Design of a Comprehensive 5MW Direct-Driven PMSG Wind Turbine Emulator Using FAST Nonlinear Wind Turbine Model

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Abstract

Wind has become one of the most attractive energy resources worldwide. As a result, most of the development is focused on the large scale wind turbines. Due to these developments, it is necessary to study the effect on these wind turbines.

This paper presented the development of a 5MW direct driven wind turbine simulator using dc motor driven by a current controlled dc drive that emulates the wind turbine system. The wind profile is generated inside the digital signal processing (eZdsp tms320 F28335) which includes the same wind profile generated by TurbSim which is a Full field wind simulator developed by the National Renewable Energy Laboratory (NREL). Also, the mathematical model taking the rotor inertia effect of the system into consideration was presented using the DSP.

Keywords

FAST; Permanent Magnet Synchronous Generator (PMSG); TurbSim; Vector Control and Hardware in the Loop (HIL)

Introduction

Wind power has become the most attractive and efficient for generation of electricity due to its clean power and low running cost. As a result, most of the development of wind turbines is focused on the large scale wind turbines. Due to these developments, it is necessary to study the effect of wind flow variations on power system and connection of grid. At present, wind turbine emulator has become very necessary for laboratories testing these large scale wind turbines to examine the quality of wind turbines.

The basic requirement of the emulator is to get the same dynamics and statics of the wind turbine and this is called the Hardware-in-the-Loop-Principle (HIL). To get these characteristics, separately excited dc motor is utilized. A current controlled dc drive system is used to control the torque of the dc motor by controlling its armature current as it has the same image of the torque. The wind speed is generated inside the DSP using the same wind profile generated by TurbSim from the National Renewable Energy Laboratory (NREL). The power rotational speed pattern of the wind is used from the data generated using FAST (Fatigue, Aerodynamics, Structures and Turbulence) model [Jon 2005]. Then the transient response is studied taking into account the large inertia of the 5 MW wind turbine by generating the mechanical torque set-point added with the effect of the inertia [Mun 2010].

In this paper, the PMSG is used to emulate the wind turbine 5 MW generator and to study the effect of the generator side converter used to maximize the output power capture of the wind system. The optimal operating point (OOP) is used to maximize the energy captured by sending the required electromagnetic torque to the field oriented control algorithm which is used to control the torque of the generator side converter.

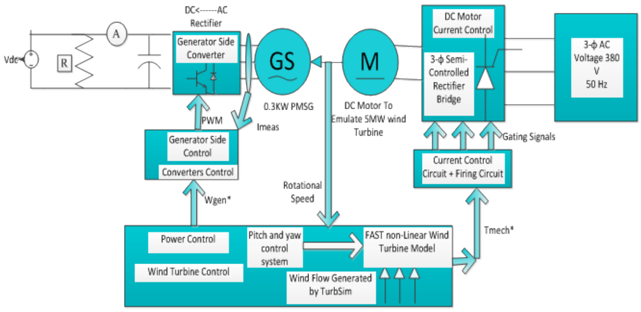

FIG. 1 PROPOSED WIND TURBINE EMULATOR

The complete model of the wind turbine system is shown in Fig. 1. A DC separately excited motor of 300 W is used to emulate the 5 MW wind turbine system. Also PMSG of 300W is used to emulate the characteristics of the 5 MW generator. The Digital Signal Processing (DSP) eZdsp TMS320 F28335 used to control the whole system is also connected to the laptop using serial communication RS232 for data acquisition and display relevant parameters.

Wind Speed Simulation

Turbsim, a stochastic, full field wind simulator, uses statistical model to numerically simulate time series of three wind components in a dimensional grid. It is used to be an input to FAST program to provide the required wind field data. Spectra of velocity components and spatial coherence are defined in the frequency domain, and an inverse Fourier transform produces time series [Jon 2012].

Its purpose is to provide the wind turbine designer with the ability to drive design code simulations of advanced turbine designs with simulated inflow turbulence environments that incorporate many of the important fluid dynamic features known to adversely affect turbine aero elastic response and loading [Kri 2009].

Modeling of Rotor Blade Characteristics

The emulation of the wind turbine system was done by controlling the current of a separately excited dc motor supplied via 3-Phase semi-controlled rectifier bridge to act as a wind turbine as illustrated in Fig. 2 that shows also the complete emulation process. The PMSG is connected to the generator side converter used to obtain the maximum power of the wind turbine system. The main controller chosen is the DSP TMS320F28335. The data of the 5 MW wind turbine, dc motor, PMSG and the DSP unit are mentioned in the appendix.

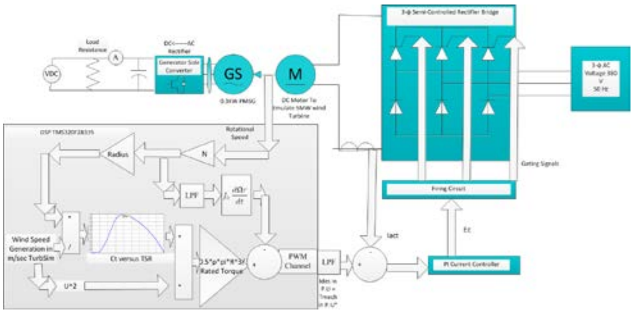

FIG. 2 WIND TURBINE EMULATION PROCESS

The calculated data is transmitted to the vector drive through RS-232 communication. The communication period and speed are determined to be 10 ms and 19200 bps.

A ratio N will be taken to convert the rated rotational speed of the lab system to the actual turbine (5MW).

In the following paragraphs, the mathematical model will be derived. The output power of wind turbine can be defined as the difference between the power in the moving air before and after the rotor as:

$$P_{wt}(\lambda, V_w) = 0.5\rho\pi R^2 V_w^3 C_p(\lambda) \tag{1}$$

where ρ represents the air density, V_w represents the wind speed, R represents the blade radius and C_P represents the power coefficient. The value of C_P is function of tip speed ratio λ that is:

$$\lambda = \frac{\Omega_m * R}{V_w} \tag{2}$$

where Ω_m is the rotational speed (rad/sec).

The rotor torque can be expressed as;

$$T_{wt}(\lambda, V_w) = 0.5\rho\pi R^3 V_w{}^2 C_t(\lambda) \tag{3}$$

where Ct(λ)=Cp(λ)/λ, which is the torque coefficient.

The electromechanical equation of the system can be expressed as;

$$T_{wt}(\Omega_m, V_w) - T_e(\Omega_m) = J_h \frac{d\Omega_m}{dt} \tag{4}$$

where T_{wt} is the shaft torque, T_e is the electromagnetic torque provided by the generator, and J_h is the inertia of the 5 MW system. The turbine inertia at the low speed shaft is $J_h = J_{wt} + J_g$ where J_{wt} and J_g are the turbine rotor and electrical generator inertias, respectively. It appears from equation (4) that the generator is directly coupled to the wind turbine.

Let the dc servo motor torque be noted as Tdcsim. It is proportional to Idcm and must emulate the evolution of T_{wt}. The real dynamical evolution, inside the simulator, of the response variable Ω_{sim} inside the Hardware in the Loop (HIL) simulator has the following form:

$$T_{dcsim} - T_e(\Omega_{sim}) = J_{sim} \frac{d\Omega_{sim}}{dt} \tag{5}$$

If it is required to get the same dynamical performance of the real system which has nominal power of P_n, and nominal speed of Ω_n, a dc motor is used that has a simulator nominal power of P_s, and nominal speed of Ω_s. So to get the same dynamical performance of the 5 MW system from the scaled one, Equation (4) should be multiplied by $((\Omega_n/\Omega_s)/n)$, where $n = P_n/P_s$, the following result will be obtained.

$$T_{sim}{}^{*} - T_g(\Omega_{sim}) = J_h \frac{(\frac{\Omega_n}{\Omega_s})^2}{n} \frac{d\Omega_{sim}}{dt} \tag{6}$$

where $T_{sim}{}^{*}$ is the required torque from the small lab system. By supposing that Ω_{sim} exhibits the same dynamic in both the 5 MW system and the lab system, one subtracts (5) from (6) and obtains the following dc machine reference torque:

$$T_{sim}^{*} = T_{dcsim} - \left(J_h \frac{(\frac{\Omega_n}{\Omega_s})^2}{n} - J_{sim} \right) \frac{d\Omega_{sim}}{dt} \tag{7}$$

where the dc simulator torque Tdcsim is computed by using a synthesized wind speed Vw generated by TurbSim in relation (3). Therefore, the emulation will be divided into two sections. The first one will be the steady state characteristics of the 5MW system; while the second term will be the transient characteristics and represent the required inertia of the system Jreq.

Steady State Response

The steady state response is calculated from FAST capable of predicting both the extreme and fatigue loads of two-and three-bladed horizontal-axis wind turbines. It is proven that the structural model of FAST is of higher validity than other codes. [Kri 2009; Jon 2005]

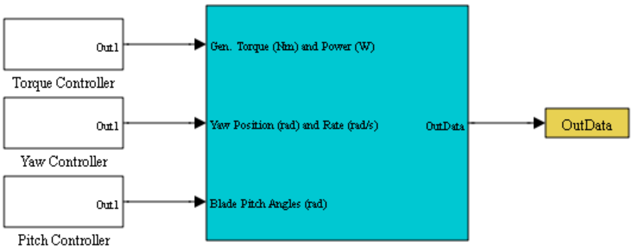

FIG. 3 FAST NONLINEAR WIND TURBINE MODEL IN SIMULINK

An interface has also been developed between FAST and Simulink with Matlab enabling users to model the wind turbine in Simulink as shown in Fig. 3. The FAST subroutines have been linked with a Matlab standard gateway subroutine in order to use the FAST equations of motion in an S-Function that can be incorporated in a Simulink model. [Jon 2012]

The power coefficient Cp versus the tip speed ratio (TSR) λ is shown in Fig. 4.

The shaded part in Fig. 2 shows the complete program of the system. The Cp value is curve fitted and will be function of the tip speed ratio which is programmed in the DSP. Then by generating synthesis wind speed using TurbSim in the DSP and using (3), the steady state characteristics of the 5MW wind turbine could be obtained.

Then this value of torque will be normalized to be 1 per unit of the system. Further, this value will be generated by the output of a pwm and fed to the current controller board shown in Fig. 2 through a low pass filter.

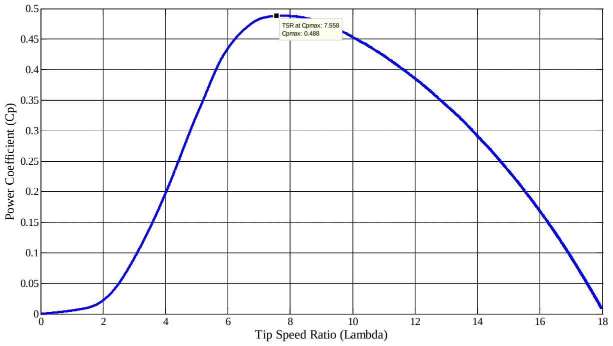

FIG. 4 CP VERSUS TSR VALUES

The following test was done to ensure that the system will respond to the current controller and hence emulating accurately the wind turbine. In this test, the generator converter will operate as uncontrolled rectifier (i.e. by making the converter transistors idle). At specific wind speed, the load current of the generator was increased from the minimum value to the maximum one and the input power to PMSG, PGen-in(W), was measured by multiplying the armature current of the dc motor by its induced e.m.f. The above work was repeated at different wind speeds shown in Fig. 5 at the dotted lines. The recorded PGen-in(W) readings will be normalized by the rated PGen (W) (i.e. 300 W that is equivalent to 5 MW). The test results are fitted on the graph in Fig. 5. When the 5 MW per unit output was compared with the 300 W lab system, the results were very comparable and satisfactory as shown in Fig. 5.

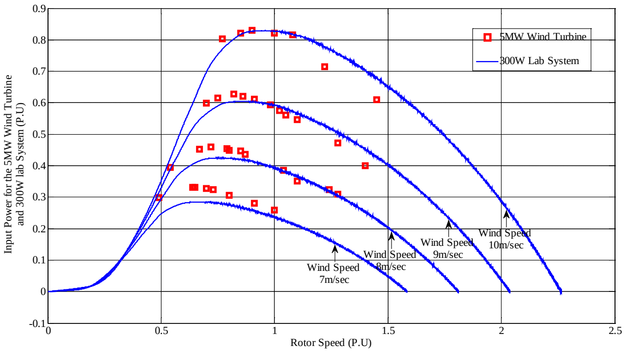

FIG. 5 POWER FOR THE 5MW WIND TURBINE AND 300W LAB SYSTEM IN PER UNIT FOR DIFFERENT WIND SPEEDS

Transient Characteristics

By supposing that Ω_{sim} exhibits the same dynamic in both 5 MW wind turbine and 300 W system, it is clear from (7) that to exhibit the same dynamics of the 5 MW wind turbine, the inertia of the 300W system should be Jreq. The inertia of the 300 W system isn't very high to exhibit this dynamics of the 5 MW. So a control loop is made to compensate this action in the DSP programming board by measuring the rotor speed and adding the Jreq to the system as shown in fig. 6.

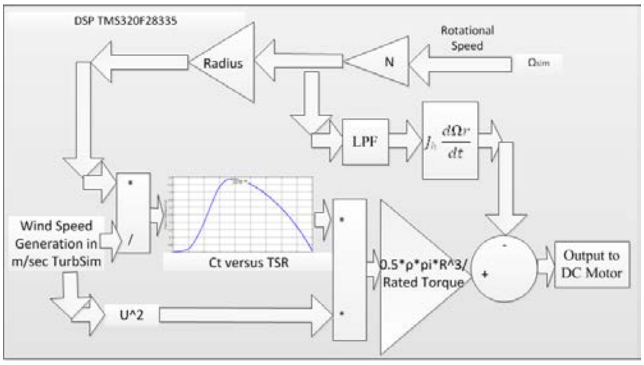

FIG. 6 CONTROL LOOP OF DC MOTOR

To test this control loop transient action, the system is tested under step and stochastic wind and the transient response is compared with the real simulator action.

Control of PMSG Wind Turbines

Machine equations based on the rotor reference position are described in (8) and (9) and they are marked with the subscript "r". [Kra 2002]

$$V_q^r = -R_s I_q^r - L_q \frac{dI_q^r}{dt} - \omega_r L_d I_d^r + \omega_r \varphi_{pm} \tag{8}$$

$$V_d^r = -R_s I_d^r - L_d \frac{dI_d^r}{dt} + \omega_r L_q I_q^r \tag{9}$$

The Variables Rs, Ld and Lq are the stator resistance, direct and quadrature inductance, respectively, of permanent magnet synchronous generator, where Ld = Lq = Ls.

The electrical torque is shown in (10). It is clear that to control the electrical torque the q-axis current can be controlled.

$$T_e = \frac{3}{2} P \varphi_{pm} I_q^r \tag{10}$$

Type of control used is field oriented control (FOC) as shown in Fig. 7 holding high performance. The FOC uses the shaft speed, obtained by a pulse encoder as a feedback in the control strategy.

Constant Torque Angle Control (CTA) is the control technique used to control the d and q axis currents. The stator current reference in q-axis is calculated from the reference torque using (10) [Bus 2010]. The required d,q components of the voltage vector are derived from two PI current controllers.

Space Vector Modulation (SVM) is the technique used to create the duty cycles of the desired reference voltages. The PI parameters are designed by using sisotool in matlab as described in [Cim 2010].

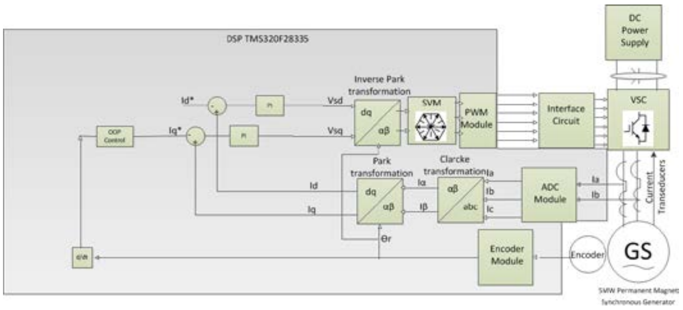

FIG. 7 CONTROL OF PMSG WIND TURBINES

The reference of the electromagnetic torque Tem* can be calculated by using optimal torque control (OOP) method. This control method uses the measured rotational speed (rad/sec) of the shaft and the parameters of the wind turbine to obtain the optimal operating point. The output wind turbine power is obtained from (1).

By replacing λ(t) by λopt and Cp(λ,β) = Cp(λopt,β), the reference power can be obtained.

$$P_{wt_{opt}} = K\Omega_m{}^3 \tag{11}$$

where;

$$K = \frac{1}{2}\frac{C_p(\lambda,\beta)}{\lambda^3}\rho\pi R^5 \qquad N.m/(\frac{rad}{\sec})^2 \tag{12}$$

The reference torque is calculated as follows;

$$T_{wt_{opt}} = K\Omega_m{}^2 \tag{13}$$

Experimental Setup Results

The complete experimental setup of the system is shown in Fig. 8. First of all, the system was tested with the OOP control with step wind speed to ensure that the controller has succeeded in capturing almost all the available power in the wind turbine system. Then it was tested under stochastic wind generated by Turbsim [Jon 2012], in addition, the wind profile named great planes wind profile (GP_LLJ), was standard, and validated by IEC. The wind profile has a coherent structure, and a hub-height average wind speed of 9.5 m/sec, standard deviation of 0.381 and a power law exponent of 0.143. This wind profile is applied to this control technique and the results are observed.

The response was compared for both simulation and experimental results. All values are in per unit and the bas values are in the appendices.

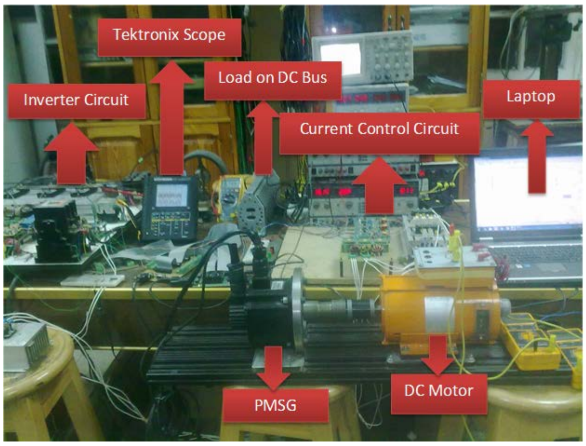

FIG. 8 COMPLETE EXPERIMENTAL SETUP

Step Wind Speed

A step change in wind speed from 7 to 10 m/sec was applied to the system as shown in Fig. 9 and the output waveforms were observed.

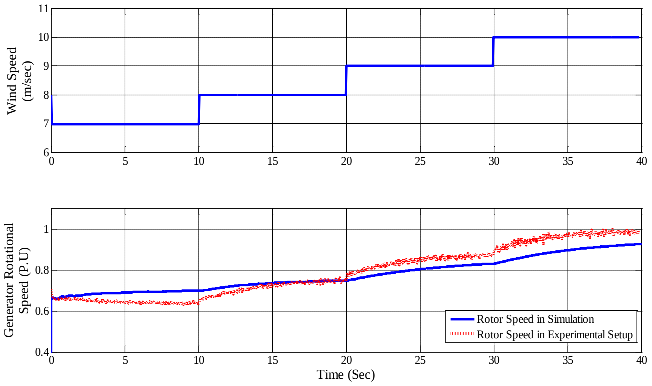

FIG. 9 ROTOR SPEED RESPONSE IN SIMULATION AND EXPERIMENTAL SETUP

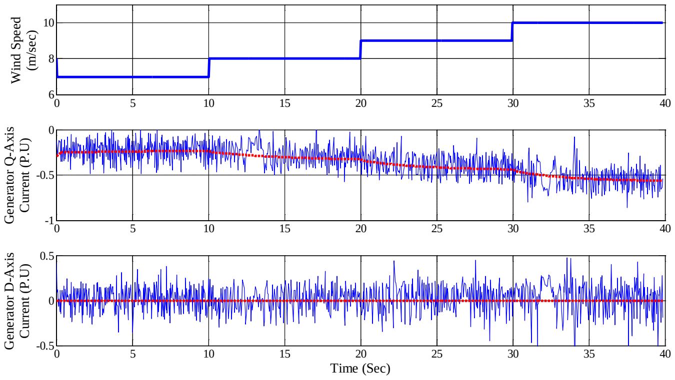

FIG. 10 GENERATOR Q AND D AXIS CURRENT RESPONSE FOR WIND SPEED VARIATIONS

In Fig. 9, the optimum speed is determined by the value of the q-axis current which makes the system go through the speed. It can be observed that both 5 MW system and 300 W system has the same response. It can be noticed that for steady state they become the same value.

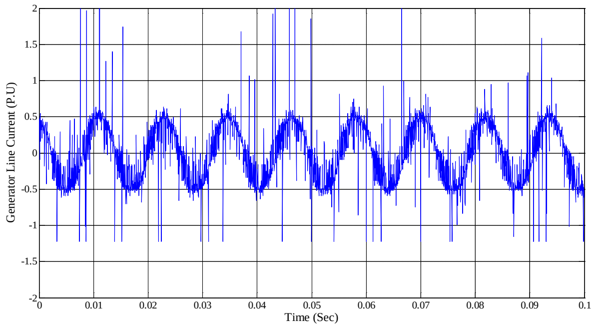

FIG. 11 GENERATOR LINE CURRENT AT 10M/SEC

In Fig. 10, the generator q axis changes according to the speed loop. The d-axis current is set to be zero according to the Maximum Torque per Ampere theory MTPA theory.

Fig. 11 shows the generator current.

TABLE 1 shows that the controller for maximum power point tracking succeeds to obtain all the available power from the wind turbine system.

TABLE 1 OUTPUT POWER AT DIFFERENT WIND SPEED

Wind Speed (m/sec)	Available Output Power from system (P.U)	OOP Control Output Power from System (P.U)
7 m/sec	0.1315	0.113
8 m/sec	0.206	0.193
9 m/sec	0.3	0.286
10 m/sec	0.412	0.41

Stochastic Wind Speed

A stochastic change in wind speed was applied to the system and the output waveforms were observed.

The same waveform of the wind speed applied in the simulation was applied in the experimental with a mean of 9.189 and a standard deviation of 0.3709.

In Fig. 12, the speed changes according to the q-axis current requirement. The same response for the simulation and the experimental results has been obtained at steady state. The transient was different because they started from different iniy=tial rotor speed.

In Fig. 13, the generator q axis changes according to the speed loop. The d-axis current is set to be zero according to the MTPA theory.

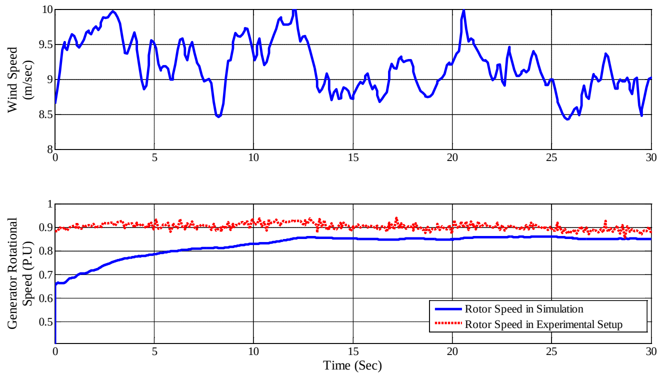

FIG. 12 ROTOR SPEED RESPONSE IN SIMULATION AND EXPERIMENTAL SETUP

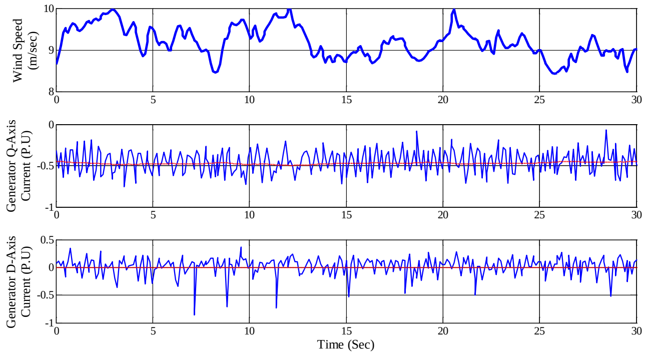

FIG. 13 GENERATOR Q AND D AXIS CURRENT RESPONSE FOR WIND SPEED VARIATIONS

Conclusions

This paper presented the development of the 5 MW wind turbine emulator through a dc motor set controlled by current controlled drive. The DSP was used to emulate the same characteristics of the 5 MW system through controlling the dc motor current and hence controlling the torque. The results showed that the system succeeded to emulate the transient and steady state characteristics of the 5 MW wind turbine. The system was tested and verified firstly with simulation results through the usage of Matlab/Simulink connected with FAST and TurbSim model. Then it was experimentally verified and tested with step and stochastic wind. The maximum power point tracking technique which is optimal operating point control succeeded to obtain almost all the available power in the wind turbine system.

The developed wind turbine emulator can be used to analyze various mechanical and electrical characteristics of PMSG.

Appendices

TMS320F28335 speed is 150 MHz clock/instruction cycle and has 2 high resolution (150 picosecond) PWM modules which can operate 2 three phase inverters. It has also analog to digital (ADC) module of 16 channels which can be synchronized with the PWM modules. It has also 2 enhanced quadrature encoder pulses and 88 configurable general purposes I/O (GPIO) pins; as well as 12-bit, 16-channel A/D converter.

TABLE 2 DATA OF DC MOTOR AND 5MW WIND TURBINE

Differences	5MW Wind Turbine System	DC Motor
Nominal Power	5.3 MW	300 W
Nominal Torque	4.18 MN.m	2.86 N.m
Nominal Speed	12.1 rpm	1000 rpm
Rotor and turbine inertia about the shaft	43.8e6 Kg.m^2	8.41e-4 Kg.m^2

TABLE 3 DATA FOR PMSG TO BE INVESTIGATED

Nominal Power	0.3 KW
Nominal Torque	2.86 N.m.
Nominal Speed	1000 rpm
No. of Pair Poles	5
Armature Resistance	1.06Ω
Armature Inductance	14.29mH
Voltage Constant	42.5 mV/rpm

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