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Modeling and Simulation of 1.5MW Wind Turbine

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Abstract

In this paper, the relationship between output power with respect to each one (wind speed and turbine speed). Wind turbine is used to capture the wind energy association with the wind for driving the electrical generator which in turn feeds the load. Power output of wind turbine changes in accordance to the wind disturbance. Matlab / Simulink are used to simulate this turbine.

Keywords: Wind turbine, Pitch angle, PID control, DC actuator, wind turbine.

INTRODUCTION

With the growing demand for cost-effective wind energy, optimization of wind turbine a component has been gaining increasing attention for its acknowledged contributions made to design enhancement, especially in early stages of product development. One of the major design goals is the accurate determination of structural dynamics and control, which is directly related to fatigue life and cost of energy production [1]. Pitch variable speed wind turbines have become the dominating type in recent years. There are typically two control strategies for the variable-speed wind turbines. In low wind speed below a rated value, the speed controller can continually adjust the speed of the rotor to maintain the speed at a level, which gives the maximum power coefficient, and then the efficiency of the turbine will be increased. Pitch angle regulation is required in conditions above the rated wind speed when the rotational speed is kept constant. Small changes in pitch angle can affect the power output [2]. The purpose of the pitch angle control might be expressed as follows:

- Optimizing the wind turbine power output. Below rated wind speed, the pitch setting should be at its optimum value to give maximum power.
- Preventing the mechanical power input to beat the design limits. Above rated wind speed, pitch angle control provides an effective method of regulating the aerodynamic power and loads produced by the rotor.
- Minimizing fatigue loads of the turbine mechanical component. It is clear that the action of the control system can have a major impact on the loads experienced by the turbine. The design of the controller must take into account the effect on loads, and the controller should ensure that excessive loads will not result from the control action. It is possible to go further than this, and explicitly design the controller with the reduction of certain fatigue loads as an additional objective. [3]

WIND TURBINE SPECIFICATIONS.

The shape of a 1.5 MW wind turbine is depicted in figure (1) and the specifications of this wind turbine are illustrated in table (1).

Figure 1. Wind turbine 1.5 MW.

Table 1. Specifications of wind turbine 1.5 MW.

Symbol	Quantity	Values and units
P_{DFIG}	Rated power of DFIG	1.5 MW
	Cut-in speed, cut-out speed	3 m/s, 20 m/s
w_s	Rated wind speed	11 m/s
V_s, f	Stator voltage/frequency	575 V/ 50 Hz
R_s	Stator resistance	0.023 pu
R_r	Rotor resistance	0.016 pu
L_{ls}	Stator leakage inductance	0.18 pu
L_{lr}	Rotor leakage inductance	0.16 pu
H	Generator inertia constant	0.685
V_{dc}	Nominal DC bus voltage	1150 V
	Converter rating	30 %
P_{DVR}	DVR capacity	1.5 MVA
L_{DVR}	DVR Filter inductance	0.1 mH
C_{DVR}	DVR Filter capacitance	1 μF
f_{DVR}	DVR Switching frequency	10 kHz
	DC-link voltage	300 V
	Series transformer ratio	1:1

PITCH ANGLE WIND TURBINE MODEL.

In a pitch controlled wind turbine the electronic controller of turbine checks the power output of the turbine several times per second. When the power output cross a threshold limit, it sends an actuating signal to the blade pitch mechanism which quickly turns the rotor blades slightly out of the wind. On the other hand, the blades are turned back into the wind whenever the wind goes down again. Thus the rotor blades have to be able to twist around their longitudinal axis (to pitch). This results in variation of the force exerted by the wind on the rotor shaft. The pitch mechanism is usually operated using hydraulics. The advantages of this type of control are good power control, assisted startup and emergency stop [4].

The power curve of a wind turbine shows the relationship between the electrical power output of the wind turbine and the wind speeds as shown in the figure (2).

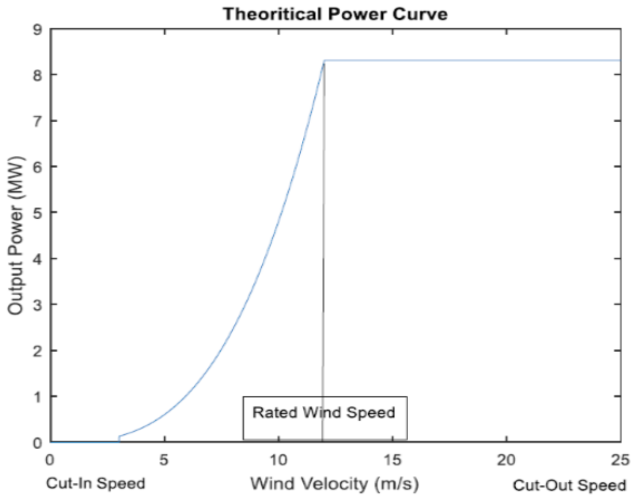


Figure 2. Power curve characteristics of a wind turbine.

The wind turbines have a 'cut -in' speed, around 3-5 m/s. This is the speed at which wind turbines are designed to start running. Below this speed of wind, the energy in wind is not sufficient to overcome the inertia of the rotor; hence, the machine does not produce any power below this speed of wind. Likewise, at high wind speeds above, say, 25 m/s, the wind turbine will be programmed to stop to avoid damaging the turbine or its surroundings. The stop wind speed is called the 'cut-out' wind speed. The "rated wind speed" is the wind speed at which the "rated power" is achieved. This value for megawatt size turbines is about 12– 15 m/s, and it corresponds to the point at which the conversion efficiency is near its maximum [5].

Wind power is proportional to the cubic of the wind speed as depicted in equations (1).

$$P = 0.5\, \rho . A . v^3 \qquad \text{………………..(1)}$$

Where,

ρ = air density (kg/m^3).

A = area swept by the blades (m^2).

v = wind speed (m/s).

The output turbine power with respect to wind speed is shown in figure (3).

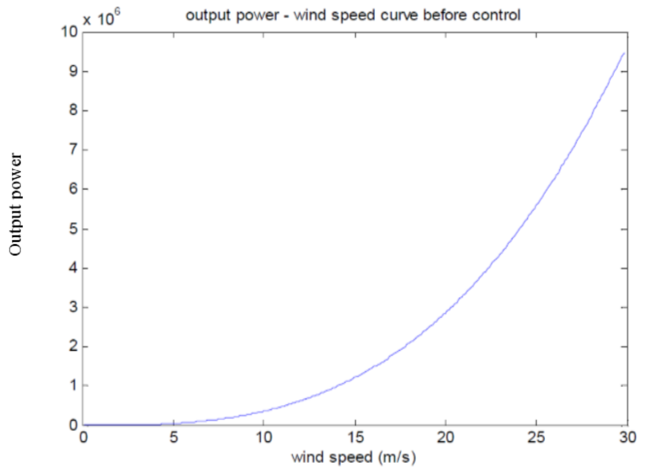


Figure 3. Power wind turbine with respect to wind speed.

A wind turbines can be turned into energy from wind power and is limited to a portion of the Betz limit cannot exceed 59%. The amount of power that can be taken from the wind turbine blades pitch angle (β) and the blade tip speed ratio (λ), the power coefficient (C_p) variation curve is given by the blade tip speed ratio [6]. Therefore, the mechanical power of the wind turbine extracted from the wind is:

$$P_{wt} = 0.5 * \rho * A * v^3 * C_p(\beta, \lambda) \qquad \text{…..……………(2)}$$

$$C_p = 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-21}{\lambda_i}} + 0.0068\lambda \qquad \text{………………..(3)}$$

Where,

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

The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed.

$$\lambda = \frac{\omega_{wt} R}{v} \qquad \text{…………………………(5)}$$

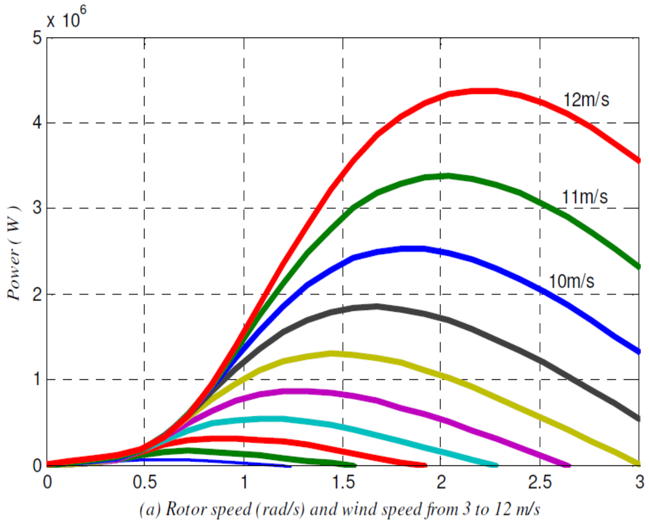
Where,

w_{wt}: tip speed ratio.

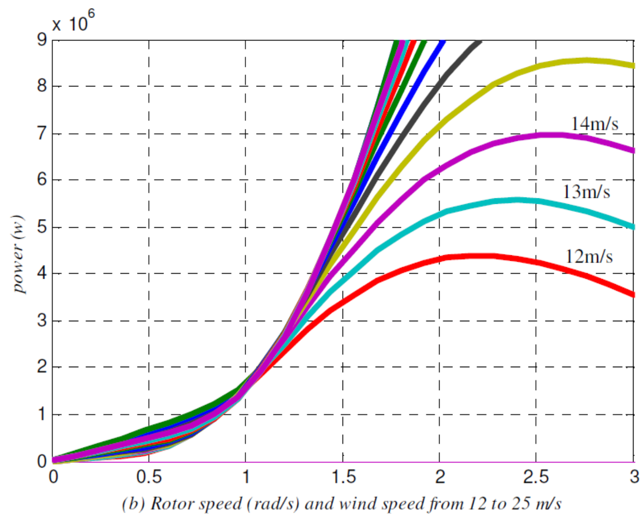
R: is the radius of the wind turbine.

Thus any change in the rotor speed or the wind speed induces a change in the tip speed ratio leading to power coefficient variation. Figure (4) shows the mechanical power for 1.5 MW wind rotor vs. rotor speed at different wind velocity.

The power extracted by the turbine increases as the wind speed increases. At rated wind speed, the generating power reaches the rated power of the turbine. If the wind speed continues to rise the output power will also increase, so the control system is required to keep the power constant at the design limit. The turbine is shut down at speed exceeding cutout wind speed for the safety consideration [2].



(a) Rotor speed (*rad/s*) Vs wind speed from 12 to 25 *m/s*.



(b) Rotor speed (*rad/s*) Vs wind speed from 12 to 25 *m/s*.

Figure 4. Wind power Vs rotor speed at different wind speed [2].

ACTUATOR MODEL

The pitch actuator consists of a mechanical and a hydraulic system, which is used to turn the blades along their longitudinal axis. The actuator model describes the dynamic behavior between a pitch demand β_d from the pitch controller and the measurement of a pitch angle β [2].

The dynamics of the blades are non-linear with saturation limits on both pitch angle and pitch rate. This saturation is caused by high frequency components of the pitch demand spectrum, via measurement noise, and spectral peaks induced by rotational sampling [1]. The change in the pitch angle is:

$$\dot{\beta} = \frac{\beta_d - \beta}{\tau_\beta} \quad \text{.......................(6)}$$

From above equation, the transfer function for the actuator is:

$$\frac{\beta}{\beta_d} = \frac{1}{\tau_\beta s + 1} \quad \text{..................... (7)}$$

Where τ_β is a time constant depends on the pitch actuator as shown in block diagram below.

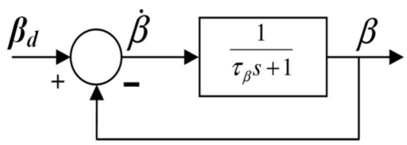


Figure 5. Actuator transfer function.

QUADRATIC CONTROL LAW.

Below rated wind speed, optimizing the power output of the wind turbine is achieved by using the torque control scheme for a variable-speed wind turbine, which is written as

$$T_{e(ref)} = \frac{P_{wt(max)}}{\omega_m} \quad \text{...................... (8)}$$

Where,

$Te_{(ref)}$: is the reference electrical torque.

$$T_{e(ref)} = \frac{0.5\rho\pi R^2 C_{p\_max} (\frac{R\omega_{wt}}{\lambda_{opt}})^3}{\omega_m} \quad \text{...................... (9)}$$

C_{p_max} is the maximum power coefficient and λ_{opt} is the tip speed ratio at C_{p_max}, Since in the steady state $\omega_m = ng\omega_{wt}$, we defined the optimal gain:

$$K_{opt} = \frac{0.5\rho\pi R_w^5 C_{p\_max}}{\lambda_{opt}^3 n_g^3} \quad \text{..................... (10)}$$

Thus, the quadratic control law can be rewritten as:

$$T_{e(ref)} = K_{opt}\omega_m^2 \quad \text{........................ (11)}$$

PI CONTROLLER GAINS

The output signal from PI controller is β_d as showing in the Figure (6), which also contains the actuator's transfer function that obtained from equation (7). Then PI controller and desired pitch angle can be expressed as follows:

$$\beta_d = K_p e + K_i \int e \, dt \quad \text{....................(12)}$$

$$e = \omega_{m\_ref} - \omega_m \qquad \text{……………………. (13)}$$

To find the solution, let:

$$x = K_i \int e\, dt \qquad \text{………………….. (14)}$$

or

$$\frac{dx}{dt} = K_i e \qquad \text{………………….. (15)}$$

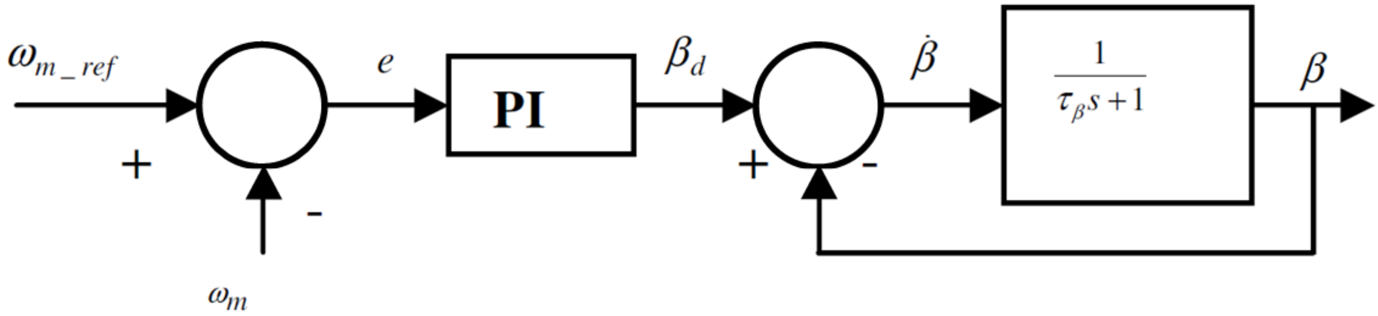


Figure 6. PI Controller.

From equations (12) and (14), the partial derivatives of β_d,

$$\frac{d\beta_d}{de} = Kp + \frac{dx}{de} = Kp + \frac{dx/dt}{de/dt} = Kp + K_i \frac{e}{\frac{de}{dt}} \qquad \text{….. (16)}$$

For an adjustable-slip asynchronous generator, the variation range of e is very small. Moreover, K_p is far greater than K_i. Hence equation (16) can be simplified as follows.

$$K_p = \frac{d\beta_d}{de} \qquad \text{……………………. (17)}$$

$d\beta_d = \beta_d$ (β_{d0} =0 (initial value)), to find the direct relation between β and β_d , we reduce inner closed loop for the actuator in Fig. (6), to the forward path, and assuming τ_β =1s. Thus, we obtain the following transfer function:

$$\frac{\beta}{\beta_d} = \frac{1}{s+2} \qquad \text{…………………….. (18)}$$

In the steady state s = 0, and $\beta_d = 2\beta$. From the equations (13, 16, and 17), the Kp and Ki are:

$$K_p = \frac{2\beta}{\omega_{m\_ref} - \omega_m} \qquad (19)$$

$$K_i = \frac{1}{\omega_{m\_ref} - \omega_m} * \left(\frac{2\beta}{\omega_{m\_ref} - \omega_m} - Kp\right) * \frac{\partial \Delta\omega}{\partial t} \qquad (20)$$

MODELING OF WIND TURBINE.

This paper selects one type of wind turbine with rated power of 1.5 MW for the simulation object using Matlab/Simulink. The simulated electrical circuit of wind turbine is illustrated in the figure (7).

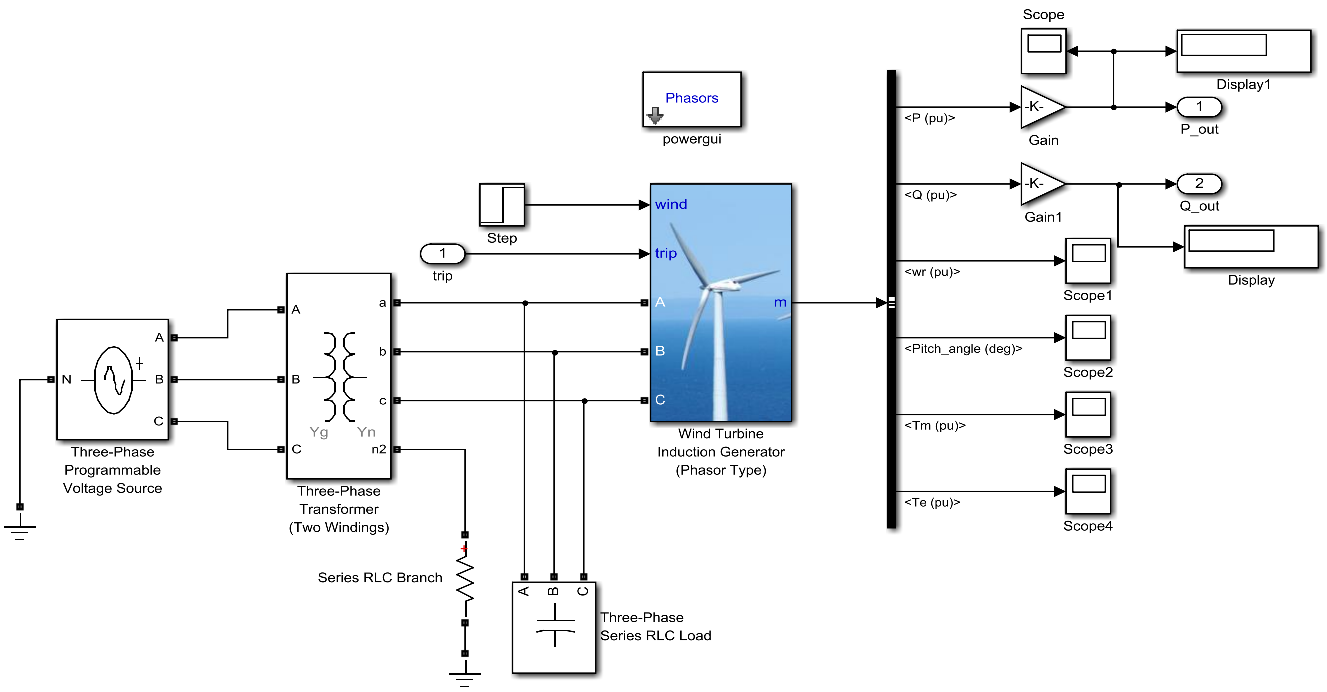


Figure 7. Electrical circuit of wind turbine.

Figure (8) represents the relationship between the wind turbine output power (MW) and the wind speed (m/s).

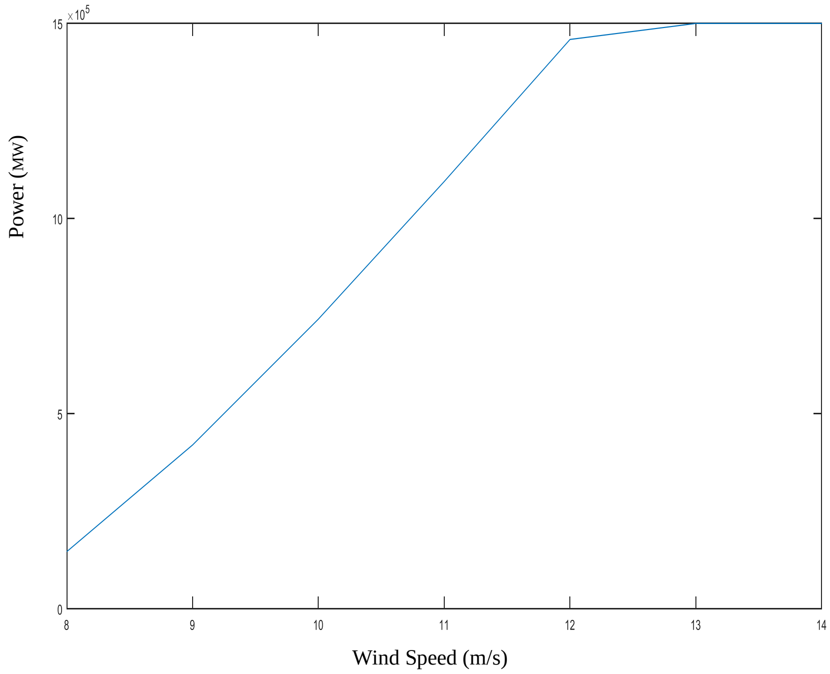


Figure 8. Output power vs wind speed.

Figure (9) represents the relationship between the wind turbine output power (MW) and the turbine (rotor) speed.

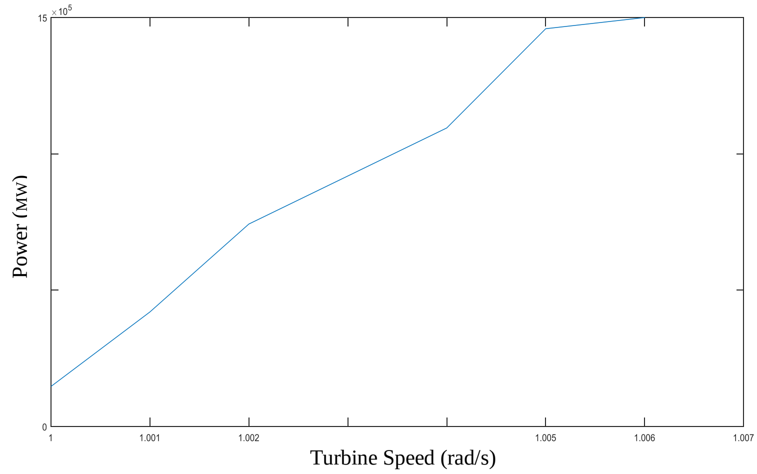


Figure 9. Output power Vs turbine speed.

Figure (10) represents the output power (Mw) response with time.

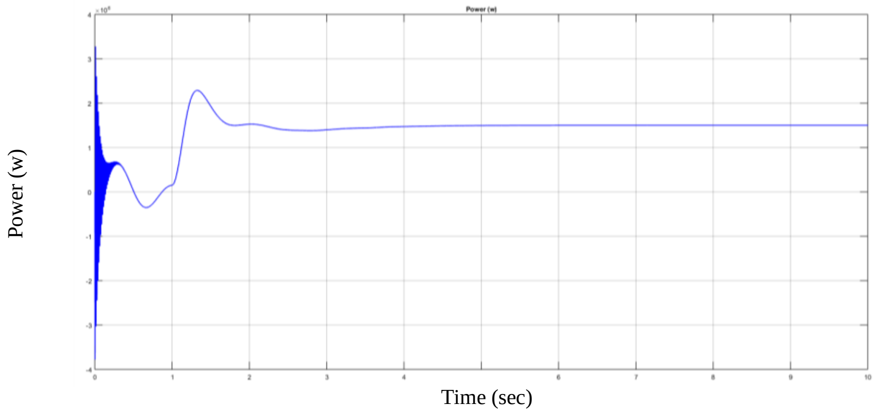


Figure 10. Output power response with time.

Figure (11) represents the turbine electrical torque with respect to time.

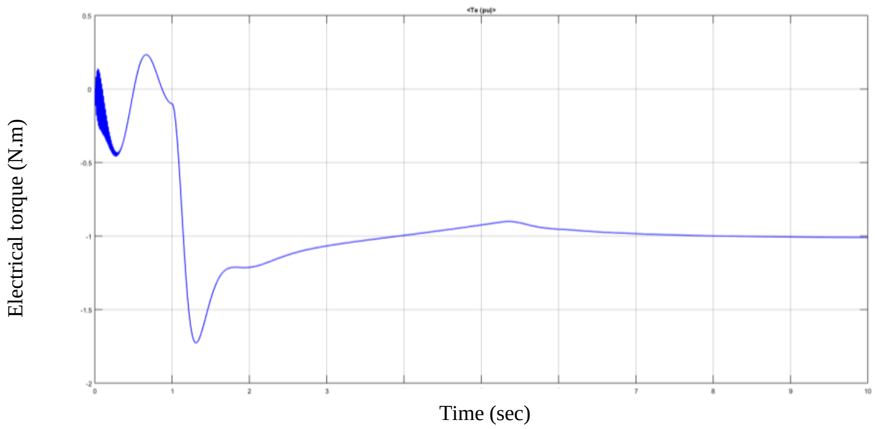


Figure 11. Turbine electrical torque variation with time.

Figure (12) represents the turbine mechanical torque with respect to time.

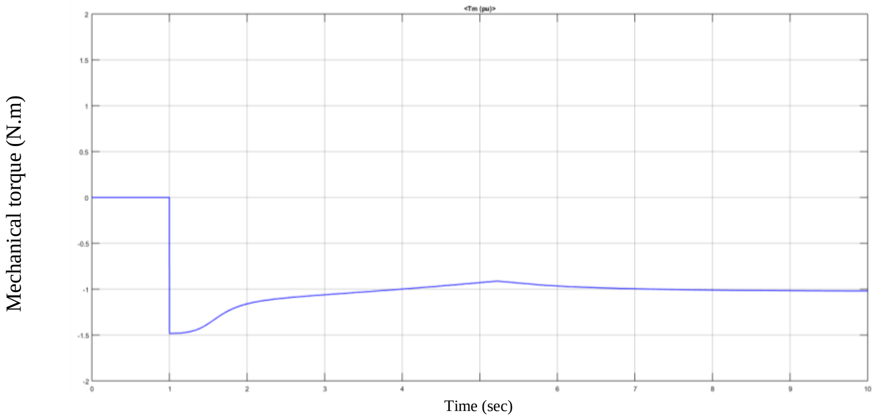


Figure 12. Turbine mechanical torque variation with time.

CONCLUSIONS:

From the relationship between the output power and the wind turbine speed we notice that the cut_in speed equal (4 m/s) and the cut_out speed equal (14 m/s). Also the output power reached the rated value at wind speed (14 m/s).

From figure (9) we observe that the behavior of power against the turbine speed curve is non-liner as compared with power against wind speed.

As compared with theoretical power curve [see pervious fig.(2)]. We conclude from figure (10) that the output power is settled at rated power (1.5 MW) after transient oscillated.

The shape of the electrical and the mechanical torque curve is approximately similar to the curve of (output power vs time) to the relationship between torque and power as cleared by general equation (Torque = Power/speed).

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