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A MORE ACCURATE DYNAMIC WIND ENERGY CONVERSION SYSTEM EMULATOR

Mohammad MONFARED, Hasan RASTEGAR, Benyamin MORADZADEH
Department of Electrical Engineering, Amirkabir University of Technology, Tehran, Iran

***Abstract*:** This paper explains how an advanced emulator is constructed to simulate the static and dynamic characteristics of a wind energy conversion system. This system consists of a 3 kW dc motor, which emulates the mechanical drive train and drives a synchronous generator. A developed MATLAB/Simulink model obtains wind profiles and calculates the command shaft torque of a real wind turbine by applying real wind turbine characteristics in dynamics. These characteristics are compensated for more accurate results. Based on the comparison between the calculated torque and command one, the shaft torque of the dc motor is regulated by controlling the armature current demand of a single-phase half-controlled ac-dc converter. The effectiveness of the developed system is increased by proposing some novel ideas. This paper reports the operating principles, theoretical analyses, and test results under several cases of study.

***Keywords*:** Wind energy conversion system, emulator, dynamic, pulsation torques, turbine inertia compensation, simulation bandwidth, dynamic torque estimation.

1. Introduction

A novel idea recently employed in the field of wind energy technology is the utilization of wind turbine emulator (WTE) to study the steady-state and dynamic phenomena related to wind energy conversion system in a controlled environment without reliance on natural wind resources and actual wind turbines. Also, it can be used as an educational tool to teach the behavior, operation and control of a wind turbine. In the past few years there have been various studies on wind turbine emulators. Authors of [1]-[3] utilized separately excited dc motors with controlled armature current. Reference [1] presented a wind turbine emulator (WTE) using the electromagnetic (EM) torque equation of a dc machine. The armature and the field circuits were controlled so that the dc machine generated the static characteristics of a constant pitch wind turbine. In [4], a microcomputer-controlled SCR-DC motor was used to supply the shaft torque. This emulator only contains steady-state behavior of a real wind turbine. Tower shadow and larger turbine inertia to DC motor shaft inertia effects are usually neglected [5]. In [6] for the first time IGBT inverter controlled IM has been used as a wind turbine emulator. The armature current and frequency demand values were controlled in such a way that the IM shaft generated the steady state characteristics of a constant pitch wind turbine. In order to have accurate study on wind turbine behavior having tower shadow and larger turbine inertia effects is necessary. For the first time tower shadow effect of wind turbine has been added to real wind turbine modeling in [7]. The emulator reproduced the mean torque of the turbine and the oscillating torque due to wind shear and tower shadow without taking into consideration the large turbine inertia in modeling. Dolan, et, al. in [8] modeled the torque oscillations caused by wind shear, tower shadow, and the obvious pulsations caused by variable wind speed. But they failed to include the dynamic effects of a larger turbine inertia that would be seen in real systems. Meanwhile their model needs torque transducer to determine what compensation is required to emulate the driving torque of the wind turbine and inertial dynamics. Also the steady state characteristics of real wind turbine have not been presented as they claimed in abstract. In Ref [9] even though the dynamic effects of a large turbine inertia and tower shadow has been modeled but the effect of gear ratio for inertia and torque has been omitted, in other words the gear ratio is considered as unit that is not the case in real world. Permanent magnet dc motor has been used in [10]. This paper presents an improved version that considers the harmonic torques due to the gradient and tower shadow effects, and inertia of the wind turbine drive train. The shaft mechanical model of the real wind turbine is distinctly different from the emulator system in which the real wind turbine shaft is replaced by a dc motor shaft. Obviously these two systems have different inertias, friction coefficients and elasticity's. So the dynamic equations presented in [10] for rotational shafts not only do not improve the dynamic accuracy of the emulator but also these may lead to much worse results than ignoring the elasticity and friction. On the other hand, modeling the turbine shaft elasticity while assuming a rigid coupling between the generator and the motor has no advantages. Meanwhile, the effect of large turbine inertia has not been clearly presented in dynamic equations of WTE.

The wind turbine emulator described in this paper aims to reproduce the mechanical behavior of the wind turbine rotor, drive train and a gear box under dynamic conditions. The reference for the torque developed by the wind turbine includes the gradient and tower shadow effects that result in pulsating torques. The larger inertia effect is efficiently modeled. The steady state behavior of real wind turbine such as $C_p - \lambda$ and $P_m - n$ characteristics are remarkably in accordance with real turbine studied. It is important to mention that WTEs with some of these characteristics have been discussed in the literature before but they were not described in details to allow their easy replication [4]-[11]. The emulator outlined in this paper includes several important components of which one or more was missing in other emulators. These components are: a variable wind speed, turbine inertia and a wind shear, tower shadow model, and steady state characteristics. One of the most important goals of this paper is to find very easy way for dynamic behavior description of real wind turbine for electrical engineers and researchers including the torque oscillations caused by wind shear, tower shadow, the obvious pulsations caused by variable wind speed, and the dynamic effects of large turbine inertia. To do this we used MATLAB/Simulink software that includes all the necessary blocks in detail for dynamic modeling of real wind turbine, also its real time windows target toolbox provides sufficient tools for exchanging data with interface hardware.

2. Emulator concept

The emulator is based on the energy conversion (wind turbine) system shown in Fig. 1. The lab system is realized by replacing the wind, gearbox and turbine rotor with a PC, ac-dc converter (dc drive) and dc motor as shown in Fig. 2. The PC implementing MATLAB/Simulink uses a wind shear/tower shadow model, an inertial model, steady state characteristics, and a variable wind to control the dc system to emulate the driving torque of a wind turbine. These models will be briefly outlined as will the computer hardware components along with the drive components and control methodology used.

2.1. Pulsating torques

In order to increase the emulator reliability and to avoid the delay time of torque transducer and also to reduce the overall cost of the emulator the dc motor torque will be estimated. Since this torque has been calculated from dc motor current in order to have accurate torque calculation the dc motor losses such as copper and rotational losses will be added to calculated power of wind profile as shown in Fig. 3. Torque pulsations, and therefore power pulsations, are observed due to the periodic variations of wind speed experienced at different heights. Power and torque oscillate due to the different wind speeds encountered by each blade as it rotates through a complete cycle. For instance, a blade pointing upwards would encounter wind speeds greater than a blade pointing downwards. During each rotation the torque oscillates three times because of each blade passing through minimum and maximum wind. To determine control structures and possible power quality issues, the dynamic torque generated by the blades of a wind turbine must be represented. It is therefore important to model these wind shear and tower shadow induced 1P and 3P torque pulsations for a meaningful wind turbine emulator as (1) [10].

$$T_{mech} = T_{mill}\left[\frac{1}{n} + A_1 \sin(\omega_{mill} t) + A_3 \sin(3\omega_{mill} t)\right] \quad (1)$$

where $A_1 = 0.2$ and $A_3 = 0.4$, T_{mill} and T_{mech} are average and aerodynamic torques of wind turbine, respectively.

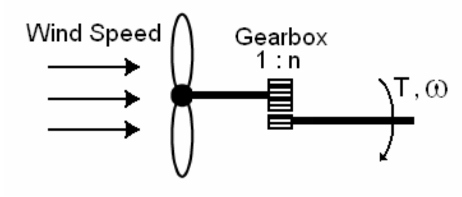

Fig. 1. Wind turbine system

The average power and torque developed by a wind turbine are functions of the wind speed (u), the rotational speed of the shaft (ω_{mill}), the tip-speed ratio (λ) and the torque and power coefficients (C_q & C_p) as given by (2) and (3) where r_m is the radius of the turbine and ρ is the air density.

$$P_{mill} = 0.5 \times \rho \pi r_m^2 C_P u^3 \quad (2)$$

$$T_{mill} = 0.5 \times \rho \pi r_m^3 C_q u^2 \quad (3)$$

$$\lambda = \frac{r_m n \pi}{30u} \quad (4)$$

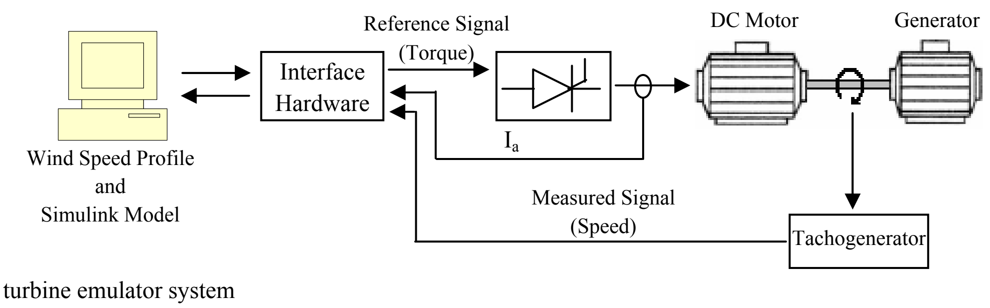

Fig. 2. Wind turbine emulator system

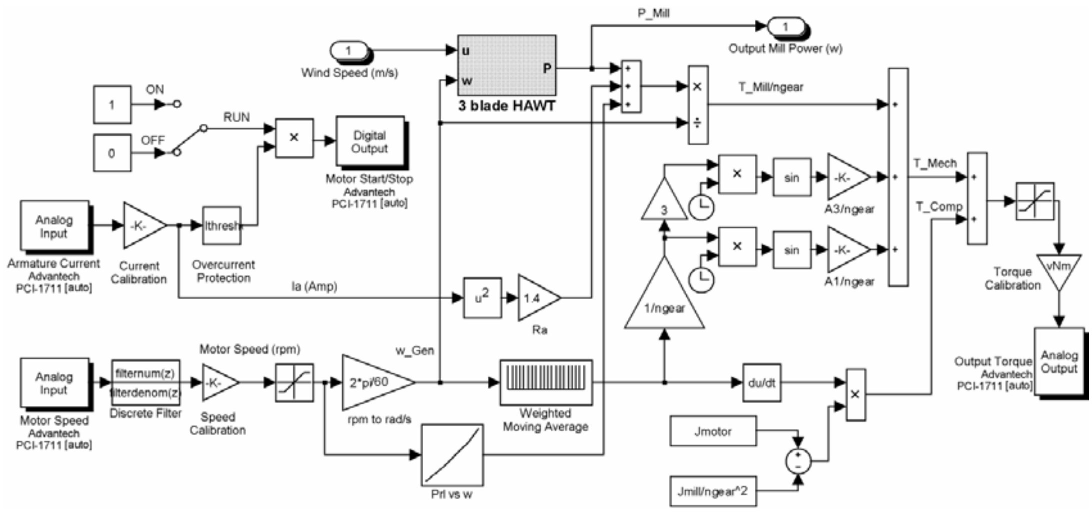

Fig. 3. MATLAB/Simulink model of wind turbine emulator

2.2. Turbine inertia model

The inertia model is determined by equating the generator acceleration in the field and lab systems. The effect is to alter the turbine torque that the dc motor will produce in response to a given wind, such that the effect of the larger turbine rotor inertia is emulated. A mechanical diagram of both the field system and the representative lab system is shown in Fig. 4, where T_{motor} = dc motor's torque, T_{mill} = aerodynamic turbine rotor torque, T_{gen} = generator torque, J_{motor} = dc motor inertia, J_g = generator inertia, and J_{mill} = turbine rotor inertia. Equations of motion may be written for both systems, real wind turbine (5) and emulator (6) and solved to determine the reference torque (7) required for the dc motor.

$$\frac{T_{mech}}{n} = \left(\frac{J_{mill}}{n^2} + J_g\right)\frac{d\omega_{gen}}{dt} + T_{gen} \tag{5}$$

$$\frac{T_{mech}}{n} = \left(\frac{J_{mill}}{n^2} + J_g\right)\frac{d\omega_{gen}}{dt} + T_{gen} \tag{6}$$

$$\frac{T_{mech}}{n} = \left(\frac{J_{mill}}{n^2} + J_g\right)\frac{d\omega_{gen}}{dt} + T_{gen} \tag{7}$$

where n is gear ratio and the second term of right hand side of (7) represents the compensation torque of wind turbine emulator. Therefore the wind turbine emulator will accurately represent the field wind turbine system if the driving torque T_{motor} is controlled according to (7). Fig. 3 shows the wind turbine simulation block diagram which consists of torque calculation block, torque pulsations due to wind shear and tower shadow effects and, compensation torque effect due to larger turbine inertia.

3. System implementation

A dc motor was used in the WTE prototype. The parameters of motor and real wind turbine under study are presented in appendix. The maximum speed for the wind turbine is 1 rps. Therefore, the bandwidth required from the current control loop so that the WTE can reproduce a torque with the gradient and the tower shadow effects is equal to 3 Hz. The single phase half-controlled drive used in this emulator for dc motor control as shown in Fig. 5 produces harmonics (ripples) with 100 Hz that outside the required bandwidth of gradient and the tower shadow effects of 3 Hz. The sampling frequency of emulator has been chosen 100 Hz that this is equal to ripples produced by converter, with this sampling frequency the harmonics produced by converter will be avoided.

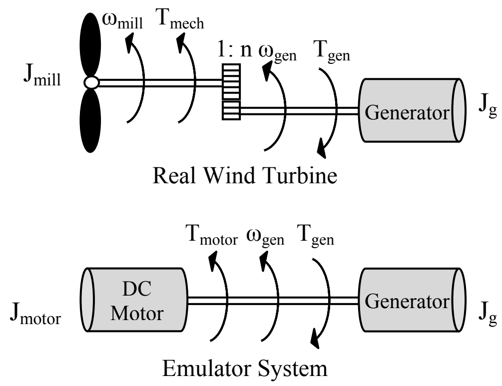

Fig. 4. Mechanical models of real and emulated WT

3.1. Steady State Characteristics of wind turbine

The wind turbine model is developed on a MATLAB/simulink platform for easy access, programming and modifications. As can be seen in Fig. 6, the interface between the Simulink model and the control and measurement hardwares is accomplished via real time windows target associated with a Data Acquisition Interface I/O board. This I/O system provides enough A/D channels and D/A channels for control and acquisition purposes. The model generates the current demand for the single phase half-controlled converter drive. In this research a horizontal axis wind turbine as described by Fig. 7 is used. The parameters of dc motor and wind turbine are listed in appendix. The power-speed characteristics of WTE at different wind speeds as measured during tests are shown in Fig. 7, and are compared with those of a real wind turbine which verifies that the developed wind turbine emulator reproduces the steady state characteristics of a given wind turbine at various wind conditions accurately.

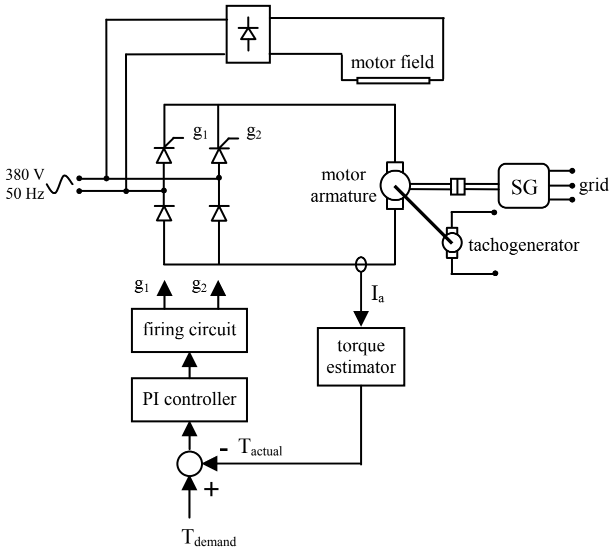

Fig. 5. Single phase half controlled dc drive

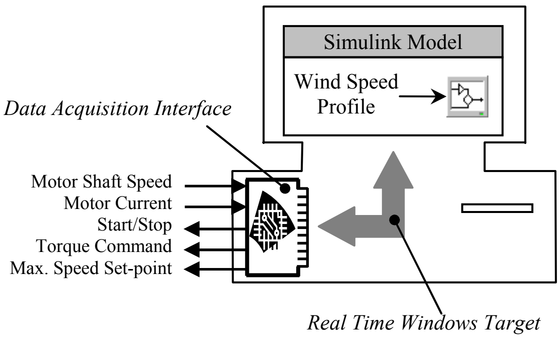

Fig. 6. Interface between Simulink model and the control and measurement hardwares

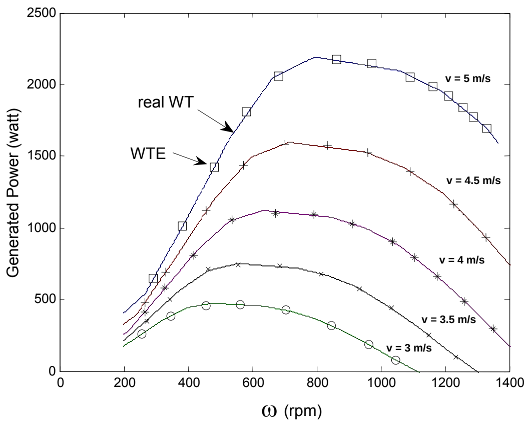

Fig. 7. Power - speed characteristics of a real WT and WTE

3.2. Tower shadow and wind shear effects

The turbine torque oscillations due to tower shadow and wind shear were calculated based on the turbine specifications. These oscillations were sufficient to cause a resultant fluctuation in the output current, such that the effects due to tower shadow could easily be distinguished in the time domain. For this purpose we apply constant wind speed such that the generator shaft speed rises to 1319 rpm. Since the gear ratio is 1:25 so the 1P and 3P frequency of oscillations due to tower shadow and wind shear effects can be calculated as:

$$1P = 1310/(60\times25) \approx 0.87\ Hz,\ 3P = 3\times1P \approx 2.6\ Hz \quad (8)$$

Fig. 8 shows frequency spectrum induced in output power of emulator for J = 0.25 kgm^2. Figs. 9 and 10 illustrate the effect of these pulsating torques on the motor current and consequently on the output torque of emulator.

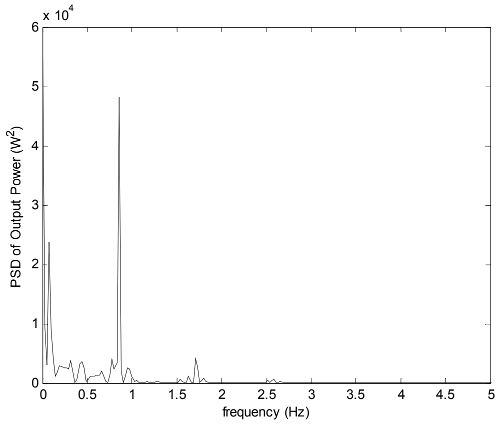

Fig. 8. Frequency spectrum of the emulator output power considering the pulsating torques (J = 0.25 kgm^2)

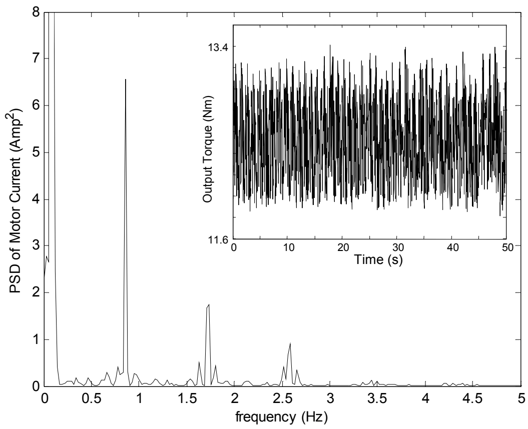

Fig. 9. Frequency spectrum of the motor current considering the pulsating torques (J = 0.25 kgm^2)

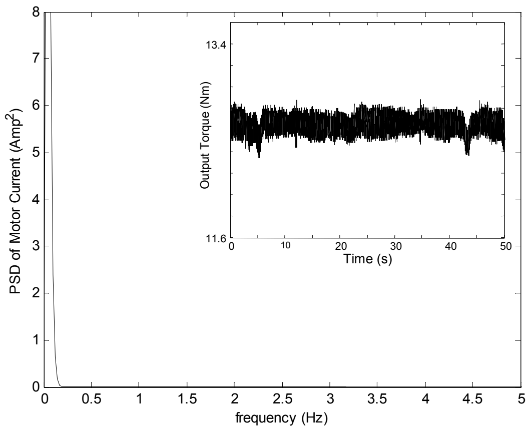

Fig. 10. Frequency spectrum of the motor current ignoring the pulsating torques (J = 0.25 kgm^2)

3.3. Inertia model

The inertia model is determined by equating the generator acceleration in the field and lab systems. The effect is to alter the turbine torque that the dc motor will produce in response to a given wind, such that the effect of the larger turbine rotor inertia is emulated. Frequency spectrum of the emulator output power including tower shadow effect and larger inertia (J = 7 kgm^2) is shown in Fig. 11. By comparing Figs. 8 and 11 one can see that the turbine with larger inertia demonstrates reduced magnitude for 1P and 3P harmonics. Fig. 12 shows how the wind turbine speed developed by the WTE varies for different values of moment of inertia (J = 0.25, and 7 kgm^2) for the wind turbine rotor. One can see that rotors with higher values of moment of inertia yield reduced oscillations in the shaft and slower dynamics.

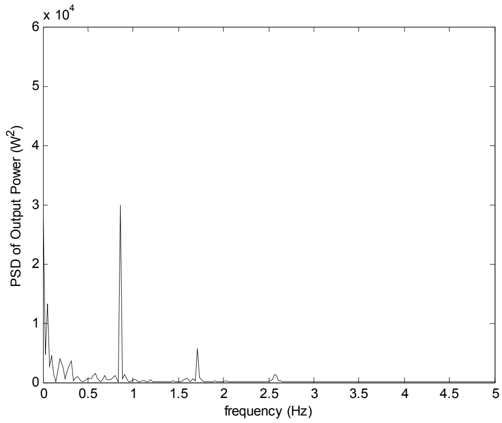

Fig. 11. Frequency spectrum of the emulator output power considering pulsating torques and larger inertia (J = 7 kgm^2)

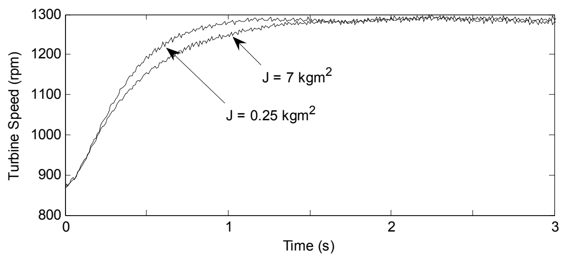

Fig. 12. Effect of J on the transient response of the turbine speed following a step variation of the wind speed

3.4. Oscillating wind speed

Frequency spectrum of applied wind speed is shown in Fig.13. While the mean value is assumed to be 4 m/s, one can see that the wind speed has the harmonics of 0.8 Hz, 3.2 Hz, and 15.9 Hz. From Fig. 14 it is clear that due to low pass filter behavior of wind turbine which its cutting frequency in this case is about 2.5 Hz, the 15.9 Hz harmonic has been disappeared in frequency spectrum of the dc motor current due to oscillating wind speed also the 3.2 Hz is significantly damped. Fig. 15 shows variable wind speed effects on turbine speed for different values of moment of inertia. Larger turbine inertia reduces the magnitude of oscillations in turbine speed.

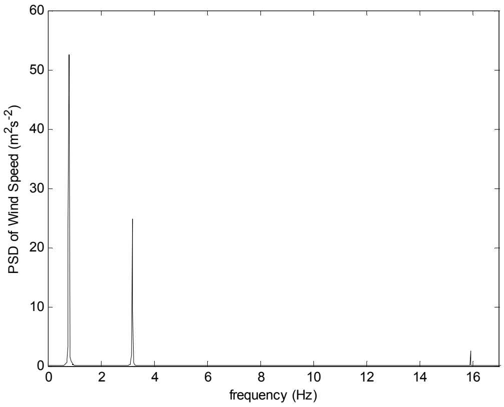

Fig. 13. Frequency spectrum of the wind speed

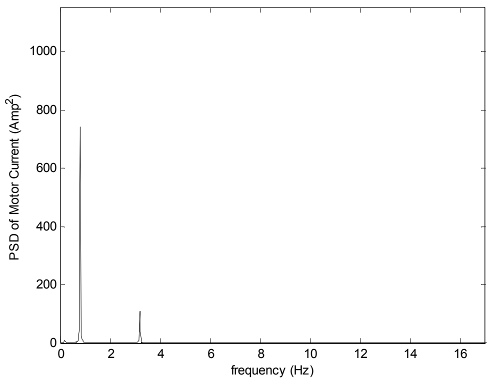

Fig. 14. Frequency spectrum of the dc motor current due to oscillating wind speed (J = 7 kgm^2)

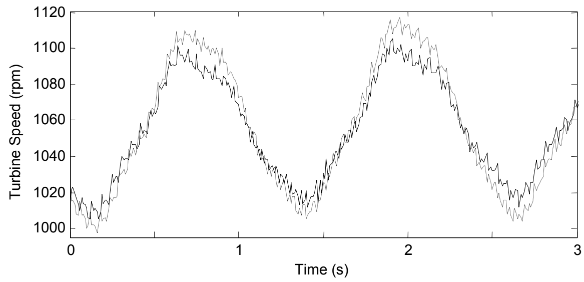

Fig. 15. Effects of wind speed variations and larger inertia in turbine speed; J = 0.25 kgm^2 (…), J = 7 kgm^2 (—)

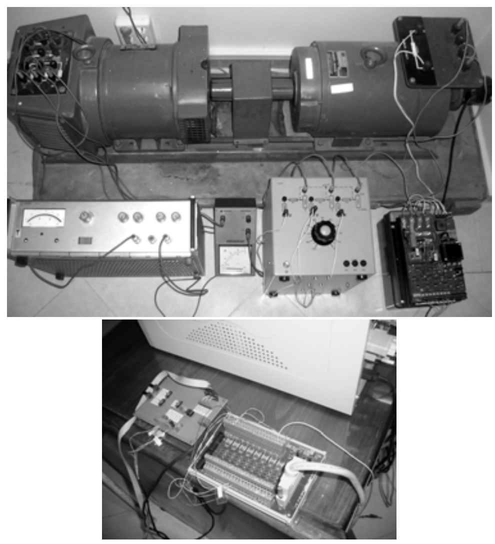

Fig. 16. Emulator system hardware

4. Conclusions

In order to improve the effectiveness and efficiency of research into wind energy conversion systems, a dc motor based wind turbine emulator has been developed to create a controlled test environment for study of wind turbines. The wind turbine model and the digital controller are developed on a MATLAB/Simulink platform for easy access, programming and modification. Various wind turbines and wind profiles can be incorporated in the control software. In this paper very accurate and detailed dynamic behavior of real wind turbine has been introduced. The emulator outlined in this paper includes several important components of real wind turbine including, wind shear and tower shadow effects, larger turbine inertia, variable wind speed, and steady state characteristics which one or more was missing in other emulators. Various tests conducted on the developed WTE and the resultant responses of a variety of WTE parameters have confirmed the good performance of the wind turbine emulator under the designed digital controllers.

5. Appendix

DC motor parameters:
Field: 220 V/0.7 A, nominal power: 3 kW, nominal speed: 1500 rpm, J: o.25 kgm^2, R_a: 1.4 Ω, L_a: 27 mH.
Wind turbine parameters:
Rated power: 2.5 kW, gearbox ratio: 25, J: 7 kgm^2, rotor radius: 4.5 m.

6. References

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