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MODELING AND SIMULATION OF DOUBLY FED INDUCTION GENERATOR FOR WIND TURBINE

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ABSTRACT

The construction of modern wind turbine is costly, complex and risky. In this paper, modeling and simulation of doubly fed induction generator (DFIG) for wind turbine is presented to investigate the dynamic behavior of the system. The behavior of the system is described in mathematical equations, modeled and simulated in MATLAB/Simulink using field orientation principle. Simulation results are presented in two operation modes namely below and above synchronous speed. Measurement obtained from 5 MW wind turbine confirmed the theoretical result. The created modeled can be used to simulate the behavior of DFIG for wind turbine inexpensively, efficiently and safely.

Keywords: doubly fed induction generator, field orientation principle, voltage model, current controller, flux observer.

1. INTRODUCTION

The development of wind turbines for electricity generation in 1973 is due to the sudden increase in oil prices and limited fossil resources [1-3]. During that time, a number of programs for research and technological development in USA, UK, Germany and Sweden have been initiated. Through the programs financed by the government, two generator concepts for wind turbines were introduced, namely fixed speed and variable speed generator systems [4-6]. The variable speed generator system is the preferred design for large wind turbines, providing more efficient utilization of power and the ability to reduce the mechanical stress on the system under changing wind conditions [7-9]. There are two types of variable-speed generator used in large wind power plant: synchronous generator with full power converter and DFIG. About two-thirds of the wind turbines are operated with a DFIG, while about a third of them are operated with a high pole synchronous generator [14]. The DFIG has many advantages compared to the synchronous generator includes wider speed range, lower cost of power electronic and better efficiency [10, 13]. In this paper, modeling and simulation of DFIG is performed in order to analyze the behavior of the system. The behavior of DFIG is described in mathematical equations and followed by modeling in the form of block diagrams and simulation using MATLAB/Simulink [11, 12]. Field orientation principle is applied to mimic the behavior of DFIG. The structure of a field-oriented drive with current injection and DFIG consists of several models such as voltage model, current controller and flux observer including coordinate transformation blocks (stator-related (α, β), rotor-related (d, q), and flux-related (m, l) coordinate system) [15].

2. MODELLING OF DOUBLY FED INDUCTION GENERATOR

2.1. Coordinate system

Three coordinate systems exist namely stator-related (*α, β*), rotor-related (*d, q*) and flux-related (*m, l*) coordinate system as shown by Figure-1. For a correct field orientation, the angle between the coordinate systems must be calculated. The angle between flux and stator is denoted as ϑ. The angle between rotor and stator is denoted as λ . The angle between flux and rotor δ is the difference between ϑ and λ.

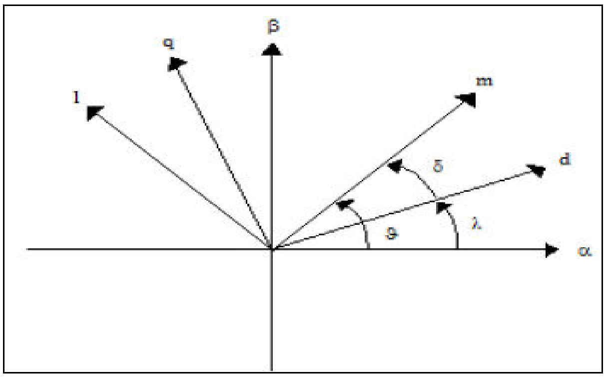

Figure-1. Coordinate system.

$$\vartheta = \delta + \lambda; \vartheta = \int w_s dt \approx w_s * t; \lambda = \int w_n dt \approx w_n * t; \quad (1)$$
$$\delta = \int w_L dt \approx w_L * t$$

w_s : stator frequency; w_n: mechanical rotational frequency; w_L : rotor frequency

2.2. Field orientation principle

In rotor-related coordinate system, the magnetizing current $\underline{i}_\mu$ is only located on d-axis and the stator voltage *US* on q-axis. Based on field orientation principle, the rotor current component on d-axis $\underline{i}_{Ld}$ influences the flux linkage and the rotor current component on q-axis $\underline{i}_{Lq}$ influences the internal torque *M* of the machine. The first rotor current component controls the power factor and reactive power while the second rotor

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current component controls the active power, which is proportional to the torque. Subsequently, the torque equation, M is a function of the rotor current component, whereby the flux value remains constant.

$$M = 3 * p * \underbrace{L_h * i_\mu}_{\psi_h} * i_{Lq} \tag{2}$$

3. MATHEMATICAL MODEL

Figure-2. shows the structure of a field-oriented drive with DFIG. The vector of rotor current is located in flux-related coordinate system. The m-component of the rotor current is set as zero. Hence, the rotor current only consists of the l-component($iL = iLl$), which is calculated from the nominal value of the stator flux and torque. The rotor voltage is calculated by the voltage model. This voltage is rotated to the angle δ to be available in rotor-related coordinate system. The vector of rotor voltage must be transformed into three winding axes to obtain three phase voltage desired values of the machine. By a subordinate current control, the voltage actuator (inverter) is converted into a current control element. Current set points are then impressed using current actuator in three windings of the machine. The stator voltage vectors are located in flux-related coordinate system. The m-component of the stator voltage is equal to zero and the value of the l-component is predetermined. The stator voltage is rotated to angle ϑ in the stator-related coordinate system. The stator voltage is then rotated back to angle λ in the rotor-related coordinate system. Using coordinate transformation the stator voltage is transformed into three winding axes. The three voltages are supplied to the stator side in the machine. Figure-2. indicates that current controller is used in the structure of field-oriented drive. By using this controller, measured and set value of rotor current can be compared. Manipulated variable UL_stell is determined from the difference between the two variables (deviation). The manipulated variable influences the control path resulting in fastest approach of set and measured value of the rotor current to each other. In the structure, a PI controller is used. The voltage model serves as a feedforward control. The manipulated variable UL is calculated in the voltage model.

$$\begin{aligned} \underline{U_{Lm}} &= \underline{i_{Lm}} * R_L - jw_L * L_\sigma * \underline{i_{Li}}; \\ \underline{U_{Ll}} &= \underline{i_{Li}} * R_L - jw_L (L_\sigma^{+} * i_{Lm} + \psi_s^{+}) \end{aligned} \tag{3}$$

Flux observer model is used in the structure to determine the flux. For DFIG with field orientation, the flux $\psi S+$ is related to stator voltage and frequency. In this case, the flux is constant, because the two variables remain unchanged. Following are the flux equations:

$$\psi_{S\alpha} = \frac{U_{S\beta}}{w_s}; \psi_{S\beta} = -\frac{U_{S\alpha}}{w_s} \tag{4}$$

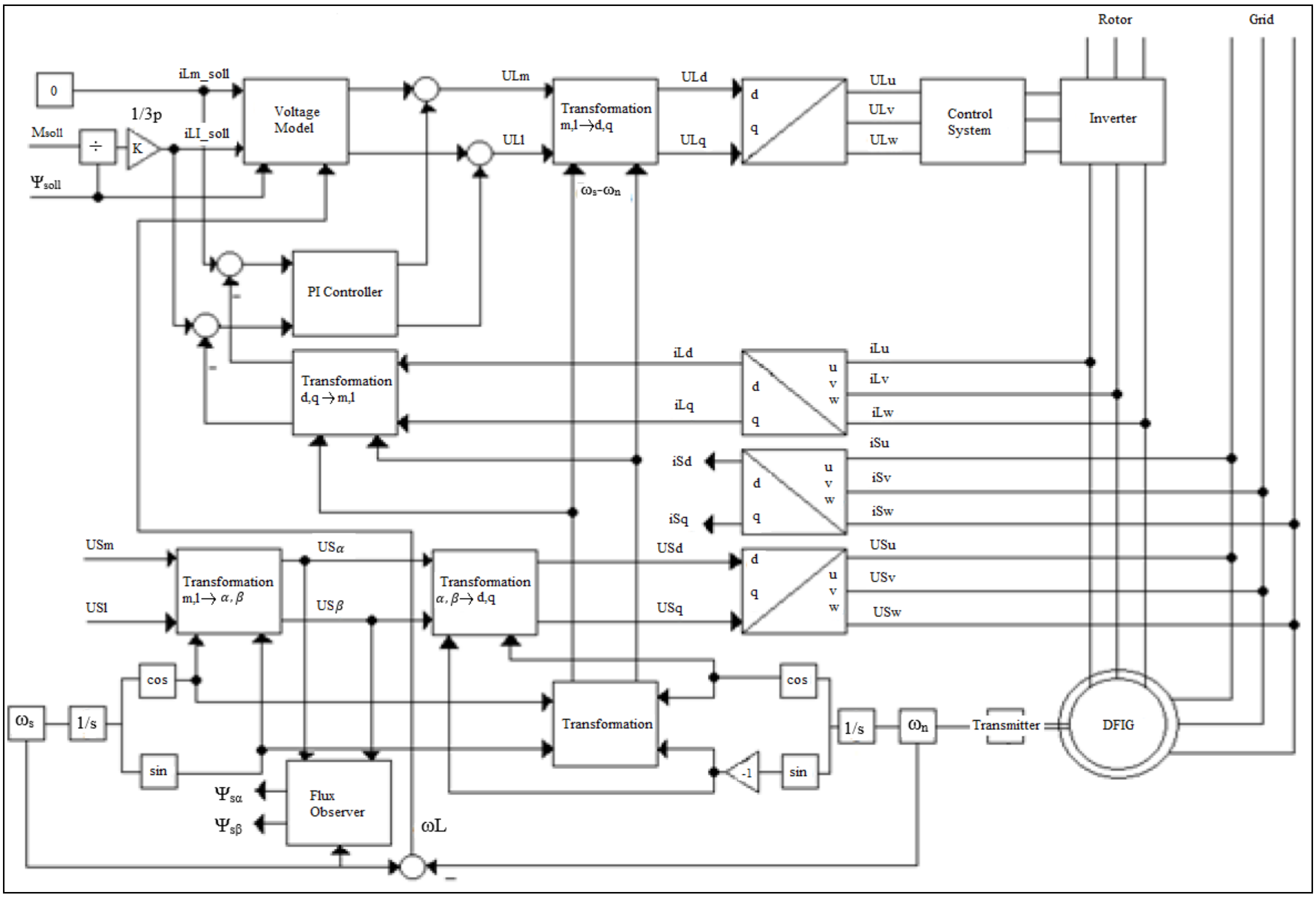

Figure-2. Structure of a field-oriented drive with doubly fed induction generator.

In simulation of DFIG, two circuits (refer Figure-3.) are built using SimPowerSystems. It is sufficient to establish two circuits instead of three for three-phase machine. A current-fed power supply is installed in the simulation.

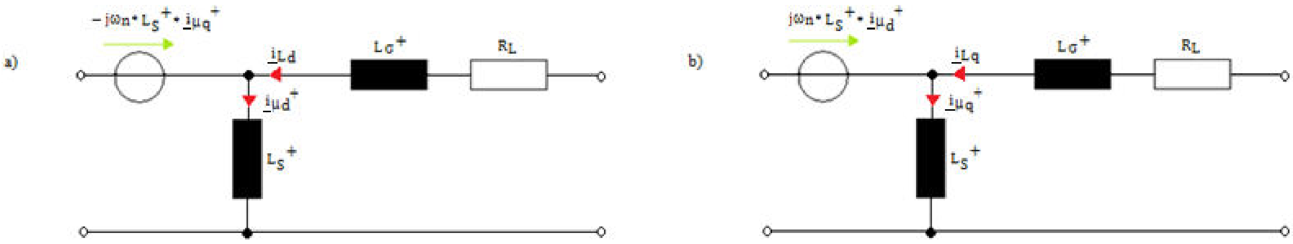

Figure-3. Circuits in doubly fed induction generator for three-phase machine.

DFIG works as generator by referring to the voltage and current direction of the stator which is oppositely directed. In the generator mode, the DFIG delivers both the active power *Pact* and the reactive power *Qrea*. The active power and reactive power can be calculated as follows:

$$P_{act} = 3*I_S*U_S*\cos\varphi; Q_{rea} = 3*I_S*U_S*\sin\varphi \quad (5)$$

Another feature is the DFIG operated below synchronous speed. It can be stated that the stator voltage is greater than the induced voltage, which means the stator frequency is greater than the mechanical rotational frequency.

4. RESULTS AND DISCUSSIONS

Table-1. shows the measured and calculated value for below synchronous speed mode. From the table, it can be seen that measured values confirmed the calculated values. A very small deviation of 1% in torque measurement arises because the software MATLAB/Simulink is not a real-time system.

Table-1. Calculated value and measured value.

Physical Quantity	Calculated Value	Measured Value
Stator Voltage (V)	942.23	942.23
Induced Voltage (V)	848.01	848.00
Main Voltage (V)	94.22	94.23
Magnetizing Current (A)	678.40	678.40
Rotor Current (A)	1696.00	1495.15
Torque (Nm)	4.081×10^4	4.039×10^4
Electrical Rotor Frequency (Hz)	5	5

Figure-4. illustrates the simulation results for below synchronous speed. The yellow curve represents the d-component of current and voltage indicator, while the purple curve represents the q-component of these pointers. The amount of voltage and current vector can be determined by reading its characteristics at time t = 0 s. To determine the direction of the current and voltage vector the corresponding characteristics must be considered at two points in time. For example, the stator voltage characteristics are considered (see Figure-4a). At this time, the d-component of the voltage is equal to zero, and the q-component represents a positive value. It means that the stator voltage vector consists only of the q-component and it is at this time exactly on the q-axis. The stator voltage characteristics are now considered at the time t = 0.05 s. The q-component of the voltage is equal to zero, and the d-component is negative. At this point, the stator voltage pointer is located on the negative d-axis. From these two considerations, it can be summarized that the voltage vector rotates counterclockwise. These considerations are also applied to other voltage and current pointers. Figure-4. shows that voltage and current vectors are oppositely directed in the stator. It means that the DFIG operates as a generator. It can be stated that the induced voltage vector is smaller than the stator voltage vector due to $\omega n < \omega S$ (see Figure-4d.) for below synchronous speed. In this operation, all voltage and current vectors rotate at the electrical rotor frequency counterclockwise. The electrical rotor frequency is calculated from the cycle time. The half wave of the stator voltage has for example, a period of 0.1 s and frequency of 10 Hz. The frequency of the stator voltage wave with the period of 0.2 s gives the value of 5 Hz. In Figure-4e., it can be seen that the stator current consists of d- and q-component. The d-component of the stator current corresponds to the magnetizing current and q-component of the stator current equal to the inductor current. The q-component of the stator and rotor current are oppositely directed. Figure-4h. shows a constant torque characteristic due to the field-oriented operation. Simulation results for above synchronous speed is shown in Figure-5. Compared to below synchronous speed, all voltage and current pointers are in clockwise direction. In addition, the induced voltage vector is greater than the stator voltage vector.

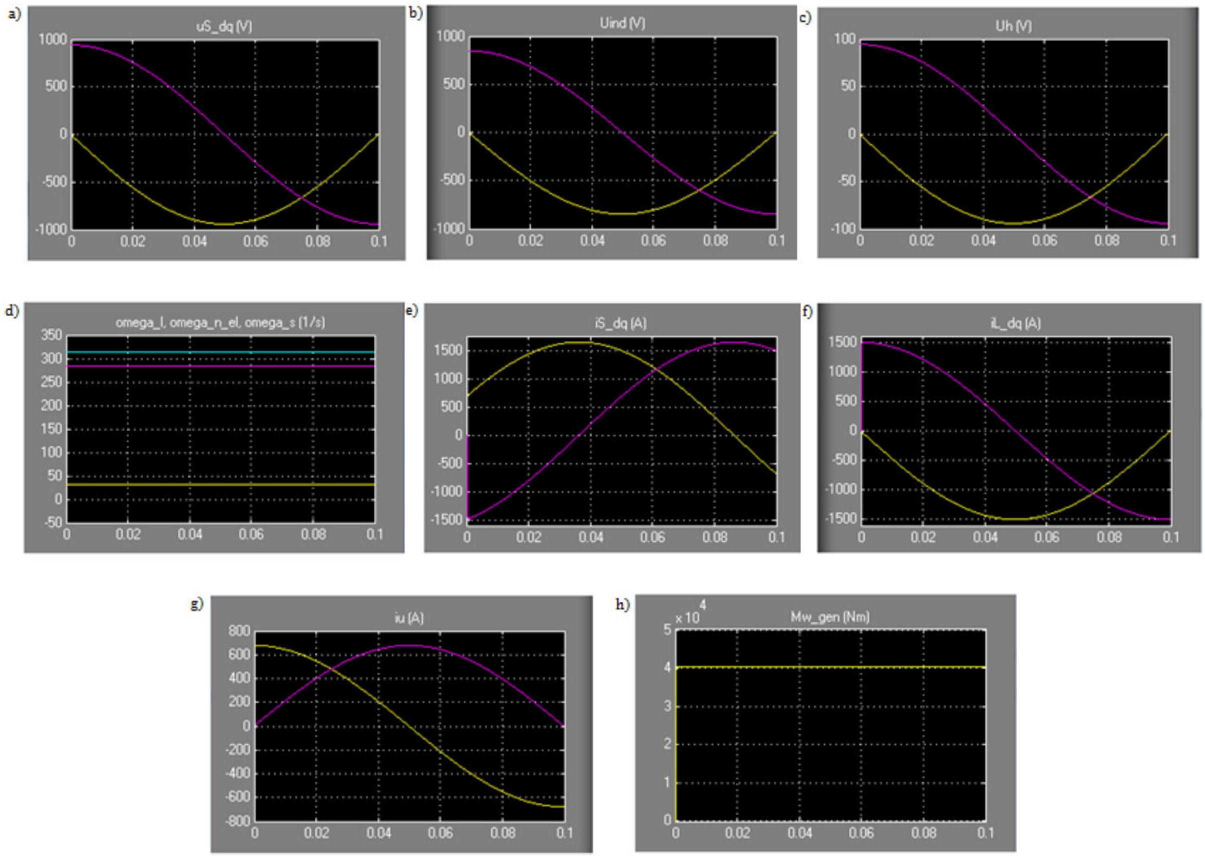

Figure-4. Below synchronous speed.

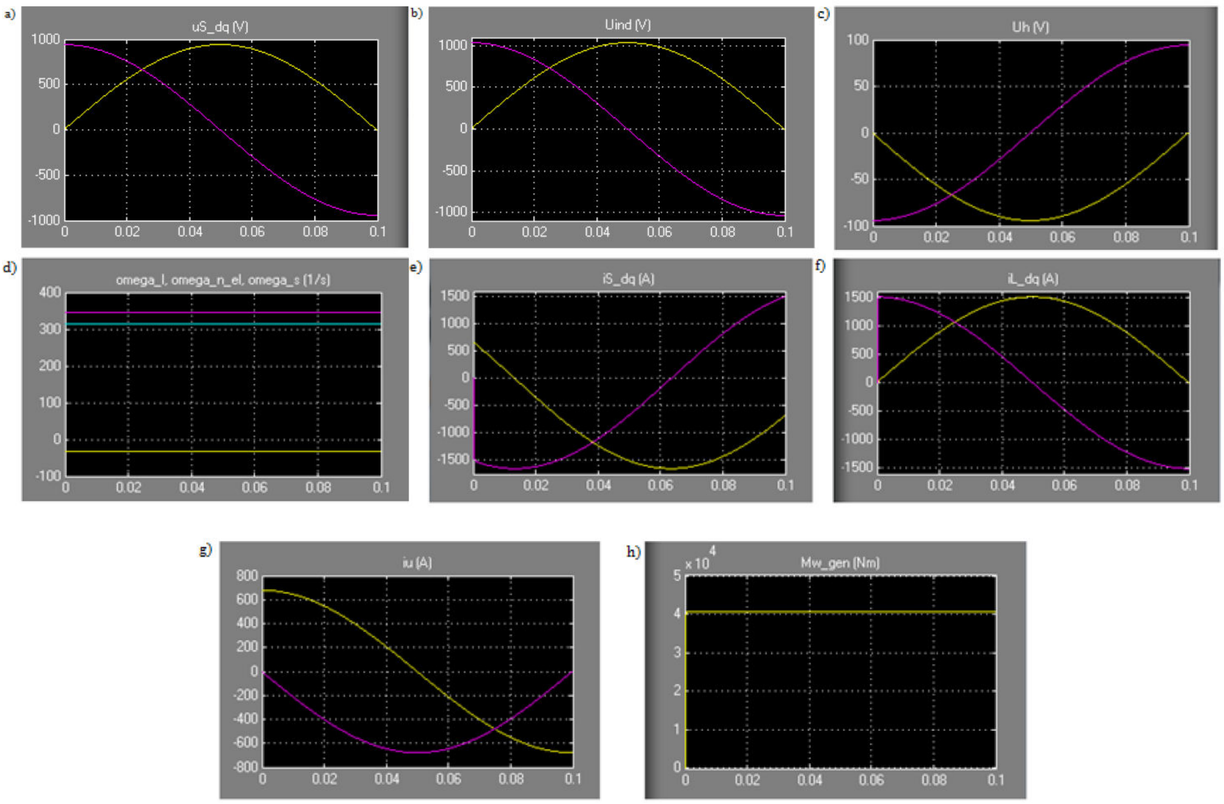

Figure-5. Above synchronous speed.

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5. CONCLUSIONS

In this paper, the modeling and simulation of a wind turbine with DFIG is performed to study the behavior of the system. The behavior of key components of DFIG is described mathematically in the form of differential equations. Using these equations, a simulation model is constructed. From the simulation model, the characteristics of DFIG in below and above synchronous speed are observed. The simulation results are then compared with theoretical data and evaluated. It shows that the values correspond very well. This research has successfully shown that the modeling and simulation of DFIG using the described software can be carried out. Thus, this software is a convenient tool in modeling and simulation of DFIG for wind turbine.

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