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MODELLING OF INDUCTION GENERATOR FOR WIND POWER APPLICATIONS

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ABSTRACT

Over the past few decades, there has been an increasing use of induction generator particularly in wind power applications. In generator operation, a prime mover (turbine, engine) drives the rotor above the synchronous speed. Stator flux still induces currents in the rotor, but since the opposing rotor flux is now cutting the stator coils, active current is produced in stator coils, and motor now operates as a generator, and sends power back to the electrical grid. Based on the source of reactive power induction generators can be classified into two types namely standalone generator and Grid connected induction generator. In case of stand-alone IGs the magnetizing flux is established by a capacitor bank connected to the machine and in case of grid connection it draws magnetizing current from the grid.

This project explicitly deals with the study of grid connected induction generators where frequency and voltage of the machine will be dictated by the electric grid. Among these types of IGs, Doubly Fed Induction Generator (DFIG) wind turbines are nowadays increasingly used in large wind farms because of their ability to supply power at constant voltage and frequency. Modern control techniques such as Vector control and MFC (magnitude and frequency control) are studied and some of proposed systems are simulated in MATLAB-SIMULINK environment.

Keywords: Doubly fed induction generator (DFIG), MFC, Vector control

I. INTRODUCTION

Wind power is the conversion of wind energy into a suitable form of energy, such as using wind turbines to generate electricity, windmills for mechanical power, wind pumps for water pumping, or sails to propel ships. The total amount of economically extractable power available from the wind is considerably more than present human power use from all sources. Wind power, as an alternative to fossil fuels, is abundant, renewable, widely spread, clean, and produces no greenhouse gas emissions during operation. Wind power is the world‘s rapid growing source of energy.

The majority of electricity is generated by burning coal, rather than more eco-friendly methods like hydroelectric power. This use of coal causes untold environmental damage through CO2 and other toxic emissions. The energy sector is by far the biggest source of these emissions, both in the India and globally, and

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if we are to tackle climate change it is clear we need to move away from burning limited fossil fuel reserves to more sustainable and renewable sources of energy.

Wind power has many advantages that make it a lucrative source of power for both utility-scale and small, distributed power generation applications. The beneficial characteristics of wind power include:

• Clean and endless fuel—Wind power doesn‘t produce any emissions and is not run down with time. A one megawatt (1 MW) wind turbine for one year can displace over 1,500 tons of carbon dioxide, 6.5 tons of sulphur dioxides, 3.2 tons of nitrogen oxide, and 60 pounds of mercury (based on the U.S. average utility generation fuel mix).

• Local financial development—Wind plants can provide a firm flow of income to landowners who lease their land for wind development, while increasing property tax revenues for local communities.

• Modular and scalable technology—Wind applications can take many forms, including large wind farms, distributed generation, and single end-use systems. Utilities can use wind resources tactically to help reduce load forecasting risks and trapped costs.

• Energy price stability—by further diversifying the energy mixture, wind energy reduces dependence on conventional fuels that are subject to price and supply instability.

• Reduced dependence on imported fuels—Wind energy expenditures don‘t need to obtain fuels from abroad, keeping funds closer to home, and lessening reliance on foreign governments that supply these fuels.

II. WIND ENERGY-GENERATING SYSTEMS

Wind turbines produce electricity by using the power of the wind to drive an electrical generator. Passing over the blades, wind generates lift and exerts a turning force. The rotating blades turn a shaft inside the nacelle, which goes into a gearbox. The gearbox adjusts the rotational speed to that which is appropriate for the generator, which uses magnetic fields to convert the rotational energy into electrical energy. The power output goes to a transformer, which converts the electricity from the generator at around 700V to the appropriate voltage for the power collection system, typically 33 kV.

A wind turbine extracts kinetic energy from the swept area of the blades. The power contained in the wind is given by the kinetic energy of the flowing air mass per unit time. That is

$P_{air} = 0.5\rho A V_\infty^3$

Where P_{air} is the power contained in wind (in watts) , ρ is the air density (1.225 kg/m3 at 15°C and normal pressure), A is the swept area in (square meter), and V_∞ is the wind velocity without rotor interference, i.e., ideally at infinite distance from the rotor (in meter per second).

Although the above equation gives the power available in the wind, the power transferred to the wind turbine rotor is reduced by the power coefficient, C

$C_p = P_{wind\ turbine} / P_{air}$

$P_{wind\ turbine} = 0.5\rho\, C_p A V_\infty^3$

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Maximum value of Cp is defined by the Betz limit, which states that a turbine can never extract more than 59.3% of the power from an air stream. In reality, wind turbine rotors have maximum Cp values in the range 25-45%.

2.1 Characteristics of Wind Turbine

2.1.1 Power-Speed Characteristics

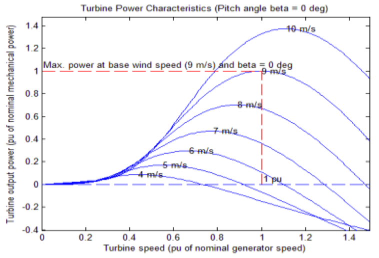

Fig 2.1: Typical Power versus speed characteristics of a wind turbine

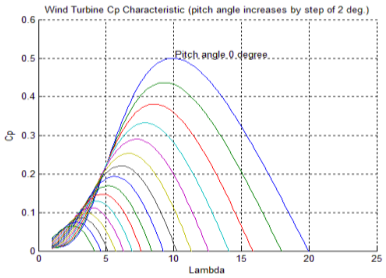

Fig 2.2: Typical curve of power coefficient (Cp) versus Tip speed ratio (λ) for various angles of pitch angle

2.1.2 Torque –Speed Characteristics

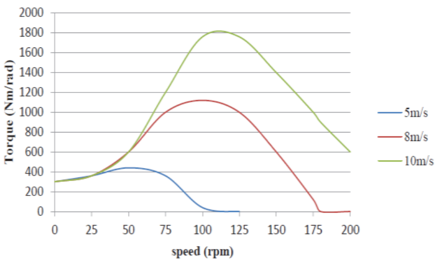

Fig 2.3: Torque versus speed characteristics

III. DOUBLY FED INDUCTION GENERATOR

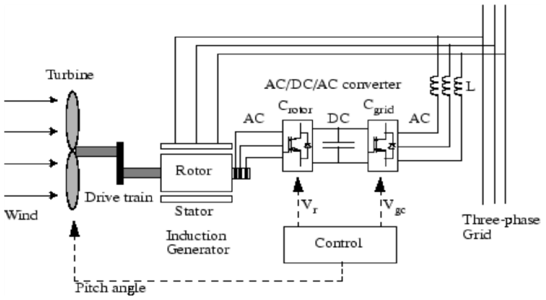

Fig 3.1: A DFIG and wind turbine system

3.1 Operation

When the rotor speed is greater than the rotating magnetic field from stator, the stator induces a strong current in the rotor. The faster the rotor rotates, the more power will be transferred as an electromagnetic force to the stator, and in turn converted to electricity which is fed to the electric grid. The speed of asynchronous generator will vary with the rotational force applied to it. Its difference from synchronous speed in percent is called generator‘s slip. With rotor winding short circuited, the generator at full load is only a few percent.

With the DFIG, slip control is provided by the rotor and grid side converters. At high rotor speeds, the slip power is recovered and delivered to the grid, resulting in high overall system efficiency. If the rotor speed range is limited, the ratings of the frequency converters will be small compared with the generator rating, which helps in reducing converter losses and the system cost.

Since the mechanical torque applied to the rotor is positive for power generation and since the rotational speed of the magnetic flux in the air gap of the generator is positive and constant for a constant frequency grid voltage, the sign of the rotor electric power output is a function of the slip sign. C_{rotor} and C_{grid} have the capability of generating or absorbing reactive power and can be used for controlling the reactive power or the grid terminal voltage. The pitch angle is controlled to limit the generator output power to its normal value for high wind speeds. The grid provides the necessary reactive power to the generator.

3.2 Control Strategies for a DFIG

1. Vector control
2. Magnitude and frequency control

3.3 Modelling of DFIG in Synchronously Rotating Frame

The equivalent circuit diagram of an induction machine is shown in Fig.4.7 and Fig.4.8. In this figure the machine is represented as two phase machine, it has already been discussed before that a three phase machine can be represented as two phase machine obeying certain rules. For the modelling of DFIG in synchronously rotating frame we need to represent the two phase stator (d^s-q^s) and rotor (d^r-q^r) circuit variables in a synchronously rotating (d-q) frame.

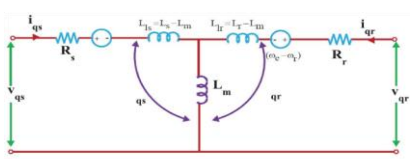

Fig 3.2: Dynamic d-q equivalent circuit of DFIG (q-axis circuit)

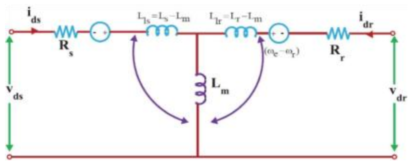

Fig 3.3: Dynamic d-q equivalent circuit of DFIG (d-axis circuit)

The stator circuit equations are given below:

$$v^s{}_{qs} = R_s i^s{}_{qs} + \frac{d}{dt}\psi^s{}_{qs}$$

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$$v^{s}{}_{ds} = R_s i^{s}{}_{ds} + \frac{d}{dt}\psi^{s}{}_{ds}$$

Where $\psi^{s}{}_{qs}$and $\psi^{s}{}_{ds}$are q-axis and d-axis stator flux linkages, respectively.

Converting above equations to d-q frame the following equations can be written as:

$$v_{qs} = R_s i_{qs} + \frac{d}{dt}\psi_{qs} + \omega_e \psi_{ds}$$

$$v_{ds} = R_s i_{ds} + \frac{d}{dt}\psi_{ds} - \omega_e \psi_{qs}$$

Where all the variables are in synchronously rotating frame. The bracketed terms are defined as the back e.m.f. or speed e.m.f or counter e.m.f. due to the rotation of axes as in the case of DC machines. When the angular speed ω_e is zero the speed e.m.f due to d and q axis is zero and the equations changes to stationary form.

Owing to the rotor circuit, if the rotor is blocked or not moving, i.e. ω_r=0, the machine equations can be written in similar way as stator equations:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + \omega_e \psi_{dr}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - \omega_e \psi_{qr}$$

All the parameters are referred to the primary circuit, which is a stator in this case. Let the rotor rotates at an angular speed ω_r, then the d-q axes fixed on the rotor fictitiously will move at a relative speed ω_e-ω_r to the synchronously rotating frame.

The d-q frame rotor equations can be written by replacing ω_e-ω_r in place ω_e of as follows:

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\psi_{qr} + (\omega_e - \omega_r)\psi_{dr}$$

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\psi_{dr} - (\omega_e - \omega_r)\psi_{qr}$$

The flux linkage expressions in terms of current can be written from Fig.3.2 and Fig.3.3 as follows:

$$\psi_{qs} = L_{ls} i_{qs} + L_m (i_{qs} + i_{qr}) = L_s i_{qs} + L_m i_{qr}$$

$$\psi_{ds} = L_{ls} i_{ds} + L_m (i_{ds} + i_{dr}) = L_s i_{ds} + L_m i_{dr}$$

$$\psi_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr}) = L_r i_{qr} + L_m i_{qs}$$

$$\psi_{dr} = L_{lr}i_{dr} + L_m(i_{ds} + i_{dr}) = L_r i_{dr} + L_m i_{ds}$$

$$\psi_{qm} = L_m\left(i_{qs} + i_{qr}\right)$$

$$\psi_{dm} = L_m(i_{ds} + i_{dr})$$

Equations describes the complete electrical modelling of DFIG. Whereas it expresses the relations of mechanical parameters which are essential part of the modelling. The electrical speed ω_r cannot be treated as constant in the above equations. It can be connected to the torque as

$$T_e = T_L + J\frac{d\omega_m}{dt} + B\omega_m = T_L + \frac{2}{p}J\frac{d\omega_r}{dt} + \frac{2}{p}B\omega_r$$

3.3.1 Modelling of DFIG Stator

It is assumed that the stator transient can be neglected in this paper. The effects of neglecting stator transients in DFIG model were analysed. Besides analysis, includes simulated waveforms which establish that the stator transients in DFIG can be neglected and the accuracy is not affected after the transients have damped out.

By neglecting the stator transient, the voltage equations of the DFIG in the arbitrary d-q reference frame can be expressed as follows (stator in generator convention and rotor in motor convention)

$$u_{d1} = -r_1 i_{d1} - \psi_{q1}\omega_1$$

$$u_{q1} = -r_1 i_{q1} - \psi_{d1}\omega_1$$

$$u_{d2} = -r_2 i_{d2} + p\psi_{d2} - \psi_{q2}\omega_2$$

$$u_{q2} = -r_2 i_{q2} + p\psi_{q2} - \psi_{d2}\omega_2$$

The corresponding flux linkage equations:

$$\psi_{d1} = -L_1 i_{d1} - L_m i_{d2}$$

$$\psi_{q1} = -L_1 i_{q1} + L_m i_{q2}$$

$$\psi_{d2} = L_2 i_{d2} - L_m i_{d1}$$

$$\psi_{q2} = L_2 i_{q2} - L_m i_{q1}$$

Setting the d-axis to align with the rotor flux vector, one defines $\psi_2=\psi_{d2}$. A consequence of the rotor flux alignment is $\psi_{q2}=0$.

Thus, rotor currents can be expressed in terms of stator currents as:

$$i_{d2} = \frac{\psi_2 + L_m i_{d1}}{L_2}$$

$$i_{q2} = \frac{L_m}{L_2 i_{q1}}$$

In order to eliminate the rotor variables in stator equations, define

$$E'_q = \omega_1 \frac{L_m}{L_2} \psi_2$$

$$X'_1 = \sigma \omega_1 L_1$$

Where E'_q is the equivalent _emf behind the internal transient reactance which is generated by the rotor flux linkage ψ_2, X'_1 is the transient reactance of the stator, and $\sigma = (L_1 L_2 - L^2_m)/ L_1 L_2$ is the leakage factor.

By substituting, the stator voltage equations can be written as follows:

$$u_{d1} = -r_1 i_{d1} + X'_1 i_{q1}$$

$$u_{q1} = -r_1 i_{q1} - X'_1 i_{d1} + E$$

Neglecting the stator resistance, the vector diagram of the DFIG stator can be drawn as shown in Fig 4.7according to above equations.

In this vector diagram, δ is the power angle between the vector $\boldsymbol{E'_q}$ and $\boldsymbol{U_1}$and ϕ is the phase angle between the vector $\boldsymbol{U_1}$ and $\boldsymbol{I_1}$. Based on Fig 4.7, the stator currents can be calculated as

$$i_{d1} = \frac{E'_q - U_1 \cos\delta}{X'_1}$$

$$i_{q1} = \frac{U_1 \sin\delta}{X'_1}$$

Then the equations of active and reactive powers of the DFIG stator:

$$P_1 = U_1 I_1 \cos\phi = \frac{E'_q U_1}{X'_1} \sin\delta$$

$$Q_1 = U_1 I_1 \sin\phi = \frac{E'_q U_1}{X'_1} \cos\delta - \frac{{U_1}^2}{X'_1}$$

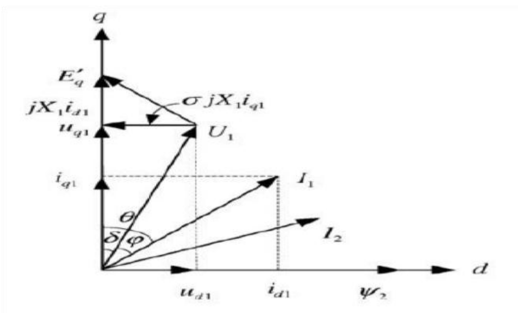

Fig 3.4: Vector diagram of the DFIG

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It can be seen that the DFIG has the same expression of active and reactive powers as the synchronous machine. Developing from and adding the stator resistance r1, Fig 4.11 is the single line equivalent circuit of the DFIG. It is similar to that of the synchronous generator except the excitation voltage is different, because it is controlled from a more complex rotor equivalent circuit.

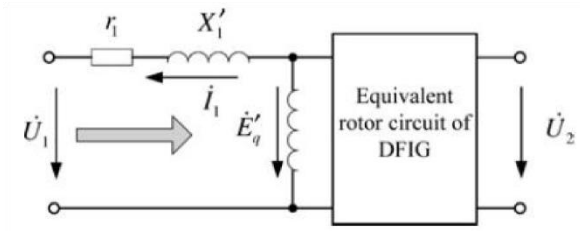

Fig 3.5: Equivalent circuit of DFIG

The power angle in synchronous generator is relatively small in normal operation which is often below 30 degrees. This condition can be also met in DFIG. With this condition the classic synchronous generator theory indicates that the active power transfer depends mainly on the power angle and the reactive power transfer depends mainly on the voltage magnitude of $\boldsymbol{E}_q^{'}$, respectively. By similarity of synchronous generator, the control of the stator active power and reactive power of the DFIG can be seen as the control of phase and magnitude of$\boldsymbol{E'}_q$. The DFIG has a benefit in that the power angle δ (and therefore the active power) is controllable by the rotor converter whereas δ in the synchronous generator is determined by the axis of the field winding.

3.3.2 Modelling of the DFIG Rotor

By substituting rotor flux equations into the rotor voltage equations, the rotor voltages can be expressed as:

$$u_{d2} = r_2\frac{\psi_2}{L_2} + r_2\frac{L_m}{L_2} + p\psi_2$$

$$u_{q2} = r_2\frac{L_m}{L_2}i_{q1} + \psi_2\omega_2$$

Equation above can be re-expressed in the vector form as follows:

$$\boldsymbol{U_2} = r_2\frac{L_m}{L_2}\boldsymbol{I_{1+}}\left(\frac{r_2 + \omega_2 L_2 + p}{\omega_1 L_m}\right)\boldsymbol{E_q'}$$

Replacing the stator current vector with $I_1= (E'_q - U_1)/ X'_1$, becomes

$$\boldsymbol{U_2} = \left(\frac{r_2 L_m}{\sigma L_2 X_1} + \frac{r_2}{X_m} + \frac{\omega_2 L_2}{X_m} + p\right)\boldsymbol{E_q'} - \frac{r_2 L_m}{\sigma L_2 X_1}\boldsymbol{U_1}$$

Equation above describes the relationship between the stator voltage vector $\boldsymbol{U_1}$, the rotor voltage vector $\boldsymbol{U_2}$and the internal transient EMF vector$\boldsymbol{E'_q}$. The stator voltage $\boldsymbol{U_1}$ is the same as the grid voltage and thus $\boldsymbol{E'_q}$ can be controlled by U_2.

Unlike the exciter of the synchronous generator which can only adjust the magnitude of the exciter voltage only, the rotor controller of the DFIG can manipulate both the magnitude and the phase angle of $\boldsymbol{U_2}$ vector. Thus, the active and reactive powers of the DFIG can be controlled by $\boldsymbol{U_2}$ vector.

3.3.3 Modelling the DFIG-Based Wind Turbine

The active power of the DFIG rotor can be expressed as:

$$P_2 = u_{d2}i_{d2} + u_{q2}i_{q2}$$

From the above equations, the active power of the rotor can be expressed as:

$$P_2 = P_{r2} + \frac{\omega_2}{\omega_1}P_1$$

Where,

$$P_{r2} = r_2 i_{d2}^2 + r_2 i_{q2}^2$$

is the power losses associated with the rotor resistance, which is small enough to be ignored. It can be shown that the active power of the rotor depends on the rotor current frequency, stator frequency and the active power of the stator. Depending on the rotor speed ω_r, the rotor current frequency, $\omega_2 = \omega_1 - \omega_r$, can be positive and negative and therefore the rotor power changes direction. The active power of the rotor is positive when the DFIG operates at the sub-synchronous mode ($\omega_1 > \omega_r$) and negative when the DFIG operates at the super synchronous mode ($\omega_1 < \omega_r$). The grid-side converter, in maintaining the DC-link voltage regulated, feeds or absorbs the slip dependent rotor active power. The reactive power of the grid side converter is set to zero to give a unity displacement factor.

3.2.1 Principle of Vector Control

The fundamentals of implementation of vector control technique can be explained using the Fig 4.9 In this figure the machine model is in synchronously rotating frame. The vector control uses unit vectors to obtain the appropriate control action. The main role of unit vector is to convert the 2-phase model to 3-phase model and vice versa. Though the control techniques used for DFIG uses two axes parameters as explained in the modelling via vector control but the model is virtual representation of the original machine. The control signals which will be fed to the original machine or converters should be in three axes form, so the process requires repeated conversion of two-phase to three-phase parameter or vice versa following the necessary action being taken for the system. There are essentially two general method of vector control

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- Direct or feedback method (which is invented by Blaschke)
- Indirect or feed forward method (which is invented by Hasse)

The two methods are different from each other by the process of generating unit vector for control. Unit vectors ($\cos\theta_e$, $\sin\theta_e$) are generally generated using the flux vectors, but it can also be generated using voltage vectors. The name of the orientation of unit vector is given according to the vector taken for generation of θ_e. The names of the orientations used are given below.

- Rotor flux orientation
- Stator flux orientation
- Air gap flux orientation

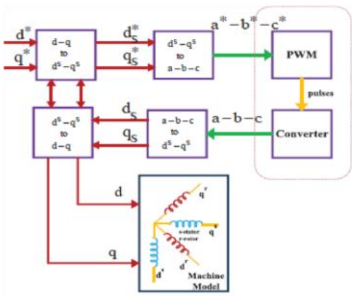

Fig 3.6: Implementation of vector control principle

The detail vector control strategy is shown in above figure. The a, b, c components are generated from the controlled components a*, b*, c* respectively using vector control techniques. The machine terminal parameters (either voltages or currents) are converted to $d^s q^s$ components by 3-phase to 2-phase transformation. These are then converted to synchronously rotating frame by the unit vector before applying to the 2-phase machine model.

3.2.2 Mechanical Equation of Motion

The stator voltage vector $\boldsymbol{U_1}$ rotates at the speed of ω_1 of the grid frequency. The rotating speed of $\boldsymbol{E'_q}$ is the algebraic sum two speeds: the rotor speed ω_r and the rotor current angular frequency ω_2. So the equation of the power angle is:

$$\dot{\delta} = (\omega_r + \omega_2) - \omega_1$$

Equation of motion of the rotor is:

$$J\dot{\omega}_r = T_m - T_{em}$$

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Where T_m is the input torque from the wind turbine and T_{em} is the electromagnetic torque of the DFIG.

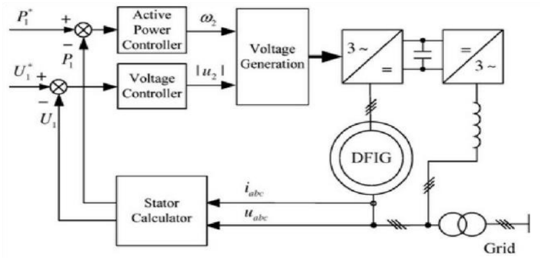

Fig 3.7: MFC Controller Diagram

IV. SIMULATIONS

Pitch Control Analysis by MATLAB

Explanation:

$$P_m = 0.5C_p(\lambda, \beta)\rho A V_w^3$$

Where

P_m is mechanical output power of the wind turbine;

$C_p(\lambda, \beta)$ is the performance coefficient of the turbine;

ρ is the density of air in kg/m^3;

A is the swept area of turbine;

V_w is the wind speed(m/s);

λ is the tip speed ratio;

β pitch angle of blade in degrees;

A basic equation used to model $C_p(\lambda, \beta)$:

$$C_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda} - c_3\beta - c_4\right)e^{\frac{c_5}{\lambda_i}} + c_6\lambda$$

and

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}$$

The coefficients c1 to c6 are: c1 = 0.5176, c2 = 116, c3 = 0.4, c4 = 5, c5 = 21 and c6 =

0.0068. The Cp-λ characteristics, for different values of the pitch angle β, are illustrated below. The maximum value of Cp (Cpmax = 0.48) is achieved for β = 0 degree and for λ = 8.1. This particular value of λ is defined as the Nominal value (λ_nom).

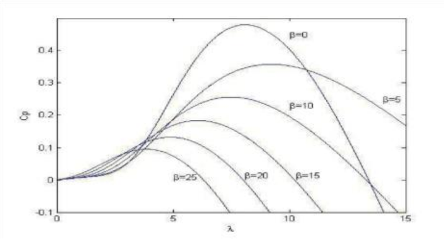

Fig: 4.1 Power coefficients versus tip speed ratio

Mechanical Characteristics Analysis by MATLAB

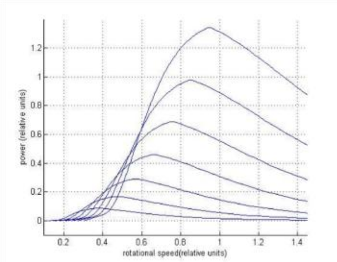

Fig: 4.2 Wind turbine output power vs. rotational speed, with wind speed as parameter

Torque-Slip Characteristics

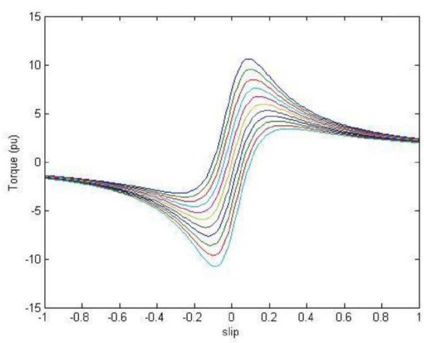

Fig: 4.3 Torque-slip characteristic when the angle of Vr is 0.

|Vr| is changing from -0.05 to +0.05 pu.

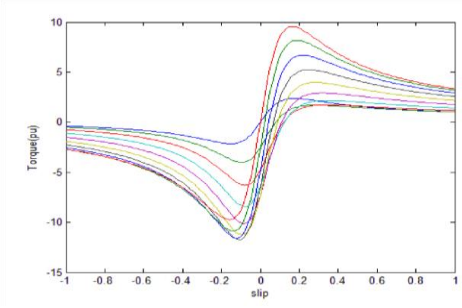

Fig: 4.4 Torque-slip characteristic when |Vr| is 0.05 pu.

The angle of Vr is changing from -90°to + 90°

Study of WTDFIG in A 9MW Wind Farm Connected to a 25kV, 60 Hz System

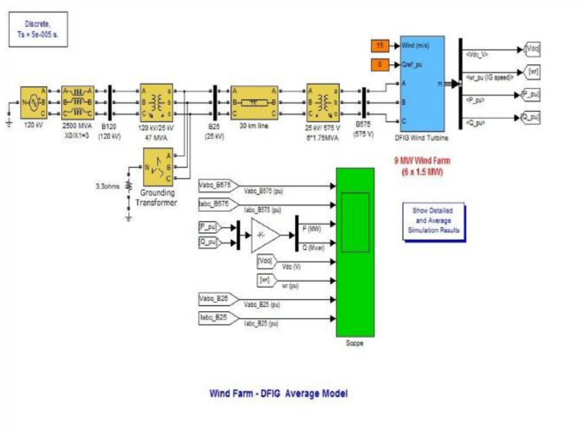

Fig: 5.5 Wind farm DFIG Average Model

Simulation Results of DFIG Average Model

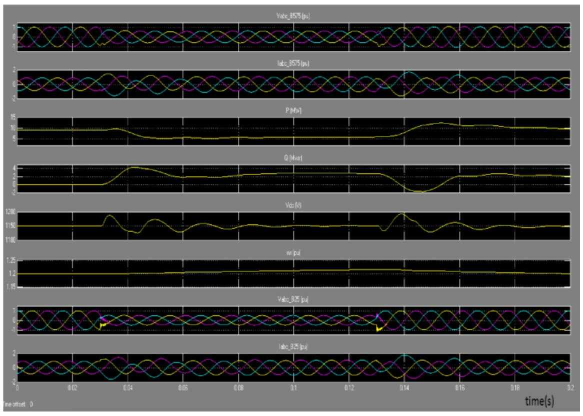

Fig: 5.6 Simulation results of DFIG average model

Simulink Model for Magnitude and Frequency Control of DFIG

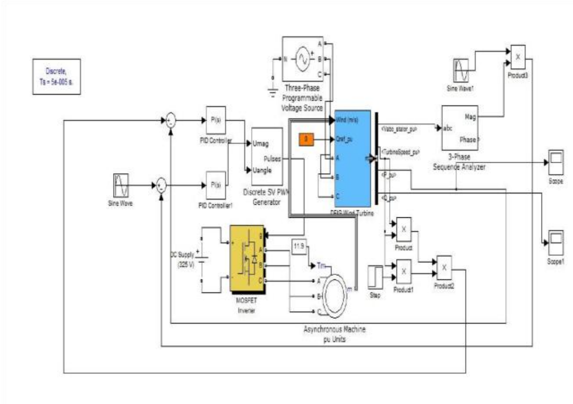

Fig: 5.7 Simulink model for MFC

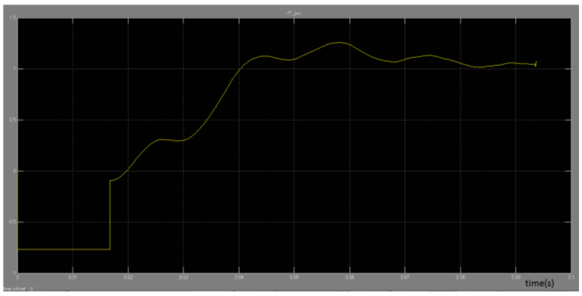

Fig: 5.8 Active Power

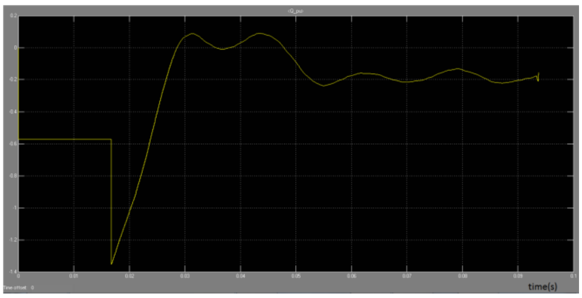

Fig: 5.9 Reactive Power

V. CONCLUSION

DFIGs are enormously used in Wind farms because of their ability to supply power at constant voltage and frequency. Characteristics of DFIG are studied in MATLAB environment. Control techniques of DFIG have been analyzed. Magnitude and Frequency control has been studied and a Simulink model for the same has been proposed. Unlike traditional methods like Stator flux orientation vector control and FMAC, the MFC method manipulates the magnitude and frequency of the rotor voltage. This simplifies the design of the control system and improves system reliability.

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