Modeling and Simulation of Doubly Fed Induction Generator Driven by Wind Turbine

Pooja A. Patel[1] Sweta Chauhan[2]
[1]Student [2]Asst. Professor
[1, 2]Electrical Engineering Department
[1, 2]PIET, Vadodara, India

Abstract---Environmental pollution and shortage of conventional fossil fuel are the two major concerns which have led to the global emergence of wind energy as an effective means of power production. The evolution of technology related to wind systems industry leaded to the development of a generation of variable speed wind turbines that present many advantages compared to the fixed speed wind turbines. These wind energy conversion systems are connected to the grid through Voltage Source Converters (VSC) to make variable speed operation possible. The studied system here is a variable speed wind generation system based on Doubly Fed Induction Generator (DFIG). This paper deals with mathematical modelling of doubly fed induction generator driven by wind turbine. The modelling procedure is briefly explained, mathematical descriptions and Simulink models of the wind power plant basic parts are shown and the model of the whole system is presented.

Keywords: Voltage source converter (VSC), Doubly fed induction generator (DFIG)

I. INTRODUCTION

A. *Introduction of dfig*

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 50 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. Back-to-back converter consists of rotor side converter (RSC) and grid side converter (GSC). The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind. The optimum turbine speed producing maximum mechanical energy for a given wind speed is proportional to the wind speed.

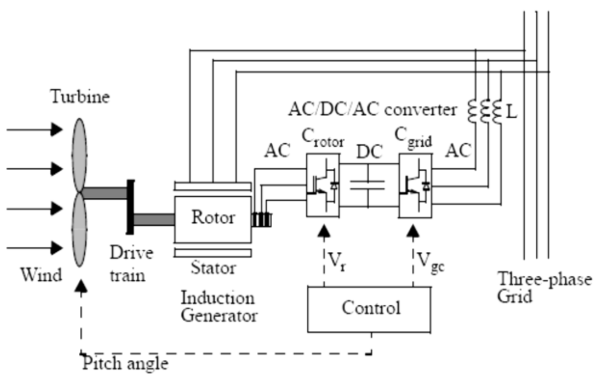

Fig. 1: Basic diagram of doubly fed induction generator with converters

Another advantage of the DFIG technology is the ability for power electronic converters to generate or absorb reactive power, thus eliminating the need for installing capacitor banks as in the case of squirrel-cage induction generator.

Where V_r is the rotor voltage and V_{gc} is grid side voltage. The AC/DC/AC converter is basically a PWM converter which uses sinusoidal PWM technique to reduce the harmonics present in the wind turbine driven DFIG system. Here C_{rotor} is rotor side converter and C_{grid} is grid side converter. To control the speed of wind turbine gear boxes or electronic control can be used.

B. *Operating principle of DFIG*

The stator is directly connected to the AC mains, whilst the wound rotor is fed from the Power Electronics Converter via slip rings to allow DIFG to operate at a variety of speeds in response to changing wind speed. Indeed, the basic concept is to interpose a frequency converter between the variable frequency induction generator and fixed frequency grid. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation.

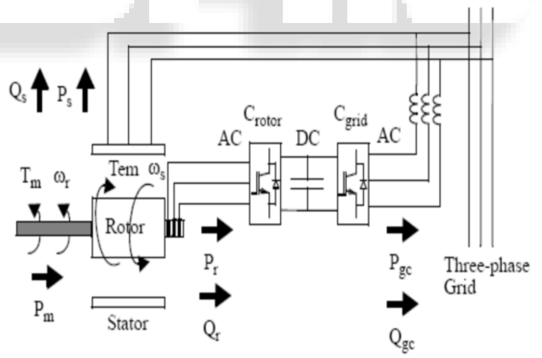

Fig. 2: Power flow diagram of DFIG

To achieve full control of grid current, the DC-link voltage must be boosted to a level higher than the amplitude of grid line-to-line voltage. The slip power can flow in both directions, i.e. to the rotor from the supply and from supply to the rotor and hence the speed of the machine can be controlled from either rotor- or stator-side converter in both super and sub-synchronous speed ranges. As a result, the machine can be controlled as a generator or a motor in both super and sub-synchronous operating modes realizing four operating modes. Below the synchronous speed in the motoring mode and above the synchronous speed in the generating mode, rotor-side converter operates as a rectifier and stator-side converter as an inverter, where slip power is returned to the stator. Below the synchronous speed in the generating mode and above the synchronous speed in the

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motoring mode, rotor-side converter operates as an inverter and stator side converter as a rectifier, where slip power is supplied to the rotor. At the synchronous speed, slip power is taken from supply to excite the rotor windings and in this case machine behaves as a synchronous machine.

II. WIND TURBINE AND DFIG MODEL

A. *Modeling of wind turbine*

The first part of the studied system is the wind turbine, which is used to conversion of wind kinetic energy to mechanical work. The kinetic energy produced by the wind linear speed v rotates the turbine with the speed ω_t which produces mechanical power P_m.

$$P_m = \frac{1}{2}\rho\pi R^2 C_p(\theta,\lambda)v^3 \qquad (2.1)$$

Where, ρ is the air density; Cp=f(θ, λ) is the efficiency coefficient and

$$\lambda = \frac{v}{\omega R} \qquad (2.2)$$

is the speed factor. For a known wind turbine, C_p can be determined by measurement but in some restrictive conditions can be approximated by exponential relations as follows:

$$C_p = c_1\left(\frac{c_2}{\lambda_t} - c_3\theta - c_4\right)e^{\frac{c_5}{\lambda_t}} + c_6\lambda \qquad (2.3)$$

$$\frac{1}{\lambda_t} = \frac{1}{\lambda^{-1} + g\theta} - \frac{h}{(l\theta)^3 + 1} \qquad (2.4)$$

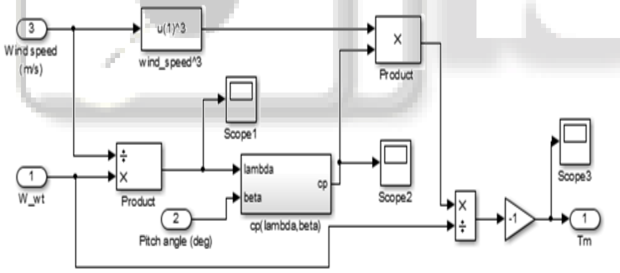

Fig. 3: Simulink model of wind turbine

B. *Modeling of drive train*

When studying the stability of DFIG wind turbine, the two-mass model of the drive train is important, as the wind turbine shaft is relatively softer than the typical steam turbine shaft in conventional power plants.

$$\frac{d\omega_r}{dt} = \frac{1}{2H_g}(T_{sh} - T_e - B\omega_r) \qquad (2.5)$$

$$\frac{d\theta_t}{dt} = \omega_b(\omega_t - \omega_r) \qquad (2.6)$$

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t}(T_m - T_{sh}) \qquad (2.7)$$

Where ω_b, ω_r, ω_t and are the base, generator, and wind turbine speeds, respectively. H_g and H_t [SI unit(s)] are the generator and turbine inertias, respectively. θ_t is the shaft twist angle. The electromagnetic torque T_e, the shaft torque T_{sh}, and the mechanical torque T_m , which are the power input of the wind turbine, are as follows:

$$T_e = L_m(i_{ds}i_{qr} - i_{qs}i_{dr}) \qquad (2.8)$$

$$T_{sh} = K_{sh}\theta_t + D_{sh}\omega_b(\omega_t - \omega_r) \qquad (2.9)$$

$$T_m = \frac{P_m}{\omega_t} \qquad (2.10)$$

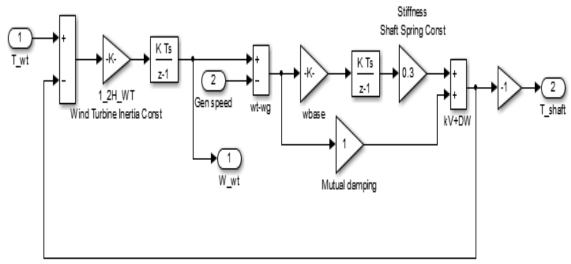

Fig. 4: Simulink model of drive train

C. *Modeling of induction generator*

The induction machine d-q or dynamic equivalent circuit is shown in Fig. 5.The modeling equations in flux linkage form are as follows:

$$\frac{d\psi_{qs}}{dt} = v_{qs} - R_s i_{qs}$$
(2.11)

$$\frac{d\psi_{ds}}{dt} = v_{ds} - R_r i_{ds} \qquad (2.12)$$

$$\frac{d\psi_{dr}}{dt} = -\omega_r\psi_{qr} - R_r i_{rd} \qquad (2.13)$$

$$\frac{d\psi_{qr}}{dt} = \omega_r\psi_{dr} - R_r i_{qr} \qquad (2.14)$$

$$i_{ds} = \left(\frac{1}{L_s - L_m^2 L_r}\right)\left(\psi_{ds} - \psi_{dr}\frac{L_m}{L_r}\right) \qquad (2.15)$$

$$i_{qs} = \left(\frac{1}{L_s - L_m^2 L_r}\right)\left(\psi_{qs} - \psi_{qr}\frac{L_m}{L_r}\right) \qquad (2.16)$$

$$i_{dr} = \left(\frac{1}{L_r - L_m^2 L_s}\right)\left(\psi_{dr} - \psi_{ds}\frac{L_m}{L_s}\right) \qquad (2.17)$$

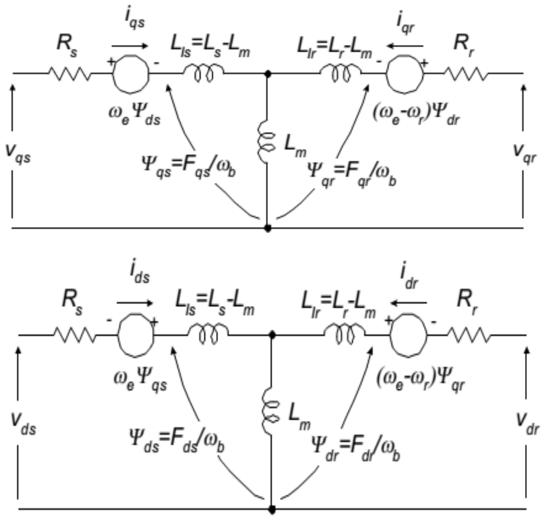

Fig. 5: Dynamic or d-q equivalent circuit of inductionmachine

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$$i_{qr} = \left(\frac{1}{L_r - L_m^2 L_s}\right)\left(\psi_{qr} - \psi_{qs}\frac{L_m}{L_s}\right) \quad (2.18)$$

$$T_e = \frac{3}{2}\left(\frac{p}{2}\right)\frac{1}{\omega_r}\left(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}\right) \quad (2.19)$$

$$T_e - T_M = J\left(\frac{2}{p}\right)\frac{d\omega_r}{dt} \quad (2.20)$$

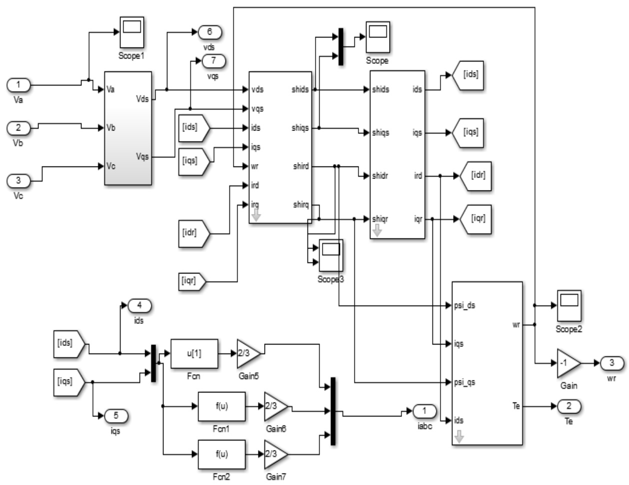

Fig. 6: Simulink model of induction generator

Where;
ψij: the flux linkage,
vqs, v_{ds}: q and d- axis stator voltages,
vqr, v_{dr}: q and d- axis rotor voltages,
Rr: rotor resistances,
Rs: stator resistances,
Ls: stator inductance,
Lr: rotor inductance,
Lm: mutual inductance,
iqs, i_{ds}: q and d- axis stator currents,
iqr, i_{dr}: q and d- axis rotor currents,
P: number of poles,
J: moment of inertia,
T_e: electrical output torque,
T_m: mechanical torque,
ωr: rotor angular speed.

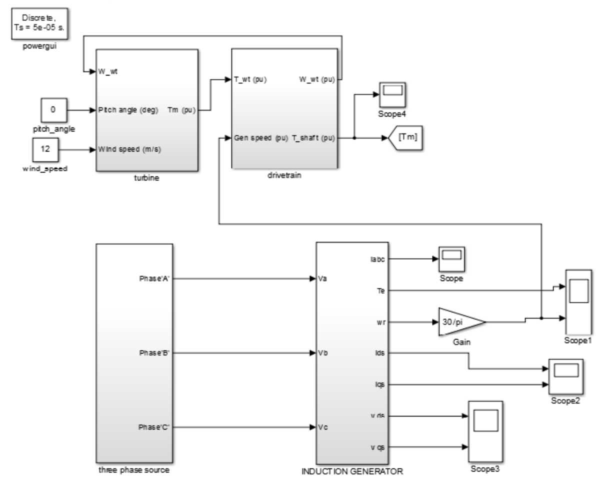

Fig. 7: Simulink model of induction generator with turbine and drive train

D. AC-DC-AC converters

For a variable-speed wind power system, the generator is connected to the grid through power electronic converters connected back-to-back. The converter is needed because the variable speed generator produces a variable frequency voltage that has to be converted to match the constant grid frequency.

The power converters are connected to the rotor in the DFIG configuration and need to carry only the slip power. The stator is directly connected to the grid while the rotor is connected to the grid through back to- back converters, rotor side and grid side converters.

Wind turbines use a doubly-fed induction generator (DFIG) consisting of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter.

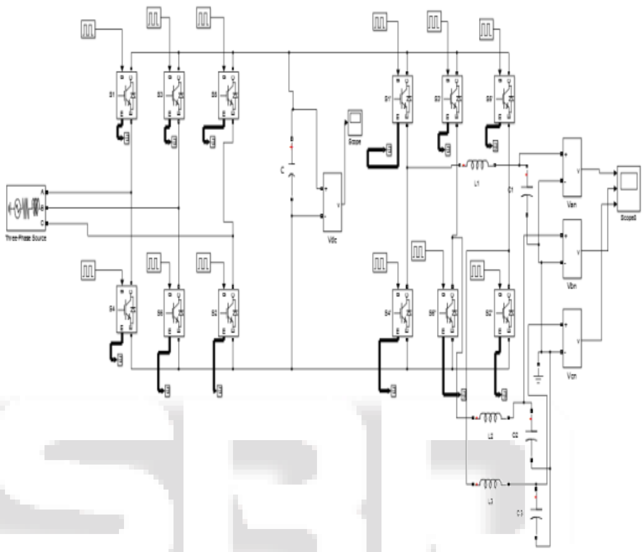

Fig. 8: Back-to-back PWM converter

Fig. 8 shows the three phase two level back-to-back PWM converter systems. This converter is connected to the induction generator.

III. SIMULATION RESULTS

The simulation results obtained are shown below. Fig. 9 shows three phase generator current. Fig. 10 shows electrical torque of induction generator which is linear after few seconds. Fig. 11 shows generator speed which is increases rapidly and after few seconds it attains constant value. Fig. 12 and Fig. 13 shows d-q axes current and voltage waveforms.

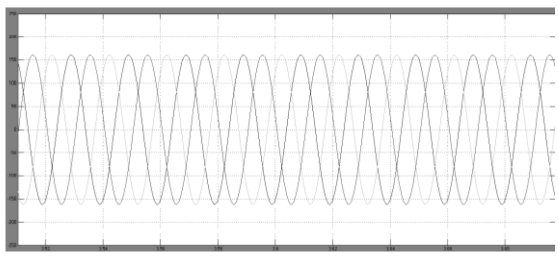

Fig. 9: Generator current (i_{abc})

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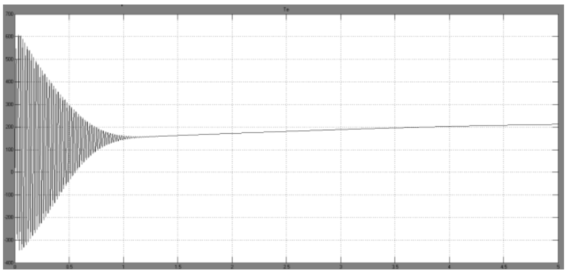

Fig. 10: Electrical torque (T_e)

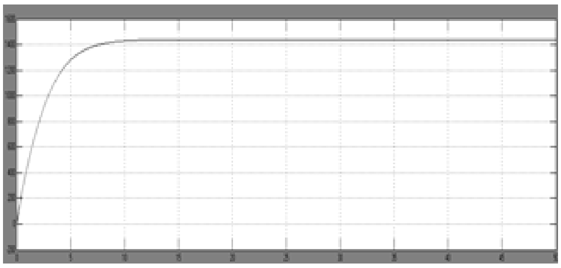

Fig. 11: Rotor speed (ω_r)

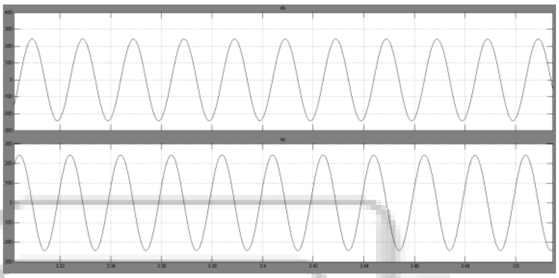

Fig. 12: d-q currents (i_d & i_q)

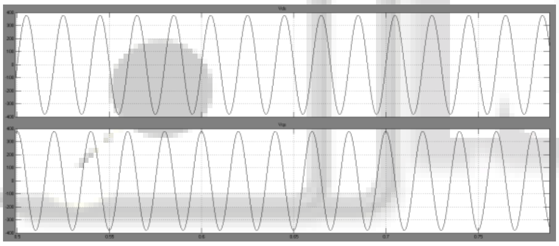

Fig. 13: d-q voltages (Vds & Vqs)

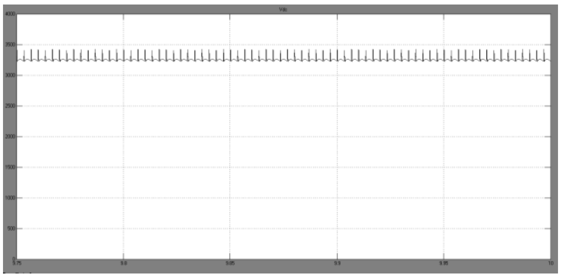

Fig. 14: DC link capacitor voltage

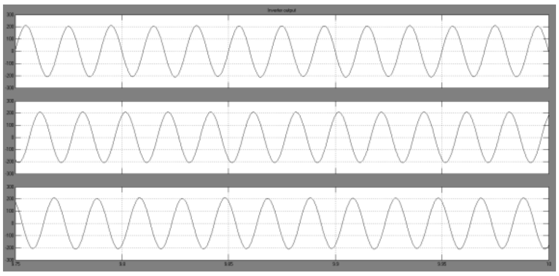

Fig. 15: Inverter output

Parameters	**Value**
Wind speed	12m/s
Stator resistance (R_s)	0.1589 Ω
Rotor resistance (R_r)	0.2447 Ω
Stator inductance (L_s)	62.6956e-3 H
Rotor inductance (L_r)	63.456e-3 H
Mutual inductance (L_m)	60.6639e-3 H
Moment of inertia (J)	2.018 kg.m^2
C_1	0.5176
C_2	116
C_3	0.4
C_4	5
C_5	21
C_6	0.0068

IV. CONCLUSION

In this paper wind turbine, drive train and induction generator with three phase back-to-back PWM converters is modelled. The next work of author is to design controller loops of rotor side converter and grid side converter.

V. ACKNOWLEDGMENT

Success of any work depends upon the dedication, sincerity and hard work. It also requires some ingredients such as motivation, guidance, encouragement and time.

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