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Emulation of a 1 MW Wind Turbine System with a Separately Excited: DC Motor Using MATLAB-SIMULINK

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Abstract:
Power generation based on wind energy has become a significant component in modern power system which has caused substantial increase in the wind power based research. In order to study the functionality of a Wind Turbine, this paper presents an emulation system that replicates the behavior of a real wind turbine for the purpose of creating a convenient test set to be used in a laboratory environment. The goal of the proposed model is to design, build, and test a wind turbine emulator capable of modeling the behavior of a 1 MW Wind Turbine. First, a mathematical model was developed using one of Power coefficient expression given for a 1 MW Wind Turbine. Then, the Model was implemented in a software simulation along with DC Motor acting as the Wind Turbine. The effectiveness of the developed model was found feasible as the simulation results of the developed wind turbine system verified the high feasibility and good performance.

Keywords*: DC Motor, Simulation, Wind Turbine, Wind Turbine Emulation, Wind Turbine Simulator*

1. Introduction

Electricity generation using wind power has undergone rapid advancement in the past few decades. Large scale wind power generation systems are primarily used for community power; they are complex in operation and deploy a multitude of control methods [4]. With the rapid increase of wind power installations, research related to wind energy systems has also boomed. One of the leading prospects in this search for clean and commercially viable production is horizontal axis-wind turbines. Developing innovative solutions in this area requires a rigorous testing procedure, a testing procedure which can be controlled in a laboratory condition without the unpredictable effects of wind [1]. As a result, a device that can mimic the functionality of a wind turbine in a laboratory environment is of utter importance. The foremost requirement of such a device is called wind turbine simulator. The Wind Turbine Simulator has the ability to produce the same static & dynamic characteristics of a real wind turbine.

The computer model for the proposed work was created in a software package called SIMULINK, which is the control systems software component of MATLAB, a Math works Inc. software package. Wind Turbine Simulators using DC Motors (separately excited) often use armature and field voltage control methods to achieve static characteristics of a fixed pitch wind turbine. These simulators are simple, uncomplicated and usually do not consider the transients operations. The motivation of the proposed model is to form an emulation system that draws an exact replication of a wind turbine in a steady-state condition, which will allow the testing of equipments designed to maximize the turbine power output. The built simulation system eradicates the unpredictability that goes with testing a turbine under real wind conditions thus it also eliminates the need for large expensive wind tunnel testing.

2. Characteristics Comparison of a wind turbine with DC Motor

A DC Motor imitates the characteristics of a wind turbine [2]. A thorough investigation was carried according to their operating principles [6]. The conclusion contrasted the characteristics of the wind turbine with those of the DC motor as follows:

- The power and torque characteristics of the wind turbine and the DC Motor were a bunch of curves with angular velocity as their abscissa. As the change in wind speed gives rise to varying output torque characteristics of a wind turbine, similarly, any change in terminal voltage of armature winding regulates the DC Motor power characteristics.

- When the values of the wind speed of the wind turbine and the terminal voltage of armature winding of DC Motor are constant, the output power of a wind turbine or a DC motor is directly related to their angular velocity. As a result, as their angular velocity changes, there is an optimal angular velocity at which the maximum output power can be attained. If angular velocity is greater or less than the optimal angular velocity, output power would decrease. Therefore, there are optimal power curves for both Wind Turbines and DC Motors.

3. Mathematical Analysis & Model Development

In the previous section, a comparative feature of DC Motor with that of Wind turbine was drawn. Based on the comparative observations a wind turbine emulator system using dc motor was developed. The establishment of the emulated model was introduced in two parts namely consisting of main circuit model and the wind turbine model. The main circuit model is a DC Motor model, the input of this model is the armature voltage U_a . The output of this model is the angular speedω, the armature currentI_a, the electromagnetic torque T_e. The power supply is 150v, frequency is 50Hz. The armature rotate speed of the DC motor simulates the rotate speed of the wind turbine. The rotation speed of DC motor is equal to the rotation speed of the wind turbine and assuming the wind speed is stable, the angular velocity measured calculate tip speed, then the tip speed ratio λ can be obtained from them. As λ and β are obtained, the wind turbine torque coefficient C_t can be calculated.

3.1. Wind Turbine Modeling

In designing the wind turbine emulator, a power curve for the turbine was developed. This curve defines the relationship between the maximum mechanical powers a turbine can produce versus the wind speed. Using translational momentum theory [4] the total amount of energy extractable can be calculated. Power extractable from the wind passing across an area *A*, when the speed is *v* can be expressed as,

$$P_w = \frac{1}{2}\rho A V^3 \qquad (1)$$

Here, ρ is the density of air, which depends on the pressure and moisture levels of air. Betz's law states that the maximum fraction of power extracted by a wind turbine would be theoretically 16/27 of P_w [16]. However, the modern commercial wind turbines extract about 0.45 of P_w [1]. Thus, a coefficient can be defined as to express the useful mechanical power extracted from the wind by the turbine. It is called the power coefficient or the Betz factor, C_p and it is defined as

$$\text{Power Coefficient } C_p = \frac{\text{Turbine Power}}{\text{Power of wind}} \qquad (2)$$

Power coefficient, C_p is a function of two variables, namely, tip speed ratio λ, and pitch angle β. Tip Speed ratio λ, is the ratio between the speed of the tip of the blade, wR, and the velocity of wind, *v*. Here, ω is the radius of the turbine blade.

$$\lambda = \frac{\omega R}{v} \qquad (3)$$

The turbine power extracted by a fixed pitch wind turbine can be expressed as,

$$P_t = \frac{1}{2}\rho A V^3 C_p(\lambda) \qquad (4)$$

In the equation (4), the circular swept area of the turbine πR^2 is given as *A* [9]. Similarly, a coefficient can be defined for the torque extracted as C_t, and the torque output of a fixed pitch wind turbine can be given can be given as,

$$\tau_t = \frac{1}{2}\rho A V^3 C_t(\lambda) \qquad (5)$$

Torque of the turbine can also be expressed as,

$$\tau_t = \frac{1}{2}\frac{\rho A V^3 C_p(\lambda)}{\omega} \qquad (6)$$

Furthermore, $$C_t(\lambda) = \frac{C_p(\lambda)}{\lambda} \qquad (7)$$

Some numerical approximations were developed in [3], to calculate the coefficient C_p, a set of different expressions were proposed. Table 1 shows different form of expressions for approximation used in different scientific papers to determine the power coefficient since the power coefficient of wind turbine are different from one another [3].

No.	C_p Expressions	The affected constants
1.	$C_{p1}(\lambda,\beta) = [0.5+0.167(\beta-2)]\sin\left[\frac{\pi(\lambda+0.1)}{18.5-0.3(\beta-2)}\right] - 0.0018(\lambda-3)(\beta-2)$	λ: Reduced-Speed β: Pitch –angle
2.	$C_{p2}(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda i}} + C_6\lambda$; Where $\frac{1}{\lambda_i} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3}$	$C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$ and $C_6 = 0.0068$.
3.	$C_{p3}(\lambda,\beta) = 0.22\left(\frac{116}{\lambda} - 0.4*\beta - 5\right)e^{-\frac{12.5}{\lambda}}$	$\frac{1}{\lambda} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1}$
4.	$C_{p4}(\gamma,\beta) = 0.73\left(\frac{151}{\lambda} - 0.58\beta - 0.002\beta^{2.14} - 13.2\right)e^{\frac{-18.4}{\lambda}}$	$\frac{1}{\lambda} = \frac{1}{\lambda-0.02\beta} - \frac{0.003}{\beta^3+1}$

Table 1: C_p Coefficients of Different Types according to the Wind Turbine Designs

The equation (2) from table- 1 has been used to develop the emulation system; In the process an internal subsystem was added in the developed model

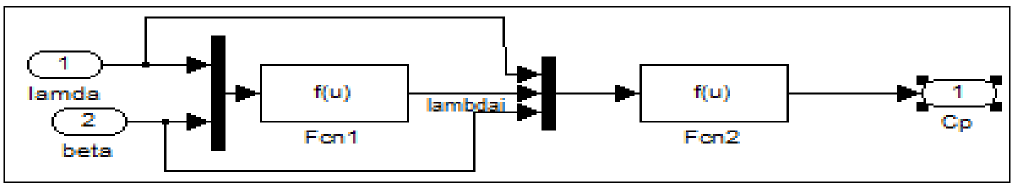

Figure 1: The Developed Model - Internal subsystem

The subsystem defines two functions namely Fcn1 and Fcn2,
Where

$$F_{cn1} = \lambda_i = \frac{1}{\frac{1}{(u[1]+0.08*U[2])} - \frac{0.035}{U[2]^3+1}} \quad (8)$$

$$F_{cn2} = C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda i}} + C_6\lambda \quad (9)$$

3.2. DC Motor Modeling

The direct current (DC) motor is one of the first machines devised to convert electrical power into mechanical power. The operation of DC motor is described briefly at first. A symbolic representation of a separately- excited DC motor is shown below. The R_a,L_a represent the resistance and inductance of armature winding, and R_f, R_f represent the resistance and inductance of exciting coil respectively. R_f. R_f & I_a are the terminal voltage of armature winding and the armature current, and the exciting current respectively. U_f and I_f are the terminal voltages of exciting coil and the exciting current respectively. E_a is the electromotive force of armature winding.

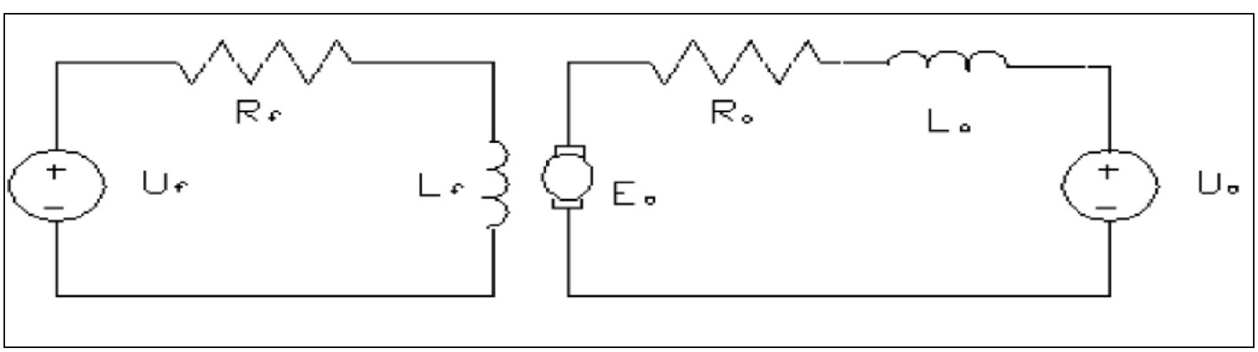

Figure 2: Equivalent Circuit Diagram of the separately-excited DC motor

The steady-state mathematical model of the DC motor is given as follow.

$$T_e = C_t \ \emptyset \ I_a \quad (10)$$

$$E_a = C_e \ \emptyset \ n \quad (11)$$

$$U_a = I_a \ R_a + R_a \quad (12)$$

Where, C_e and C_t are the electromotive force constant and torque constant respectively and torque constant respectively, and $C_t = 9.55C_e$, $\emptyset$ is the main flux linkage. *N* is the DC Motor rotational speed, T_e is the electromagnetic torque, from equation (10).

$$T_e = \frac{(U_a - C_e \ \emptyset n)C_t}{R_a} \quad (13)$$

If various losses of the DC Motor can be ignored, the electric power of the moto is equal to its mechanical output power as follows:

$$P_{do} = T_e * \omega = \frac{C_t \ \emptyset \ (U_a - C_e \ \emptyset n)\omega}{R_a} \quad (14)$$

From

$n = \frac{60\omega}{2\pi}$, it can be given that

$$P_{do} = \frac{1}{R_a} C_t \ \emptyset\left(U_a - C_e \ \emptyset \frac{60\omega}{2\pi}\right) \omega \quad (15)$$

4. Simulation Model and Result Analysis

4.1. Developed Simulink Model

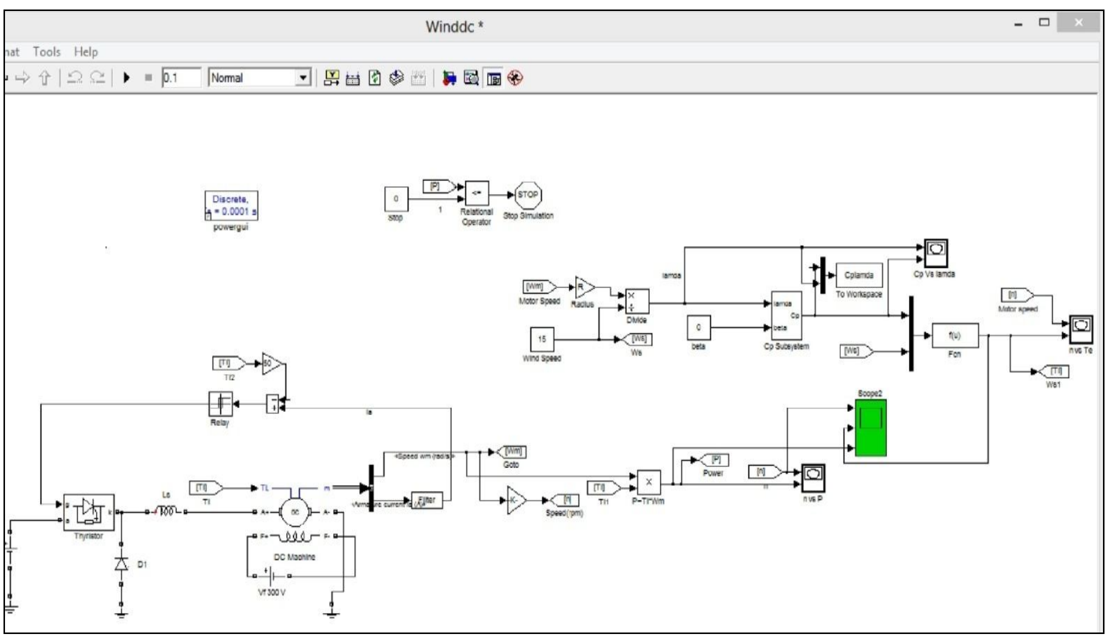

Figure 3: Simulink Model of the developed Emulation system.

4.2. Simulation Results

The Simulation work was carried out in Matlab- Simulink Environment. The simulations were made to run on two different levels of wind speed. The simulation results focused on four outcomes namely the *Te~n* Curve, *P~n* Curve, *Cp~λ* Curve and the scope output display of DC Motor Speed, Power and F(u) output characteristic at different wind speed.

- **Under different values of wind speed *v* on the curves of $T_e - n$**

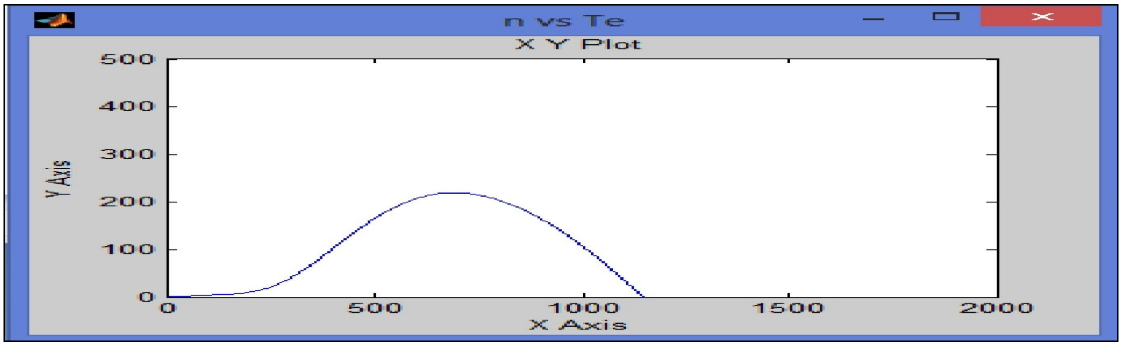

Figure 4: $T_e - n$ curve at wind speed 11 m/s

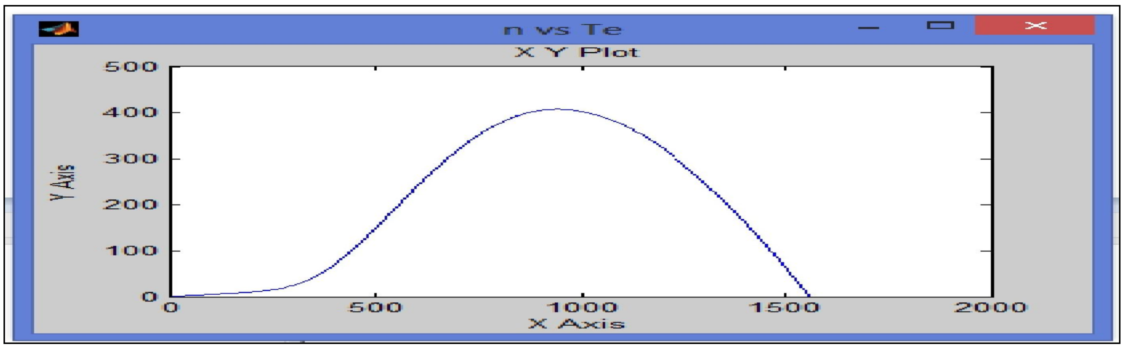

Figure 5: $T_e - n$ curve at wind speed 15 m/s

- **Under different values of wind speed v on the curves of $P_{do} - n$**

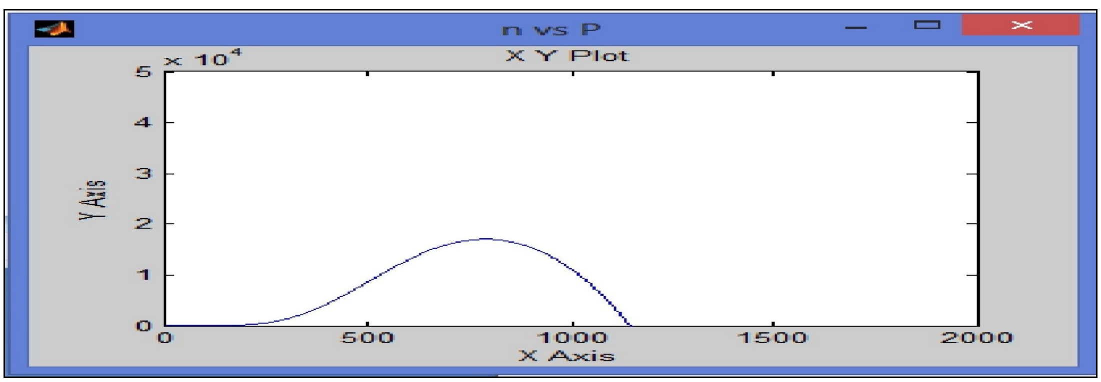

Figure 6: $P_{do} - n$ curve at wind speed 11 m/s

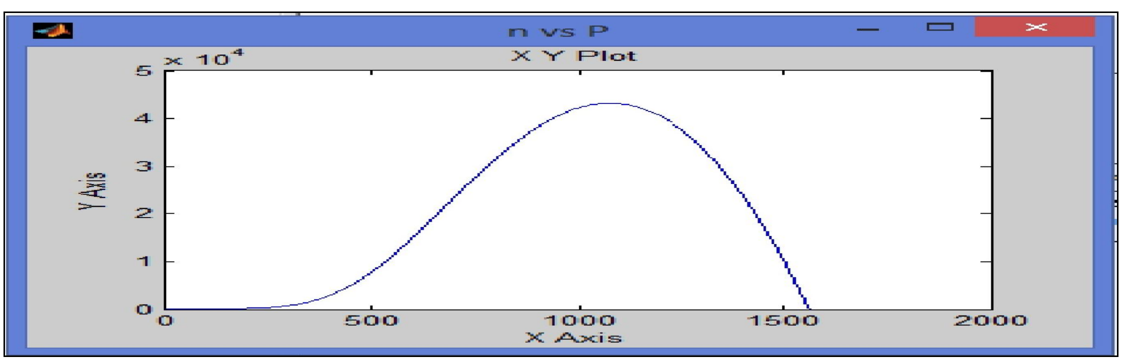

Figure 7: $P_{do} - n$ curve at wind speed 15 m/s

- **Under different values of wind speed v on the curves of $C_p - \lambda$:**

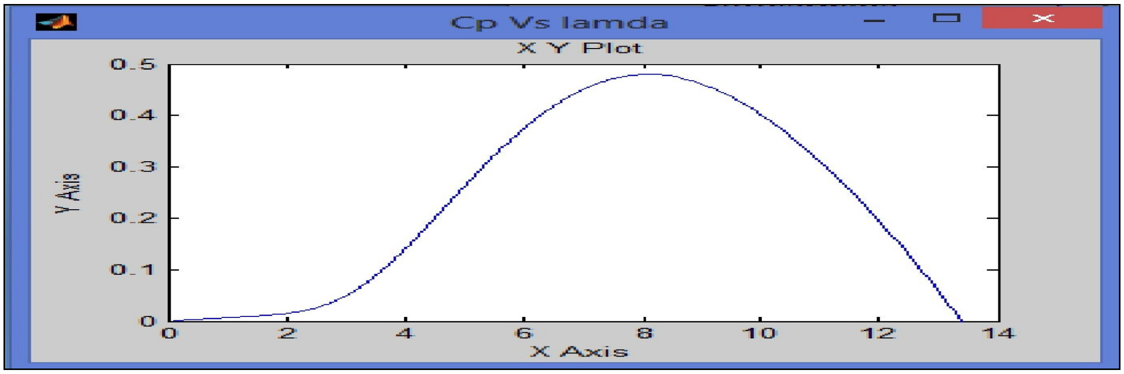

Figure 8: $C_p - \lambda$ curve at wind speed 11 m/s

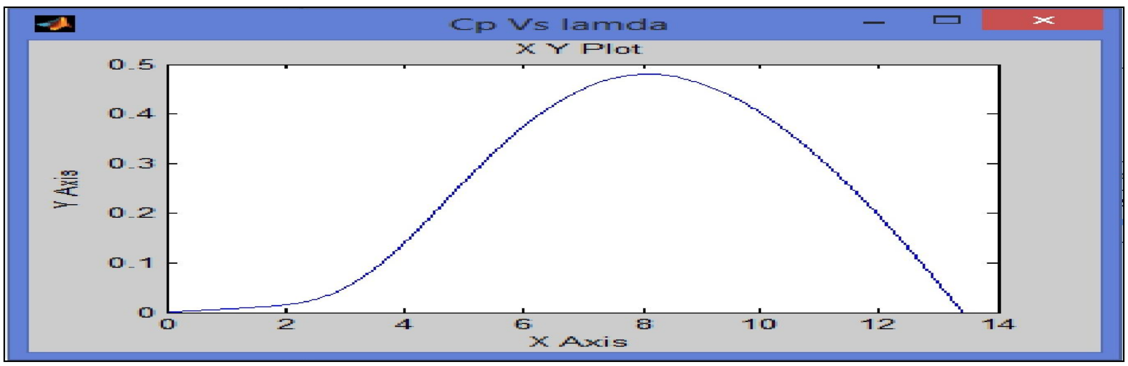

Figure 9: $C_p - \lambda$ curve at wind speed 15 m/s

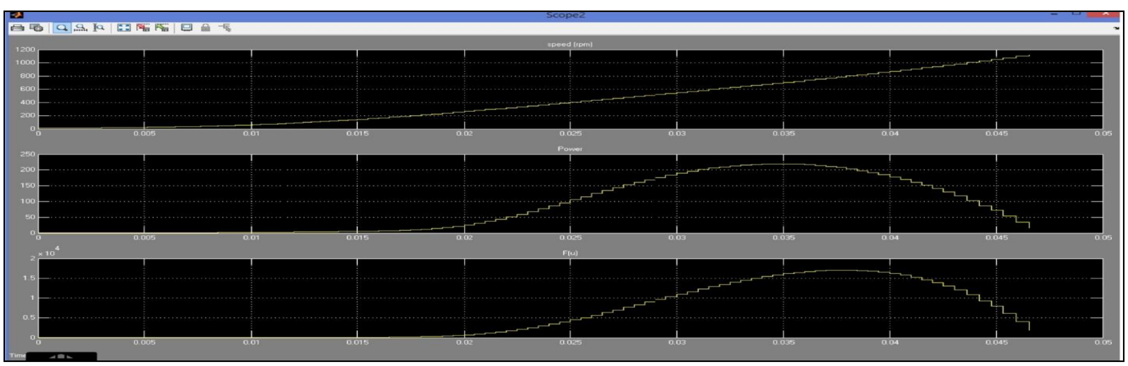

Figure 10: At wind speed 11 m/s DC Motor Speed, Power and F(u) output characteristic

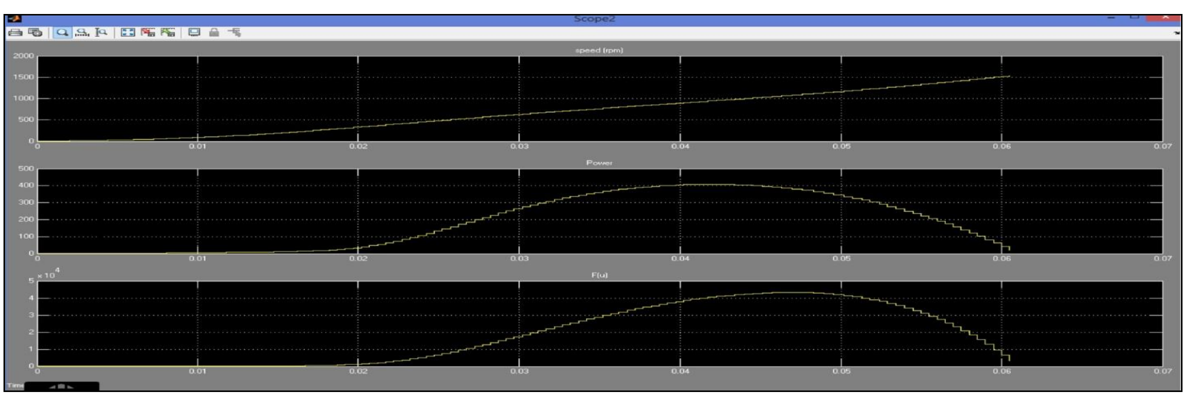

Figure 11: At wind speed 15 m/s DC Motor Speed, Power and F(u) output characteristic

5. Conclusion

Comparing simulation results of the *Te~n* and *P~n* curves of the DC motor with those of typical power and torque of the wind turbine, it can be concluded that there is almost no difference in the curves, and *Cp~λ* curves are exactly the same at different wind speed. The Simulation Results observed under the varying wind speed reflects the typical characteristic of a wind turbine so the developed Wind turbine Simulation System verifies high performance. Based on the development and experimentation thus far, the emulator in its current state provides reasonable emulation of a wind turbine system built by using a separately excited DC Motor. The developed system is highly feasible as emulator system functions for all wind speeds.

6. Future Work

The Wind Turbine Emulator designed and implemented successfully accomplished the basic turbine emulation. For significant research opportunities there is a need to legitimize this emulator as a useful development tool by validating the emulator against real-world data. Next step would be hardware implementations and further analysis regarding the characteristics of the wind turbine should be carried out. In future, to check whether the developed system has the potential of integrating small household wind turbines into micro grids.

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