

Simulation and Control of A Doubly Fed Induction Generator (DFIG) Using Artificial Neural Networks

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ABSTRACT

The paper describes the design of a doubly fed induction generator (DFIG), using back-to-back PWM voltage-source converters in the rotor circuit. A vector-control scheme for the supply-side PWM converter results in independent control of active and reactive power drawn from the supply. Slip ring induction machine in the variable speed wind turbine popularly known as double fed induction generator is mostly used in wind power generation. The main reasons for the popularity of the doubly fed wind induction generators connected to the power network is their ability to supply power at constant voltage and frequency while the rotor speed varies and motor converter handles fraction of stator power. The main goal of my project is to design doubly fed induction generator (DFIG) & to control the rotor and stator voltages by injecting the proper rotor voltage to the DFIG derived from PI and ANN controller so as to maintain the constant terminal voltage. The results also verify the simulation model can meet the requirement of the VSCF wind energy conversion system.

KEYWORDS - DFIG, Stationary Reference frame, Dynamic Model, Artificial Neural Networks.

I. INTRODUCTION:

Wind power is a clean, non-polluting and renewable energy. There are many advantages of wind power conversion system compared with the thermal power generation unit and nuclear power unit[1]. For example, wind power conversion system can reduce the emissions of CO₂ and other harmful gases. A 1-MW wind power generator reduces 2000 tons CO₂, 10 tons SO₂ and 6 tons of NO₂ emissions to the atmosphere each year [3]. Therefore, wind energy is always known as “blue sky anthracite”. Among the renewable energy conversion systems, wind power has the most commercial prospects. Especially in the last few years due to the rapid development of wind power industry, the world wind power capacity increased by a linear trend. The DFIG can achieve VSCF power generation and decoupled stator active and reactive power control due to its AC variable-frequency excitation power supply.

Moreover, the capacity of the excitation power supply is only 25%~30% of the whole power unit. This would save a large expense to a certain extent. Because of these advantages, DFIG is one of the main generators in the wind farms. The structure of the DFIG system is as shown in fig1[1]. The wind turbine is connected with the generator rotor by a gearbox. The stator of the generator could parallel with the electricity grid through a contractor.

Induction generator is coupled with a wind mill offers an ideal solution. Wind energy is available in abundance in our environment. When compared with the conventional sources of energy, wind energy is clean, efficient, and sustainable form of energy. When the cost of supplying electricity to remote locations is expensive, wind energy provides a cost effective alternative. So to convert this wind energy into electrical energy, an induction generator will offer an ideal solution.

II. WIND TURBINE WITH A DOUBLY FED INDUCTION GENERATOR:

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[3]. It is a 4-quadrant converter which can realize bidirectional flowing of energy. On the one hand, the rotor can absorb energy from power grid and on the other hand, it can feed the energy back to the power grid under certain conditions. 4-quadrant means the excitation power supply can operate on positive resistive, pure capacitive, negative resistive and pure inductive the four typical state.

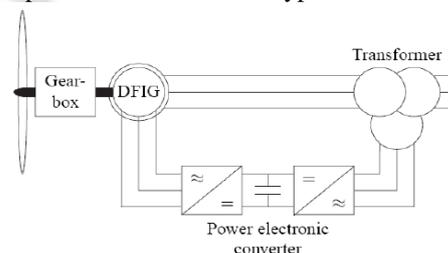


Fig 1. Wind turbine with a doubly-fed induction generator (DFIG)

2.1. Operation 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[4],[5]. The DC capacitor linking stator- and rotor-side converters allows the storage of power from induction generator for further generation. 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. 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. The mechanical power and the stator electric power output are computed as follows

$$P_r = T_m \cdot \omega_r \tag{1}$$

$$P_s = T_m \cdot \omega_s \tag{2}$$

For a loss less generator the mechanical equation is

$$J (d\omega_r/dt) = T_m - T_{em} \tag{3}$$

In steady-state at fixed speed for a loss less generator $T_m = T_{em}$ and $P_m = P_s + P_r$

And it follows that:

$$P_r = P_m - P_s = T_m \omega_r - T_m \omega_s = -S P_s$$

Where

$S = (\omega_s - \omega_r) / \omega_s$ is defines as the slip of the generator.

2.2. Back-to-Back AC/DC/AC Converter Modeling:

Mathematical modeling of converter system is realized by using various types of models, which can be broadly divided into two groups: mathematical functional models and Mathematical physical models (either equation-oriented or graphic-oriented, where graphic-oriented approach is actually based on the same differential equations)[6].

III. MATHEMATICAL REPRESENTATION OF DFIG:

Assuming that the three-phase power grid voltages are balance and the three-phase circuits are symmetrical, the sum of the three-phase currents in the three-phase non-median line system is zero.

An induction motor can be looked on as a transformer with a rotating secondary, where the coupling coefficients between the stator and rotor phases change continuously with the change of rotor position[7]. The machine model can be described by differential equations with time varying mutual inductances, but such a model tends to be very complex, such as vector control, based on the dynamic d-q model of the machine. Therefore to

understand vector control principle, a good understanding of d-q model is mandatory.

The transformation equation from a-b-c to this d-q-o reference frame is given by

$$f_{qdo} = K_s \cdot f_{abc} \tag{5}$$

where, $(f_{qd0s})^T = [f_{qs} \quad f_{ds} \quad f_{0s}]$,

$$(f_{abcs})^T = [f_{as} \quad f_{bs} \quad f_{cs}]$$

$$K_s = \frac{2}{3} \begin{bmatrix} \cos \theta & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin \theta & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

Where the variable f can be the phase voltages, current, or flux linkages of the machine. The transformation angle θ_r between the q- axis of the reference frame rotating at a speed of w and the a-axis of the stationary stator winding may be expressed as

$$\theta = \int_0^t \omega(t) dt + \theta(0) \tag{6}$$

3.1 Torque Equations:

The sum of the instantaneous input power to all six windings of the stator and rotor is given by:

$$P_{in} = V_{as} I_{as} + V_{bs} I_{bs} + V_{cs} I_{cs} + V_{ar} I_{ar} + V_{br} I_{br} + V_{cr} I_{cr} \tag{7}$$

Using stator and rotor voltages to substitute for the voltages on the right hand side of (4.8), we obtain three kindsof terms: i_r^2 , $id\psi/dt$ and $\omega\psi i$. (i_r^2) terms are the copper losses. The electromagnetic torque developed by the machine is given by the sum of the $(\omega.\psi i)$ terms divide by mechanical speed, that is:

$$T_{em} = (3/2) (p/2 \omega_r) [\omega(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) + (\omega_r - \omega)(\psi_{dr} i_{qr} - \psi_{qr} i_{dr})] \tag{8}$$

Using the flux linkage relationships, T_{em} can also be expressed as follows:

$$T_{em} = (3/2) (p/2 \omega_r) [\omega(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) + (\omega_r - \omega)(\psi_{dr} i_{qr} - \psi_{qr} i_{dr})] \tag{9}$$

Using the flux linkage relationships, one can show that

$$\begin{aligned} T_{em} &= (3/2) (p/2) [(\psi_{qr} i_{dr} - \psi_{dr} i_{qr}) \\ &= (3/2) (p/2) [(\psi_{ds} i_{qs} - \psi_{qs} i_{ds}) \\ &= (3/2) (p/2) L_m [(i_{dr} i_{qs} - i_{qr} i_{ds})] \end{aligned} \tag{10}$$

One can rearrange the torque equations by inserting the inserting the speed voltage terms given below:

$$E_{qs} = \omega\psi_{ds} \quad E_{ds} = -\omega\psi_{qs}$$

$$E_{qr} = (\omega_r - \omega)\psi_{dr} \quad E_{dr} = -(\omega_r - \omega)\psi_{qr}$$

3.1.1 Induction Machine Equations In Stationary Reference Frame:

Stator circuit equations:

$$V_{qs}^s = d/dt (\psi_{qs}^s) + r_s i_{qs}^s \tag{11}$$

$$V_{ds}^s = d/dt (\psi_{ds}^s) + r_s i_{ds}^s \quad (12)$$

Rotor circuit equations:

$$V_{qr}^s = d/dt (\psi_{qr}^s) + r_r i_{qr}^s \quad (13)$$

$$V_{dr}^s = d/dt (\psi_{dr}^s) + r_r i_{dr}^s \quad (14)$$

Flux linkage equations:

$$\begin{aligned} \psi_{qs}^s &= L_l i_{qs}^s + L_m (i_{qs}^s + i_{qr}^s) = (L_l + L_m) i_{qs}^s + L_m i_{qr}^s \\ \psi_{dr}^s &= L_l i_{dr}^s + L_m (i_{dr}^s + i_{qr}^s) = (L_l + L_m) i_{dr}^s + L_m i_{qr}^s \end{aligned} \quad (15)$$

$$\begin{aligned} \psi_{qr}^s &= L_l i_{qr}^s + L_m (i_{qs}^s + i_{qr}^s) = (L_l + L_m) i_{qr}^s + L_m i_{qs}^s \\ \psi_{ds}^s &= L_l i_{ds}^s + L_m (i_{ds}^s + i_{dr}^s) = (L_l + L_m) i_{ds}^s + L_m i_{dr}^s \end{aligned}$$

$$\begin{aligned} \psi_{dr}^s &= L_l i_{dr}^s + L_m (i_{ds}^s + i_{dr}^s) = (L_l + L_m) i_{dr}^s + L_m i_{ds}^s \\ \psi_{ds}^s &= L_l i_{ds}^s + L_m (i_{ds}^s + i_{dr}^s) = (L_l + L_m) i_{ds}^s + L_m i_{dr}^s \end{aligned}$$

3.1.2. d-q Torque Equations:

$$\begin{aligned} T_{em} &= (3/2) (p/2) [(\psi_{qr} i_{dr} - \psi_{dr} i_{qr})] \\ &= (3/2) (p/2) [(\psi_{ds} i_{qs} - \psi_{qs} i_{ds})] \\ &= (3/2) (p/2) L_m [(i_{dr} i_{qs} - i_{qr} i_{ds})] \quad (16) \end{aligned}$$

IV. SIMULINK IMPLEMENTATION OF DFIG:

Based on the control strategy discussed above, Fig.6 shows the rotor side converter control strategy with current regulated PWM. A current-regulated PWM voltage source inverter provides field oriented currents i_{qr} and i_{dr} to the rotor circuit, controlling active power and stator reactive power, respectively. Active power command is given by the turbine optimal torque speed profile and reactive power command is calculated to minimize the machine copper losses. Overall active power generated is directly related to the torque, as indicated by (7) and (8). In the d-q reference frame as determined by the machine stator flux, its currents i_{qr} and i_{dr} are also field oriented, controlling Active and Reactive power of grid (Ps and Qs) respectively.

Simulink is a software package for modeling, simulating, and analyzing dynamical systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a hybrid of the two. Systems can also be multirate, i.e., have different parts that are sampled or updated at different rates. This is a far cry from previous simulation packages that require you to formulate differential equations and difference equations in a language or program. Simulink includes a comprehensive block library of sinks, sources, linear and nonlinear components, and connectors. You can also customize and create your own blocks. For information on creating your own blocks, see the separate Writing S-Functions guide.

4.1. Simulink Implementation Of Mechanical System

The electromagnetic torque developed is $T_e = 2Hd/dt (\omega_m) + B_m \omega_m + T_l$ (17)

Where $T_e = T_g$ and $T_{shaft} = T_l$

By neglecting the torque due to friction ($B_m \omega_m$) $T_e - T_l = 2Hd/dt (\omega_m)$ (18)

From above equation, the rotor speed (ω_m) is $\omega_m = (T_e - T_l) / (2H) dt$

$$= (0.5/Hg) (T_e - T_l) dt \quad (19)$$

similarly the turbine speed is

$$\omega_t = (T_l - T_w) / (2Hw) dt = (0.5/Hw) (T_l - T_w) dt \quad (20)$$

from the above equations, we have

$$T_l = K_m (\theta_m - \theta_t) = K_m (\omega_m - \omega_t) dt$$

where $\theta = \omega dt$

In the doubly fed induction generator is runned at a specified speed with the stator disconnected from the grid. The rotor is suddenly excited with the slip frequency voltages derived from voltage regulator so as to produce commanded open circuit stator terminal voltage. The specified operating conditions and final values of the variables reached in the steady state are all saved in the workspace to serve as initial conditions in a subsequent simulation.

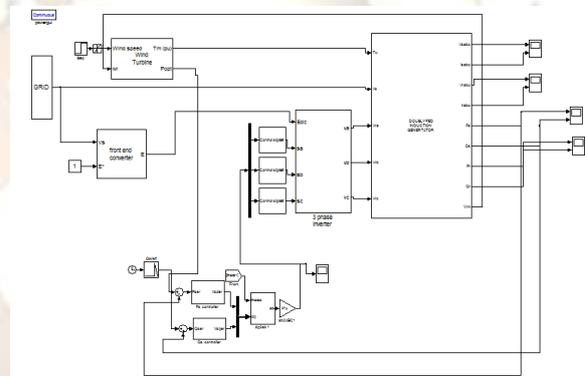


Fig.2: DFIG with PI CONTROLLER

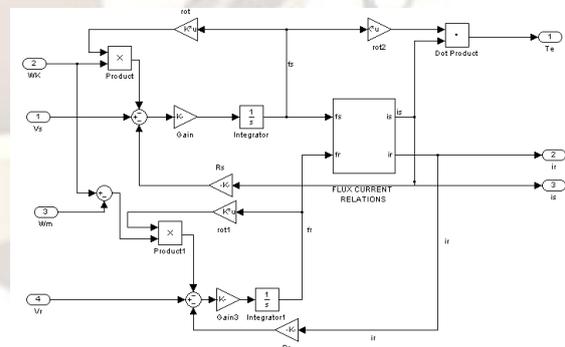


Fig.3: Dynamic Model of Induction Machine in Arbitrary Reference Frame

The rotor-side converter is used to control the wind turbine output power and the voltage measured at the grid terminals. The power is controlled in order to follow a pre-defined power-speed characteristic, named tracking characteristic. This characteristic is illustrated by the ABCD curve

superimposed to the mechanical power characteristics of the turbine obtained at different wind speeds.

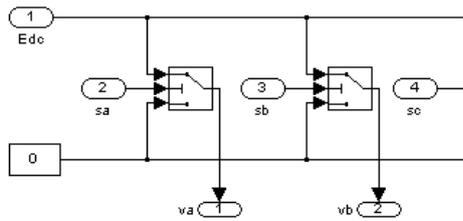


Fig.4: Simulink Diagram for Rotor Side Converter

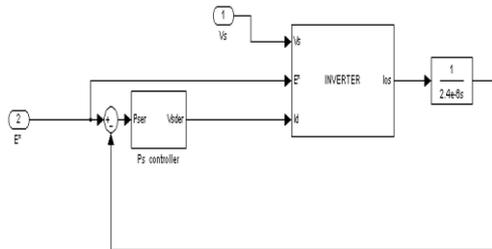


Fig.5: Simulink Diagram for Stator Side Converter

Artificial Neural Networks

Numerous advances have been made in developing intelligent systems, some inspired by biological neural networks. Researchers from many scientific disciplines are designing artificial neural networks to solve a variety of problems in pattern recognition, prediction, optimization, associative memory, and control. Conventional approaches have been proposed for solving these problems. Although successful applications can be found in certain well-constrained environments, none is flexible enough to perform well outside its domain[8]. ANNs provide exciting alternatives, and many applications could benefit from using them. This article is for those readers with little or no knowledge of ANNs to help them understand the other articles in this issue of Computer.



Fig. 6 Simple Artificial Neuron

The long course of evolution has given the human brain many desirable characteristics not present in von Neumann or modern parallel computers. These include massive parallelism, distributed representation and computation, learning ability, Generalization ability.

The above figure shows three phase open circuit voltages e_a , e_b , e_c which are displaced by 120 electrical degrees apart. Hence from this we can say that power is generated from doubly fed induction generator.

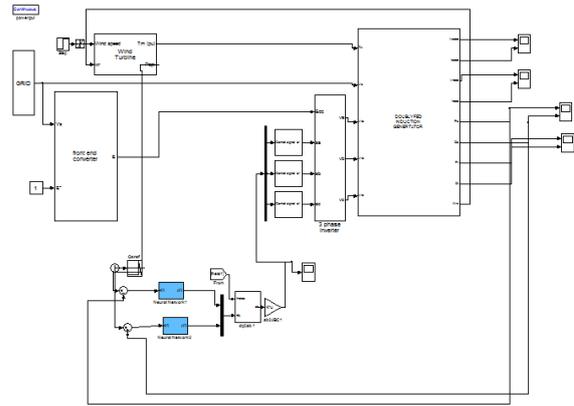


Fig.7 DFIG with ANN

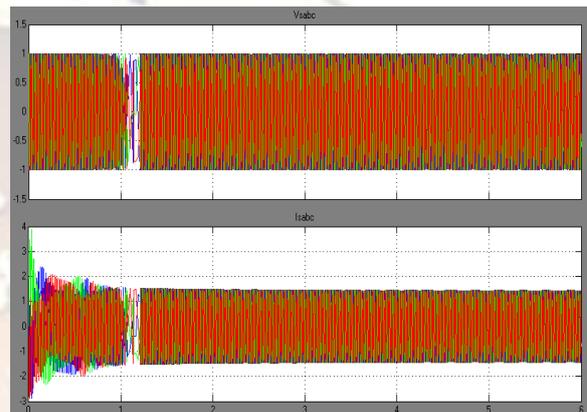


Fig.8: Stator Output Voltage and Current using PI controller

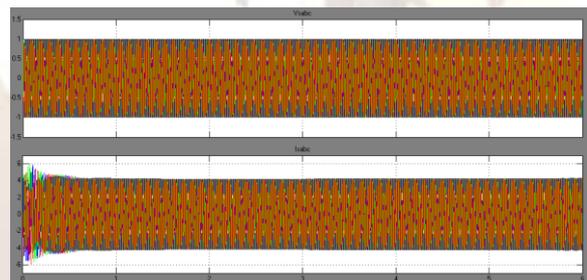


Fig.9: Stator Output Voltage and Current using Artificial Neural Networks

VII. CONCLUSIONS:

The modeling and simulation of a DFIG was carried out with vector control of the parameters in the stator voltage DQ reference frame. The DFIG was modeled in both Matlab software packages. The behavior of the models was examined by injecting rotor voltage at a constant torque. An attempt was also made to derive the existing controllers adopted in the rotor side converter to control the output Voltage and the current of the DFIG. The PI controller and ANN are used for grid control. As compared the response between two controllers ANN gives the better results.

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