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MATHEMATICAL MODELING AND ANALYSIS OF STAND-ALONE WIND POWER GENERATION

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Abstract: This paper presents the modeling and analysis of a small wind turbine based PMDC generator for low power generation. The performance of the wind generator under various wind speed is simulated by MATLAB/SIMULINK environment and simulated results demonstrate the feasibility of the proposed system.

Key words: *WTG, PMDC, MATLAB/SIMULINK*

1. INTRODUCTION

Electrification of the remote and the rural areas is important for sustainable development of any country. But electrification of the remote areas is not techno-economically feasible. These remote areas are blessed with renewable energy sources like wind, solar, bio-mass, thus a suitable stand-alone system using locally available energy sources have become a preferred option. Traditionally there are three main types of wind turbine generators (WTGs), which can be considered for various wind turbine systems, these being direct current (DC), alternating current (AC) synchronous and alternating current (AC) asynchronous generators. In principle each can be run at fixed or variable speed. Due to the fluctuating nature of the wind power, it is advantageous to operate WTG at variable speed, which reduces the physical stress on the turbine blades and drive train [1-2]. In general, this DC WTGs are unusual in turbine application, except in low power demand situation, where the load is physically closed to the wind turbine, in heating application or in battery charging [3]. This paper mainly deals with mathematical modeling and analysis of the wind turbine, shaft and gear box, and PMDC generator.

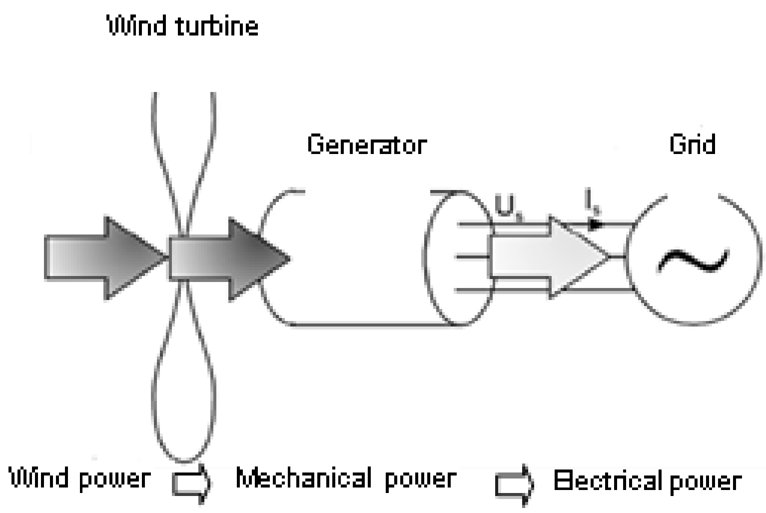

Figure 3 Schematic diagram of the wind turbine based generator

2. MATHEMATICAL MODELING OF WIND TURBINE

The mechanical power extracted from the wind by the wind turbine is given by [4]

$$P = 0.5\rho A V_w^3 C_p \tag{1}$$

where, ρ $\rightarrow$ density of air (kg/m^3), A $\rightarrow$ area swept by the blades of the wind turbine (m^2)

$V_w \rightarrow$ speed of wind (m/s), $C_p \rightarrow$ power coefficient

A generic equation can be used to model $C_p(\lambda, \beta)$. The modeling of the turbine characteristic is based on the given equation (5).

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{-\frac{C_5}{\lambda_i}} + C_6\lambda \tag{2}$$

Where,

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

$\lambda =$ tip speed ratio of the wind turbine $= \dfrac{\omega_b R}{V_w} = \dfrac{V_T}{V_w}$ $\beta =$ pitch angle of the blade of wind turbine and the coefficients C_1 to C_6 are respectively, $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, and $C_6 = 0.0068$.

The maximum theoretical value of C_p is 0.59. This is known as Betz limit. Practically, however, the maximum value of the power coefficient $C_{p(\max)} = 0.48$. This maximum value is achieved for $\beta = 0$ degree and $\lambda = 8.1$ [5].

In simulation, the pitch angle (β) of the turbine is taken as zero degree, i.e., a fixed pitch wind turbine. Hence, the mechanical power extracted from the wind turbine can be modified as

$$P = 0.5\rho A V_w^3 \left[0.5176\left(\frac{116}{\lambda} - 9.06\right) e^{-\frac{21}{\lambda}+0.735} + \frac{68\lambda}{10^4} \right] \tag{3}$$

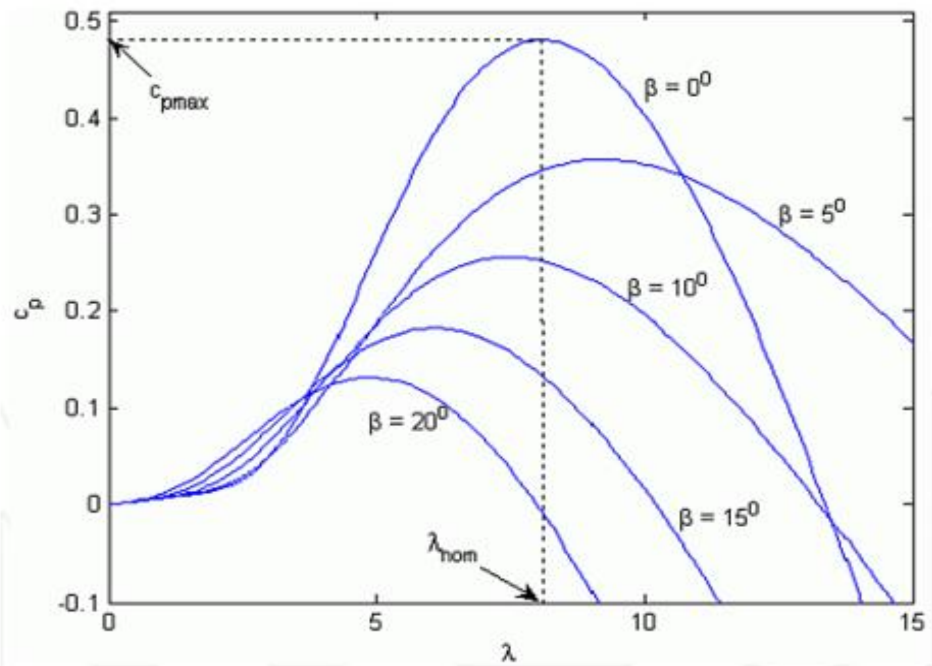

Figure 4 Cp versus λ characteristics.

3. MATHEMATICAL MODELING OF SHAFT AND GEAR BOX

The turbine is connected to the rotor of the generator through a gear box. The gear box is used to step up the low angular speed of the turbine to the high rotational speed of the generator. Figure 3 shows the shaft and the gear box model with all the torques acting on the system and the angular velocity of the different masses [8].

The turbine torque T_m (produced by the wind) accelerates the turbine inertia and is counter balanced by the shaft T_{s1} (produced by the torsional action of the low speed shaft). Thus

$$T_m - T_{s1} = J_m \frac{d\omega_b}{dt} \tag{4}$$

where, $\omega_b \rightarrow$ angular velocity of the turbine, $J_m \rightarrow$ moment of inertia of the turbine

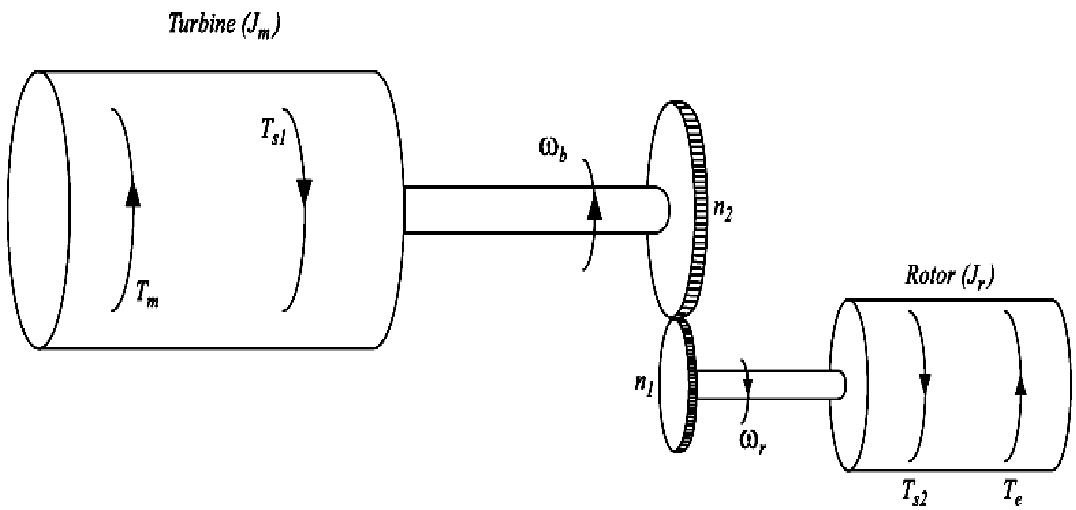

Figure 5 Shaft and gear box model.

Similarly, the shaft torque produced by the high speed shaft (T_{s2}) accelerates the rotor and is counter balanced by the electromagnetic torque (T_e) produced by the generator. Thus

$$T_{s2} - T_e = J_r \frac{d\omega_r}{dt} \tag{5}$$

where, $\omega_r \rightarrow$ angular velocity of the rotor, $J_r \rightarrow$ moment of inertia of the rotor

Assuming that the gear box is ideal, with no backlash or losses and the shafts are rigid, it satisfies the relation

$$\frac{T_{s1}}{T_{s2}} = \frac{\omega_r}{\omega_b} = \frac{n_1}{n_2} \tag{6}$$

Where, $\frac{n_1}{n_2}$ = gear box ratio

Eliminating the shaft torque from Eqs. (4) and (5), we get

$$T_m\left(\frac{n_2}{n_1}\right) - T_e = \left[J_m\left(\frac{n_2}{n_1}\right)^2 + J_r\right]\frac{d\omega_r}{dt} \tag{7}$$

4. MATHEMATICAL MODELING OF PMDC GENERATOR

The PMDC generator consists of stator having rare earth permanent magnets such as Neodymium or Samarium cobalt to produce a very strong stator field flux instead of field coils and a commutator connected through brushes to a wound armature. The PMDC generators are generally light in weight, more reliable, higher efficiency and can operate at low operational speeds. There are no field windings in stator, therefore the field coil losses are zero [6].

The total generated voltage from the PMDC generator is given by

$$E_g = k_g\, w_r\, \varphi \tag{8}$$

where, $w_r \rightarrow$ speed of the generator (r.p.m), $\varphi \rightarrow$ stator flux (Wb/m^2), $k_g \rightarrow$ voltage constant

The terminal voltage from the generator is given by

$$V_t = E_g - L_a \frac{dI_a}{dt} - R_a I_a \tag{9}$$

where, $L_a \rightarrow$ armature inductance (H), $R_a \rightarrow$ armature resistance (Ω), $I_a \rightarrow$ armature current (A)

The load torque is written as

$$T_l = k_L \varphi\, I_a \tag{10}$$

where, $k_L \rightarrow$ the load torque constant (N-m/A), The shaft torque is related by moment of inertia (J) and viscous friction (B) of the generator and is given by

$$T_{shaft} = T_l + J\frac{dw_r}{dt} + B\,w_r \tag{11}$$

Therefore,

$$\frac{dw_r}{dt} = \frac{1}{J}\left(T_{shaft} - T_l - B\,w_r\right) \tag{12}$$

5. SIMULATION AND RESULTS

The different Simulink models of the wind generator set are listed below:

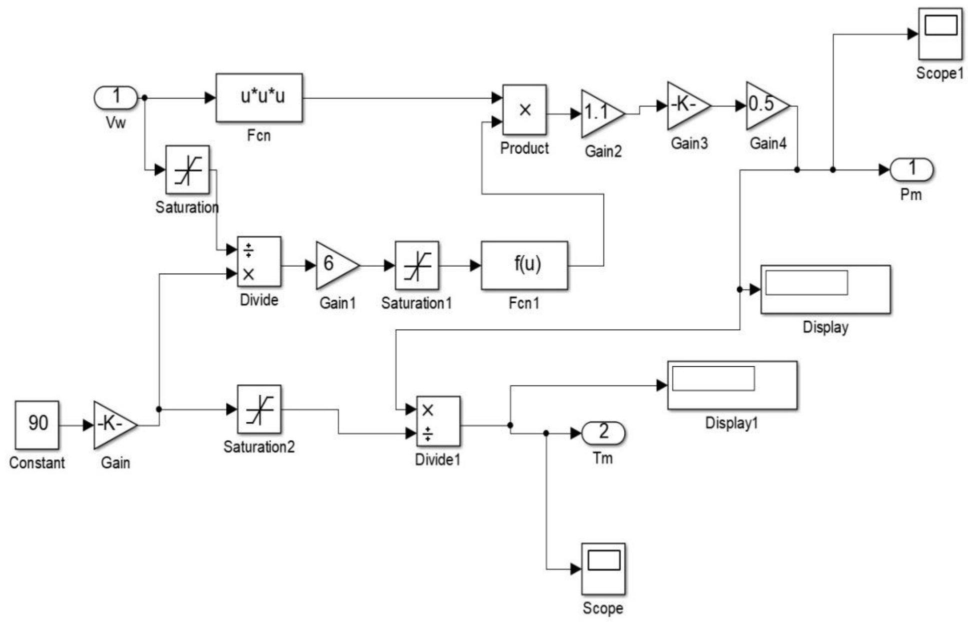

Figure 6 Simulink Model of the Turbine

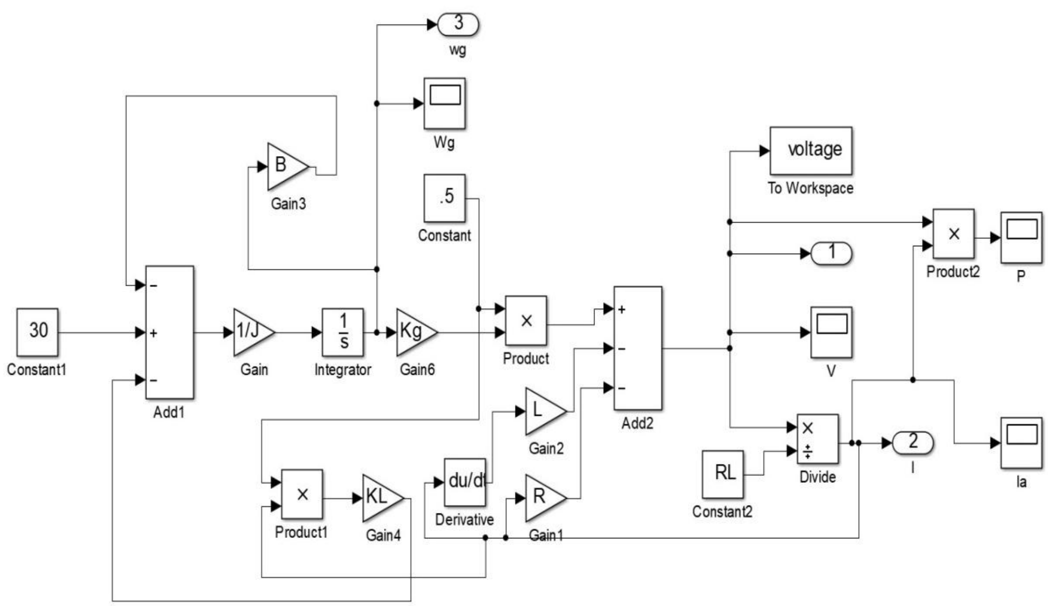

Figure 7 Simulink Model of the Generator

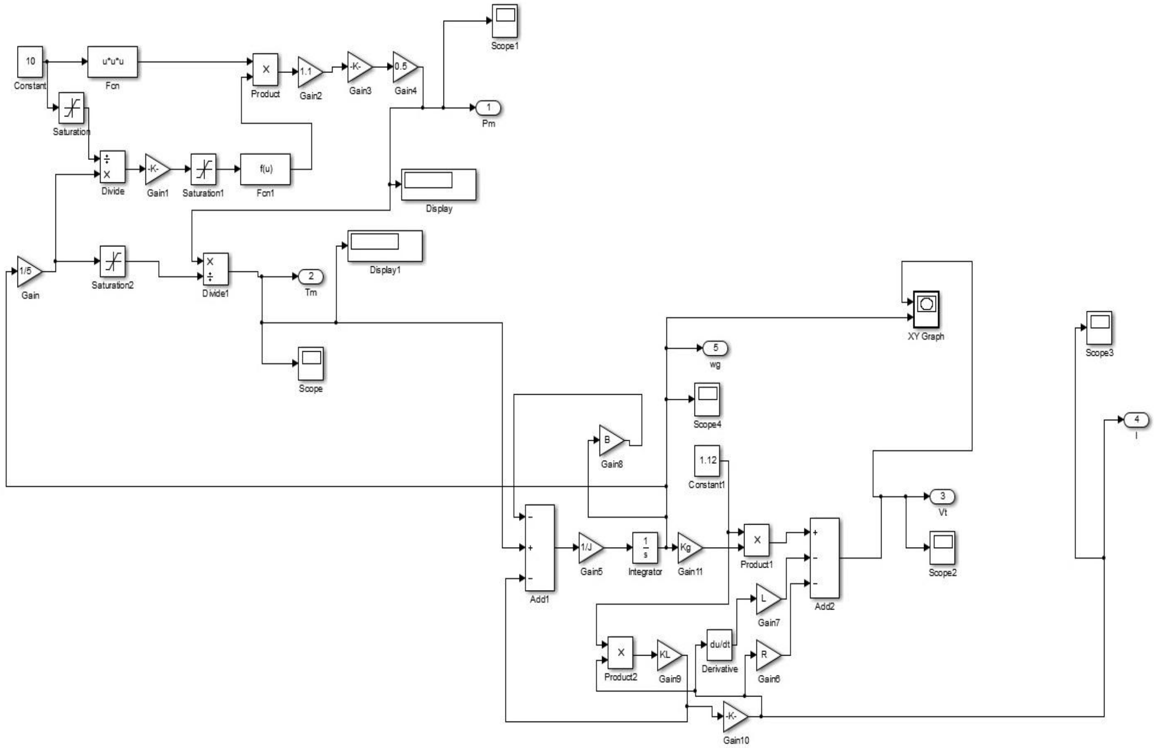

Figure 8 Simulink Model of the Turbine Generator set

Simulation has been carried out at MATLAB/SIMULINK environment by varying wind speed from 6m/sec to 12m/sec and different results have been recorded in terms of current (I), voltage (V) and power (P) in fig. 7 and fig 8 with the help of the listed below parameters value.

Table: 1 (Different parameters of the wind generator set used for MATLAB/SIMULATION)

Parameter	Value
Moment of Inertia (J) of the Generator	0.01 kg m^2
Viscus Friction (B) of the Generator	0.1
Armature Resistance (R) of the Generator	1 ohm
Armature Inductance (L) of the Generator	0.4 H
Voltage Constant (K_g) of the Generator	0.27
Load Torque Constant (K_L) of the Generator	0.11 N-m/A

Load Resistance across Generator (R_L)	3 ohm
Number of Blade of the Turbine	3
Radius of the Turbine Blade	0.65 m
Flux Density of each Pole of the Generator	1.12 T

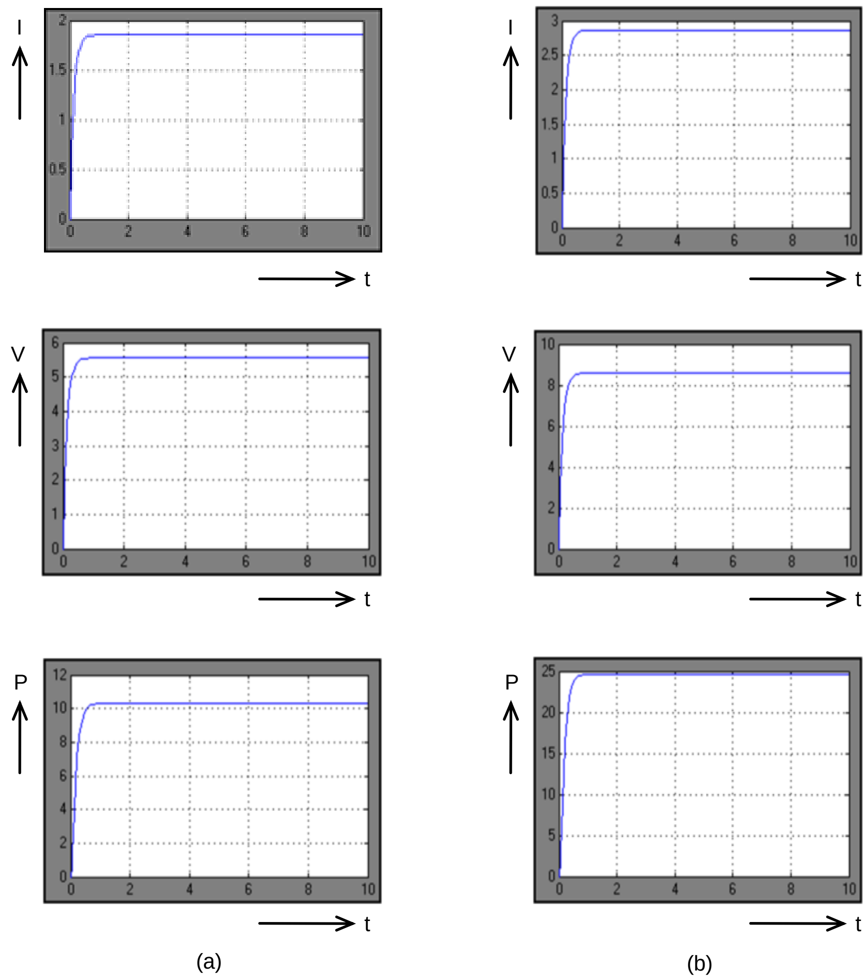

Figure 9Simulated results of wind speed at a) 6 m/s, and b) 8 m/s

X axis: Voltage (V), Current (I) , Power (P) & Y axis: Time (t)

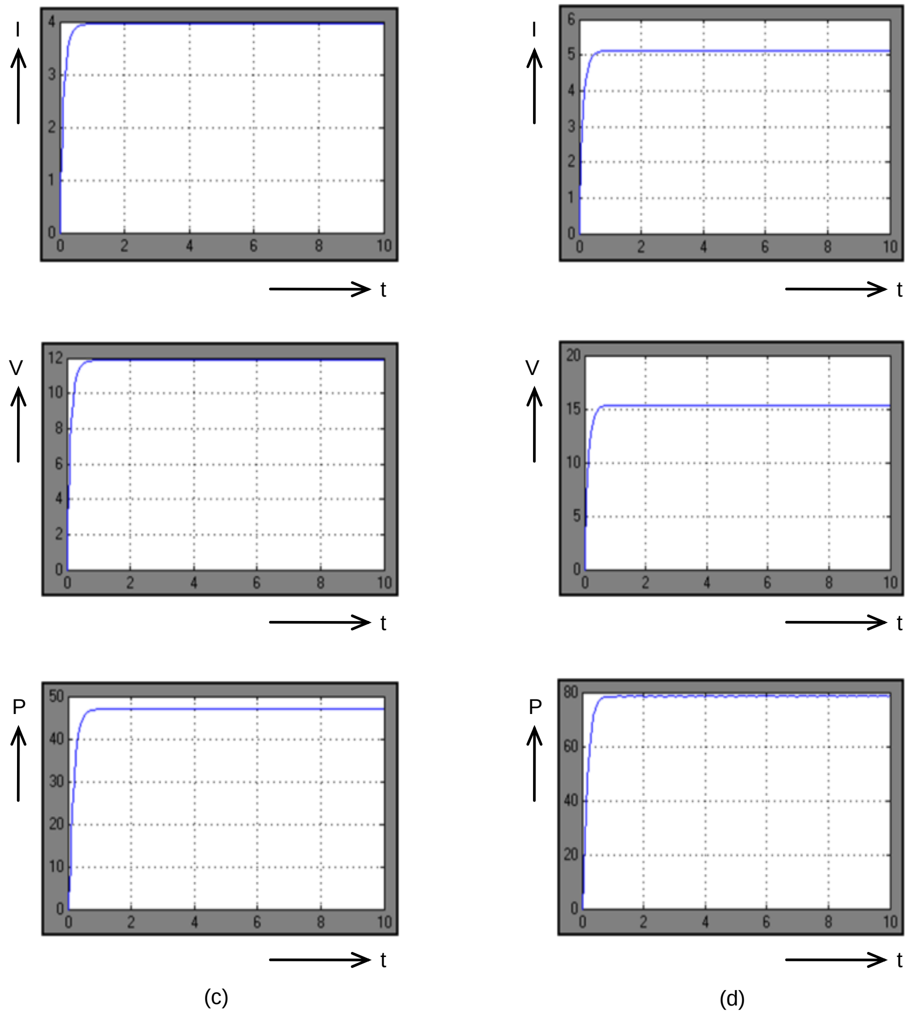

Figure 10Simulated results of wind speed at c) 10 m/s, and d) 12 m/s.

X Axis: Voltage (V), Current (I), Power (P) & Y Axis: Time (t)

The result has shown that at low wind speed the wind-generator set is developing very less power whereas at very high wind speed, it is developing better power.

6. CONCLUSION

The detail mathematical model of PMDC generator for wind turbine has been developed and simulation has been carried out. The analysis has revealed that with the given specifications, it can produce power up to 150 watts. By incorporating a charge controller and a suitable converter, it is possible to achieve applications such as battery charging, water heating and so on.

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