor-induced EMF, as isthe case for the implementation with naturally commutated converters. Since the stator isconnected to the grid, and the influence of the stator resistance is small, the statormagnetising current i_{ms} can be considered constant Rotor excitation current control is realised by controlling rotor voltage. The $i_{rd}$and i_{rq}errorsignals are processed by associated PI controllers to give $v_{rd}$and v_{rq}, respectively.

$$V'_{rd} = R_r i_{rd} + \sigma L_r\frac{di_{rd}}{dt}$$
$$V'_{rq} = R_r i_{rq} + \sigma L_r\frac{di_{rq}}{dt}$$

To ensure good tracking of the rotor *dq*-axis currents, compensation terms are added to V_{rd}' and V_{rq}' to obtain the reference voltages V_{rd}^* and V_{rq}^* according to

$$V_{rd}^* = V_{rd}' - \omega_{slip}\sigma L_r i_{rq}$$
$$V_{rq}^* = V_{rq}' - \omega_{slip}(L_m i_{ms} + \sigma L_r i_{rd})$$

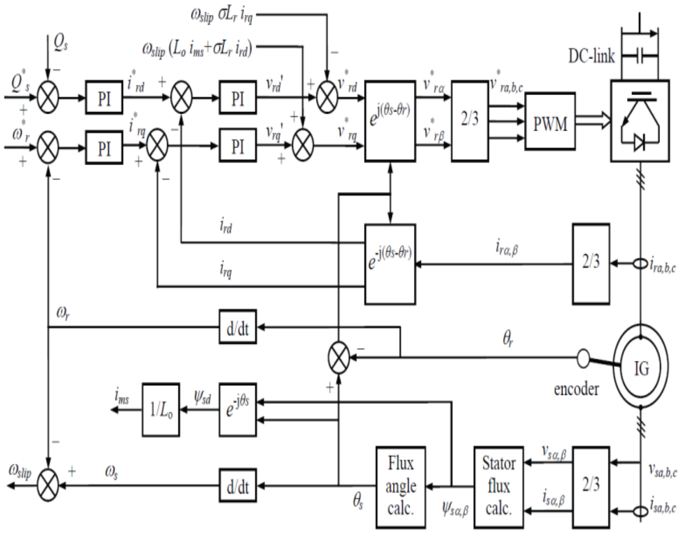


Figure 5 Rotor-side converter control scheme

V. SIMULATION RESULTS AND DISCUSSION

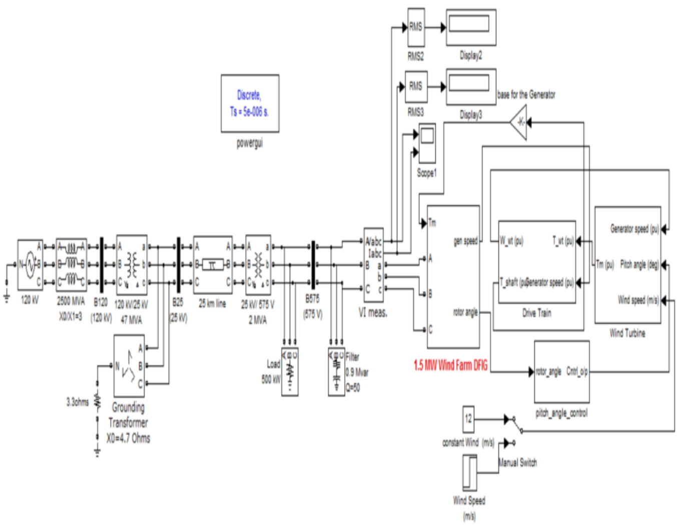


Figure 6 1.5MW Wind Generator systems connected with Grid using DFIG

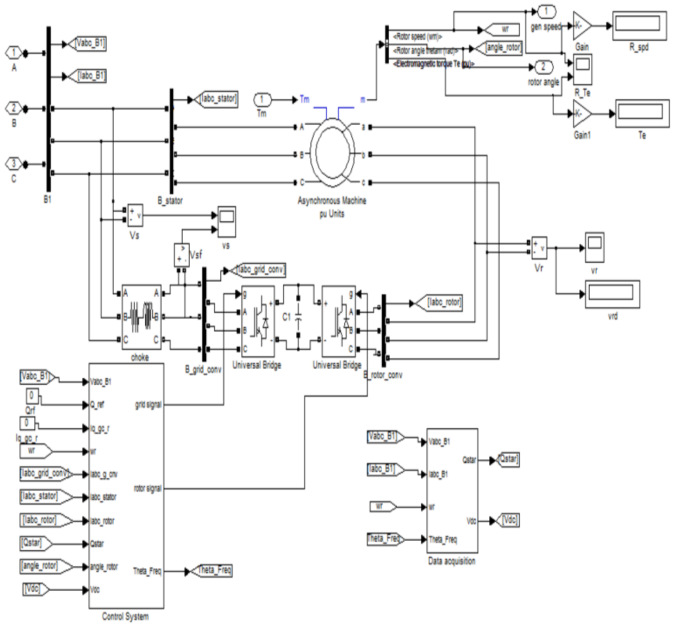
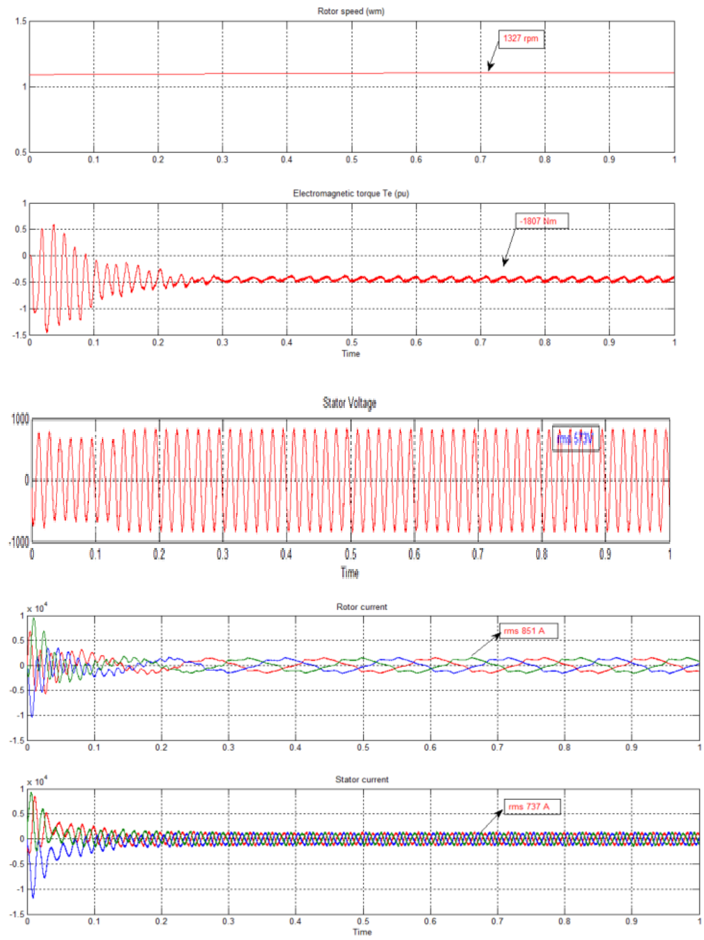


Figure 7 1.5MW DFIG Block diagram

Case: 1 Wind Speed – 12 m/s



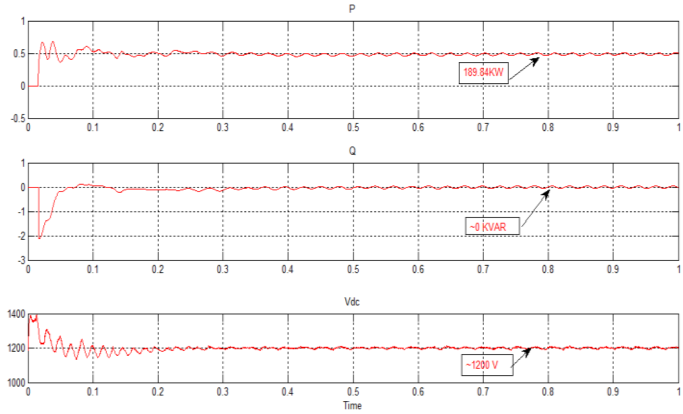
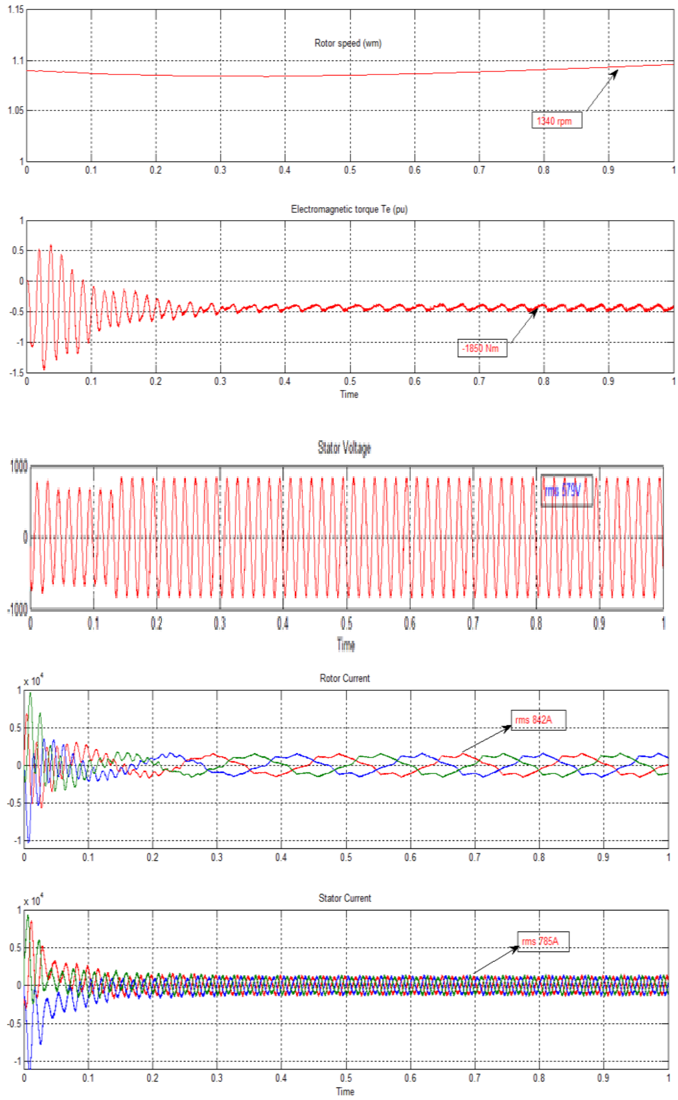


Figure 8 Waveforms of Rotor Speed, electromagnetic torque, stator voltage, Rotor Current, stator Current, Active Power, Reactive Power and Voltage of DC Link at fix Speed

Case: 2 Wind Speed – 10 to 14 m/s



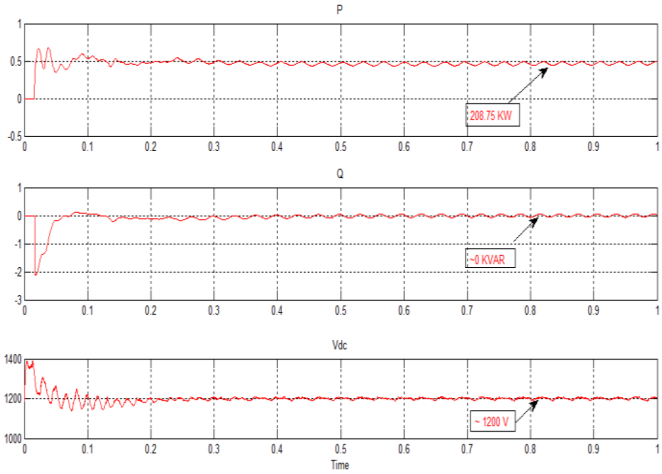


Figure 9 Waveforms of Rotor Speed, electromagnetic torque, stator voltage, Rotor Current, stator Current, Active Power, Reactive Power and Voltage of DC Link at Variable Speed

In fix wind speed genrator stator vaoltage consatnt and voltage across DC Link capacitor also constant.And Variable wind Speed Stator voltage t and DC Link also constant .but Active power change acording to load and wind Speed. In normal balance condition Rective power is zero. This can be seen in matlab simulation result.

Table 1 Result table

	Fix Speed:12 m/s	**Variable speed: 10 to 14 m/s**
Rotor speed	1327 rpm	1340 rpm
Electromagnetic Torque	-11640 Nm	-11930 Nm
Stator Voltage	rms573V	rms579V
Rotor Current	rms 831A	rms 842A
Stator Current	rms 737A	rms 785A
Active Power	328.81KW	361.51KW
Reactive Power	~0 KVAR	~0 KVAR
DC Link voltage	~1200V	~1200V

VI. CONCLUSIONS

The detailed mathematical model developed in this paper provides an analytical platform for evaluating the robustness of the wind-power system.The rotor side converter usually provides active and reactive power control of the machine. The grid-side converter keeps the voltage of the DC-link constant.RSC and GSC are controlled independently. DFIG maintain grid voltage constant for fix and variable speed. Due to thisDFIG proved to be more reliable and stable system when connected to grid side with the proper converter control systems.

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