

Dynamic Modeling and Analysis of Wind Turbine Driven Doubly Fed Induction Generator

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Abstract— The doubly-fed induction machine used as a wind turbine generator has recently received a great attention from the industrial and scientific communities. The reason is twofold: first, this machine easily produces a fixed frequency voltage from the stator windings when the rotor is driven at variable speed; second, the excitation power electronics converter feeding the rotor windings needs to be rated at a fraction of the nominal power of the generator. Consequently, this machine is often the natural choice for electricity generation from renewable energy sources. The aim of the paper is to develop and discuss a dynamic model of the doubly fed induction generator used in wind turbines for various operating conditions. Power electronic converters are used to achieve the three phase constant output voltage with constant frequency irrespective of load conditions.

Index Terms— Modeling, Wind power generation, wound rotor induction machine, wind turbine

I. NOMENCLATURE

V_{qs}	q-axis stator voltage, V
V_{ds}	d-axis rotor voltage, V
V_{qr}	q-axis rotor voltage, V
V_{dr}	q-axis rotor voltage, V
I_{qs}	q-axis stator current, A
I_{ds}	d-axis rotor current, A
I_{qr}	q-axis rotor current, A
I_{dr}	q-axis rotor current, A
λ_{ds}	d-axis stator flux linkage, Wb/m ²
λ_{qs}	q-axis stator flux linkage, Wb/m ²
λ_{qr}	q-axis rotor flux linkage, Wb/m ²
λ_{dr}	d-axis rotor flux linkage, Wb/m ²
R_s	stator resistance, Ω
R_r	rotor resistance, Ω
ω_s	angular speed of the synchronously rotating reference frame, rad/s
ω_r	Rotational speed of rotor, rad/s
s	Rotor slip

II. INTRODUCTION

Due to the energy crisis, alternative renewable resources have assumed increased importance leading to relevant technological efforts. Wind energy has been identified as an affordable promising resource for such exploitation. The wind energy conversion system safely and efficiently turns wind into electrical energy. It is predicted that nearly 10 % of the world energy needs could be met by the wind energy by the year 2020.

In India, the estimated wind energy potential is about 45,000 MW. The country currently ranks fourth in the global wind energy installation list with about 6018 MW installed capacity, a figure placing it right behind

Germany, Denmark and United states. As per the current projections, the country will require an additional 1,50,000 MW of installed power generation capacity by 2012 which would entail an annual addition of about 10,000 MW every year. The introduction of the Public Utilities Regulatory Act (PURPA) of 1978 in the USA and later on the Energy Act of 1983 in the UK and similar Acts in other countries paved the way for integrating embedded generation including the wind power with the utility network [13]. For low and medium power generation, induction generators are preferred as they have certain inherent advantages in the aspects of unit cost, maintenance, ruggedness and asynchronous operation.

Wind turbines (WTs) can either operate at fixed speed or variable speed. For a fixed speed wind turbine the generator is directly connected to the electrical grid or load. For a variable speed wind turbine, the generator is controlled by power electronics equipment.

There are several reasons for using variable-speed operation of wind turbines; among those are possibilities to reduce stresses of the mechanical structure, acoustic noise reduction and the possibility to control active and reactive power. Most of the major wind turbine manufactures are developing new larger wind turbines in the 3MW-5MW range. These large wind turbines are all based on variable-speed operation with pitch control using a direct driven synchronous generator (without gearbox) or a doubly-fed induction generator (DFIG). Fixed-speed induction generators with stall control are regarded as unfeasible for these large wind turbines [13].

The major advantage of the doubly-fed induction generator, which has made it popular, is that the power electronic equipment only has to handle a fraction (20–30%) of the total system power. This means that the losses in the power electronic equipment can be reduced in comparison to power electronic equipment that has to handle the total system power as for a direct-driven synchronous generator, apart from the cost saving of using a smaller converter.

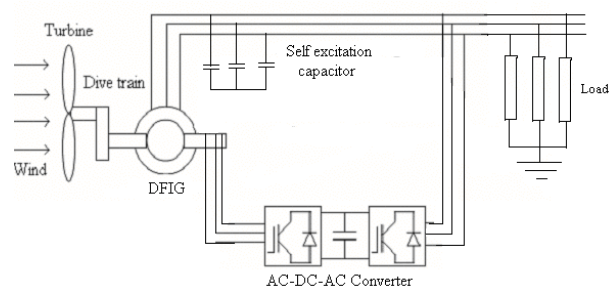


Fig. 1. Block Schematic of Wind Turbine Driven Self-Excited DFIG

For fixed speed wind turbines, the generator is directly connected to the load or grid. Since the speed is almost fixed to the grid frequency and most certainly not controllable, it is not possible to store the turbulence of the wind in form of rotational energy. Therefore, for a fixed speed system the turbulence of the wind will result in power variations and thus affect the power quality of the grid. For a variable speed wind turbine the generator is controlled by power electronics equipments, which make it possible to control the rotor speed. In this way the power fluctuations caused by wind variations can be more or less absorbed by changing the rotor speed and thus power variations originating from the wind conversion and the drive [11].

The rotational speed of a wind turbine is fairly low and must therefore be adjusted to the electrical frequency. This can be done in two ways: with a gear box or with number of pole pairs of the generator. The number of pole pairs sets the mechanical speed of the generator with respect to the electrical frequency and the gear box adjusts the rotor speed of the turbine to the mechanical speed of the generator [1].

Variable-speed turbines have many advantages in comparison with constant-speed turbines. Variable speed improves the dynamic behaviour of the turbine, alleviating the stresses on the mechanical construction, increases the power production and reduces the noise at low wind speed. In addition, by using a voltage source converter for the variable-speed system, grid currents can be controlled to be sinusoidal without low-frequency harmonics and the reactive power can be chosen freely.

The ac-dc-ac converter is divided in to two components, the rotor side converter and the grid side converter. Both are voltage source converters. The capacitor connected on the dc side act as the dc voltage source. The rotor winding is connected to the rotor side converter by using slip rings. The rotor side converter and the grid side converter have the capability for generating or absorbing reactive power and could be used to control the reactive power or the voltage at the grid terminals. Rotor side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The grid side converter is used to regulate the voltage of the dc bus capacitor [11].

A typical scheme of a DFIG equipped wind turbine is shown in Fig 1. Two voltage fed PWM converters are inserted back-to-back in the rotor circuit, which connect the slip ring terminals to the ac supply network. By proper switching of the Insulated Gate Bipolar Transistors in both converters, the power flow between the rotor circuit and the supply can be controlled both in magnitude and in direction. This is effectively the same as connecting a controllable voltage source to the rotor circuit [10].

I. WIND TURBINE MODEL

The basic wind energy conversion device is the wind turbine. A wind turbine is a machine used for converting the kinetic energy into the mechanical energy. Most of the wind turbine generators use horizontal axis wind turbine due to the advantage of ease in design and cheaper in cost for higher power ratings. Wind turbines of 250 kW to 2 MW systems are being manufactured in India for power generation. The gear box connects the low speed shaft to high speed shaft and increase the rotational speed from

about 30 to 60 rpm to about 1200 to 1500 rpm. Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the wind turbine. For steady-state calculations of the mechanical power from a wind turbine, the so called $C_p V_s (\lambda, \beta)$ curve can be used. The typical approximate output characteristic of the wind turbine is give by [9] [10].

$$P_w = 0.5 C_p \rho A V_w^3 \tag{1}$$

Where ρ (kg/m³) is the air density and A (m²) is the area swept out by the turbine blades and V_w (m/s) is the wind velocity. C_p is the power coefficient of the turbine which highly depends on the rotational speed, the wind velocity and constructional characteristics of the turbine. The Matlab/Simulink Model of wind turbine is shown in fig 2.

$$\lambda = \frac{\omega_t * R}{V_w} \tag{2}$$

$$C_p(\lambda) = \left(\frac{116}{\lambda^1} - (0.4\beta) - 5 \right) 0.5 e^{-\frac{16.5}{\lambda^1}} \tag{3}$$

(3)

where

$$\lambda^1 = \frac{1}{\left(\frac{1}{(\lambda + 0.089\beta)} - \frac{0.035}{\beta^3 + 1} \right)} \tag{4}$$

(4)

R is the radius (m) of the wind turbine rotor, ω_t (rad/sec) is the angular speed and β (deg) is the blade pitch angle. Based on the theory of fluid mechanics, it can be shown that C_p reaches the maximum value of 0.593, referred to as the Betz limit. This limit defines the maximum energy that can be extracted from wind. However C_p for practical turbines is in the order of 0.3. The blade pitch angle can be adjusted to achieve the rated power at rated operating condition [2].

The rotor speeds vary with the wind speed for a variable-speed wind turbine. The rotor speed in the variable-speed area is controlled in order to keep the optimal tip speed ratio, λ i.e., C_p is kept at maximum as long as the power or rotor speed is below its rated values. The pitch angle at higher wind speeds is controlled in order to limit the input power to the wind turbine, when the turbine has reached the rated power [7]. The typical power curves are illustrated in figures 3 & 4.

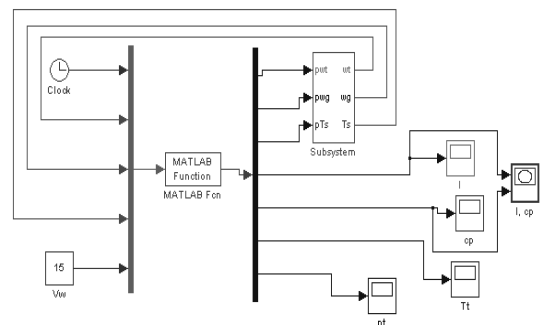


Fig. 2. Matlab/Simulink model of wind turbine

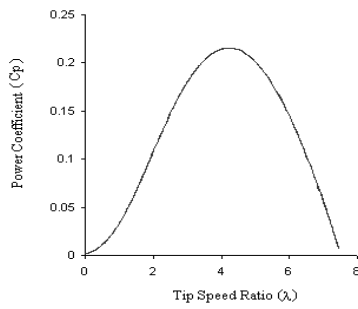


Fig. 3. Tip Speed Ratio versus Power Co-efficient

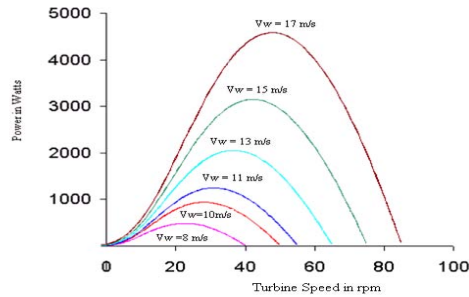


Fig. 4. Typical Power Speed curves for 2 kW Wind Turbine

II. DOUBLY FED INDUCTION GENERATOR MODEL

Fig. 5 shows the d-q axis equivalent circuit model for a no-load, three phase symmetrical induction machine. The per-unit stator and rotor voltage equation using Krause transformation based on stationary reference frame are given as follows: [6] [4].

$$\begin{aligned} V_{qs} &= -R_s I_{qs} + \omega_s \lambda_{ds} + p \lambda_{qs} \\ V_{ds} &= -R_s I_{ds} - \omega_s \lambda_{qs} + p \lambda_{ds} \\ V_{qr} &= -R_r I_{qr} + s \omega_s \lambda_{dr} + p \lambda_{qr} \\ V_{dr} &= -R_r I_{dr} - s \omega_s \lambda_{qr} + p \lambda_{dr} \end{aligned} \tag{5}$$

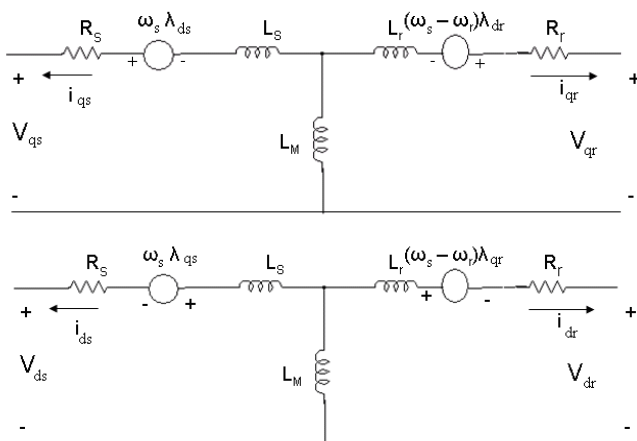


Fig. 5. d-q Equivalent Circuit of DFIG

$$s = \frac{\omega_s - \omega_r}{\omega_s} \tag{6}$$

$$s \omega_s = (\omega_s - \omega_r) \tag{7}$$

The stator and rotor flux linkages are given by

$$\begin{aligned} \lambda_{qs} &= -(L_s + L_m) I_{qs} - L_m I_{qr} \\ \lambda_{ds} &= -(L_s + L_m) I_{ds} - L_m I_{dr} \\ \lambda_{qr} &= -(L_r + L_m) I_{qr} - L_m I_{qs} \\ \lambda_{dr} &= -(L_r + L_m) I_{dr} - L_m I_{ds} \end{aligned} \tag{8}$$

where

$$\begin{aligned} L_{ss} &= L_s + L_m \\ L_{rr} &= L_r + L_m \end{aligned} \tag{9}$$

The induction generator model in the stator reference frames can be written in the following form: [12]

$$[L_1(X) * [pI]] = -\{[R] * [I] + \omega_r * [G_2(X) * [I] + [V] \} \tag{10}$$

where

$$L_1(X) = \begin{bmatrix} (L_{ss} + ab^2) & abc & (M + ab^2) & abc \\ abc & (L_{rr} + ac^2) & abc & (L_{rr} + ac^2) \\ (M + ab^2) & abc & (L_{rr} + ab^2) & abc \\ abc & (M + ac^2) & abc & (L_{rr} + ac^2) \end{bmatrix} \tag{11}$$

$$\begin{aligned} [pI] &= [pI_{qs} \quad pI_{ds} \quad pI_{qr} \quad pI_{dr}]^T \\ [I] &= [I_{qs} \quad I_{ds} \quad I_{qr} \quad I_{dr}]^T \\ [V] &= [V_{qs} \quad V_{ds} \quad V_{qr} \quad V_{dr}]^T \end{aligned} \tag{12}$$

Where

$$G_2(X) = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & -M & 0 & L_{rr} \\ M & 0 & L_{rr} & 0 \end{bmatrix} \quad [R] = \begin{bmatrix} R_s & 0 & 0 & 0 \\ 0 & R_s & 0 & 0 \\ 0 & 0 & R_r & 0 \\ 0 & 0 & 0 & R_r \end{bmatrix} \tag{13}$$

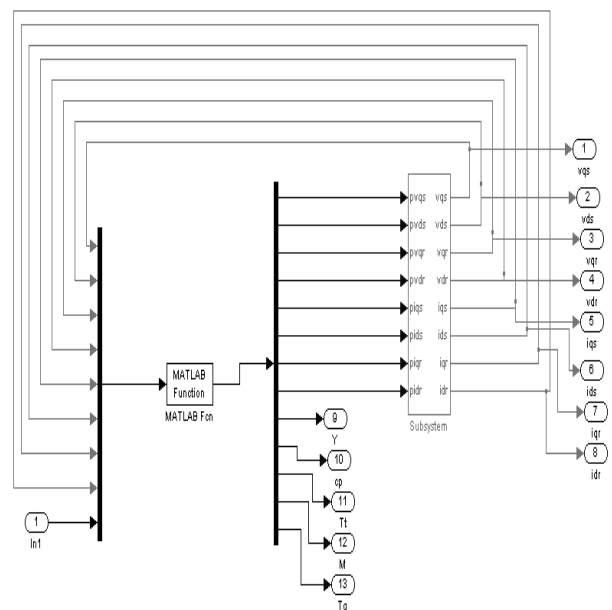


Fig. 6. Matlab/Simulink Model of double output induction generator

III. MODELING OF POWER ELECTRONICS INTERFACE

Two voltage fed PWM converters are inserted back to back in the rotor circuit, which connect the slip ring terminals to the ac supply network. By adjust the pulse width of reference signal, the power flow between the rotor circuit and the supply can be controlled both in magnitude and in direction.

Each phase has two switching functions SF_{1_a} & SF_{2_a} , SF_{1_b} & SF_{2_b} , SF_{1_c} & SF_{2_c} . Using the switching function $SF_{1_a,b,c}$ the V_{ao} , V_{bo} and V_{co} can be obtained as given by the equations (14).

$$V_{ao} = \frac{V_d}{2} \cdot SF_{1_a} = \frac{V_d}{2} \cdot \sum_{n=1}^{\infty} A_n \sin(n\omega t)$$

$$V_{bo} = \frac{V_d}{2} \cdot SF_{1_a} = \frac{V_d}{2} \cdot \sum_{n=1}^{\infty} A_n \sin n(\omega t - 120)$$

$$V_{co} = \frac{V_d}{2} \cdot SF_{1_a} = \frac{V_d}{2} \cdot \sum_{n=1}^{\infty} A_n \sin n(\omega t + 120)$$

(14)

The inverter line to line voltages can be derived as follows:

$$V_{ab} = V_{ao} - V_{bo} = \frac{\sqrt{3}}{2} V_d \cdot \sum_{n=1}^{\infty} A_n \sin n(\omega t + 30)$$

$$V_{bc} = V_{bo} - V_{co} = \frac{\sqrt{3}}{2} V_d \cdot \sum_{n=1}^{\infty} A_n \sin n(\omega t - 90)$$

$$V_{ca} = V_{co} - V_{ao} = \frac{\sqrt{3}}{2} V_d \cdot \sum_{n=1}^{\infty} A_n \sin n(\omega t + 150)$$

(15)

Also, in order to calculate the inverter phase voltage (V_{an} , V_{bn} , V_{cn}), V_{no} is calculated as

$$V_{no} = \frac{1}{3} (V_{ao} + V_{bo} + V_{co})$$

(16)

The phase voltages are obtained as

$$V_{an} = V_{ao} - V_{no}$$

$$V_{bn} = V_{bo} - V_{no}$$

$$V_{cn} = V_{co} - V_{no}$$

(17)

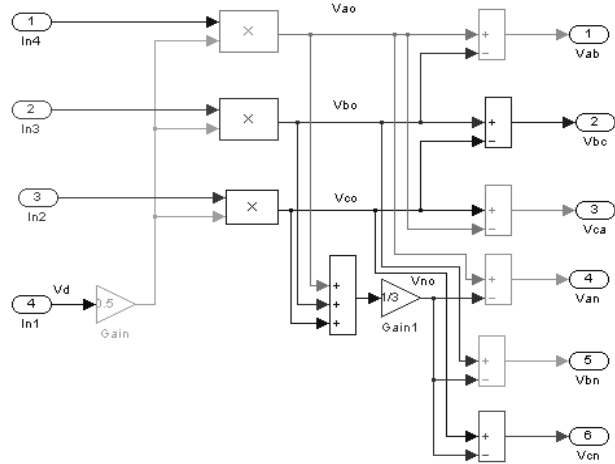


Fig. 7. Matlab/Simulink Model of Inverter

Figure 7 shows the Matlab/Simulink model for SPWM inverter. In this Pulse Width Modulation technique pulses are generated by comparing the sinusoidal reference voltage with the triangular carrier voltage. The ratio of A_r to A_c is the control variable and defined as the amplitude modulation index (M). The output voltage can be varied by varying the modulation index and range from 0 to 1 [8]. The entire model of wind turbine driven double output induction generator along with the network components is shown in fig 8.

IV. RESULTS AND DISCUSSION

The modeling of wind driven DFIG along with power electronics interface feeding an isolated load is done and performance is analysed under various operating conditions. The simulation results are shown in figures 9-16. It is observed from the simulation results that the output voltage vary both in magnitude and frequency when there is change in wind velocity or load. For voltage sensitive loads, the voltage should be regulated irrespective of the operating conditions. Hence a controller for SPWM inverter is to be designed. To overcome this drawback the variable magnitude, variable frequency voltage at the generator terminal is rectified and the DC power is transferred to the load through PWM inverter. To track and extract maximum power from the wind energy system and transfer this power to the isolated load, a digital controller which regulates the modulation index of the PWM inverter based on the input signals may be designed.

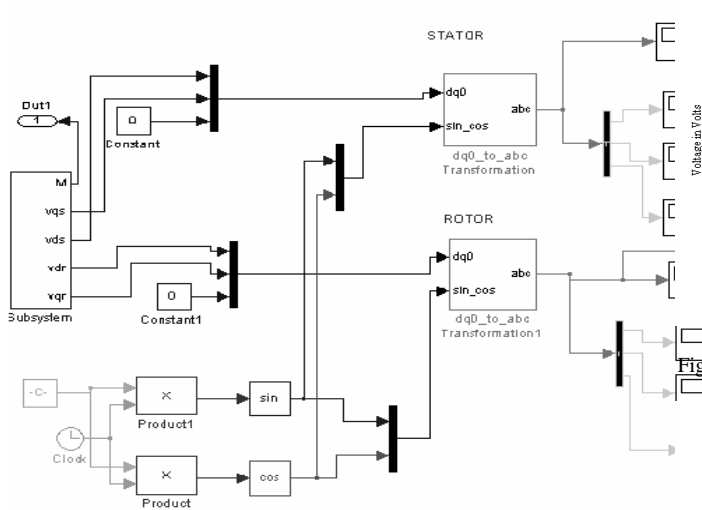


Fig. 8. Matlab/Simulink Model of DFIG Coupled with Rectifier and Inverter

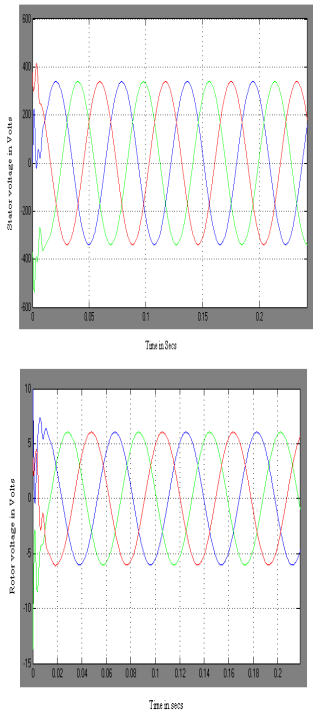


Fig. 9 Stator Voltages (V) Vs Time (s) Fig. 10. Rotor Voltages (V) Vs Time (s)

Table 1 Value of wind velocity and load used for simulation

Time in seconds (s)	Wind Velocity in m/s	Load in p.u
0-100	15	0.72
100-200	10	0.72
200-300	15	0.5
300-400	10	0.5
400-500	15	0.4

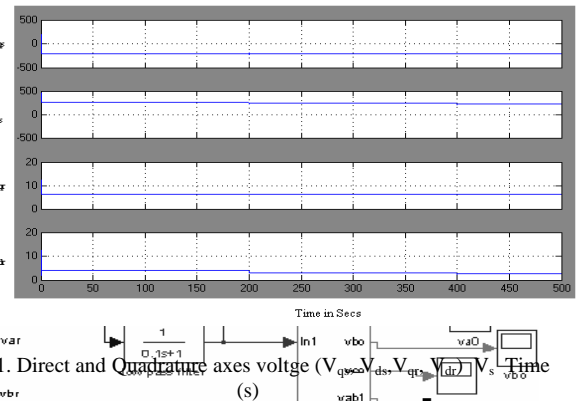


Fig. 11. Direct and Quadrature axes voltage (V_{qds} , V_{qdr} , V_{dqs} , V_{ddr}) Vs Time (s)

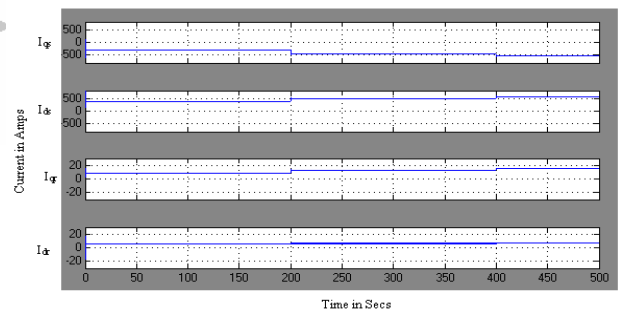


Fig. 12. Direct and Quadrature axes current V_s Time (s)

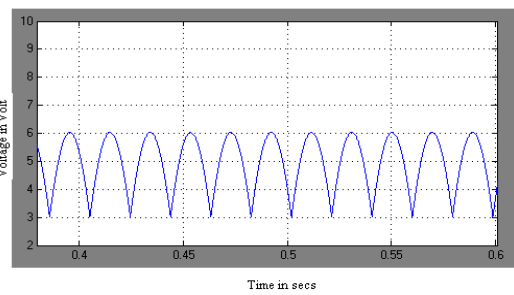


Fig. 13. Rectifier output voltage (v) Vs Time (s)

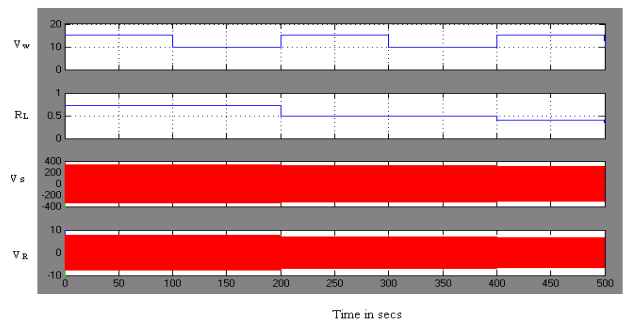


Fig. 14. Stator & Rotor Voltages for Step Change in Wind Velocity and Load

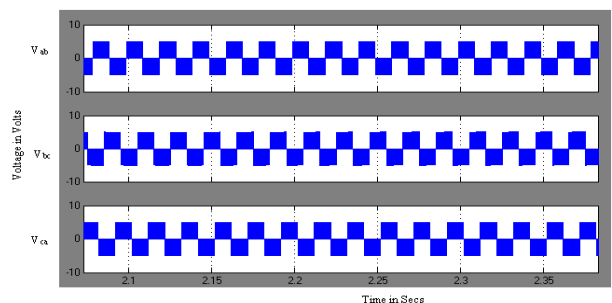


Fig. 15. Line voltage waveform of Inverter

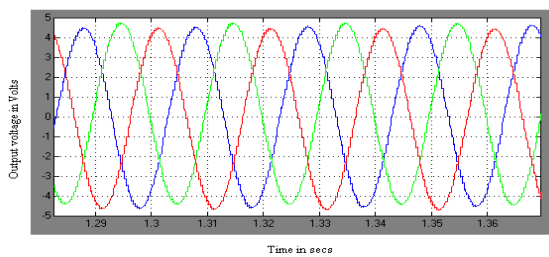


Fig. 16. Sinusoidal Output voltage waveform from SPWM inverter

V. CONCLUSION

In this paper, the dynamic model of wind turbine driven double output induction generator simulated using Matlab/Simulink is obtained and the simulation results for various loads and wind velocities are analysed. Also a model of rectifier and inverter set coupled through the dc link are simulated and the results are obtained. The present work has the scope of application in the wind farms where power utilization under various operating conditions is of most importance and where the power is fed to the grid. The analysis of wind energy conversion system is done under open loop condition. The work can be further extended to the closed loop model of wind energy conversion system either connected to grid or to the local load. With help of analysis made in the closed loop condition, a controller may be designed in order to maintain the terminal voltage and frequency of the induction generator constant irrespective of the variation in operating conditions.

VI. REFERENCES

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