A Proposed Wind Turbine Test-bed for Inclusion in Power Systems Engineering Education

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Abstract

In recent years the high demand of alternative energy applications created the need to have more qualified and well trained professionals capable to design, operate and maintain optimized solutions of highly efficient power systems and equipment. To meet that increasing demand of professionals having proper theoretical and practical knowledge, the instructional laboratories of Electric Power and Energy Systems, within the Electrical and Computer Engineering department at Purdue University Calumet, often require platform based on real system emulation and demonstration in the laboratory sessions.

In this paper, an innovative platform realization of a variable speed wind turbine system with permanent magnet synchronous generator (PMSG) has been proposed and described. The simulation platform and experimental test-bed are designed and built for educational and training purposes to improve the teaching and learning effectiveness in the area of Electric Machines and Drives. This platform makes use of MATLAB\Simulink programming and graphical environment, a NI Data Acquisition (NI DAQ) board and allows the modeling, simulation and performance studies of an emulated wind energy conversion system with alternating current (AC) machine and drives.

The emulated wind turbine system on the test-bed is using a direct coupling of a squirrel-cage induction motor with a 1KW PMSG. The experimental setup also includes a rectifier for battery charging applications, and sensors measuring the generator's line-to-line voltage, two phase currents, rectifier's DC output current and the rotational speed of the common shaft. Based on the simulation and real-time data acquired from the test-bed, the system's operating characteristics are analyzed and the results are presented. In this work, the complete system model is flexible enough to allow the change of parameters for other types of AC machines and drives configurations to study more efficient electric power generation systems for small-scale applications.

The possibility for integration of the proposed platform into the undergraduate and graduate curricula in Electric Power and Energy Systems programs has been discussed. The developed new instructional materials and projects will be using the simulation platform for AC machines and drives controls and electric power generation systems to enhance the existent instructional materials and address industry's needs for continuing education.

Keywords: Instructional Laboratory Development, Power Systems, Wind Energy, Permanent Magnet Synchronous Generator, Electric Drives.

1. Introduction

In recent years, the use of renewable clean energy like wind energy has been increased because of the environmental issues and availability of the source. The possibilities of energy storage also increased interest to use wind energy for generating electricity. For many years people has been using this concept to produce power and supply in commercial or residential scale. These kinds of systems are also used for power storage or battery charging. There exist many possible configurations of wind turbines in the wind energy conversation system (WECS).

Among the other renewable energy sources, wind power has been one of the most common and popular form of energies in recent years to produce electricity. It can be considered as the fastest growing energy field having an increase rate of 25% on the last 20 years. Using wind as an alternative source of energy can be cost effective and environment friendly compared to the other forms of energy sources. Due to the technological advancements in today's world, in many parts of the United States the costing of wind energy (installation of wind turbines and maintenances) is around 5 cents per kilowatt hour and expected to decrease more [1].

The development of wind turbine power generating system has been expanded significantly in the recent years. The potential is immense for wind energy and it can supply almost 20% of world electricity demand. It has become one of the main alternatives for non-pollutant and environment friendly power generation which is affordable, clean and also provides jobs.
Due to the need of increased power production, various wind turbine concepts have been developed and implemented to maximize the annual energy capture, reduce production cost, improve power quality and also provide consistent output power [1].

To produce electrical energy from wind, several types of generators could be coupled with the rotating shaft of a wind turbine, which include DC and AC generators, permanent magnet or field excitation type and synchronous or induction type of generators. Among all other types of generators, the use of both induction and synchronous generators are popular for wind energy conversion system and widely chosen because of their numerous advantages. However, in past couple of years the use of PMSG has become increasingly popular for their higher efficiency and power density compared to wound rotor generators. This technology is advancing greatly because of their low maintenance and long term reliability while enabling mass reduction option for the system. Due to the low rotational speed, this kind of generator offers advantages for small-scale, low-speed wind energy applications.

The present research paper analyzes the modeling and simulation of a variable speed wind energy conversion system to understand the behavior of the PMSG. During this research work, a complete experimental test-bed was designed and implemented for real-time data acquisition and behavior analysis of an emulated PMSG based WECS for educational and training purposes. The performance analysis model has been developed using the aerodynamic subsystem equations and space phasor theory applied for AC machines and implemented in MATLAB\Simulink® environment [2].

2. System Components Modeling

The system analyzed in this work includes a PMSG connected directly with a vertical axis wind turbine system reducing the cost, having no gearbox mounted and thus, a simpler structure.
A diode rectifier has been used in the system to converts AC to DC for battery charging applications. For the future grid tied system, an AC/DC/AC back to back power electronic converter configuration can be integrated. Here, an open loop system is considered which does not focus on the power electronics or their controls but more in to analyzing the generator behavior and performance.

2.1 Wind Turbine Model

To achieve the rotor aerodynamics of a wind turbine, the wind power captured by the turbine blades and converted in to mechanical power is given by the well known equation [3]

$$P_m = \frac{1}{2}\rho\pi R^2 v_w^3 C_p \, , \tag{1}$$

Eqn. (1) is used to model the wind turbine system to obtain graphical simulation for better understanding of the turbine behavior. In addition, this modeling and simulation method is helpful to observe the visual impact of different parameters on the wind turbine output for power system and electric drives courses. In Eqn. (1), P_m is the mechanical power delivered in (W), ρ is the density of air in (kg/m^3), R is the rotor radius in (m), v_w is wind speed upstream of the rotor in (m/s) and C_p is the power coefficient. The aerodynamic torque T_m in (Nm) can be given by the ratio of power extracted by the blade from wind to the mechanical rotational speed ω_m in (rad/second). The aerodynamic torqueT_m in (N-m) can be given by the ratio of power extracted by the blade from wind P_m to the mechanical rotational speed ω_m in (rad/second) [4]

$$T_m = \frac{P_m}{\omega_m} = \frac{1}{2}\rho\pi R^2 \frac{v_w^3}{\omega} C_p \tag{2}$$

In this section, the graphical modeling of wind turbine system has been presented using Eqn. (2). For high power wind turbines, a gearbox inside the drive train connects the low-speed shaft with the high-speed shaft and provides high rotational speed required by the generator to produce electricity. In this work, no gearbox has been considered for the system analysis since the wind turbine is considered to be directly connected with the PMSG for small-scale power applications. This approximation allows choosing the model of the mechanical drive train defined by the following equation [5]

$$\frac{d\omega_m}{dt} = \frac{1}{J_{eq}}(T_m - T_e - B\omega_m) \tag{3}$$

where, J_{eq} is the equivalent rotational inertia in (kgm2), T_e is the electromagnetic torque in (Nm) and B is the viscous damping coefficient in (Nms). Eqn. (3) is useful to demonstrate and understand the torque-speed relationship in a wind turbine system for electric drives courses. Using the model different parameters can be changed to observe the impact on the output of the drive train system. Fig. 1.shows the Simulink block diagram of the wind turbine model using Eqn. (2)

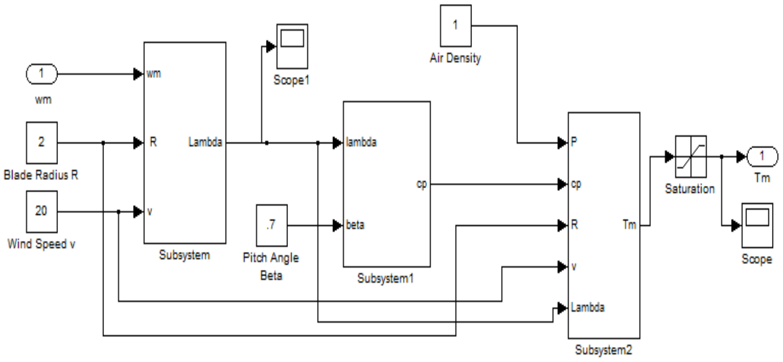

Fig.1. Wind Turbine Model using Simulink.

The output of the aerodynamic and mechanical subsystem seen in Fig. 1.has been used as an input for the electric subsystem of the turbine presented in section 2.2 (Fig. 2.).

2.2 State Space Model for the PMSG:

In this section, the power generating unit of the wind turbine system has been expressed with mathematical equations. The PMSG is the specific unit of this wind energy conversion system that produces electrical energy from the mechanical power delivered by the wind turbine. The modeling of PMSG is necessary for proper analysis of the system and better understanding of the machine behavior and performance. For this purpose, the state space representation approach has been chosen and the dynamic model of the PMSG is obtained by applying the d-q reference frame theory. The state equations presenting PMSG voltage are written as [6]

$$u_{sq} = R_s i_{sq} + \omega_e \Psi_{sd} + \frac{d\Psi_{sq}}{dt}$$
$$u_{sd} = R_s i_{sd} - \omega_e \Psi_{sq} + \frac{d\Psi_{sd}}{dt} \tag{4}$$

Eqn. (4) model the relationship between the stator voltages, currents and fluxes of the PMSG. Here, the subscripts d and q indicate the space vector components transformed into the rotating reference frame, R_s is the stator resistance per phase in (Ω) and ω_e is the electrical synchronous speed in (rad/sec). By expressing the fluxes in terms of currents in Eqn. (4), the state space stator currents are written as [5]

$$\frac{di_{sd}}{dt} = \frac{1}{(L_{sd} + L_{sl})}\left(-R_s i_{sd} + \omega_e\left(L_{sq} + L_{sl}\right) i_{sq} + u_{sd}\right)$$
$$\frac{di_{sq}}{dt} = \frac{1}{\left(L_{sq} + L_{sl}\right)}\left(-R_s i_{sq} - \omega_e (L_{sd} + L_{sl}) i_{sd} + u_{sq}\right) \tag{5}$$

where, L_{sd}, L_{sq} are the stator inductances and L_{sl} is the stator leakage inductance in (H). To complete the mathematical model for PMSG, the produced electromagnetic torque equation is needed which is given in Eqn. (6) [5]

$$T_e = \frac{3}{2} z_p \left(\Psi_m i_{sq} + i_{sd} i_{sq} \left(L_{sd} - L_{sq} \right) \right) (6)$$

In Eqn. (6), T_e is electromagnetic torque in (Nm), z_p represents number of pole pairs and Ψ_f is the permanent magnet flux in (Wb). Fig. 2.shows the Simulink block diagram of the PMSG using Eqn. (5) and (6)

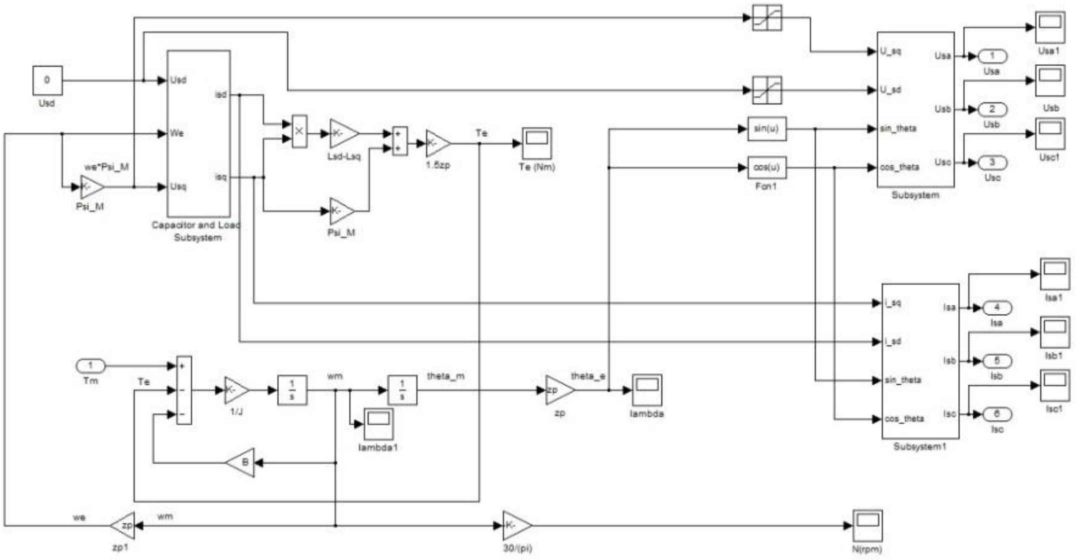

Fig.2. PMSG Simulink Block Diagram.

3. Simulation Results for the Modeled Wind Turbine System

In this work a typical wind turbine system configuration equipped with a PMSG has been modeled and simulated using the MATLAB/Simulink software. The use of this software allows modeling of different WECS's physical dynamic subsystems and the coupling with data acquisition board for post processing of real-time sensor data.

3.1 Simulation Results of the Wind Turbine Model Using Simulink:

The final output of wind turbine subsystem is the mechanical torque which is fed in the electrical generating system as an input. The mechanical rotational speed, wind velocity and blade radius are the three inputs fed in to the wind turbine system producing tip speed ratio lambda as the subsystem output. For simulation, wind velocity and blade radius have been chosen according to the turbine model. By entering different values for different wind speeds we can achieve the relationship between the tip speed ratio λ and wind speed v of a wind turbine system as shown in Fig. 3.

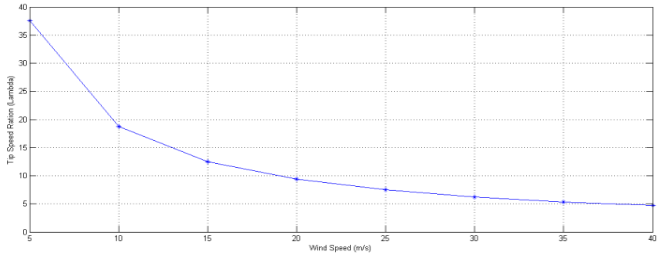

Fig.3. Analytical Relationship between the Tip Speed Ratio and Wind Speed

The power coefficient for a wind turbine is dependent on the wind speed value along with the turbine size. Fig. 4.presents the relation between the wind speed and power coefficient for the considered turbine

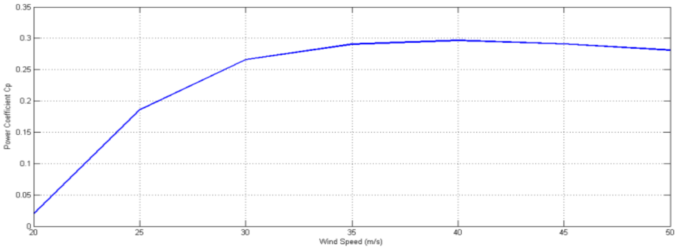

Fig.4. Approximation of Power Coefficient with Different Wind Speed

From Fig. 4.it is observed that the value of power coefficient increases with the increased wind speed and after a certain value for the wind speed, the power coefficient starts to decline. It is also observed that power coefficient value never exceeded the Betz's limit which is 0.593 even for a very high wind speed [4]

3.2 Simulation Results for PMSG System Model:

In this work, the wind turbine system includes PMSG as a generating unit that produces electrical power extracted from kinetic energy of the wind. Fig. 5. and 6. show the simulation for three phase currents and voltage output using the d-q components available on the system

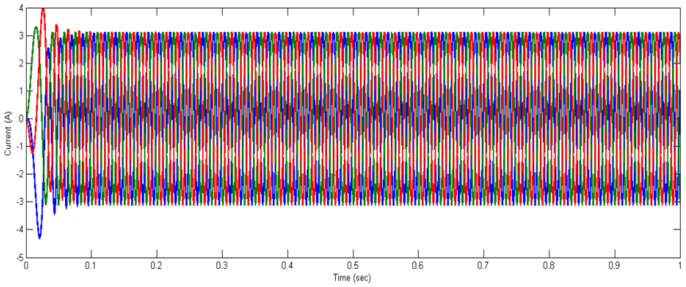

Fig.5. Simulation for Three-phase Current Output

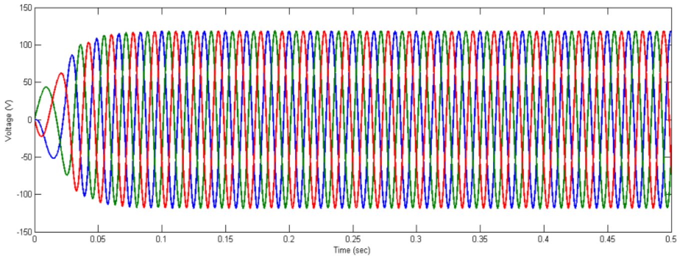

Fig.6. Three-phase Voltage Output

These current components are then used to calculate the electromagnetic torque Te of the generating system, which is presented in Fig. 7.

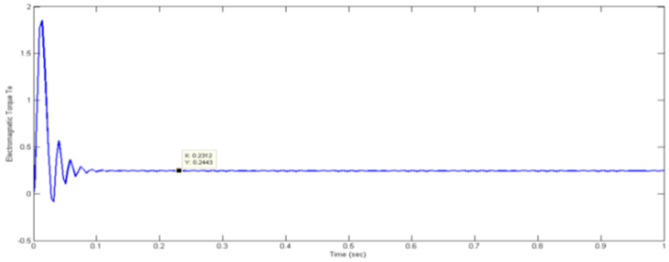

Fig.7. Electromagnetic Torque Te

4. Hardware and Software Development on the Test-Bed for Real-Time Validation

For experimental validation of the simulation results, a test-bed was designed containing different sensors used for the measurement and data analysis purpose as seen in Fig. 8.

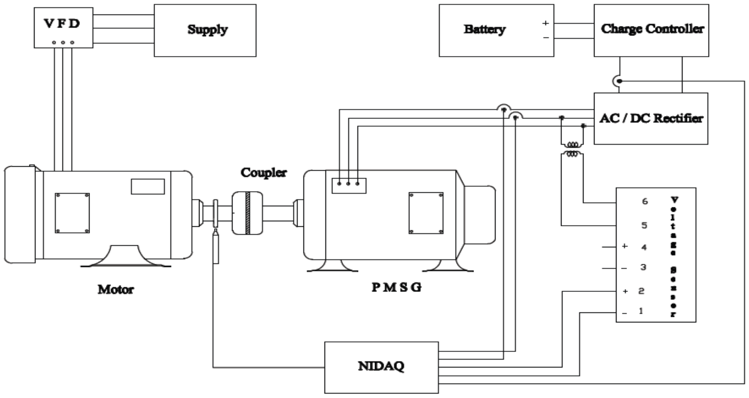

Fig.8. The Hardware design for the Test-Bed

All the real time data was obtained from the test-bed by using the NI DAQ data acquisition board and the Data Acquisition Toolbox™ functions offered by MATLAB [7]. By using the driver software of NI DAQ and MATLAB as the application software, real time data from the test-bed system was obtained, displayed and the results were analyzed at the same time. For the real-time implementation of the emulated wind turbine system an induction motor has been mechanically coupled with a PMSG on the test-bed. The main purpose of using this motor is to provide the necessary rotational torque to the generator shaft and to be able to use an existent variable frequency drive (VFD) to change the motor speed by varying voltage/frequency ratio to obtain different experimental characteristics of the PMSG system [8]. The emulated wind turbine system is seen in Fig. 9.

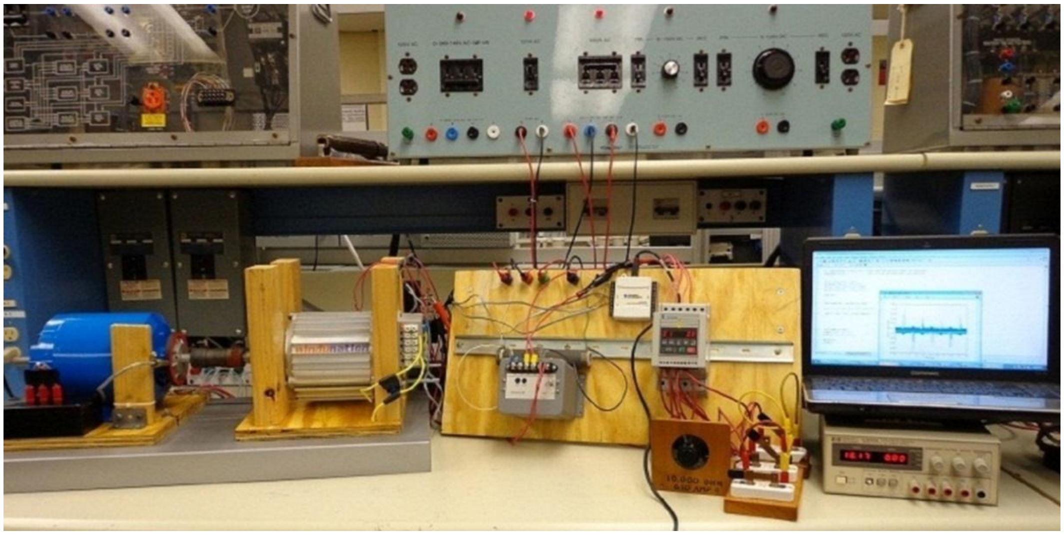

Fig.9. Complete Test-Bed Setup for Wind Turbine Emulation

5. Validation Results and Analysis

For validating the wind turbine modeling method, MATLAB/Simulink is a convenient option since it is a popular programming language for students in engineering studies for different laboratory experiments, industrial design and testing applications. Using Simulink also creates the opportunity for developing software in the loop and hardware in the loop simulation techniques for enhancing the quality of testing. In addition, LabVIEW is another graphical environment used with NI DAQ for any measurement, design and control platform which helps engineers to scale from design and test any small or large systems [7]. Using LabVIEW Nailu [9] proposed an integration of LabVIEW DSC module and MATLAB/Simulink to develop real-time simulation, monitoring and controlling for wind power generation system analysis. It was aimed at communicating and exchanging data with Simulink model and make the system run synchronously with wind generation Simulink model. In this work, to obtain the same simulation platform, MATLAB has been chosen for both simulation and system validation. The data acquisition process was done using the Hall-Effect sensors for specific measurements of the rotational speed of motor in RPM and the line currents and voltages of the generator.

5.1 Real-time Data Acquisition Output Using Hall-Effect Sensors:

The AN_131KIT-25Arms sensor and NIDAQ USB 6008 was used for line current measurement on the Test-Bed. Provided with an external power supply, the sensor output in volts is shown in Fig. 10. and Fig. 11.for different voltages at the generator output terminal [10]

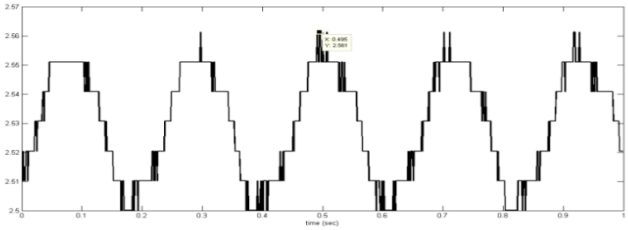

Fig.10. Sensor Output for 10 V AC

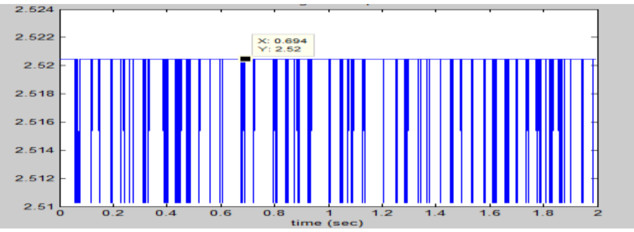

Fig.11. Sensor Output for 5 V DC

The terminal voltage on the test-bed was measured using the 2489 AC Voltage Transducer. An auxiliary supply of 120 VAC was provided to the transducer to get accurate RMS values reading. Fig. 12. shows the output of the voltage transducer used on the test-bed

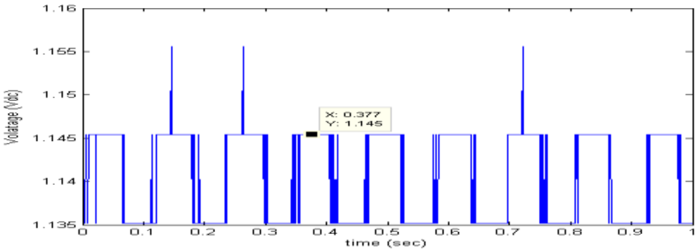

Fig.12. Voltage Transducer Output for 10 V DC

The speed sensor used in this work for measuring the shaft rotation is a1101 Hall-Effect Speed Sensor [11]. This sensor is used with a Pulse Generator that produces 60 pulses per revolution. The output of the sensor is a square wave signal where the pulses are counted using a threshold point defined by the MATLAB program as shown in Fig. 13.

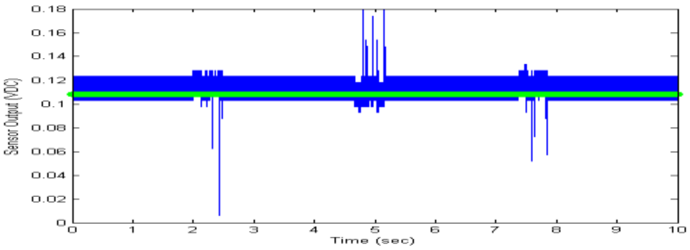

Fig.13. Pulses Generated from Hall-Effect Speed Sensor

5.2 PMSG Characteristics obtained from Real-time Data:

In this work, the Torque-Speed characteristics were obtained for the generator using the DC output (Voltage, Current) at the rectifier terminal. Fig. 14. shows that when the speed is increased the output torque decreases with time and after about 165 rpm the torque becomes almost constant.

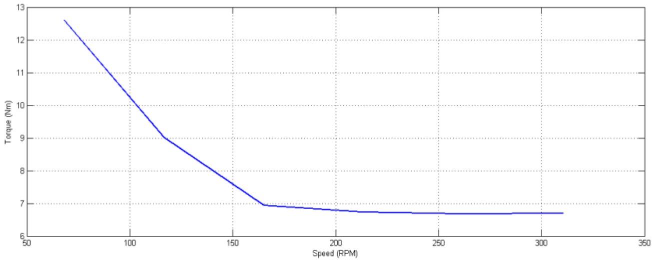

Fig.14. Torque-Speed Curve for the Generator

To find the overall efficiency, the output power was calculated at the generator DC terminal and the motor input power was obtained from the VFD. Comparing the DC output power of the generator with the motor input power, the emulated system efficiency is calculated on the test-bed which is shown in Fig. 15.

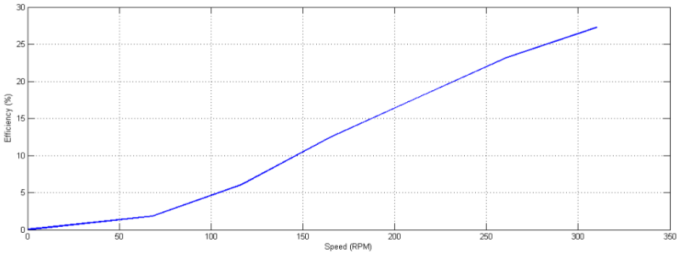

Fig.15. Efficiency Characteristic of the PMSG System

By analyzing Fig. 15.it helps to decide on choosing the architecture for a small scale wind turbine system for obtaining certain efficiency level. The turbine height, blade radius and also the wind region location can be reconsidered for having maximum output. It is seen from Fig. 15.that the efficiency increases with the increased rotational speed up to a certain limit.

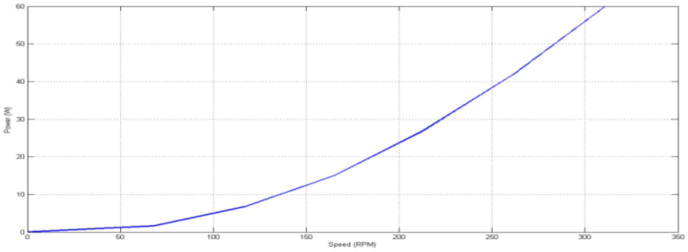

Fig.16.Power Vs Rotational Speed

Fig. 16. shows the relationship between the power produced by the generator and rotational speed of the rotor shaft. It is observed from the figure that the output power of the generator increases as the shaft rotational speed increases.

6. Test-Bed as a Teaching Tool

The test-bed platform presented in this work, containing a motor-generator configuration of two electric machines, provides a solid basis for laboratory experiments development in Electric Drives and Power Systems undergraduate courses. The students will study the motor and the generator of this system in two separate courses of the Power Systems minor program at PUC as proposed in the following two examples:

6.1 Electric Drives Laboratory:

The two main objectives of this first experiment are: (1) to study the load characteristics of a squirrel-cage induction motor driven by a variable-frequency controller (VFD) and (2) to investigate the volts-per-hertz (V/f) speed control technique. The controller-motor coupling is an open-loop (without feedback) in this experiment. An extension (may be an independent new laboratory) is intended to be developed focusing on closed loop speed control of the induction motor, the controller providing a feedback to determine the motor speed. The students are asked to record, discuss or comment the experimental data. The following are proposed as part of the laboratory report:
(a) Plot voltage, current, and frequency versus speed at no load on the same graph and using different scales
(b) Plot the output power (torque) versus speed on a second graph
(c) Plot the motor voltage versus speed on a third graph
(d) Discuss the obtained results. In particular, how do speed, voltage, current, frequency, and power vary with different load (torque)

6.2 Power Systems Laboratory:

The goal is to study the behavior of the permanent magnet synchronous generator for various resistive and reactive loading conditions. Individual student's reports are required based on recorded data, answers to the questions below and discussion or comments on the data. As part of the report students are required to:
(a) Plot the load characteristic, terminal phase voltage versus load current
(b) Plot the terminal phase voltage versus power factor of load at constant resistive load, and
(c) Calculate the generator efficiency for the above cases.

7. Conclusion

The objective of this work was to provide a basis for developing new instructional materials to enhance teaching and learning effectiveness of power engineering courses in educational institutes. After a demonstration session with the test-bed platform, students responded positively about using it for various experimental purposes and to contribute for further extensions to achieve feedback control and grid tie applications. This paper presents complex modeling techniques for an electrical power system structure design, analysis and simulation and to provide practical knowledge and experimental platform for undergraduate and graduate level power system courses. A software based simulation, hardware development and a test-bed implementation have been done to evaluate the PMSG performance characteristics using necessary interfaces to extract and process real-time data from the system. Results have been presented for the emulated wind turbine model using the MATLAB program and Data acquisition Toolbox.

To achieve further improvement, extensions of the present experimental setup could be designed and implemented to analyze the behavior of the grid-tied wind turbine system and to include necessary controls in the system.

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