Analysis and Design of Doubly Fed Induction Generator for Wind Turbines Using MATLAB

Mrs Aakansha Mercy Steele
Assistant Professor
Department of EX
UIT- RGPV, Bhopal
mercy.steele@yahoo.com

ABSTRACT: This paper presents a grid-connected wind power generation scheme using Doubly Fed Induction Generator (DFIG). This can supply power at constant voltage and constant frequency with the rotor speed varying. This makes it suitable for variable speed wind energy application. The DFIG system consists of wind turbine, asynchronous wound rotor induction generator, inverter and Pulse Width Modulation (PWM) controller. In which the stator is connected directly to the grid and the rotor winding is in interface with rotor converter and grid converter. The use of back-to-back PWM converter in the rotor circuit results in low distortion current, reactive power control and operate at variable speed. Mathematical modelling of the DFIG is done in order to analyze the performance of the systems and they are simulated using MATLAB. The simulation results for the two systems are obtained and hence it shows that the systems can operate at variable speed with low harmonic current distortion. The objective is to track and extract maximum power from the wind energy system and transfer it to the grid or useful work.

Keywords- Doubly Fed Induction Generator, Pulse Width Modulation, Mathematical modelling, Simulation, MATLAB

1. INTRODUCTION

Wind electrical power generation system has many potential benefits from both economical and environmental perspectives. As it is cost–competitive, safe, clean and abundant renewable energy as compared to fossil fuel (Nakra and Benoit, 1988; Z.Xie, et., 2007). The wind electrical power generator transforms mechanical energy into electrical energy. The blades transfer the kinetic energy from the wind into rotational energy in the transmission system and the generator is the next step in the supply of energy from the wind turbine to the electrical grid.

There has been continuous change in the technology like from the fixed speed control system to the variable speed control system. First the Self starting induction generators were used as they require generator to run in motor mode at the start, so they are not self starting (Nakra and Benoit, 1988). For this purpose squirrel cage induction generator is used because they are simple, serve the function of self starting, cheap and rugged. But they operate at constant speed and in this system there is no inherent reactive power control method so it requires capacitor banks. Due to capacitor failure use of synchronous generator in Wind Energy Conversion System (WECS) was used (Ammasaigounden. and Subbiah 1988; LeTang and Robert Zavadil, 1993). Which does not requires synchronization with the grid but all the above generator operates at constant speed. So with the advancement in the thyristor converter the turbines can be used to generator power at variable speed. In the control system converter- inverter circuit is use to control the magnitude, phase and frequency. There are different ways to control the inverter and converter output power like fuzzy logic controller, back-to back PWM converter in the rotor circuit of DFIG (M.Hussein, et., 1994; R.S.Pena, et., 1996). DC link chokes were used but they are expensive and required an extra commutation circuit for operating at synchronous speed and this result in the poor performance. It can be improved by the use of chopper but it produces current harmonics to overcome this back draw Pulse Width Modulation (PWM) converter in asynchronous wound rotor induction generator also known as DFIG is used. It has low distortion of rotor, stator and supply current. It reduces the inverter cost. It can cover a wide operation range from sub synchronous to super synchronous speed operating with the flow in both directions. So maximum energy is capture from the wind and hence enables optimal speed tracking (R.S.Pena, et, 1996; Z.Xie, et., 2007).

2. **MATERIAL AND METHOD**

In the DFIG the stator is directly connected to the grid and the rotor is connected to the variable frequency converter (PWM) how to change the frequency, phase and magnitude of the rotor current or voltage is the main aim to control the DFIG.

The wind turbine and the doubly-fed induction generator (WTDFIG) are shown in the Fig 1 called the Doubly-Fed Induction Generator System. The AC/DC/AC converter is divided into two components: the rotor-side converter (C_{rotor}) and the grid-side converter (C_{grid}). C_{rotor} and C_{grid} are Voltage-Sourced Converters which consist of forced-commutated power electronic devices (IGBTs) to synthesize an AC voltage from a DC voltage source. The three-phase rotor winding is connected to C_{rotor} by slip rings and brushes and the three-phase stator winding is directly connected to the grid. The power captured by the wind turbine is converted into electrical power by the induction generator and it is transmitted to the grid by the stator and the rotor windings. The pulse width modulation controller system generates the pitch angle command and the voltage command signals for C_{rotor} and C_{grid} respectively in order to control the power of the wind turbine.

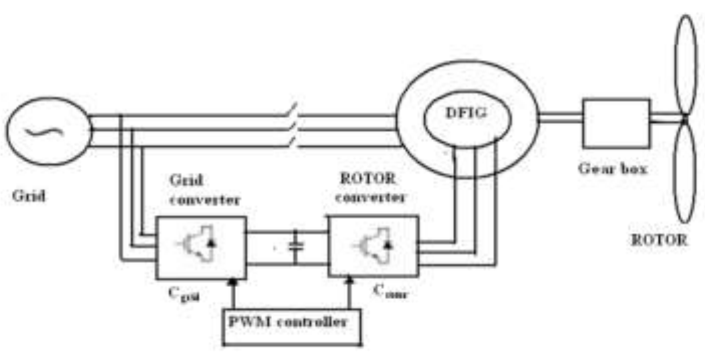


Fig. 1 Doubly-fed induction generator system

3. **MATHEMATICAL MODELING OF SYSTEM**

Wind energy, doubly fed induction generator, rotor converter, grid converter, all are derived by mathematical model. These mathematical models are used for the simulation purpose. Mathematical modelling of all system is given as follows:

3.1 MAXIMAL POWER POINT TRACKING

The power that can be captured from the wind with a wind energy converter with effective area A_r is given by

$$P_m = \frac{1}{2}\rho C_p(\lambda) A_r v^3 \quad (1)$$

Where $A_r = \pi r_m^2$

$$P_m = \frac{1}{2}\rho C_p(\lambda) \pi r_m^2 v^3 \quad (2)$$

$$\lambda = \frac{r_m \omega}{V}$$

Where,

P_m Turbine mechanical power.

C_p Turbine performance coefficient.

V Wind speed.

ω Turbine angular speed.

ρ Air density.

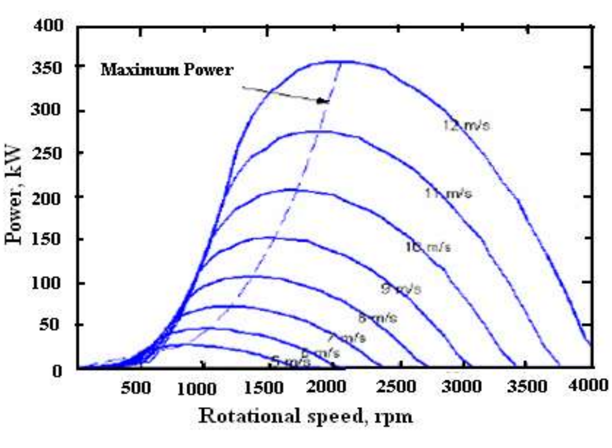


Fig. 2 Relation curve of P_m and n

So we can get the relation curve of mechanical power (P_m) and rotational speed (n) as shown in Fig.2 More energy can be captured from wind by keeping the tip speed ratio to optimal constant. The speed of wind is regulated by controlling the electromagnetic torque .The peak power depends on the turbine characteristic and air density ,the air density may vary considerably over various season, which will not result in optimal tracking of the peak power point under all condition ,there is a considerer able loss in output power energy, in order to restrain the concussion of the system and to improve the tracking, a method of tracking the peak power is proposed which is independent of the turbine parameters and air density (Z.Xie, et., 2007**).**

3.2 MODELLING OF DFIG

The following equations are derived for DFIG.

$$u_{sd} = -R_s i_{sd} + \omega_s \psi_{sq} - \frac{d}{dt}\psi_{sd} \quad (3)$$

$$u_{sq} = -R_s i_{sq} - \omega_s \psi_{sd} - \frac{d}{dt}\psi_{sq} \quad (4)$$

$$u_{rd} = R_r i_{rd} - \omega_{s\,l} \psi_{rq} + \frac{d}{dt}\psi_{rd} \quad (5)$$

$$u_{rq} = R_r i_{rq} + \omega_{s\,l} \psi_{rd} + \frac{d}{dt}\psi_{rq} \quad (6)$$

$$\psi_{sd} = L_S i_{sd} - L_m i_{rd} \quad (7)$$

$$\psi_{sq} = L_S i_{sq} - L_m i_{rq} \quad (8)$$

$$\psi_{rd} = L_r i_{rd} - L_m i_{sd} \quad (9)$$

$$\psi_{rq} = L_r i_{rq} - L_m i_{sq} \quad (10)$$

$$T_e = \frac{3}{2} p L_m \left(i_{sd} i_{rq} - i_{sq} i_{rd}\right) \quad (11)$$

Where,

u_{sd} d- axis stator voltage.

u_{sq} q-axis stator voltage.

u_{rd} d-axis rotor voltage.

u_{rq} q-axis rotor voltage.

ψ_{sd} d-axis stator flux linkage.

ψ_{sq}	q-axis stator flux linkage.
ψ_{rd}	d-axis rotor flux linkage.
ψ_{rq}	q-axis rotor flux linkage.
i_{sd}	d-axis stator current.
i_{sq}	q-axis stator current.
i_{rd}	d-axis rotor current.
i_{rq}	q-axis rotor current.
R_s	Stator resistance.
R_r	Rotor resistance.
ω_s	Synchronous angular speed.
ω_{sl}	Slip angular speed.
L_s	Stator self- inductance.
L_r	Rotor self- inductance.
L_m	Mutual inductance.
p	Pole pairs.
T_e	Electrical torque.

3.3 PULSE WIDTH MODULATION

The DC power at the rectifier output is filtered and converted to AC power using the PWM inverter employing double edge sinusoidal modulation (R.S. Pena, et., 1996). PWM signals are used to switch the transistor in the inverter. The output consists of sinusoidal modulated carrier pulses. Both the edges are modulated such that the average voltage difference between any two of the output three phase are sinusoidal.

Mathematically represented by

$$\delta_x = M\sin(\alpha_x)\delta_{max} \tag{12}$$

Where,

x = 1,2,3,4....................., 2r+1

Where,

M Modulation index range from 0 to1

X Edge being considered.

r Ratio of carrier to fundamental frequency in the inverter output.

α_x Angular displacement of the unmodulated edge.

δ_x Maximum displacement of the edge for the chosen frequency ratio r.

4. PROPOSED TECHNIQUE OF DFIG

Fig. 3 shows the schematic diagram of DFIG for step input but the results are also taken for ramp and constant input. The three phase rotor winding of the asynchronous induction is connected to the rotor and the grid converter and the stator is directly connected to the grid. The mechanical torque T_m is given the input for the variable and constant speed. AC -to-DC and then DC- to- AC converter are divided into two components rotor converter and grid converter .They are connected back -to -back by the DC links. PWM generates the pulses for the rotor and the stator converter in order to produce low distortion current, reactive power control and to operate at constant and variable speed.

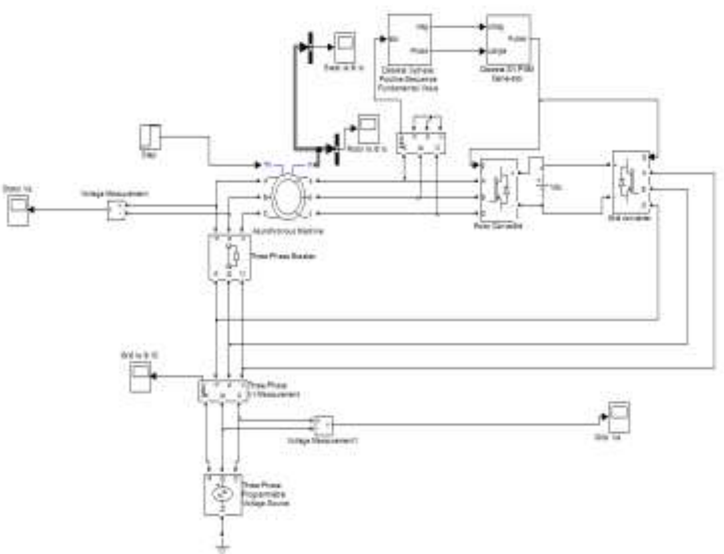


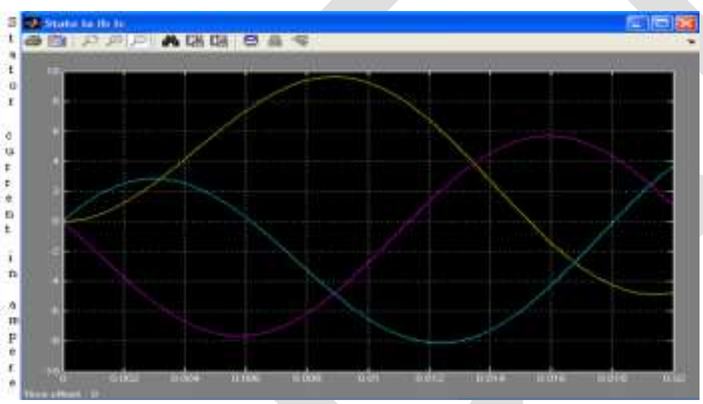
Fig. 3 Schematic diagram of DFIG

5. RESULTS AND DISCUSSIONS

The simulation results of doubly fed induction generator at constant speed and variable speed are shown using MATLAB.

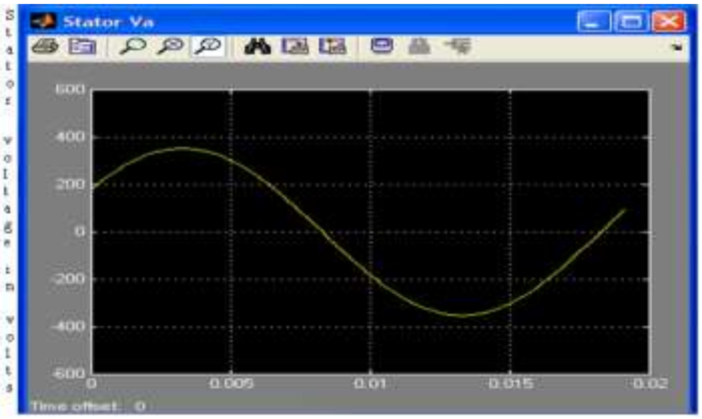
The results have been taken for different mechanical torque of the generator of 160 KW. As the wind speed varies with time so the generator should operate at constant and variable speed. This shows the optimal tracking of power point under all condition by varying the wind speed.

Fig. 4.1a to Fig. 4.5e shows the performance of DFIG. Fig. 4.1a shows the stator current waves. Fig. 4.2b shows the stator voltage waves. Fig. 4.3c shows the grid current waves. Fig. 4.4d shows the grid voltage waves. Fig. 4.5e shows the rotor current waves. For the variable speed the mechanical torque T_m is given by the step at the input the asynchronous induction generator. The step value is from -1 to -4 and step time is 0.01sec. The stator current is 9.9 Amp, stator voltage is 375Volts, grid current is 20 Amp, grid voltage is 350 Volts and rotor current is 7.9Amp.



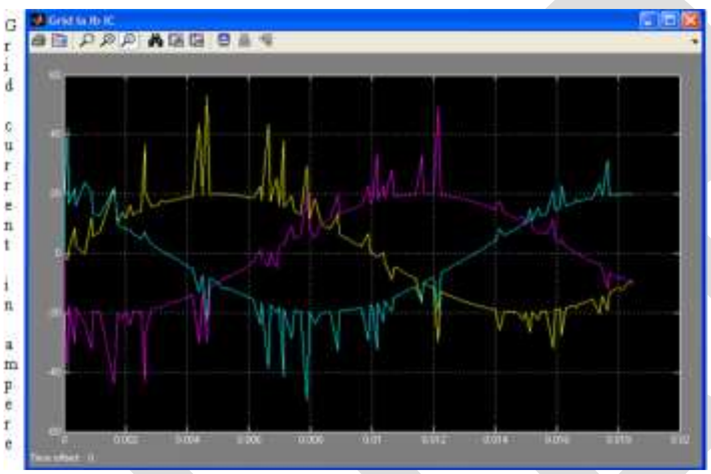
Time in sec

Fig. 4.1a Wave form between stator current wrt time



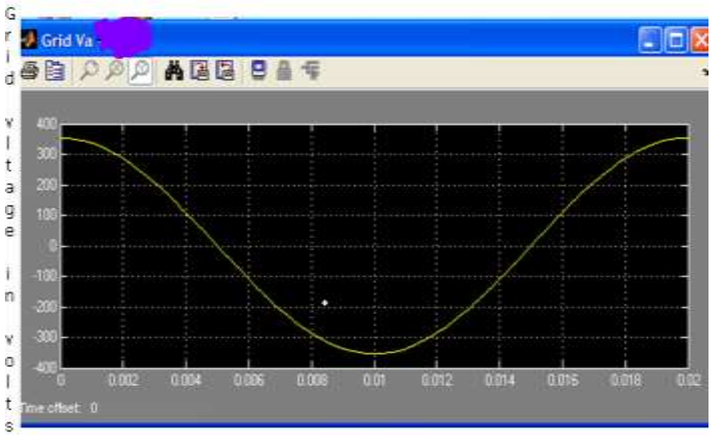
Time in sec

Fig. 4.2b Wave form between stator voltage wrt time



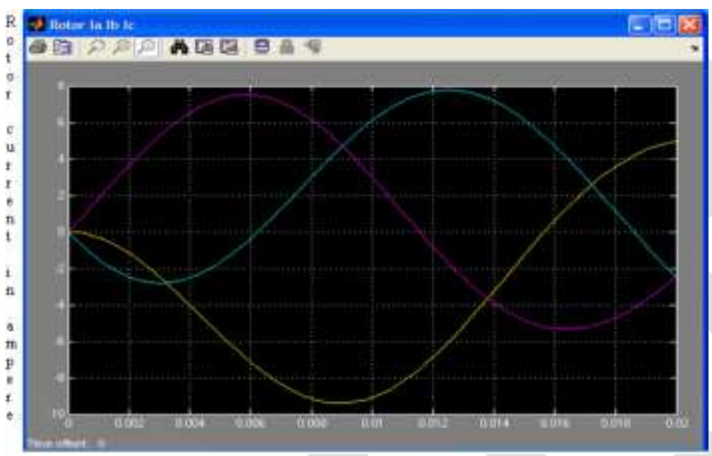
Time in sec

Fig. 4.3c Wave form between grid current wrt time



Time in sec

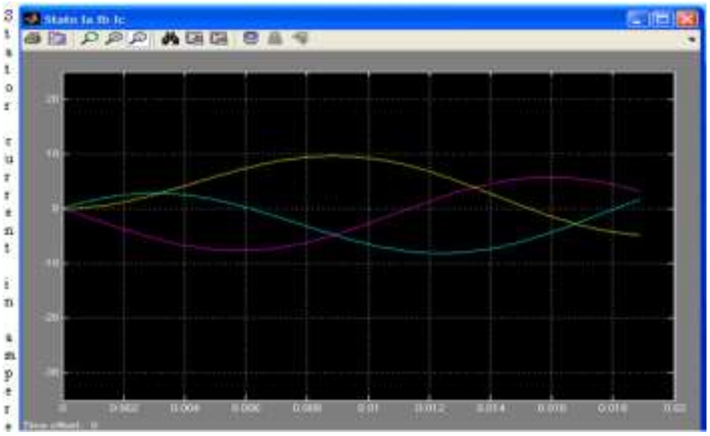
Fig. 4.4d Wave form between grid voltage wrt time



Time in sec

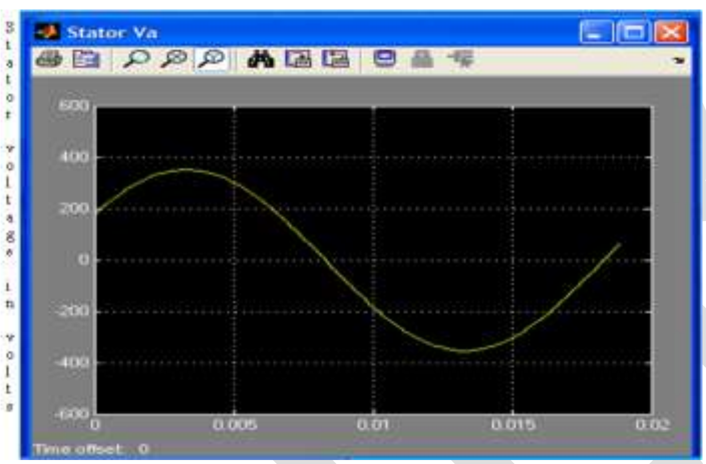
Fig. 4.5e Wave form between rotor current wrt time

Fig. 5.1a to Fig. 5.5e shows the performance of DFIG. Fig. 5.1a shows the stator current waves. Fig. 5.2b shows the stator voltage waves. Fig. 5.3c shows the grid current waves. Fig. 5.4d shows the grid voltage waves. Fig. 5.5e shows the rotor current waves. For the variable speed the mechanical torque T_m is given by the ramp input of the asynchronous induction generator. The ramp value is slope 1, start time 1.5sec and initial output -1. The stator current is 10 Amp, stator voltage is 375Volts, grid current is 12.8 Amp, grid voltage is 350 Volts and rotor current is 7.5Amp.



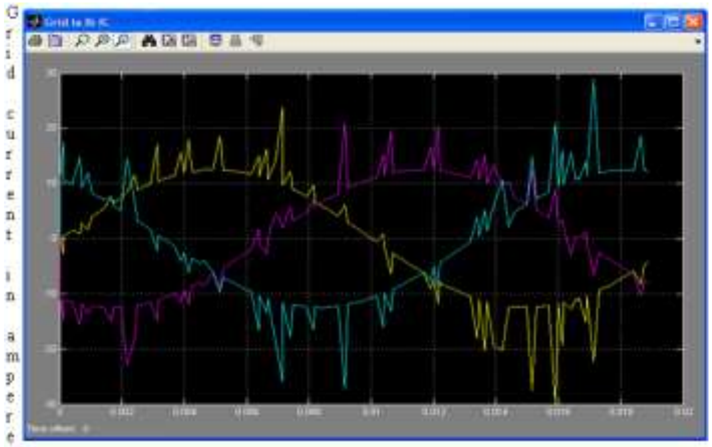
Time in sec

Fig. 5.1a Wave form between stator current wrt time



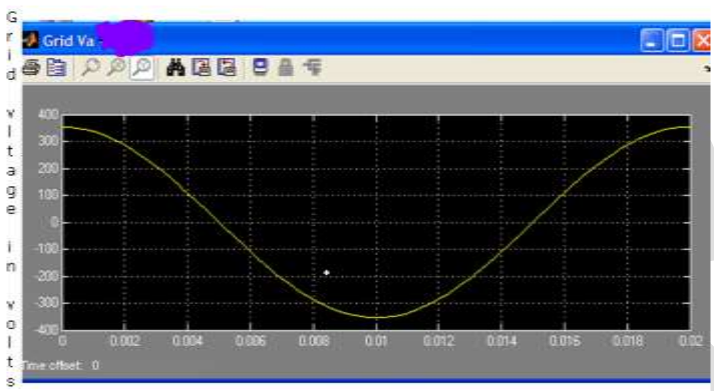
Time in sec

Fig. 5.2a Wave form between stator voltage wrt time



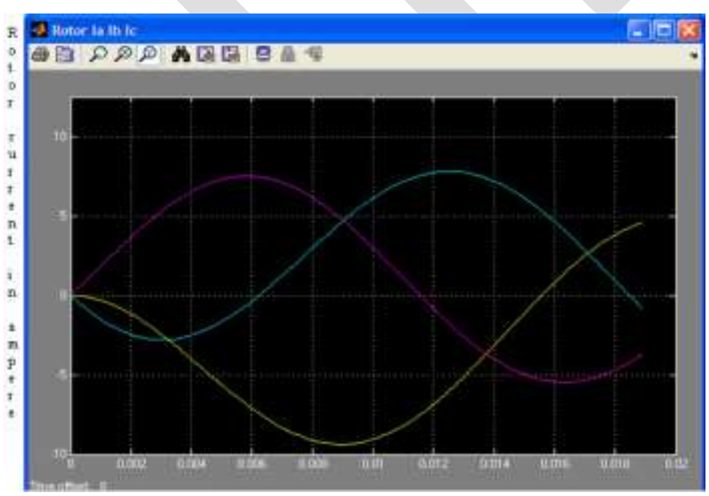
Time in sec

Fig. 5.3c Wave form between grid current wrt time



Time in sec

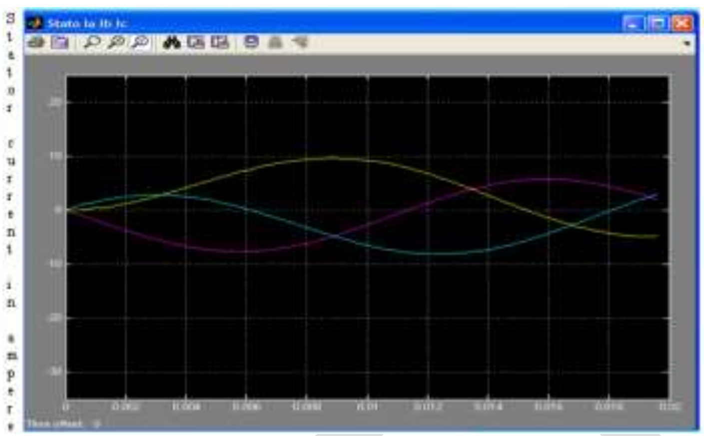
Fig. 5.4d Wave form between grid current wrt time



Time in sec

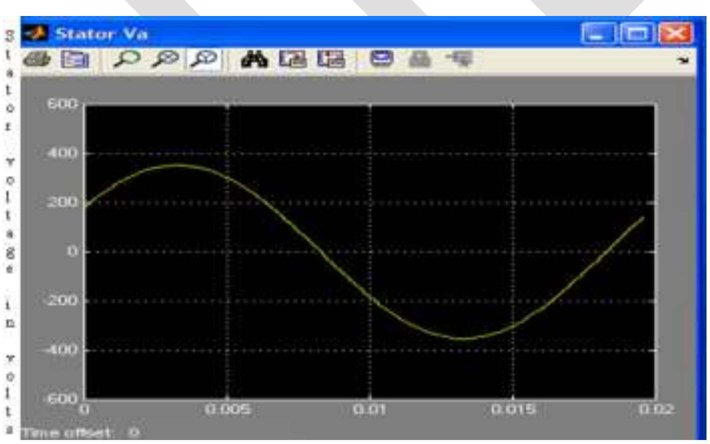
Fig. 5.5e Wave form between rotor current wrt time

Fig. 6.1a to Fig. 6.5e shows the performance of DFIG. Fig. 6.1a shows the stator current waves. Fig. 6.2b shows the stator voltage waves. Fig. 6.3c shows the grid current waves. Fig. 6.4d shows the grid voltage waves. Fig. 6.5e shows the rotor current waves. For the constant speed the mechanical torque T_m is given by the constant at the input of the asynchronous induction generator. The constant value is -1. The stator current is 10 Amp, stator voltage is 375Volts, grid current is 12.8 Amp, grid voltage is 350 Volts and rotor current is 7.5Amp.



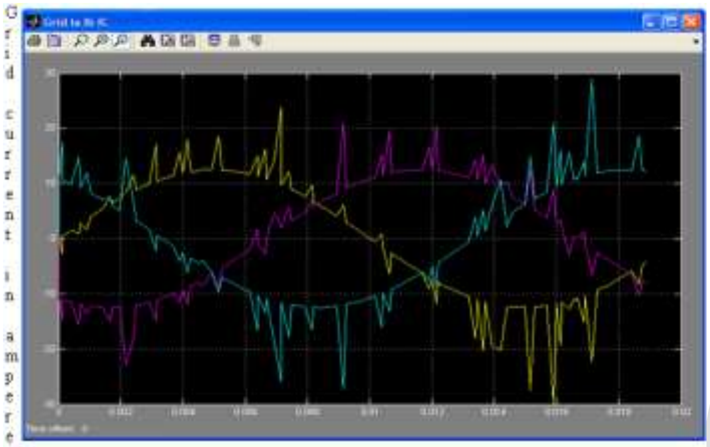
Time in sec

Fig. 6.1a Wave form between stator current wrt time



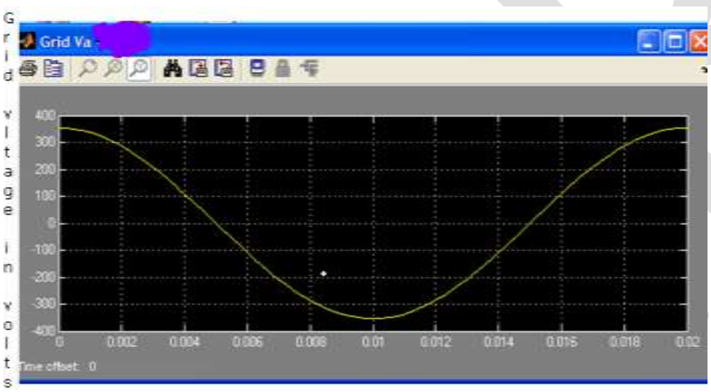
Time in sec

Fig. 6.2bWave form between stator voltage wrt time



Time in sec

Fig. 6.3c Wave form between grid current wrt time



Time in sec

Fig. 6.4d Wave form between grid voltage wrt time

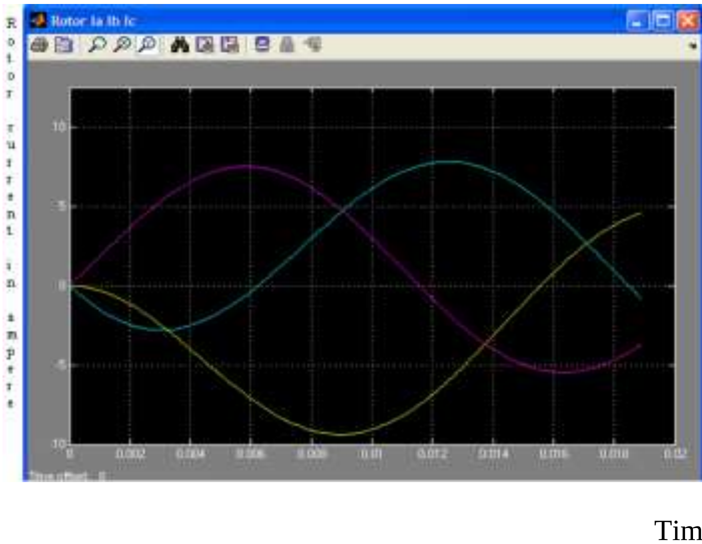


Fig. 6.5e Wave form between rotor current wrt time

In the DFIG system for constant speed and variable speed, the result shows the injection of current harmonics in the grid current but the stator voltage, stator current, grid voltage and the rotor current are all sinusoidal with respect to time. With the use of filter circuit in the DFIG system the current harmonics can be reduced.

CONCLUSION

Mathematical modelling of wind turbine, doubly fed induction generator and controller system is done. In order to find out their performance in DFIG system they are simulated using MATLAB. The simulation results of the system are show that it can operate at variable speed. As the wind speed changes from time to time due to change in temperature and pressure. It rotates the rotor blade of the wind turbine at variable speed. So the wind power can be utilize at variable speed. By the application of power electronics in the DFIG system, this can supply power at constant voltage and constant frequency. While the rotor speeds varies due to variation in the wind speed. This makes it suitable for variable speed wind energy application and hence this is useful in the maximum power tracking. The use of back-to-back PWM converter in the rotor circuit of DFIG allows the bidirectional power flow between the stator and the rotor. This have the advantage of reactive power control and low distortion currents operating at sub and super synchronous speed. The drawback of the DFIG models is that they inject current harmonics in the grid current. However they can be reduced by the implementation of the filter circuit. So further researches are going on to reduce the harmonics by improved PWM schemes and filters. Utilization of wind energy from the offshore wind farms by the selection of reliable, maintenance fee and robust generators.

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APPENDIX

Parameters of the DFIG model

Asynchronous (wound rotor) induction generator
Power P 215Hp(160KW) Voltage
V 400V
Frequency f 50Hz
Speed N 1487RPM Stator resistance R_s 0.01379Ω
Rotor resistance R_s 0.007728Ω
Stator self-inductance L_s
0.04755H Stator self-inductance L_s
Rotor self-inductance L_r 0.04775H
Mutual inductance L_m 2.416
H