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Performance of Double-Output Induction Generator for Wind Energy Conversion Systems

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Abstract

With growing concerns about environmental pollution and a possible energy shortage, great efforts have been taken by the governments around the world to implement renewable energy programs, based mainly on wind power, solar energy, small hydro-electric power, etc. With improving techniques, reducing costs and low environmental impact, wind energy seems certain to play a major part in the world's energy future. Due to its many advantages such as the improved power quality, high energy efficiency and controllability, etc., the variable speed wind turbine using a double-output induction generator (DOIG) is becoming a popular concept and thus the modeling of the DOIG based wind turbine becomes an interesting research topic. As the wind power penetration continually increases, power utilities concerns are shifting focus from the power quality issue to the stability problem caused by the wind power connection. In such cases, it becomes important to consider the wind power impact properly in the power system planning and operation. Unfortunately, few power system analysis tools have included wind turbine models such as have been developed for traditional Power generators. The paper develops analytical steady-state and Dynamic models to provide this insight and correlates the operating performance of DOIG for wind energy conversion systems using MATLAB-Simulink environment. This paper considers a grid-connected system; a further paper will describe a stand-alone system.

1. Introduction

With growing concerns about environmental pollution and a possible energy shortage, great efforts have been taken by the governments around the world to implement renewable energy programs, based mainly on wind power, solar energy, small hydro-electric power, etc. With improving techniques, reducing costs and low environmental impact, wind energy seems certain to play a major part in the world's energy future [1]-[3]. The use of wind power has been in existence for over 3000 years, especially in mechanical systems for water pumping and grain grinding. The utilization of wind power for electricity generation is not a new concept and this idea was first realized in 1891. Since then, step by step improvements were made in this technology, but it is not considered to be the consistent source for providing electric power. In 1970s, the researches on the wind power systems are encouraged by the oil price shock and the improvements of power electronics applications on power control [4]. Today, it is one of the rapidly growing technologies and markets. By the end of 2010[WWEA] the total installed capacity of wind energy is estimated to be more than 160 GW all around the world.

With increasing attention on renewable energy resources, Wind Energy Conversion Systems (WECS) are today's one of the most popular subject that the researches are intensively carried on. Many applications of wind power can be found in a wide power range from a few kilowatts to several megawatts in small scale off-grid standalone systems or large scale grid-connected wind farms. Nevertheless, this kind of power generation usually causes problems in the electrical system it is connected to, because of the lack or scarcity of control on the produced active and reactive power. This requires assessment of wind power potential and selection of appropriate wind energy conversion system. Several studies have been conducted world over on characterization of wind speed data and site matching of wind turbine generators [4]. It is also observed from literature that mathematical models of few individual components of WECS are represented and simulated for better understanding of their performances. Wind turbines often do not take part in voltage and frequency control and if a disturbance occurs, the wind turbines are

disconnected and reconnected when normal operation has been resumed, Thus, notwithstanding the presence of wind turbines, frequency and voltage are maintained by controlling the large power plants as would have been the case without any wind turbines present, This is possible,

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as long as wind power penetration is still low. However, a tendency to increase the amount of electricity generated from wind can be observed [5]. As the wind power penetration continually increases, power utilities concerns are shifting focus from the power quality issue to the stability problem caused by the wind power connection. In such cases, it becomes important to consider the wind power impact properly in the power system planning and operation. Unfortunately, few power system analysis tools have included wind turbine models such as have been developed for traditional Power generators. It is therefore important to study the behavior of wind turbines driven double-output induction generator (DOIG) in an electrical power system and their interaction with other generation equipment and with loads.

The paper develops analytical steady-state and Dynamic models to provide this insight and correlates the operating performance of DOIG for wind energy conversion systems using MATLAB-Simulink environment. The paper is organized as follows. First, the system to be modeled is described. Then, the equations describing the behaviour of the various subsystems are derived. Next, simulation results are discussed with operating performance. This paper considers a grid-connected system; a further paper will describe a stand-alone system.

2. Description of the system

There are two basic options of wind power conversion fixed speed and variable speed operation. In fixed operation, the aero turbine can be operated at a constant speed by blade-pitch control of the wind turbine even under varying wind speeds. This option was very common because of the cost involved with the power converter needed in the variable speed generation to convert the variable frequency to match the constant grid frequency. In variable speed operation, the aero turbine rotational speed can be allowed to vary with wind to maintain a constant and optimum tip speed ratio. The variable speed operation by active pitch control allows optimum efficiency operation of the turbine over a wide range of wind speeds, resulting in increasing power outputs [7].For variable speed generation, an induction generator is considered attractive due to its flexible rotor speed characteristics in contrast to the constant speed characteristics of synchronous generator. DFIG configuration is best suited for variable speed generation since it can be controlled from rotor side as well as stator side. This is possible since rotor circuit is capable of bidirectional power flow. The doubly-fed machine can be operated in generating mode in both sub-synchronous and super-synchronous modes[8].The rotor will observe slip power from the in sub-synchronous operation and can feed slip power back to grid in super-synchronous operation. The rotor converter needs thus only to be rated for a fraction 25% (Slip Power) of the total output power. All these advantages make the DFIG a favorable candidate for variable speed operation. A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Figure. 1.

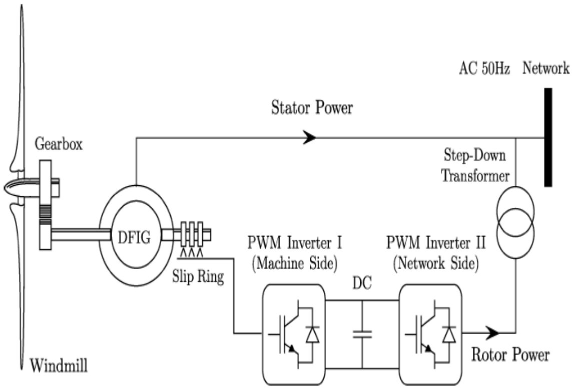

Figure 1. Basic configuration of DFIG wind turbine

The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back IGBT voltage-source inverters with a common DC bus. The network side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by the machine side power converter.

3. Steady state model

A typical scheme of a DOIG 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 adjustment of the 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 [8]. This is effectively the same as connecting a controllable voltage source to the rotor circuit [9]. The DFIG can be regarded as a traditional induction generator with a non zero rotor voltage. With the stator transients neglected, the per unit electrical equations of the DFIG can be written in phasor form as follows [9]-[12].

Stator Voltage

$$v_{ds} = r_s i_{ds} + \omega_s \psi_{qs} \quad 1$$

$$v_{qs} = r_s i_{qs} - \omega_s \psi_{qs} \quad 2$$

$$v_{dr} = r_r i_{dr} - s\omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \tag{3}$$

$$v_{qr} = r_r i_{qr} + s\omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt} \tag{4}$$

$$\psi_{ds} = -L_{ss} i_{ds} + L_m i_{dr} \tag{5}$$

$$\psi_{qs} = -L_{ss} i_{qs} + L_m i_{qr} \tag{6}$$

$$\psi_{dr} = -L_m i_{ds} + L_{rr} i_{dr} \tag{7}$$

$$\psi_{qr} = -L_m i_{qs} + L_{rr} i_{qr} \tag{8}$$

$$T_{em} = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \tag{9}$$

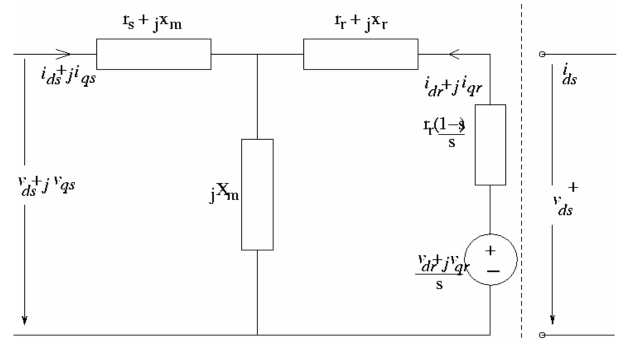

Figure 2. Steady-state and dynamic equivalent circuits of a DOIG.

In the case of the traditional induction machine, the rotor voltage in (3) and (4) are zero. To reduce (1) to (8) to a form suitable for implementation in a transient stability program, it is necessary to eliminate the rotor currents and rewrite the equations in terms of a voltage behind a transient reactance. Thus, by solving (1), (6), and (8), we get

$$v_{ds} = r_s i_{ds} - X^1 i_{qs} + E_d^1 \tag{10}$$

Similarly, we can also get

$$v_{qs} = r_s i_{qs} - X^1 i_{ds} + E_q^1 \tag{11}$$

$$E_d^1 = \frac{\omega_s L_m \psi_{qr}}{L_{rr}} \tag{12}$$

$$E_q^1 = \frac{-\omega_s L_m \psi_{dr}}{L_{rr}} \tag{13}$$

$$X^1 = \omega_s \left(\frac{L_{ss} - L_m^2}{L_{rr}} \right) \tag{14}$$

Figure 2 shows the steady-state and dynamic equivalent circuit of the DFIG, respectively. By eliminating the rotor currents i_{dr} and i_{qr} in the electromagnetic torque (9), and when w_s=1.0 pu, we find,

$$T_{em} = E_d^1 i_{ds} + E_q^1 i_{qs} \tag{15}$$

By substituting (10) and (11), the per unit electromagnetic torque can be written as

$$T_{em} = v_{ds} i_{ds} + v_{qs} i_{qs} - r_s \left(i_{ds}^2 + i_{qs}^2 \right) \tag{16}$$

Generally, the power losses associated with the stator resistance are small enough to be ignored, hence the approximation of electromagnetic power or torque can be written as

$$T_{em} = P_s = v_{ds} i_{ds} + v_{qs} i_{qs} \tag{17}$$

while the reactive power that the stator absorbs from, or injects into the power system can be calculated as

$$Q_s = v_{qs} i_{ds} - v_{ds} i_{qs} \tag{18}$$

Similarly, the rotor power (also called slip power) can be calculated as

$$P_r = v_{dr} i_{dr} + v_{qr} i_{qr} \tag{19}$$

$$Q_r = v_{qr} i_{dr} - v_{dr} i_{qr} \tag{20}$$

When the power losses in the converters are neglected, the total real power injected into the main network equals to the sum of the stator power and the rotor power .The reactive power exchanged with the grid equals to the sum of stator reactive power and that of grid side converter. In this paper, the value of was fixed to simplify the model.

4. Transient generator model and control strategy

On a practical wind turbine, the generator will have a real-time controller that will seek optimal Performance under varying wind conditions. These are commonly based upon a field-orientated control algorithm [11] that uses power and stator reactive power as the reference parameters as shown in Figure 3. The field-orientated control scheme incorporates a two-axis generator machine model and will ensure the generator operates at the reference points. To validate the steady-state algorithm described in the previous section, it is important to ensure that the dynamic real-time controller will produce the same operating point as that determined by the steady state model by matching the control reference values to the performance constraints. The results therefore include the operating performance of the generator using a simulated real-time controller.

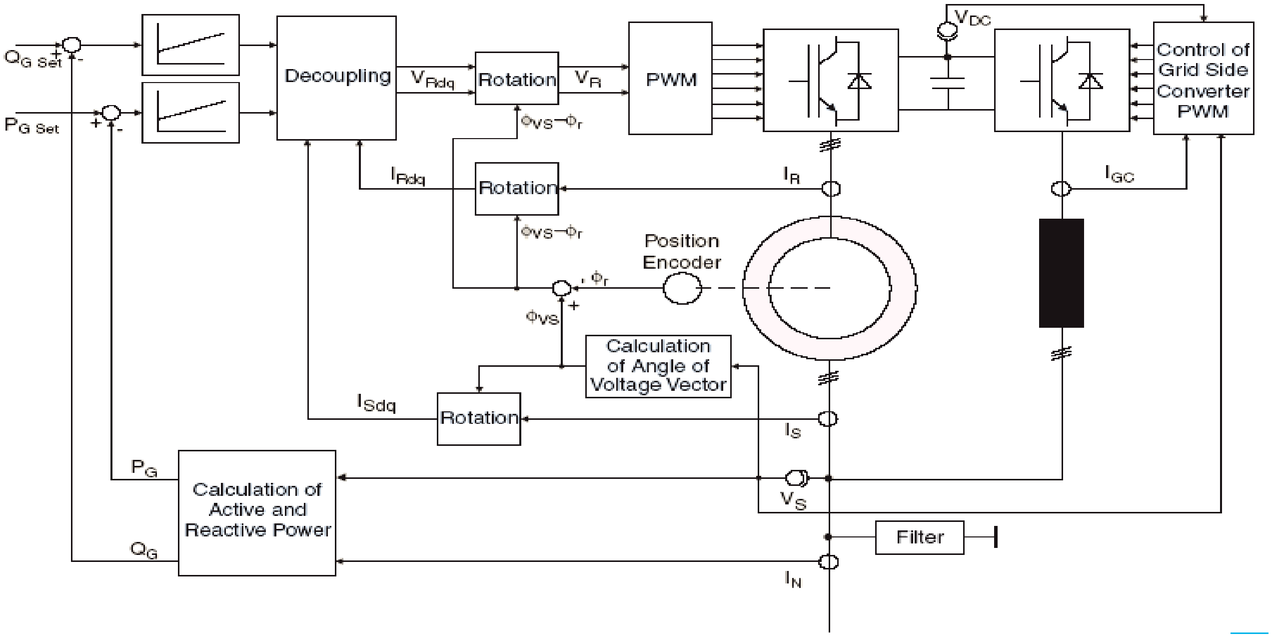

Figure 3. Vector control strategy of DOIG

5. Simulation results and discussion

The control model used in this study incorporates a conventional two-axis model of the doubly-fed machine into a field-orientated scheme orientated to the stator flux linkage [8,11]. The generator active and reactive power is used as the reference control parameters. In the IG mode, a conventional field-orientated scheme [12-14] is also used but it is adapted to reflect the fact that the converter supply is connected to the rotating rotor rather than a conventional stator connection. Figure 4 illustrates the rotor reactive power and turbine speed obtained using the steady-state model for the doubly-fed connection over a speed range increasing from the normal generator synchronous speed of 1500rpm. It is clear from this figure that constraining the stator reactive power results in a small increase in the turbine speed but a more significant increase in the rotor current. This additional current has to be provided by the rotor converter and is needed to inject reactive power into the rotor to ensure stator active power. The rotor current in this case however remains relatively constant as the speed increases. The rotor voltage on the other hand is determined mainly by the rotor speed and increases linearly as the rotor slip increases, or speed reduces. This is an important factor in determining the rating of the rotor converter. A detailed set of simulated results using both steady state and dynamic control models were undertaken over a speed range from approximately 10% below synchronous speed (1500 rpm) to 40% below.

Figure 5 illustrates the generator with vector control strategy mode over the same speed range. Again there is a close correlation between the steady-state model and the simulated results using the dynamic control model. It is evident that the search for maximum grid power results in a reducing rotor voltage as the speed reduces. This particular operational feature is important and is due to the constraint that the air gap flux is maintained below the rated value to avoid over-fluxing the machine. In this case as the speed reduces, the rotor supply frequency reduces to keep the slip low and as a result the terminal voltage also reduces to avoid saturating the magnetizing paths in the generator. Figure 6 illustrates the simulated results of rotor active power vs. reactive power using dynamic model described in the previous section. The correlation with the steady-state model results is on the whole very good. In fact at the higher speeds the DOIG produces slightly more power. The benefits would therefore appear to lie in the rotor converter ratings. The overall rating of the converter is related to the required speed range, typically 30% of the generator rating as mentioned previously. However the VA converter rating would be translated into maximum current and voltage ratings of the switching devices in the converter. Figure 7 illustrates the locus diagram of rotor active vs. reactive power using steady state operating conditions.

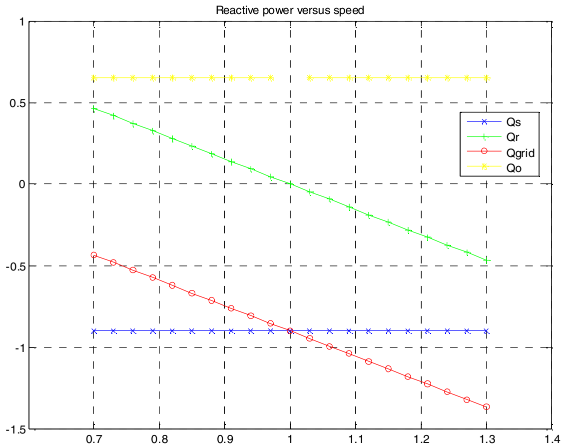

Figure 4. Response of reactive power of the stator, rotor, grid and output

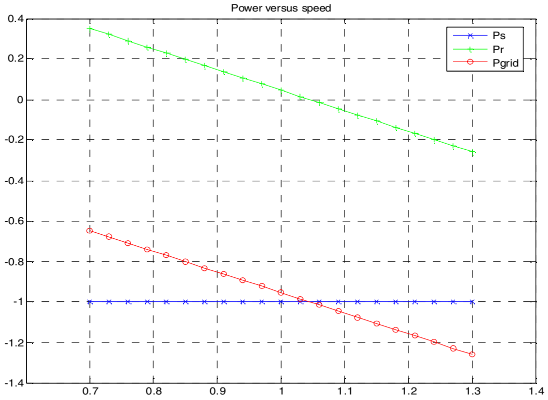

Figure 5. Response of active power of the stator, rotor and grid

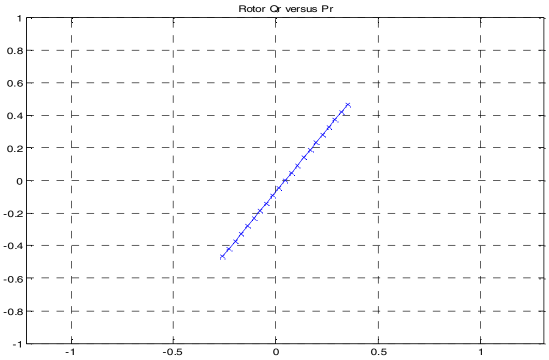

Figure 6. Response of rotor active power with respect to reactive power

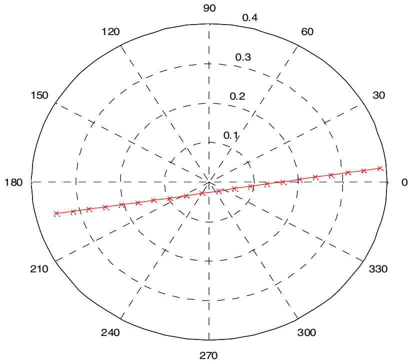

Figure 7. Locus of rotor reactive power during steady state conditions

6. Conclusion

In this contribution, the electrical equations of the induction machine in the case where the rotor voltage is not equal to zero. By eliminating the flux linkage variables in these equations, a DOIG model which is compatible with steady state and transient analysis programs has been obtained. It was shown that it is possible to develop a set of equations describing the behavior of the wind turbine. Furthermore, vector control strategy has been examined for controlling active and reactive power of grid, stator and rotor sides. The behavior of the system was investigated during steady state and transient conditions. This paper considers a grid-connected system; a further paper will describe a stand-alone system with experimental evaluation.

7. Appendix

2-KW Induction wind turbine model parameters (Star equivalent circuit)

Number of poles	4
Rated Speed	1800rpm
Rated Voltage	200 V
Rated Output Power	750 W
Stator winding resistance	3.35 ohm
Stator leakage reactance	2.616 ohm
Rotor resistance as referred to stator	1.99 ohm
Rotor leakage reactance	2.616 ohm
Rotor inertia	0.1 Kgm^2
Cut-in speed V_c	5.5 m/s
Rated speed V_R	11m/s.

Furling or cut-out speed V_F	20m/s
Gear ratio K	0.001

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