



Dynamic Model and Simulation of Wind Energy Conversion System based on Permanent Magnet Synchronous Generator

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ABSTRACT: In modern wind turbines, the energy conversion process uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting first in the production of mechanical power and then its conversion to electricity in a generator. Wind turbines, unlike most other turbines, can produce power only in response to the wind that is available at the time. The output of a wind turbine is thus inherently fluctuating with the wind and can't be directly dispatched for a purpose. Apart from this, the output depends on individual components like rotor dimension, transmission shaft, gear box and alternator. Since the wind turbine is relatively large, expensive, and Wind Energy Conversion System (WECS) is complex, it is not convenient to do research on actual wind farm. Therefore, WECS model development for steady and dynamic state analysis and design has been research issue in recent years. This paper presents a new block-based approach for WECS dynamic modeling. The blocks (modules) developed by Aalborg University - Denmark, RISO national laboratory based on Kaimal Spectra have been customized, updated and integrated into MATLAB/SIMULINK platform and then utilized to simulate performance of 5kW WECS. In addition to the developed block sets, in this paper, a proportional-integral controller is designed to control the turbine pitch and integrated with the simulation models. The simulation result demonstrates that the model output is in agreement with what is expected. The system has advantages like: research cost reduction, ease in application and control, flexibility and completeness for analysis in MATLAB/SIMULINK environment. The system can be used for assessment of power quality and design of wind turbine system for grid connection.

KEYWORDS: Wind Energy Conversion system (WECS), Permanent Magnet Synchronous Generator (PMSG), Wind Energy Block Set (WEBS), Modelling and Simulation, MATLAB/SIMULINK

I.INTRODUCTION

Over the past few years, wind energy has shown the fastest rate of growth of any form of electricity generation with its development stimulated by concerns of national policy makers over climate change, energy diversity and security of supply. Energy shortage and environmental pollution are the important problems for the human lives and social development. Traditional mineral energy such as coal, oil and gas will be used out in a few years and will cause serious environmental problems. Hence, the use of cost effective and reliable low carbon electricity generation sources, in addition to demand side measures, is becoming an important objective of energy policy in many countries (EWEA, 2006; AWEA, 2007) [10]. So the renewable energy, especially wind energy has become more and more considerable all over the world.

In the wind energy conversion system, the wind turbine captures the wind energy and then the generator converts it to the electrical power. To understand how wind turbines are used, it is useful to briefly consider some of the fundamental facts underlying their operation. In modern wind turbines, the actual conversion process uses the basic aerodynamic force of lift to produce a net positive torque on a rotating shaft, resulting first in the production of mechanical power and then in its transformation to electricity in a generator. Wind turbines, unlike most other generators, can produce energy only in response to the resource that is immediately available. The output of a wind turbine is thus inherently fluctuating and non dispatchable [8].

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Wind is variable in nature and output of wind energy conversion system is highly dependent on wind velocity. Apart from this, the output also depends on individual components like rotor dimension, transmission shaft, gear box and alternator. Therefore, the characteristic of the wind turbine is very important. A few research works about wind turbine simulator have been done in the past few years. As stated in Ref. [14] a wind turbine simulator based on a DC machine in which the armature and the field current were controlled so that the DC machine can generate the static characteristics of a wind turbine. The other one is, a wind turbine simulator based on SCR-DC motor controlled by a microcomputer. But, in both cases the DC machine is big, expensive and it need to frequent maintenance because of brushes compared with an AC machine. Then, Ref. [7] presented an IGBT inverter-controlled squirrel cage induction motor instead of a DC motor. In the other hand, several studies have been conducted worldwide on characterization of wind speed data and size matching of wind turbine generators. It is also observed from literatures that mathematical models of few individual components of WECS are represented and simulated for better understanding of their performances [3]. However, integrated dynamic models of WECS are necessary for performance analysis and evaluation of the overall system.

This paper presents block based dynamic modelling and simulation of Wind Energy Conversion System (WECS) which includes the wind model, wind turbine model, gear box model and the permanent magnet synchronous machine model. Here, the dynamic behaviour of wind energy conversion system (WECS) has been simulated in the MATLAB/SIMULINK platform by integrating wind turbine block sets developed by RISO national laboratory based on Kaimal Spectra [4].

II. WIND ENERGY CONVERSION SYSTEM BLOCK MODEL DESCRIPTION

2.1 General

Wind energy conversion system is a complex system requiring multidisciplinary approach. Its understanding and analysis requires aerodynamics, mechanical, civil and electrical engineering disciplines. Therefore, it is usually rare to get a complete system model for analysis and design of the whole system. Modularized modeling simplifies the analysis and understanding of the overall system. The wind turbine consisting of two or more blades captures the kinetic energy of the wind to convert it to mechanical energy. Aerodynamics can be used to understand and analyze the conversion mechanism. The gearbox between the turbine and the electric generator is used to increase the rotational speed of the electric machine from the generally slow speed of the turbine. It is also used to smoothen the mechanical fast wind speed variation.

In WECS with permanent magnet synchronous generator gearboxes are replaced by a large number of poles. The frequency of the generated power is the turbine speed multiplied by the pole pairs. In this work the gearbox module is included for completeness. The generator coupled with the wind turbine converts the mechanical energy to electrical energy. The electric power terminal variables are controlled to desired values using static power convertors in case of synchronous generators and doubly fed induction generators (DFIG). There are also monitoring, control and protection systems both on mechanical and electrical modules of the WECS.

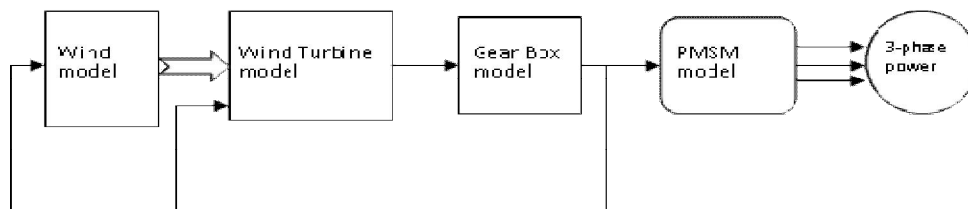


Fig. 2.1 General block diagram of WECS

Block diagram of wind energy conversion system model is shown in Figure 2.1. The four blocks of the model are represented by; wind model, wind turbine model, gearbox model and permanent magnet synchronous generator model. There is a synchronous generator speed feedback to the wind turbine model, which incorporates the pitch control system and a feed forward of the wind speed.



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2.2 Wind Model

Wind models are available in two basic versions. The first one is normally distributed white noise generator available in MATLAB/SIMULINK, while the other is new normally distributed white noise generator model which has been developed at RISO national laboratory based on the Kaimal spectra. In the new model, the wind speed is calculated as an average value of the fixed-point wind speed over the whole rotor, and it takes the tower shadow and the rotational turbulence into account [15]. In order to obtain the same wind time series in all considered simulation tools, it has been found that the built-in white noise generator from different simulation tools use different algorithm and thus different time series is obtained. The parameters defined in the block's mask are: rotor diameter of the wind turbine, average wind speed, length scale, turbulence intensity and sample time with values as shown in Table-1.

Table-1 Parameters of Wind model

Parameter	Value
Rotor blade diameter	6 meters
Average wind speed	11 meter/second
Length scale	100 meters
Turbulence intensity	2%
Sample time	0.01sec

2.3 Wind Turbine Model

The relation between the power and wind speed is derived with the identification of the wind turbines input and output variables [9]. Accordingly, the kinetic energy in air of mass m moving with speed V is given by the following expression:

$$\text{Kinetic energy} = \frac{1}{2}mV^2 \text{ [Joules]} \quad (1)$$

The power in moving air flow is the flow rate of kinetic energy per second.

$$P = \frac{1}{2} (\text{mass flow rate per second}) V^2 \quad (2)$$

The actual power extracted by the rotor blades is the difference between the upstream and the downstream wind powers. Therefore, equations (2) results in;

$$P = \frac{1}{2}(\text{Mass flow rate per second}) \times (V^2 - V_0^2) \quad (3)$$

Where:

P -The Mechanical Power extracted by the rotor in watts.

V - The upstream wind speed at the entrance of the rotor blades in m/s.

V_0 - The downstream wind velocity at the exit of the rotor blades in m/s.

Let ρ be the air density in (kg/m^3) and A is the area swept by the rotor blades in (m^2); then, the mass flow rate of air through the rotating blades is given by multiplying the air density with the average velocity.

$$\text{Mass flow rate} = \rho \cdot A \frac{V+V_0}{2} \quad (4)$$

Then, equation (3) can be expressed by

$$P = \frac{1}{2} \left[\rho \cdot A \left(\frac{V+V_0}{2} \right) \right] (V^2 - V_0^2) \quad (5)$$

After rearrangement of the terms we have:

$$P = \frac{1}{2} \rho \cdot A \cdot V^3 C_p \quad (6)$$

Where: $C_p = \frac{(1+\frac{V_0}{V})[1-(\frac{V_0}{V})^2]}{2}$

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C_p is the fraction of the upstream wind power, which is captured by the rotor blades and has a theoretical maximum value of 0.59. It is also referred as the power coefficient of the rotor or the rotor efficiency. In practical designs, the maximum achievable C_p is between 0.4 and 0.5 for high-speed, two- blade turbines and between 0.2 and 0.4 for slow-speed turbines with more blades [13].

It is also conventional to define a tip – speed ratio λ , as:
$$\lambda = \frac{\omega R}{V} \tag{7}$$

Where: ω - rotational speed of rotor,
 R - Radius to tip of rotor,
 V - Upward free wind speed, m/s

The tip-speed ratio λ , and the power coefficient C_p , are dimensionless and so can be used to describe the performance of any size of wind turbine rotor. Hence, one argument for operating a wind turbine at variable rotational speed is that it is possible to operate at maximum C_p over a range of wind speed [10]. The aerodynamic model of the wind turbine is based on the torque coefficient C_Q or the power coefficient C_p look up table. The torque coefficient C_Q is used to determine the aerodynamic torque (T_{wt}) directly by using:

$$T_{wt} = 0.5\pi\rho R^3 V^2 C_Q \tag{8}$$

Where: ρ is the air density, R is the blade radius, V is the wind speed and C_Q is the torque coefficient. Alternatively, the aerodynamic torque can be determined by using the power coefficient C_p based on:

$$T_{wt} = 0.5\pi\rho R^3 V^2 C_p \tag{9}$$

Here, it is important to underline that both coefficient C_p and C_Q can be function of the tip speed ratio λ for passive stall wind turbines or function of tip speed ratio λ and pitch angle θ for active and variable pitch/ speed wind turbines [4]. The Simulink model for the variable pitch wind turbine rotor developed by RISO is presented in fig.2.2.

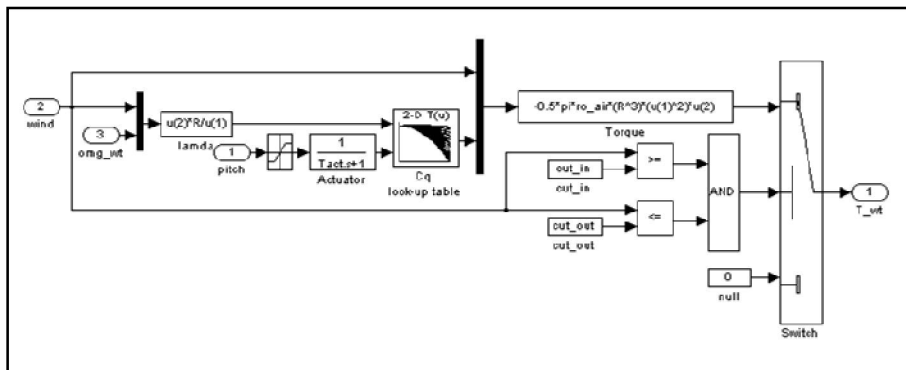


Fig. 2.2 Simulink model of the wind turbine rotor [4].

Parameters of the wind turbine rotor aerodynamic model are blade radius, air density, cut-in speed and cutout speed whose values are given in table-2.

Table-2 Parameters of wind turbine model

Parameter	Value
Blade radius	3 meters
Air density	1.23 kg/m ³
Cut-in speed	3 meter/second
Cut-out speed	25 meter/second

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2.4 Gearbox Model

Most wind turbine drive trains include a gearbox to increase the speed of the input shaft to the generator. An increase in speed is needed because wind turbine rotors, and hence main shafts, turn at a much lower than it is required by most electrical generators. Small wind turbine rotors run at speeds on the order of a few hundred rpm, while large wind turbines run more slowly [8]. Based on the speed-up ratio of a gearbox and number of stages, gearbox model can be categorized as a single mass, two mass and three mass models [4].

The equivalent physical model considered for the representation of the mechanical transmission system dynamics is shown in fig.2.3. The mechanical transmission includes mass of wind turbine rotor, mass of the gearbox wheels and mass of generator respectively. Parameters to be provided to the gearbox model are electric generator moment of inertia, wind turbine moment of inertia, gearbox ratio and initial condition for state variables. The values of these variables are given in Table 3.

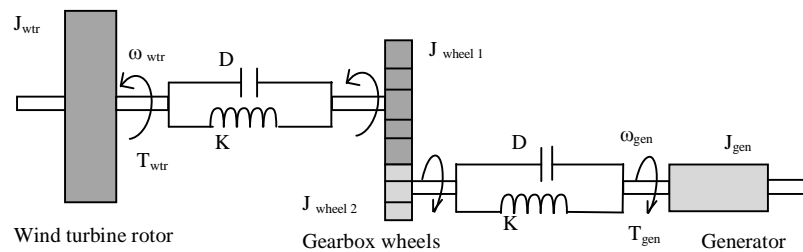


Fig.2.3 A three-mass arrangement of wind turbine drive train.

Table-3: Parameters of gearbox model

Parameter	Value
Electric machine moment of inertia	0.028kg.m ²
Wind turbine moment of inertia	72 kg.m ²
Gear box ratio	20
State variables initial condition	0

This, the three-mass model can be reduced to a two mass model by considering an equivalent system with an equivalent stiffness (K) and damping factor (D) for both low speed and high speed shafts. The moment of inertia for the shafts and the gearbox wheels can be neglected because they are small compared with the moment of inertia of the wind turbine or generator. When the stiffness and the damping factor are neglected further reduction of the drive train model can be obtained. Then, the one-mass model which is obtained in this case can be described by:

$$T_{wtr} - T_{gen} = J_{eqv} \frac{d\omega_{gen}}{dt} \quad (10)$$

In which, the equivalent moment of inertia is

$$J_{eqv} = J_{gen} + \frac{J_{wtr}}{K_{gear}^2}, \quad \text{and the equivalent wind turbine torque is } T'_{wtr} = \frac{T_{wtr}}{K_{gear}}, \quad \text{where: } K_{gear} \text{ - the gearbox ratio.}$$

The Simulink implementation of (10) developed by RISO is presented in fig .2.4.

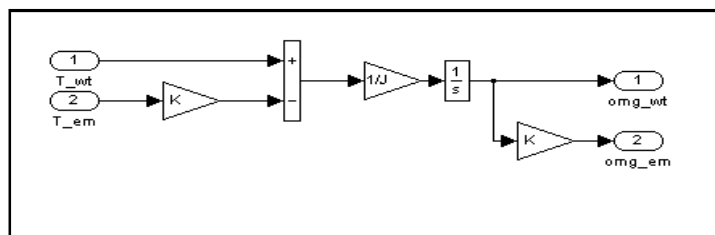


Fig.2.4 One-mass Simulink model for the turbine drive train [4].

2.5 Permanent Magnet Synchronous Generator Model

The analysis of permanent magnet (PM) synchronous machines can be made using a quadrature equivalent circuit where the damping windings are replaced with two equivalent windings D&Q in direct and quadrature axis respectively. The permanent magnet is replaced with an equivalent superconductor winding placed in the direct-axis and the current through the equivalent winding of the permanent magnet (I_f) is taken as constant in all mode of operation.

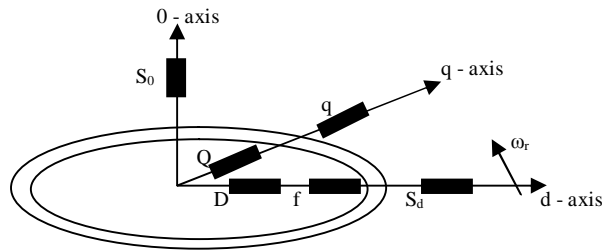


Fig.2.5 Schematic for the transformed model of PMSM in the $dq0$ rotor reference frame [4].

The voltage equation for PM synchronous machine in $dq0$ rotor reference frame can be written as [4]:

$$\begin{aligned}
 U_{sd} &= R_s i_{sd} + \frac{d\Psi_{sd}}{dt} - \omega_r \Psi_{sq} \\
 U_D &= R_D i_D + \frac{d\Psi_D}{dt} \\
 U_{sq} &= R_s i_{sq} + \frac{d\Psi_{sq}}{dt} + \omega_r \Psi_{sd} \\
 U_Q &= R_Q i_Q + \frac{d\Psi_Q}{dt} \\
 U_{s0} &= R_s i_{s0} + \frac{d\Psi_{s0}}{dt}
 \end{aligned}
 \tag{11}$$

Then, the general expression of the electromagnetic torque is given by:

$$T_e = \frac{3}{2} P (\Psi_{sd} i_{sq} - \Psi_{sq} i_{sd}) \tag{12}$$

The Simulink implementation of the model developed by RISO is based on (11) and (12). The model takes into account the iron losses as well as the parameters variation with the operating temperature. The synchronous electric motor parameters are stator winding resistance, direct axis inductance, quadrature axis inductance, magnetic flux per pole, pole pairs, and ambient temperature whose values are given in table-4.

Table-4 Parameters of Synchronous Generator

Parameters	Values
Stator winding resistance	0.01 [Ohm]
D-axis inductance	0.025[H]
Q-axis inductance	0.015[H]
Magnetic flux	0.504[Wb]
Pole pairs	1
Temperature	55 ⁰ C

2.6 Pitch control model

In addition to the block-sets developed by Aalborg University, in this paper, a subsystem (fig.2.6) has been integrated with the wind energy conversion system block models to facilitate the required pitch angle for the wind turbine model. The wind turbine speed is used as a feedback to the pitch controller and to the wind model. The wind model requires the turbine speed to calculate the mechanical energy which can be generated by the turbine while the PI controller adjusts the pitch angle depending on the turbine speed.

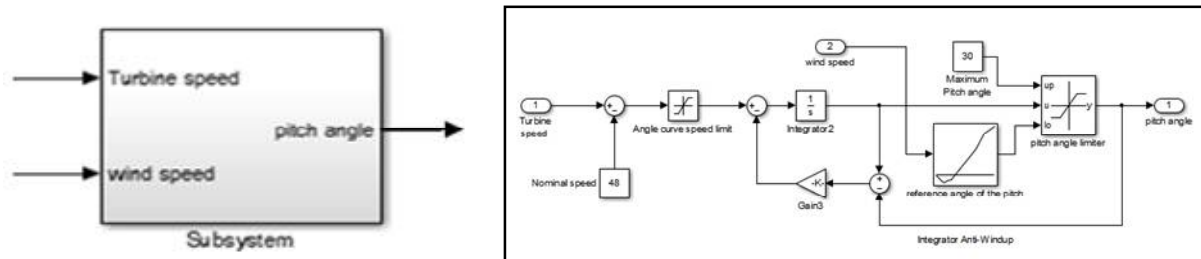


Fig. 2.6 Anti-wind up Pitch control model

The designed pitch control model adjusts the turbine blade pitch angle in the range of -4° to 30° with respect to the input values of wind and turbine speeds. In accordance to the given reference pitch angle, -4° pitch angle is taken as a value for turbines working below the nominal power. As speed increases, to limit the power and protect the turbine, the pitch angle will increase up to 30° depending upon the wind speed variation.

III. SYSTEM SIMULATION AND RESULT

Fig.3.1 is the general block diagram arrangement of a 5kW wind energy conversion system simulated using the developed model.

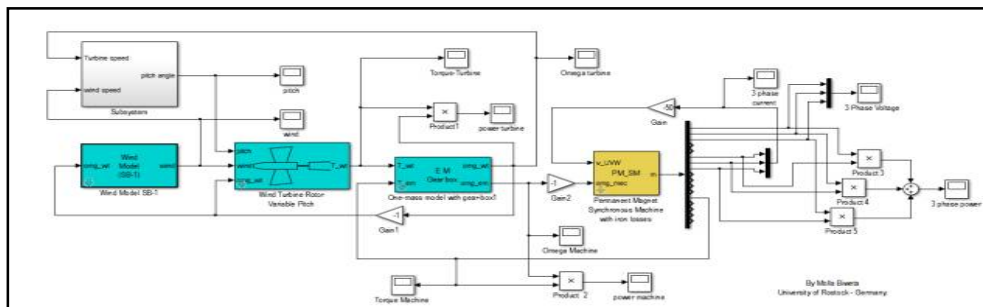


Fig. 3.1 Block diagram of 5 kW wind energy conversion system.

As shown in fig.3.1, the wind turbine model has the random wind, pitch angle control signal and its speed feedback as an input. The output of the turbine is mechanical power on its shaft which is coupled to the permanent magnet synchronous generator through the gearbox. The gearbox outputs are the shaft torque and corresponding speed of the synchronous generator which are stepped down and stepped up, respectively, of the wind turbine shaft speed and torque. The outputs of the Synchronous generator monitored are the three phase stator current and the three phase voltages. Instantaneous power is generated from the three phase voltages and currents using multipliers and adders of MATLAB/SIMULINK as shown in the block diagram. The product of synchronous generator shaft torque and the generator rotational speed also provide the mechanical input power to the generator. Figure 3.2 shows the random wind speed generated by wind model for 120 seconds while fig.3.3 is the pitch angle controller respond as the result of the PI controller.

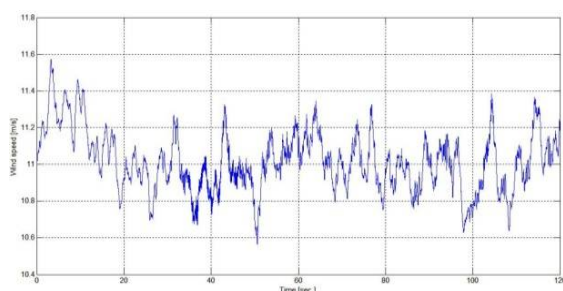


Fig. 3.2 Random wind generated over 120 seconds

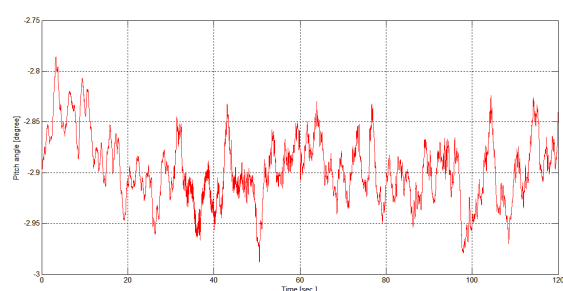


Fig. 3.3 Pitch angle controller output

Fig. 3.4 is turbine shaft rotational speed optimized and reached its steady state after 50 seconds while fig.3.5 is the torque generated on the turbine shaft. As it can be observed from these two figures, the start up speed and torque comply with the dynamic transient state of rotating machines.

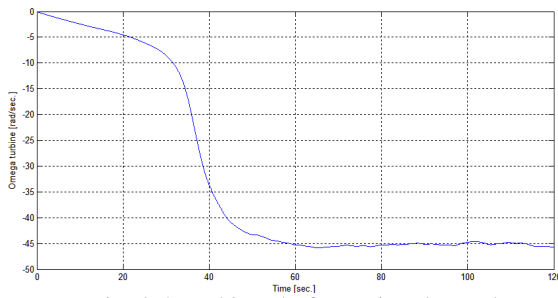


Fig. 3.4 Turbine shaft rotational speed

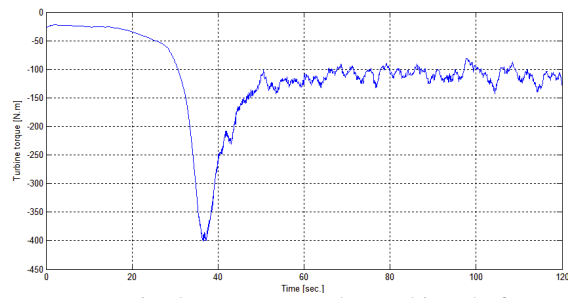


Fig. 3.5 Torque on the Turbine shaft

Fig. 3.6 shows the mechanical power output on the turbine shaft (5kW) as calculated from the turbine shaft torque and speed. Fig. 3.7 is the speed of synchronous generator which is about 900 radians per second which corresponds to 143 Hz frequency.

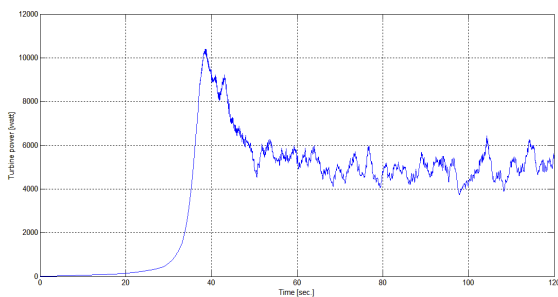


Fig. 3.6 Turbine power

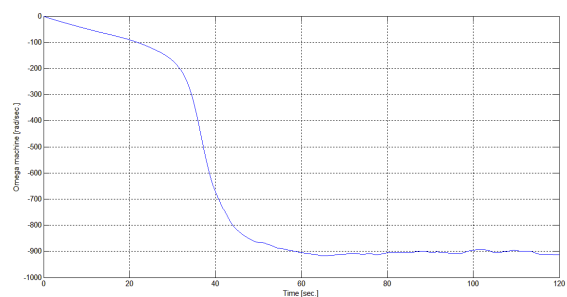


Fig. 3.7 Synchronous generator rotational speed

Fig. 3.8 shows the mechanical power input to the synchronous generator shaft while fig.3.9 shows the output electrical power of the machine. The delivered mechanical power has been converted in to electrical power by a PMSG and the output 3-phase electrical power is measured to be 4.5kw as shown in fig.3.9. The output, 3-phase electrical power is obviously less than the input power due to the encountered mechanical and electrical losses within the conversion process.

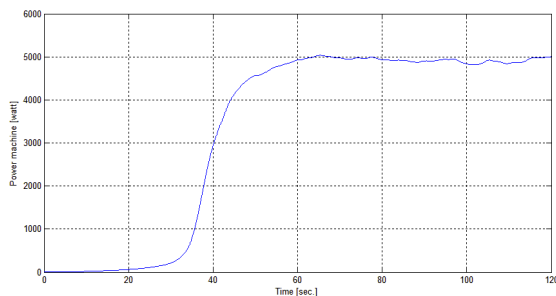


Fig. 3.8 Mechanical power on the shaft of SG

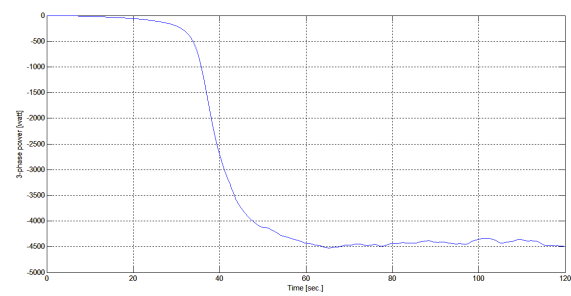


Fig. 3.9 Three-phase electrical power

The last two simulation results fig.3.10 shows the three-phase voltage (a) and current (b) at the terminals of PMSG corresponding to the given load gain. As it can be observed from the scope signals, the voltage buildup and the corresponding current reach to their steady state value (380V and 7.8A) at a time of 60 second. The value of terminal voltage and current are in line with the observed three phase electrical power (fig.3.9) at the terminals of PMSG.

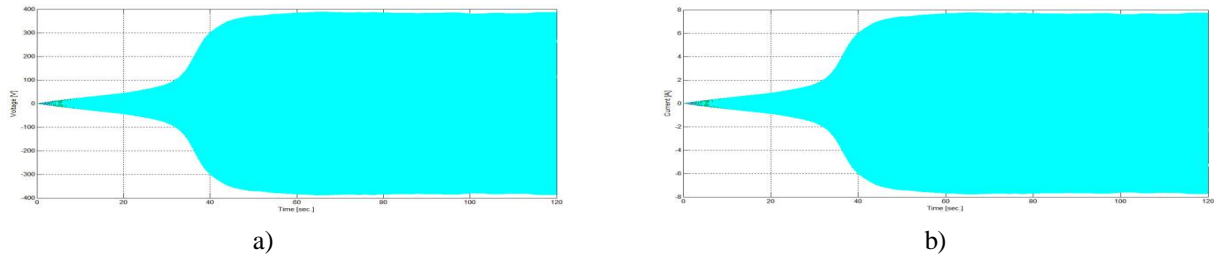


Fig. 3.10 Stator three-phase voltage (a) and current (b)

IV. CONCLUSION AND FUTURE WORK

4.1 Conclusion

In this work, dynamic simulation model for wind energy conversion system has been integrated with latest version of MATLAB/SIMULINK and used to simulate a 5 kW wind energy conversion system. The simulation result demonstrates that the power output corresponds to the intermittent wind speed and is in agreement with the expected signal values. The designed PI pitch controller also controls the turbine pitch angle following the variation of wind speed to the desired average value within 120 seconds. Furthermore, the provision of intermediate variable monitoring points between models and the possibility of parameter adjustment make the design of WECS and control system tuning very easy and fast.

4.2 Future Work

The system model can be extended to design and analysis of grid connected WECS by incorporating the static power converter modules. Inclusion of the converter modules and experimental verification of the system is underway.

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