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Simulation of a Wind Turbine Driving a Grid Connected Induction Generator

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Abstract:* *This paper presents modelling and simulation of a wind turbine driving a grid connected induction generator. A DC motor is used to emulate the performance of the wind turbine. Different parts of the system have been modelled using MatLab – Simulink. A model of a DC motor derived by a converter is employed to emulate the performance of the wind system. A speed control loop is used to force the dc motor shaft to follow the induction generator shaft which is coupled to the wind turbine.

Keywords- Wind turbine simulator, constant speed, pitch angle control, induction generator, DC motor control.

1- INTRODUCTION

In recent years, due to decrease of fossil fuels, the environmental pollution, and the increasing need to energy consumption, the renewable energy generation technology has made considerable development, especially wind power technology. For the research on wind power technology, it is necessary to construct a simulator (emulator) to act as wind turbines without reliance on natural wind resources. Also the simulator can represent different types and sizes of wind turbines. The wind turbine simulator can also reduce experimental costs and shorten R & D cycle of the new technologies.

The following paragraphs give a survey on some of the published literature concerning the Wind Turbine Emulator (WTE) subject. The previous WTE's were classified according to the motor used, the generator type, the control technique, the converter, wind turbine type, and mode of operation.

A. Motor Type

Regarding the type of the used motor, most of the published work built the WTE based on separately excited DC motor [1 - 10]. Fewer researchers used squirrel cage induction motor [11 - 13]. Also permanent magnet synchronous motor has been employed to emulate the wind turbine [14].

B. Generator Type

The authors in [2 – 6, and 13] used a permanent magnet generator coupled to the turbine shaft with a power range from 1 KW to 7.3 KW. DC generator has been used in [7, 8]. [1, 12] used a Double Fed Induction Generator DFIG as the acting generator. The authors in [9] used a dynamometer while in [10, 11 and 14] no generator type has been specified.

C. Wind Turbine Type

Papers [1, 2, 4-8, and 13] analyzed a fixed pitch small wind turbines, while the variable pitch turbines have been studied in [10 – 12]. References [3, 9, and 12] didn't mention the type of pitch angle control. The authors in [6] added the furling angle effect to the emulator controller. Also [9, 12] introduced the effect of tower shadow and wind shear in their models.

D. Control System

All of the published papers employed a closed loop control system except [7, 8] where the authors presented an emulator operating in an open loop control system. Many authors used a torque loop to control the emulator [5, 9-13]. Both torque and speed control loops have been employed in [1, 3, and 6], while [4] used only a speed loop. In [15], the author used both sliding mode control and fuzzy logic to control the emulator and held a comparison between the two methos.

E. Software

The authors in [1, 14] used real time control system employing a PC with LabWindows software and an interface card to the hardware (drivers, motor, sensors, etc.). LabView software has been used in [11, 13]. Also, MatLab – Simulink was used in many publications [3-5, 7, and 9-10].

F. Controllers

The implementation of the control hardware part has employed different types of controllers. While the Digital Signal Processor DSP was used in a many publications [1, 3, 9, 10, 12, 14], a microcontroller was employed in [2, 6]. Also, industrial type controllers and converters were used in [11, 13].

G. Converters

To supply the motor representing the wind turbine a converter is required to control the torque and speed to follow the actual wind turbine performance. For DC motors an AC-DC converter was used in most of the reviewed publications [1-3, 5, 7-9]. To reduce the torque harmonics due to the switching of the three phase source, the authors in [4-6] used a DC-DC converter to power the DC motor. For Induction motors and permanent magnet motor, an inverter was employed [11-14]. The controller used the wind speed and rotor speed information to control the duty cycle of a buck-boost converter connected to the load in order to operate the wind turbine at the optimum tip-speed ratio. Direct torque control was applied to induction machines [11 – 13] to emulate the wind turbine.

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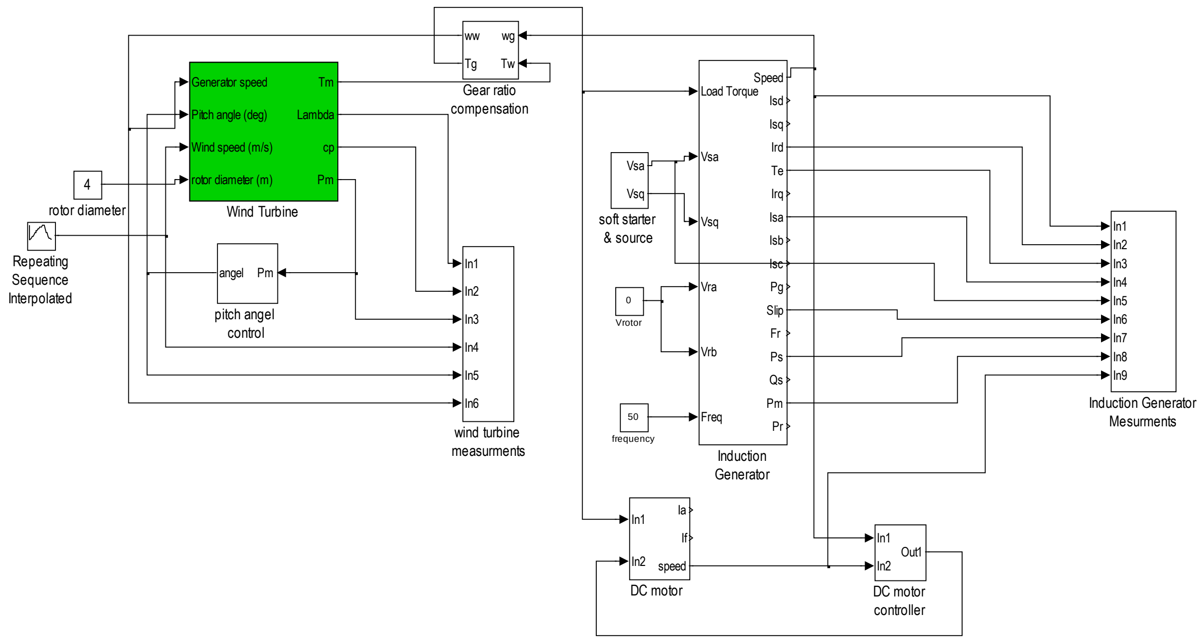

Figure 1. The Wind Turbine Simulator Model using Simulink.

System Description

The Wind Turbine Simulator system is modelled using MatLab. The system under study consists of a wind turbine coupled to a grid connected induction generator. The shaft speed and torque signals of the coupled turbine–generator set are fed to the control circuit of a DC motor to get the same performance at the motor shaft. The model is illustrated in Fig. 1.

Three main modules are included in the system model, the wind turbine model, the induction generator model and the DC motor model.

The inputs to the wind turbine model are:

- A wind speed pattern
- The rotational speed of the generator (including speed adjustment due to the gear ratio).
- The pitch angle of the turbine blade
- The turbine diameter

The outputs of the turbine model are

- Developed Torque which is an input to the induction generator model (including gear ratio conversion).
- Turbine output power which acts as control signal to the pitch angle controller.
- Measurement signals (simulation results) for the power coefficient C_p and tip speed ratio λ.

The induction generator is supplied from a source with soft starter stage to speed up the process of connecting the generator to the utility grid without drawing high current during starting. The machine starts as a motor until its speed is close to the synchronous speed. Then the input torque from the turbine starts to drive it faster than the synchronous speed and it starts to inject power to the grid. The developed power depends on the driving torque. The intersection between the turbine torque and the machine speed-torque curve determines the operating speed of the generator.

The DC motor model is fed with both the generator input torque and speed at the generator shaft. The DC motor controller forces the DC motor to follow the speed of the generator.

SYSTEM MODELLING

A. *Wind Turbine Model*

According to the aerodynamic characteristics of wind turbine, the output mechanical power is given by

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

Where ρ is the air density, R is the turbine radius, v is the wind velocity and C_p is the power coefficient of the wind turbine. C_p is a function of both the tip speed ratio λ and the blade pitch angle β according to the following equations.

$$\lambda = \omega R/v \qquad (2)$$

Where □ is theangular speed of the turbine in rad/sec.

$$C_p = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{\frac{-c_5}{\lambda_i}} + c_6\lambda \qquad (3)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \qquad (4)$$

Where c_1=0.5176; c_2=116; c_3=0.4; c_4=5; c_5=21; c_6=0.0068.

The above listed parameters are used by several authors [5, 10,].

Fig. 2 shows the variation of Cp with λ for different pitch angles β. The maximum value of Cp is about 0.48 and occurs at λ around 8 for β equals 0˚.

As β increases Cp continues to decrease and the curves are moving to the left at lower values of λ. The maximum value that λ can take is around 35˚with Cp maximum of 0.05 at λ equals 2.

The operating point of the wind turbine is determined according to the wind speed and the turbine shaft speed. Equation 2 determines the λ which is used with the pitch angle β to determine the power coefficient C_p . The mechanical output power of the wind turbine is calculated using (1). The shaft torque is then calculated using the formula

$$T_t = {}^{P_m}/_{\omega_t} \quad (5)$$

Where ωt and Tt are the generator shaft speed and torque respectively.

The generator is coupled to the turbine shaft through a gear box. The turbine torque and the generator speed are adjusted before being fed to the generator and turbine respectively. The torque is supplied to the induction generator with negative sign to force the machine to act as a generator, at the same time it is fed to the dc motor with positive sign as a load.

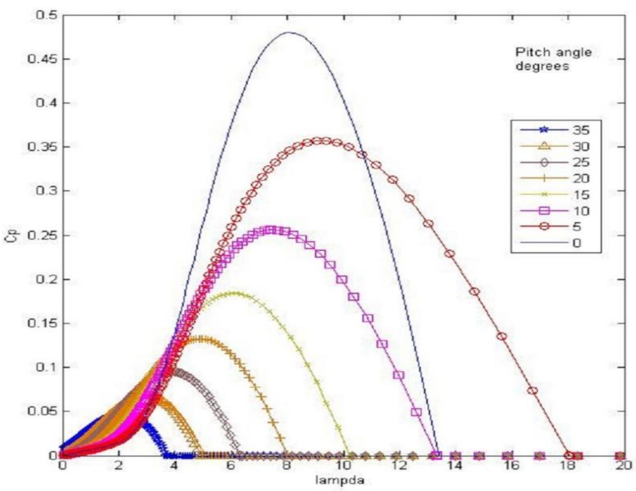

Figure 2. Cp – λ curves for different β angles.

The gear ration Kg is selected so as the rated power of the generator is produced at the average wind speed at the selected site. This means that the turbine will operate at maximum power blade angle from cut-in wind speed till rated speed before activating the blade angle control for speeds higher than the rated speed.

$$T_g = {}^{T_t}/_{K_g} \quad (6)$$

$$\omega_g = \omega_t\, K_g \quad (7)$$

Where ω_g and T_g are the generator shaft speed and torque respectively.

B. Induction Machine Model

Fig. 3 shows the equivalent circuit of the induction machine and the following equations describe it.

$$V_{ds} = r_s\,.\,i_{ds} + p\,\lambda_{ds} \quad (8)$$

$$V_{qs} = r_s\,.\,i_{qs} + p\,\lambda_{qs} \quad (9)$$

$$V_{dr} = r_r\,.\,i_{dr} + p\,\lambda_{dr} + \omega_r\,.\,\lambda_{qr} \quad (10)$$

$$V_{qr} = r_r\,.\,i_{qr} + p\,\lambda_{qr} - \omega_r\,.\,\lambda_{dr} \quad (11)$$

Where, V_{qs}, V_{ds}, i_{qs}, and i_{ds} are the stator voltages and currents, respectively. V_{qr}, V_{dr}, i_{qr}, and i_{dr} are the rotor voltages and currents, respectively. λ_{qr}, and λ_{dr} are the rotor fluxes. λ_{qs}, and λ_{ds} are the stator fluxes. r_s, L_{ls}, r_r, and L_{lr} are the resistance and the self-inductance of the stator ar.. the rotor, respectively.

The expression for electromagnetic torque in terms of the stationary reference variables can be expressed as:

$$T_{em} = \frac{3}{2}\frac{p}{2}\left(\lambda_{ds}\,.\,i_{qs} - \lambda_{qs}.\,i_{qs}\right) \quad (12)$$

Neglecting the friction effect, the rotor speed is defined by

$$p\omega_r = \frac{1}{J}\frac{p}{2}\left(T_{em} - T_L\right) \quad (13)$$

Where, J is the effective inertia of the complete system referred to the induction generator shaft. T_L is the wind turbine output torque value at the generator shaft.

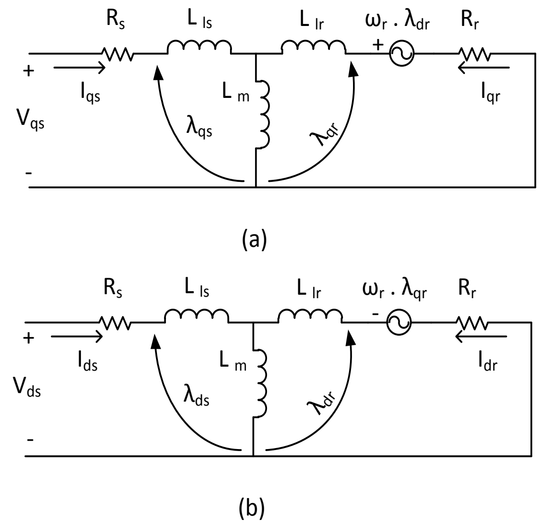

Figure 3. The induction machine equivalent circuit

C. The DC motor model

The following equations describe the DC motor

$$V_f = R_f.I_f + L_f\frac{dI_f}{dt} \quad (14)$$

$$V_a = R_a.I_a + L_a\frac{dI_a}{dt} + K_e.\omega_m \quad (15)$$

$$T_e = T_l + J_m\frac{d\omega_m}{dt} + \beta_m.\omega_m \quad (16)$$

$$T_e = K_t.I_a \quad (17)$$

$$K_e = K_t = L_m I_f \quad (18)$$

Where T_l: Load torque; L_m: mutual inductance excitation - armature

β_m: friction coefficient ; J: moment of Inertia. K_t: the torque constant

K_e:the EMF coefficient

The DC motor model is shown in Fig. 4

The DC motor is controlled using a simple PID controller to follow the induction motor shaft speed while the turbine torque act as the load torque for the motor.

D. Controllers

The system includes two controllers, the first is used to control the pitch angle of the wind turbine, and the second controls the speed of the dc motor to follow the generator speed. Fig. 4 and 5 shows the Simulink models for both the pitch angle and the dc motor respectively.

The pitch angle controller is a hysteresis type controller. The input to this block is the output power of the turbine and the output is the angle β. The angle is changed incrementally as long as the power value is above or below the rated value.

The dc motor is controlled employing only a speed control loop. The used controller is of PID type. The PID parameters are adjusted using the dc motor parameters. The gains in Fig. 6 are assigned as follows. Gain 1 is the proportional gain K_p, Gain2 is the integrator gain K_i and Gain 3 is the differentiator gain K_d. The motor speed is controlled via an AC-DC converter.

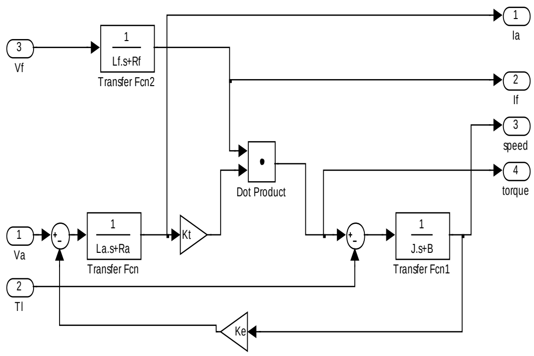

Figure 4. The DC motor MATLAB-SIMULINK model

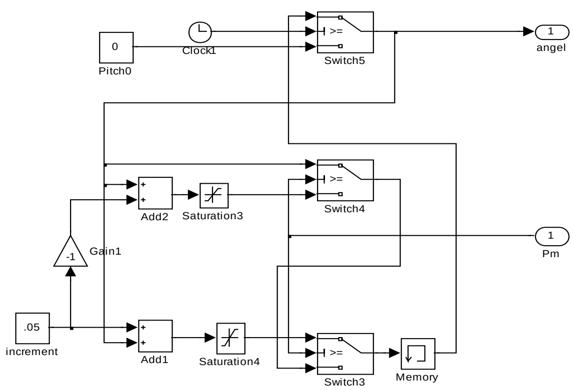

Figure 5. Hysteresis controller for the pitch angle of the turbine

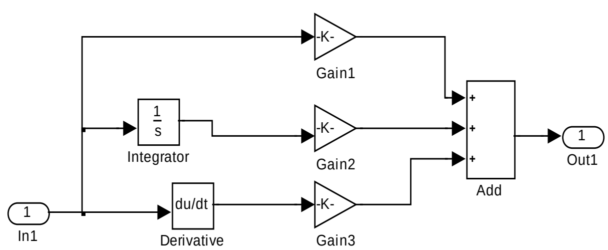

Figure 6. PID controller for the DC motor

SIMULATION RESULTS

The system model shown in Fig. 1, is fed with the wind speed pattern given in graph (a) of Fig. 7. The simulation depicts the system performance over 220 seconds with the wind speed varies as illustrated.

The turbine starts at rest then begins to turn with the generator operating in the motor mode. A soft starter is used during the first five seconds to get the generator shaft speed to synchronous speed and to reduce the starting current drawn from the grid. Above the rated wind speed of the turbine, the pitch angle β is controlled to keep the power within the rated value range. Graph (b) shows that at wind speeds higher than 8 m/s β starts to increase. The maximum value of β is about 35 degrees (Fig. 2) and at speeds higher than this value, the turbine nacelle have to be directed away from the wind direction to reduce the swept area by the blades hence reduce the extracted power from the wind.

Graph (c) shows the variation of tip speed ratio λ corresponding to every change in wind speed. Since the induction generator speed varies within a limited range λ is moving to lower values with the increase in wind speed also with the change in β, λ moves to other lower curves. The turbine efficiency Cp variation is shown in graph (d).

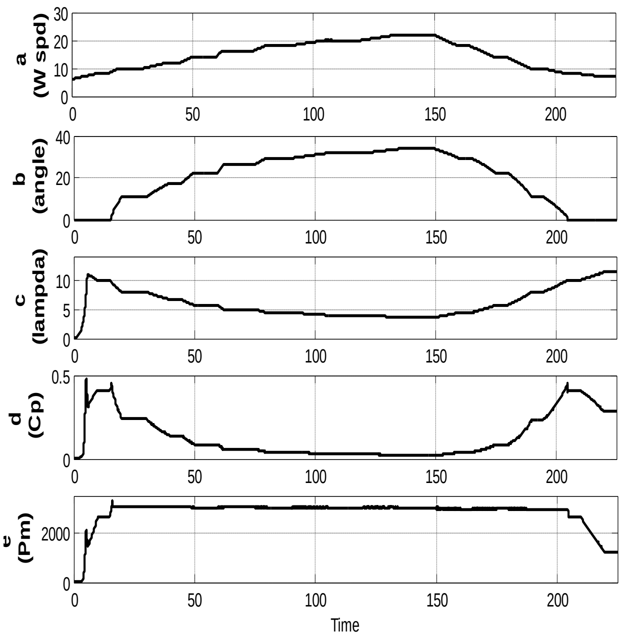

Figure 7. Wind turbine performance

It is clear that Cp reduces with the increase of the angle β. The maximum value of Cp is slightly below 0.5 and occurs only near rated wind speed value. Graph (e) of Fig. 7 shows the output mechanical power to the turbine shaft. The system is adjusted to produce a rated power of 3000 watts. If this power exceeds a value of 3050 watts due to increase in wind speed, the pitch angle control increases β and if the power goes lower than 2950 watts, β is decreased.

Fig. 8 illustrates the input and output power to the induction generator. The difference is dissipated as the generator losses. The effect of changing the pitch angle β is clear in keeping the power within the designed range.

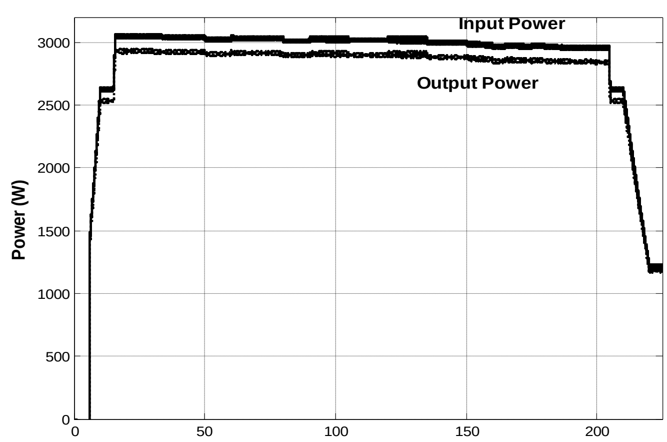

Figure 8. Input and output power of the induction generator

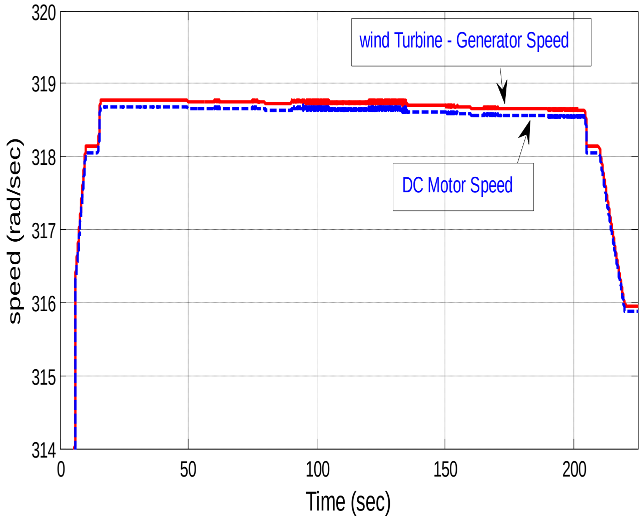

Figure 9. Induction generator and DC motor speeds

The generator speed and the speed of the dc motor representing the wind turbine are shown in Fig. 9. The difference between the two speeds is very small, even though this difference may be reduced by tuning the parameters of the PID controller used to follow the generator speed.

CONCLUSION

A system of a wind turbine coupled to a grid connected induction generator has been modelled and simulated using MATLAB-SIMULINK. A dc motor was controlled to follow the speed of the generator shaft. The simulation results show that the model represents the system under study. A model for the wind turbine, the induction generator, the dc motor and the controllers have been provided.

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