# Modeling and Analysis of DFIG Based Wind Power

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***Abstract***- *In this paper, a detailed modeling of Doubly fed Induction Generator (DFIG) and its operation in closed loop control have been realized. Vector control method based on rotor current control loops is used. Further harmonic analysis is done using Powergui FFT analysis tool. All the simulation models are built in MATLAB/Simulink software. Results and waveforms show the effectiveness of vector control strategy*

***Keywords***- DFIG modeling, Vector Control, Rotor current control loop.

## I. INTRODUCTION

With the increase in penetration of wind power in the interconnected power system grid, it has become necessary to model the complete wind energy systems to study its impact and varies control strategies. The paper tries to develop a dynamic model of induction machine that can simulated both on motoring and generating mode with their control strategies is performed.

### 1.1 DOUBLY-FED INDUCTION GENERATOR

Induction machines are used extensively in the power system as load element or machine but not as widely used as synchronous generators for generation purpose. This is due to the defined relationship between the export of P and absorption of Q. However, induction generators have the benefits of providing large damping torque in the prime mover making them suitable for the application in fixed speed wind turbines. The fixed speed wind turbine use squirrel cage induction generator which is coupled to the power system by a connecting transformer.

The mechanical power from wind turbine is transformed into electrical power by an induction generator and is fed into the main grid through the stator winding and the rotor winding. The rotor winding is connected to the main grid side by self-commutated AC/DC converters, by controlling the slip ring voltage of the induction machine in magnitude and phase angle. The electrical power of a doubly fed induction generator is independent of the speed. Hence, it is possible to have a variable speed wind generator which adjusts the mechanical speed to the wind speed and hence operating the turbine at the aerodynamically optimal point for a certain wind speed range.

Mostly wind turbine manufacturers use the doubly fed induction generator systems. The power electronic converter only has to handle a fraction (20% – 30%) of the total power, i.e., the slip power, where the speed is in the range ±30% around the synchronous speed, the converter has a rating of only 30% of the rated turbine power, reducing the power electronic converter losses, compared to a system where the converter has to handle the total power. Also, the cost of the converter becomes lower. The doubly fed induction machine has been used in wind turbines for long time. In the past, the AC-AC converter connected to the rotor consisted of a rectifier and an inverter based on thyristor bridges. Nowadays, AC-AC converters are equipped with bidirectional IGBT's, connecting the rotor of the variable speed doubly fed induction generator to the electrical grid.

To better to understand the advantages of doubly fed induction generators to generate electrical power in wind turbines, however, it is important to know a little about large-size wind turbines:

Large-size wind turbines are divided into two types which determine the behavior of the wind turbine during wind speed variations:

1. Fixed speed wind turbine
2. Variable speed wind turbine

In fixed speed wind turbines, three phase synchronous generator are used. As outputs are tied directly to grid (local ac power network), the rotation speed of the generator is fixed (in practice, vary a little as the slip can vary over range of typically 2% to 3%) and so is the rotation speed of wind turbine rotor. Any fluctuation in wind speed causes the mechanical power at the wind turbine rotor to vary and since the rotation speed is fixed, this causes the torque at the wind turbine rotor to vary accordingly. Whenever there is a wind gust occurring, the torque at the wind turbine rotor thus increases significantly while the rotor speed varies very little. Therefore, every wind gust put stress on the mechanical components (notably the gear box) in the wind turbine and causes a sudden increase in rotor torque, also in the output power of the wind turbine generator. Any fluctuation in the output power of a wind turbine generator is a source of instability in power network to which it is connected. In variable-speed wind turbines, the rotation speed of the wind turbine rotor can vary as the wind speed varies.

The double fed induction generator allows the generator output voltage and frequency to be maintained at constant values, no matter the generator rotor speed. By adjusting the amplitude and frequency of the generator rotor winding. It is possible to keep the amplitude and frequency of the voltages produced by the generator constant despite variations in the wind turbine rotor speed caused by fluctuation in wind speed. This allows operation without sudden torque variation at the wind turbine rotorside and decrease the stress imposed on the mechanical component of the wind turbine, smoothing variations in the amount of electrical power produced by the generator. Using the same, it is also possible to adjust the amount of reactive power exchanged between the generator and the ac power network. This allows the power factor of the system to be controlled. Finally using DFIG in variable speed wind turbines allows electrical power generation at lower speeds than with fixed speed wind turbines using an asynchronous generator.

This paper presents a detailed modelling of wind based DFIG machine. Further machine is modeled in (d-q) synchronous rotating reference frame. RSC and GSC control schemes are designed and developed. FFT analysis is performed to find current and voltage THD injected into the grid.

Power curve of wind turbine shows the relation between output power and hub height wind speed and is an important characteristic of the turbine. Power curve helps in energy assessment, performance monitoring of the turbines. Growth of wind power generation industry has led to turbines being installed in different climates, onshore and offshore, and in complex terrain region causing significant departure of these curves from the desired values. Accurate models of power curves will therefore play an important role in improving the performance of wind energy-based-systems.

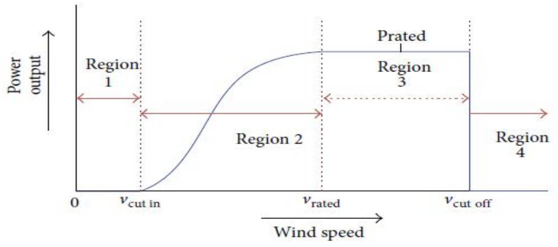


Fig.1.Typical power curve of a pitch regulated wind turbine

Typical output versus wind speed characteristics of wind turbines: cut-in, rated and cut-out speeds shown are typical for utility-scale WTGs Generally, Wind turbine generator are designed to work at maximum aerodynamic efficiency between cut-in and rated wind speed. For wind speeds ranging between: higher than rated and lower than cut-out: blade pitching or blade stalling is used to maintain loading within the equipment's rating. Wind Turbine Generator shut down for wind speeds higher than cut-out speed to avoid excessive mechanical stress.

### 1.2 VARIOUS TYPES OF WIND TURBINE GENERATOR TECHNOGIES

Presently four major types of WTG Technologies used:

1. Squirrel Cage Induction Generators with fixed-speed, stall-regulated wind turbines
2. Induction Generators with variable external rotor resistance driven by a variable-speed and pitch regulated wind turbines
3. Doubly-Fed Induction Generators driven by variable-speed and pitch regulated wind turbines
4. Synchronous or Induction Generators with back to back converter, driven by variable-speed, pitch regulated wind turbines

## II. MODELLING OF DFIG

The basic configuration of grid tied DFIG is shown in Fig.2. It is composed of blades, wind turbine, gearbox, shaft system, generator, converters and their control system. The wind turbine is connected to an induction generator through a common mechanical shaft system. This shaft system consists of a low speed shaft and a high-speed shaft through the gearbox. The operation of DFIG is controlled by two control-systems as mechanical control of wind turbine which varies blade pitch angle with wind variation. Electrical power control maintains constant voltage and frequency through vector control strategy.

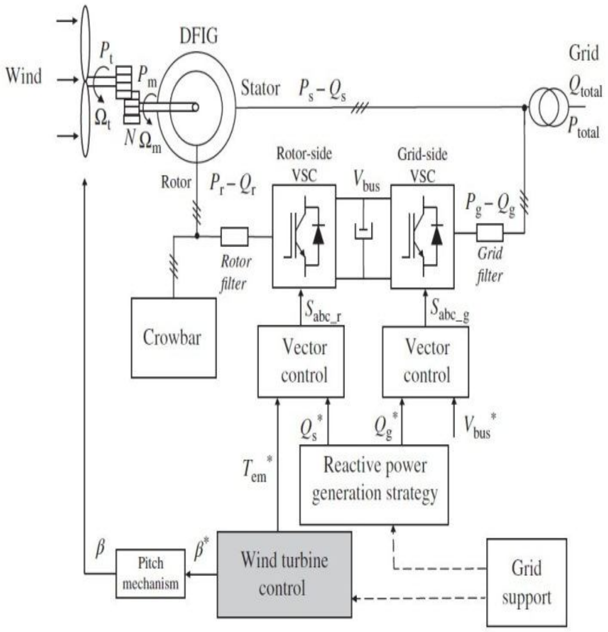


Fig. 2. DFIG

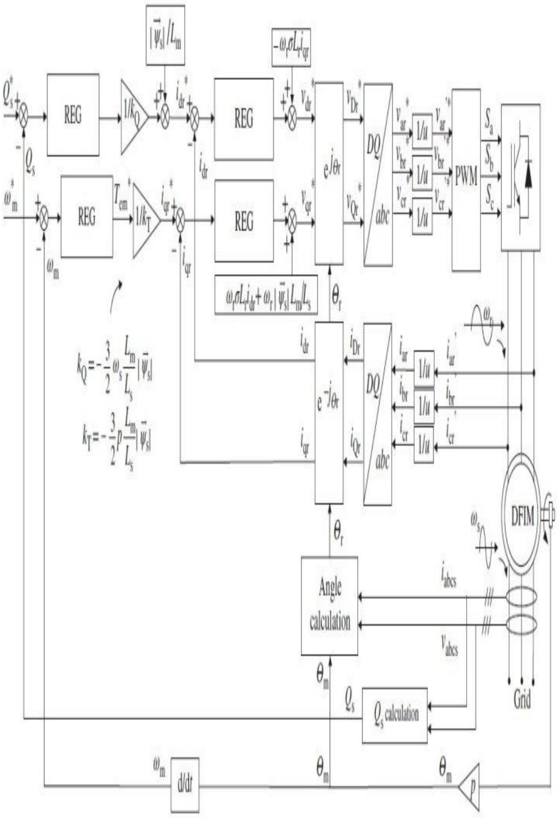


Fig.3 Complete vector control of DFIG

**A. Wind Turbine Aerodynamics**

The theory of momentum is used to study the behaviour of the wind turbine and to make certain assumptions. The assumptions are that the air is incompressible, the fluid motion is steady, and the studied variables have the same value on a given section of the stream tube of air. The power contained in the form of kinetic energy in the wind crossing at a speed Vv, surface A1, is expressed by

$$P_v = \tfrac{1}{2}\rho A_1 V_v^3$$

where r is the air density.
The wind turbine can recover only a part of that power:

$$P_t = \tfrac{1}{2}\rho\pi R^2 V_v^3 C_p$$

where R is the radius of the wind turbine and Cp is the power coefficient, a dimensionless parameter that expresses the effectiveness of the wind turbine in the transformation of kinetic energy of the wind into mechanical energy. For a given wind turbine, this coefficient is a function of wind speed, the speed of rotation of the wind turbine, and the pitch angle. Cp is often given as a function of the tip speed ratio, l, defined by

$$\lambda = \frac{R\Omega_t}{V_v}$$

where R is the length of the blades (radius of the turbine rotor) and Ωt is the angular speed of the rotor. The rotor torque is obtained from the power received and the speed of rotation of the turbine:

$$T_t = \frac{P_t}{\Omega_t} = \frac{\rho\pi R^2 V_v^3}{2\Omega_t}C_p = \frac{\rho\pi R^3 V_v^2}{2\lambda}C_p = \frac{\rho\pi R^3 V_v^2}{2}C_t$$

where Ct is the coefficient of torque. The coefficients of power and torque are related by the equation

$$C_p(\lambda) = \lambda \cdot C_t(\lambda)$$

The aerodynamic model represents the power extraction of the rotor, calculating the mechanical torque as a function of the air flow on the blades. The wind speed can be considered as the averaged incident wind speed on the swept area by the blades with the aim of evaluating the average torque in the low speed axle. The torque generated by the rotor is define by the following expression:

$$T_t = \frac{1}{2}\rho\pi R^3 V_v^2 C_t$$

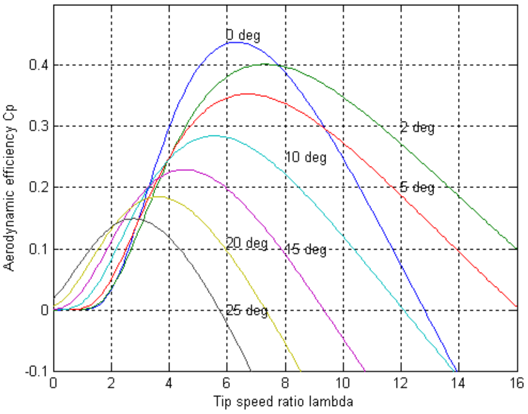


Fig 4. Cp vs λ curves with variation in pitch angle

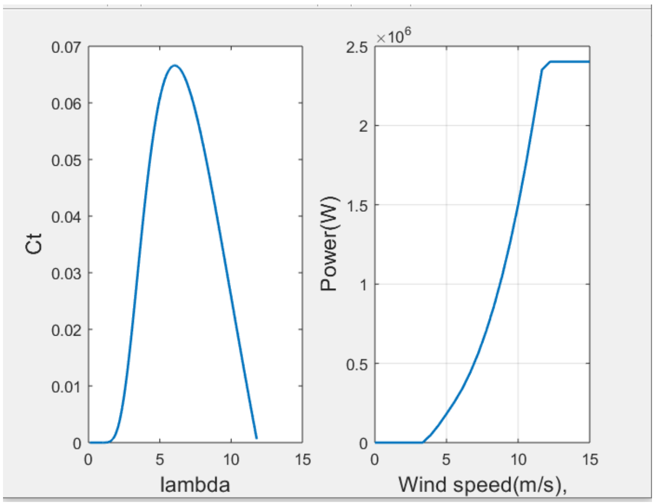


Fig5. Ct vs Lambda and Power vs wind speed

## B. Mechanical System

The power transmission train is constituted by the blades linked to the hub, coupled to the slow shaft, which is linked to the gearbox, which multiplies the rotational speed of the fast shaft connected to the generator. Inertia Jt concerns the turbine side masses, while Jm of the electrical machine. These inertia's do not always represent exactly the turbine and the electrical machine. The stiffness and damping coefficients, Ktm and Dtm, define the flexible coupling between the two inertias. Dt and Dm are the friction coefficients, they represent the mechanical losses by friction in the rotational movement. The turbine rotational speed and driving torque are expressed in the fast shaft by

$$\Omega_{t\_ar} = N\Omega_t$$

$$T_{t\_ar} = \frac{T_t}{N}$$

where N is the gearbox ratio

$$\frac{dT_{em}}{dt} = K_{tm}(\Omega_{t\_ar} - \Omega_m) + D_{tm}\left(\frac{d\Omega_{t\_ar}}{dt} - \frac{d\Omega_m}{dt}\right)$$

The model can be simplified by neglecting the damping coefficients (Dt, Dm, and Dtm), resulting in a model with two inertias (Jt and Jm) and the stiffness (Ktm).

## III. DYNAMIC MODELLING

### 1. $\alpha\beta$ Model

In developing the dynamic $\alpha\beta$ model of the DFIM, space vector theory is applied to the basic electric equations of the machine and again, as in the steady-state model that was considered, the machine is assumed both ideal and linear. Figure shows the three different rotating reference frames typically utilized to develop space vector-based models of the DFIM. The stator reference frame ($\alpha$–$\beta$) is a stationary reference frame, the rotor reference frame (DQ) rotates at $\omega$m and the synchronous reference frame (dq) rotates at $\omega$s. Subscripts “s”, “r” and “a” are used to denote that one space vector is reference to the stator, rotor and synchronous reference frames, respectively. By using direct and inverse rotational transformation, a space vector can be represented in any of these frames. Therefore, the three coils of the stator and rotor separately, by using space vector theory, can be represented by two stationary $\alpha\beta$ coils for the stator and two rotating coils DQ for the rotor, providing the following voltage equations:

$$\vec{v}_s^{\,s} = R_s \vec{i}_s^{\,s} + \frac{d\vec{\psi}_s^{\,s}}{dt} \qquad \vec{v}_r^{\,r} = R_r \vec{i}_r^{\,r} + \frac{d\vec{\psi}_r^{\,r}}{dt}$$

If both voltage equations are represented in stationary reference frame $\alpha\beta$, then the rotor equation must be multiplied by ej$\theta$m , which yields the following set of equations:

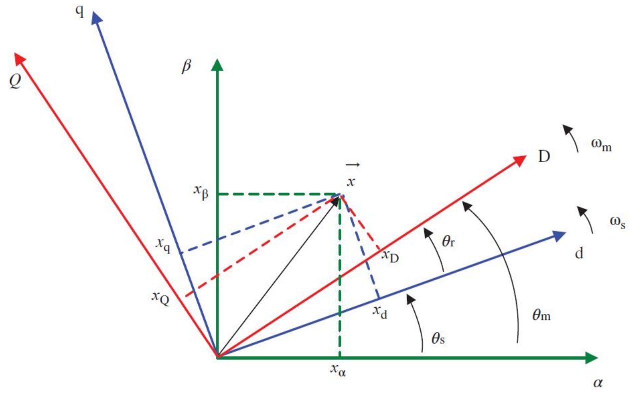


Fig.6 Different reference frames to represent space vectors of the DFIM

$$\vec{v}_s^{\,s} = R_s \vec{i}_s^{\,s} + \frac{d\vec{\psi}_s^{\,s}}{dt} \Rightarrow \begin{cases} v_{\alpha s} = R_s i_{\alpha s} + \dfrac{d\psi_{\alpha s}}{dt} \\ v_{\beta s} = R_s i_{\beta s} + \dfrac{d\psi_{\beta s}}{dt} \end{cases}$$

$$\vec{v}_r^{\,s} = R_r \vec{i}_r^{\,s} + \frac{d\vec{\psi}_r^{\,s}}{dt} - j\omega_m \vec{\psi}_r^{\,s} \Rightarrow \begin{cases} v_{\alpha r} = R_r i_{\alpha r} + \dfrac{d\psi_{\alpha r}}{dt} + \omega_m \psi_{\beta r} \\ v_{\beta r} = R_r i_{\beta r} + \dfrac{d\psi_{\beta r}}{dt} - \omega_m \psi_{\alpha r} \end{cases}$$

the active and reactive powers of the stator and rotor sides can be calculated according to the following equations:

$$P_s = \frac{3}{2}(v_{\alpha s} i_{\alpha s} + v_{\beta s} i_{\beta s}) \qquad P_r = \frac{3}{2}(v_{\alpha r} i_{\alpha r} + v_{\beta r} i_{\beta r})$$

$$Q_s = \frac{3}{2}(v_{\beta s} i_{\alpha s} - v_{\alpha s} i_{\beta s}) \qquad Q_r = \frac{3}{2}(v_{\beta r} i_{\alpha r} - v_{\alpha r} i_{\beta r})$$

The electromagnetic torque, created by the DFIM, can be calculated by the following equivalent Expressions

## 2. Machine Model (d-q)

The d — q axis representation of DFIG is used for modeling considering flux as variable based on Park's model. All rotor quantities are referred to stator side. The dc-qc notation corresponds the stator side axes and dr-qr correspond rotor side axes. Applying the synchronous rotating reference frame, thestator voltage is oriented along the flux vector position.

## 2. Vector control of RSC and GSC

The objective of the RSC is to regulate stator active Power Pc and reactive power Qc independently. The overall control scheme of RSC is shown in fig.7. The rotor current regulation is used to achieve independent control over Pc and Qc. It consists of two cascaded control loops. In outer loop, the three phase rotor currents irabc are transformed to stator flux-oriented reference frame d — q components as idr and iqr. The idr is used to control active power and iqr is used to control reactive power. The references idr× and iqr× are generated from actual measured Pc, Qc. In inner loop, the compensating terms are compared with vdr1 and vqr1 generating voltage signals vdr and vqr. These signals are used to drive IGBT module in RSC.

The purpose of GSC is to maintain dc-link voltage constant irrespective of the flow of Active and reactive power exchanged between GSC and the grid system. The corresponding control scheme is shown in Fig.4. It also composed of two control loops. In outer loop, the reference values of dc voltage Vdc and reactive power Qg are compared with their actual values. That error signals are passed through PI controllers generating references for fast acting current control loop. The grid side three phase currents igabc are transformed to synchronous rotor reference frame idg and iqg. The compared signals vdg1 and vqg1 which are passed through PI controllers. The d — q voltage signals are obtained from compensating the cross-coupling terms then they are used by the PWM block to generate control signals for GSC.

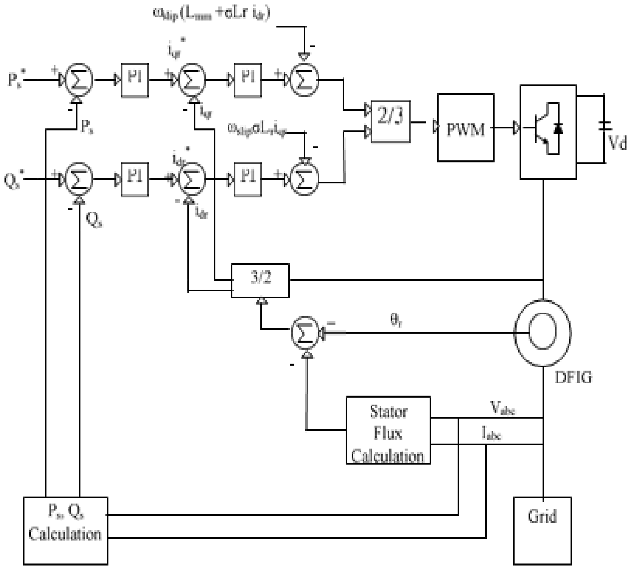


Fig7. Control Scheme RSC

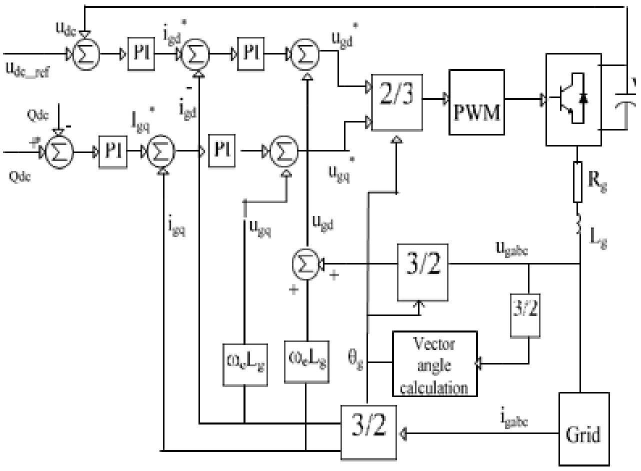
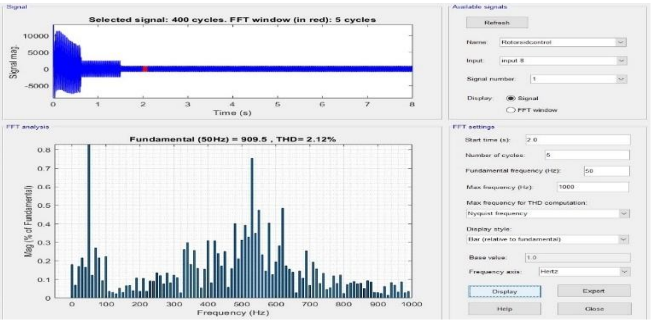


Fig8. Control Scheme GSC

## IV. SIMULATION RESULTS

To verify the proposed vector control of DFIG, a test system is built in MATLAB/Simulink simulation software. The system represents DFIGs of capacity 2 MW connected to AC network through a transformer. Parameters are tabulated in the appendix section. A vector control is implemented to control the performance of DFIG. Wind turbine is controlled by mechanical controls like; pitch angle control and toque control. A maximum power point tracking ensures the DFIG operating at optimum operating point. Pitch control is employed to control the wind turbine operation itself and to protect it from higher wind velocities or wind gusts.

Performance of DFIG on wind is shown in the following figure. Corresponding DFIG variables such as active power, rotor speed is following the input wind variation. DC link voltage is maintained at its reference value of 1150 volts which is constant throughout the simulation. Stator and rotor currents are perfectly sinusoidal and at nominal value 1 p.u.



Name: Rotorsidcontrol
Input: input 8
Signal number: 1
Display: ● Signal ○ FFT window

Start time (s): 2.0
Number of cycles: 5
Fundamental frequency (Hz): 50
Max frequency (Hz): 1000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Hertz

Fig 9. Voltage THD

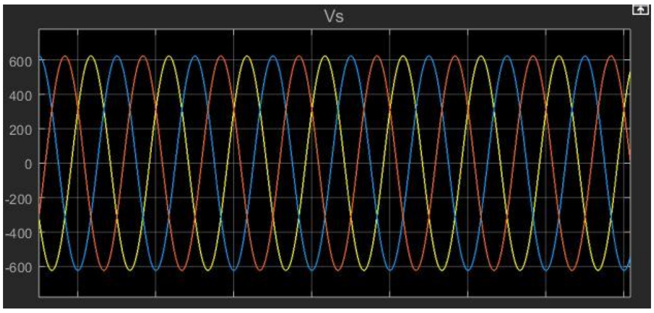


Fig 10. Stator voltage

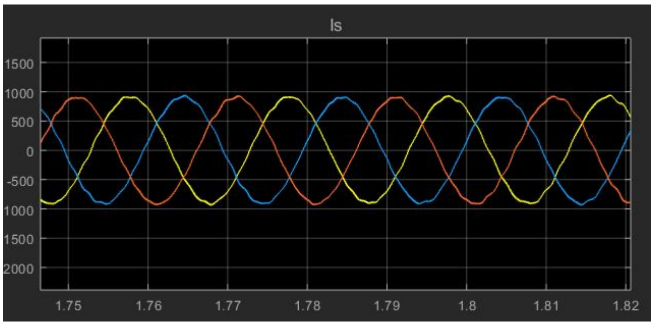


Fig 11. Stator current

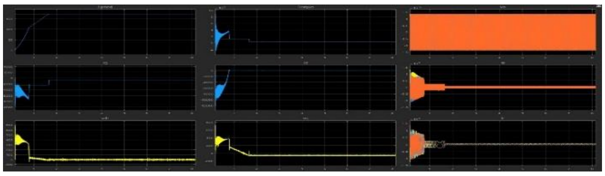


Fig 12. Tem, Ir, Is, Vs, Id, Iq, Speed

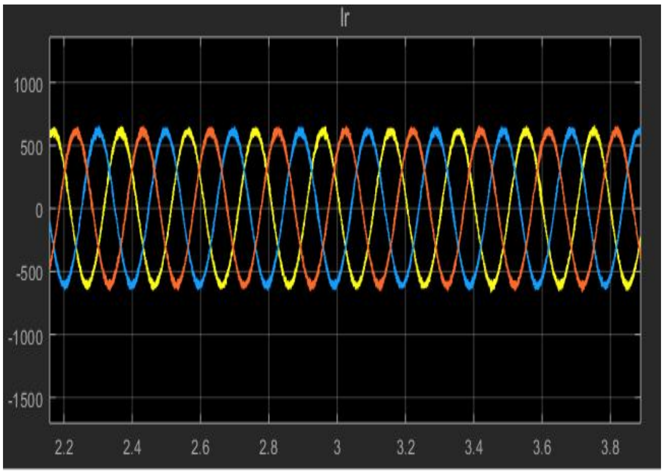


Fig 13. Rotor Current

## V. CONCLUSION

In this paper, a vector control strategy is used. Response to variation in wind speed conditions like ramp up and wind gust are also studied. A stable operation of DFIG is maintained throughout the simulation.

A 2-level PWM inverter is used to check the power quality of injected rotor voltage. And the results are promising. THD in the voltage and current has reduced by a great amount. It is found to be around 2.12%. Thus, paper achieves the verification in vector control scheme and use of 2 level PWM inverter.

## APPENDIX

**TABLE I**. WIND TURBINE PARAMETERS

| Parameters | Value |
|---|---|
| Air Density (ρ) | 1.225 Kg/$m^3$ |
| Radius (R) | 42 m |
| Nomonal Wind Speed ($V_M$) | 8 m/s |

**TABLE II**. DFIG PARAMETERS

| Parameters | Value |
|---|---|
| Nominal Power (Pn) | 2 MW |
| Stator RMS voltage ($V_S$) | 690 V |
| Rotor RMS voltage ($V_r$) | 2070 V |
| Frequency (f) | 50 Hz |
| Stator Resistance ($R_c$) | 0.026 pu |
| Stator Inductance ($L_c$) | 0.054 pu |
| Rotor Resistance($R_r$) | 0.029 pu |
| Rotor Inductance ($L_r$) | 0.054 pu |
| Magnetizing Inductance ($L_N$) | 0.025 pu |

## VI. ACKNOWLEDGEMENT

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