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EMULATION OF A SMALL WIND TURBINE SYSTEM WITH A SEPARATELY-EXCITED DC MACHINE

[1]Md. ARIFUJJAMAN, [2]M.T. IQBAL, [2]John E. QUAICOE

[1,2] Faculty of Engineering and Applied Science
Memorial University of Newfoundland
St. John's, NL, Canada A1B3X5

[1]Email: arifujjaman@engr.mun.ca

ABSTRACT

A small wind turbine emulator based on a separately excited DC machine is described in this paper. The experimental rig consists of a PC, Lab Master I/O board, power electronics circuitry and a 3HP separately excited DC motor which drives a synchronous generator. Varying aerodynamic power of the wind turbine due to furling action and its resulting dynamics are incorporated in the emulator with the use of a PC based wind turbine model. The shaft torque of the dc motor is determined from the armature current and parameters of the DC drive obtained by experimentation. In order to reflect the inertia of a small wind turbine an inertia disk is designed and coupled to the generator shaft and separately- excited DC motor. A digital PI controller is designed which makes sure that the actual rotational speed of the motor is tracking the theoretical rotational speed of the wind turbine rotor. The system design, model used and experimental results of the small wind turbine emulator are presented in the paper.

Keywords: *Wind turbine emulator, furling control, PI controller, DC machine.*

1. INTRODUCTION

Renewable energy sources have a great potential to generate electricity as they are abundant in nature, cost-effective and also cause a little harm to the nature. Wind energy has been developed rapidly as one of the best sources for electricity generation over the last few decades. Large wind turbines are complex in operation, deploy multitude of control methods and operate mainly in grid-connected mode. On the other hand, small wind turbines can be used for stand-alone as well as grid-connected applications. As long as the small wind turbines are concerned, it is necessary to emulate the steady state and dynamic behavior of the system in a laboratory environment to avoid the problems at installation and later use. This can be achieved by developing a wind turbine emulator which will reflect the actual behavior of a wind turbine. The main use of wind turbine emulator is to help design and test the wind turbine controller. Several researchers are working on control of wind turbine by implementing them in a simulator but these investigations are mainly focused on the 5 kW or more rated wind turbine [1], [2]. Research need to be further extended on small wind turbines to effectively understand and observe the behavior and control of such wind turbines. The control should ensure that no electrical or mechanical part of the wind turbine is exceeding its limits due to variations in the wind speed. This can be achieved in several ways. Hoffmann and Mutschler [3] have shown that for large wind turbines active stall, passive stall and pitch control on wind turbines can reduce the aerodynamic power. The associated problems with this scheme are the need for a good understanding on the airfoil design and the complex control system, which sometimes tends to increase the cost of the installation. For small

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wind turbines passive pitching is another suitable option to reduce the aerodynamic power, and furling control method has received a lot of attention [4, 5, 6, 7]. Most commercially available small wind turbines have furling control. Design of a maximum power controller for such wind turbines is still a research issue. This paper proposes a novel small wind turbine emulator including its aerodynamic power control achieved by furling mechanism. Emulation of wind turbine rotor has been done using a separately-excited DC motor and to represent the rotor inertia large inertia disk is designed and coupled with the systems which represent the inertia of a small wind turbine rotor.

A wind turbine emulator (WTE) is fundamentally a demonstration of a practical wind turbine in a laboratory environment. The general structure of a WTE consists of a PC where the model and characteristics of the wind turbine are written either in high or low level language, a DC or AC drives to represent a wind turbine rotor, feedback mechanism from the drive and power electronic equipment to control the drive. The feedback signal is normally acquired by the PC through an A/D converter and the signal for driving the power electronic equipment comes from the PC through a D/A converter. A detailed literature review has shown that all the components in the system are the similar except some researchers have used an AC or a DC drive to simulate the wind turbine rotor. Prior to 1980, Adjustable Speed Drives (ASD) implemented with DC motors had significant advantages over other types of AC motors. Recently, researchers more often choose an AC drive mainly due to the benefit of cost and low maintenance in contrast to DC drives. Beside this, the DC drive is bulky and costly. But the primary disadvantages of an AC drive are that speed control of AC drives requires expensive power electronic equipment and the control is more complex than a DC motor. Also it should be noted that an AC drive is not suitable to operate below 1/3 of its base speed i.e. it will not reflect properly the actual turbine characteristic below 1/3 of its base speed. On the other hand, a DC drive is easy to understand and the speed or torque control is less complex. A DC drive can operate more accurately at low speeds. Finally, in DC motors, the torque and speed can be controlled directly by controlling the armature current and speed respectively. The cost of the controlling equipment is lower than the cost of an AC drive. Due to above discussed reasons; this research uses a separately excited DC motor to reflect a wind turbine rotor. It has been found that most of the DC drives based wind turbine emulators are controlled by the armature current ([8], [9], and [10]), and few researchers have considered the armature voltage control [1] to operate a DC drive.
This paper is organized as follows. The first section is a short overview of emulator structure. In the second section, a short review of research on WTE, the modeling of a small wind turbine system with furling dynamics is presented and the emulator is described. A procedure to calculate the motor parameters and design of inertia disk is discussed in the third section, and the fourth section contains some test results. Finally, the findings of the investigations are highlighted in the conclusions.

2. WIND TURBINE EMULATOR

A wind turbine is a highly nonlinear system and to represent a realistic wind turbine several dynamics should be included in the model to build an emulator system. Several steady state wind turbine models have been used in the emulator platform based on the power speed characteristic [2], [11] and [12], torque co-efficient based wind turbine model [1], [10] and [13], power coefficient and pitch angle based wind turbine model [14]. However the problem with the static modeling is that the static behavior is unable to reflect the different dynamic aspects of a wind turbine which could be a vital issue during operation. In some publications dynamic aspects are incorporated with the model in a different way, i.e., elastic model of the turbine shaft [15]; mechanical balance equation [9], [16] for the turbine torque; aerodynamic, oscillatory and dynamic torque to combine the wind turbine torque [17]. Passive pitching mechanism and rotor blade inertia has been considered with the wind turbine model which can be well thought-out more generalized approach for a small wind turbine emulator system [8]. A review of research on the development of wind turbine emulator is given by A. D. Diop, et. al. [18], which shows that the furling action is still not considered in the wind turbine emulator raised area. From the previous investigation, it can be viewed that although static and dynamic aspects have been incorporated in the model in some way or other but there is always a scope to develop further. In this work, a wind turbine system has been developed which consist both the furling and rotor dynamics. A second order dynamics is included in the wind turbine model to describe its furling dynamics. It should be noted that furling should be achieved in a reasonable time so that it is neither too fast nor too slow. If it is fast enough then it will create excessive forces on the mechanical parts of the turbine and if it is too slow then it will decrease the overall system efficiency. In view of this, a reasonable time is chosen to allow the system to settle into steady state position after an increase in the wind speed. As the wind turbine system considered is of direct drive type, gearbox dynamics are not considered to the model. Rather an inertia disc is added to the system to represent the inertia of the wind turbine rotor. The wind turbine model is implemented in QBASIC 4.5 and the equations can be written as follows:

The output power of the wind turbine can be expressed as

$$P_{aero} = 0.5*\rho*A*C_p(\lambda)*V^3 \qquad (1)$$

The torque produced by the wind turbine is given by

$$T_w = \frac{P_{aero}}{\omega_m} \qquad (2)$$

where, ω_m is the angular velocity of the wind turbine rotor (rad/s). Also, the tip speed ratio (TSR) λ is given in terms of rotor speed, ω_m and wind speed, V (m/s) as

$$\lambda = \frac{R*\omega_m}{V} \qquad (3)$$

where, R is the radius of the wind turbine rotor (m).

Substituting eqn (1) and eqn (3) in eqn (2) the torque term can be expressed as

$$T_w = \frac{0.5*\rho*A*C_p(\lambda)*V^3}{\omega_m} \qquad (4)$$

When the wind speed increases, the wind turbine moves to an angle θ along its horizontal axis because of furling action. The effective wind velocity at the rotor plane will be $V\cos\theta$ [4]. Incorporating the furling action, the final expression of the torque is obtained as

$$T_w = \frac{0.5*\rho*A*C_p(\lambda)*(V\cos\theta)^3}{\omega_m} \qquad (5)$$

So the theoretical rotational speed of the wind turbine can be written from eqn (5) as

$$\omega_m = \frac{0.5*\rho*A*C_p(\lambda)*(V\cos\theta)^3}{T_w} \qquad (6)$$

i.e, this speed serves as the reference speed of the rotor in a specific wind speed.

The relation with the power coefficient and tip speed ratio typical and the curve has been taken from the literature [5]. A model for power coefficient (C_p) has been calculated and curve generated by the approximate model and the actual data are presented in Figure 1(a). A statistical analysis shows that the R square value of the model is 99.8% and goodness of fit is less than 0.0001, which proves that the predicted model for C_p with the fitted coefficients is fairly good enough to meet the actual value. The modeling equations has been found as

$$C_p = 0.00044*\lambda^4 - 0.012*\lambda^3 + 0.097*\lambda^2 - 0.2*\lambda + 0.11 \qquad (7)$$

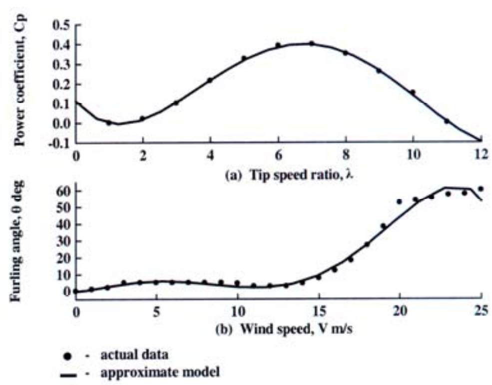

Fig. 1: (a) Power coefficient as a function of tip-speed ratio. (b) Furling angle versus wind speed.

It has been found that there is not much information in the literature about the relationship of wind speed and furling angle. The curve between wind speed and furl angle has been taken from the literature [19, 20]. An approximated model is used to determine the relation between wind speed and furling angle and found that a fifth order is model is sufficient to represent the variation. The R square value and goodness of fit of the expected model has found to be as 98.59% and less than 0.0001, thus validate the modeling approach. The modeling equation is

$$\theta = -0.00017327 * V^5 + 0.0085008 * V^4 - 0.12034 * V^3 + 0.4501 * V^2 + 1.0592 * V + 0.38972 \quad (8)$$

where, θ is the furling angle in degree and V is the wind speed in m/s. The actual data and

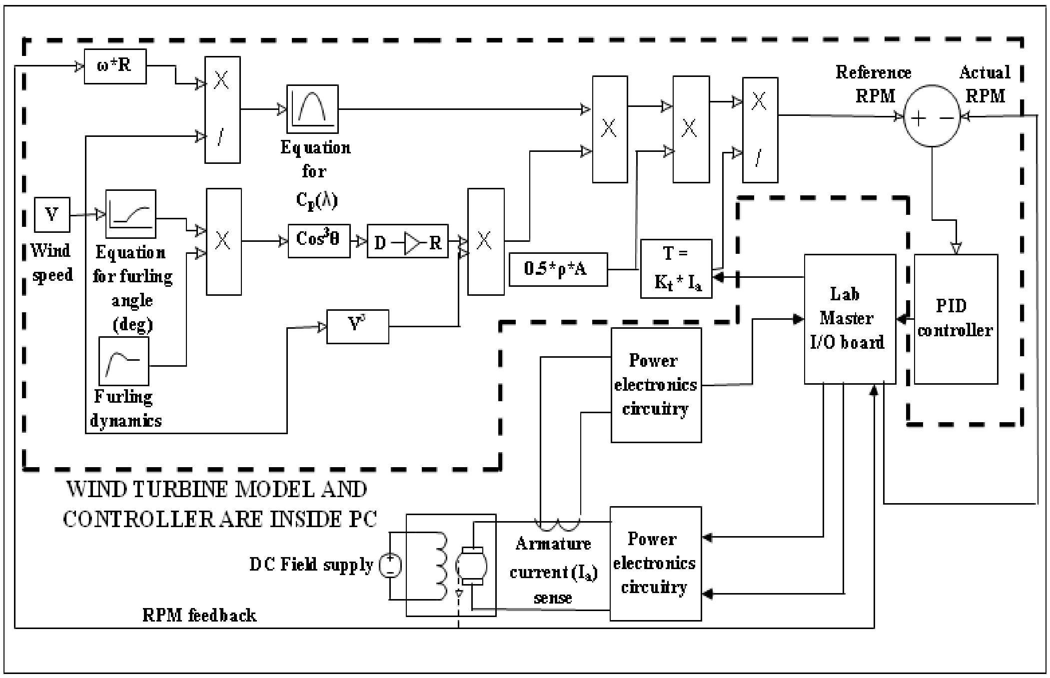

Fig. 2: Small wind turbine emulator structure with peripheral

approximated model curve are represented in Figure 1(b).

The second order dynamics $(H(s))$ for the furl angle has been considered as

$$\frac{1}{1.3 * S^2 + S + 1} \quad (9)$$

To incorporate with the digital system, a continuous function should be converted to a discrete equivalent of the continuous function. A zero order hold method for 0.1 second sampling time has been used to convert the continuous dynamics of the furling action to its discrete equivalent $(H(z))$ given by equation (10) which is derived from eqn (9) and than converted to difference equation.

$$H(z) = \frac{0.003747 * z + 0.003652}{z^2 - 1.919 * z + 0.926} \quad (10)$$

To track the theoretical rotational speed of the wind turbine rotor a digital PI controller has been used and the general transfer function of a first order digital PI controller can be written as [21]

$$G_r(z) = \frac{(q_0 + q_1 z^{-1})}{1 - z^{-1}} \quad (11)$$

where, q_0 is proportionality constant K_p

q_1 is $K_p * \left(\frac{T_s}{T_i} - 1 \right)$, T_s is the sampling time (0.1 second).

The basic structure of the wind turbine emulator including controller in conjunction with electronics schematic is given in Figure 2.

The small wind turbine emulator (SWTE) developed in the laboratory, consists of a 3HP separately-excited DC motor which drives a constant field excited three phase synchronous generator. The basic structure of the experimental rig is shown in Figure 3 and the test-rig picture is given in Figure 4.

The feedback is taken from the tacho generator to determine the rotational speed of the motor and with a current sensor armature current is sensed by the PC. A simple amplifier and filter is used in conjunction with the current sensor. Saturation of the armature current is eliminated by the adjustment of the gain of the amplifier

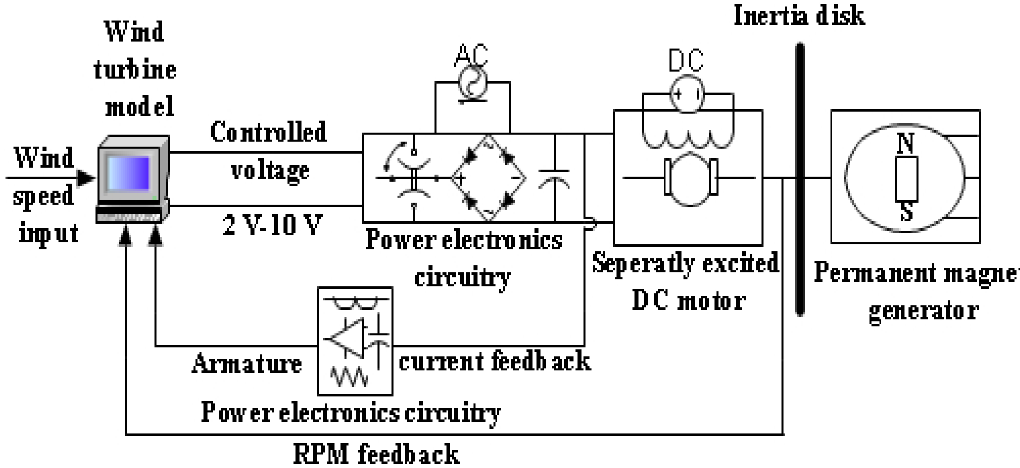

Fig. 3: Small wind turbine emulator structure

stage. It was observed that the voltage of the tacho generator was almost ripple free so a filter is avoided in this portion. The output of the controller fires the phase-controlled relay. Output of the phase-controlled relay is rectified and filtered using a capacitor to remove the noise from the rectified voltage. Figure 5 shows a schematic diagram of the emulator power electronics circuitry followed by the pictorial view of the power electronics in Figure 6.

A large inertia disk is coupled in front of the synchronous generator which is mounted at the other end of the DC motor through a flexible coupling to reflect the inertia of a real wind

Fig. 4: Photograph of the Test-Rig

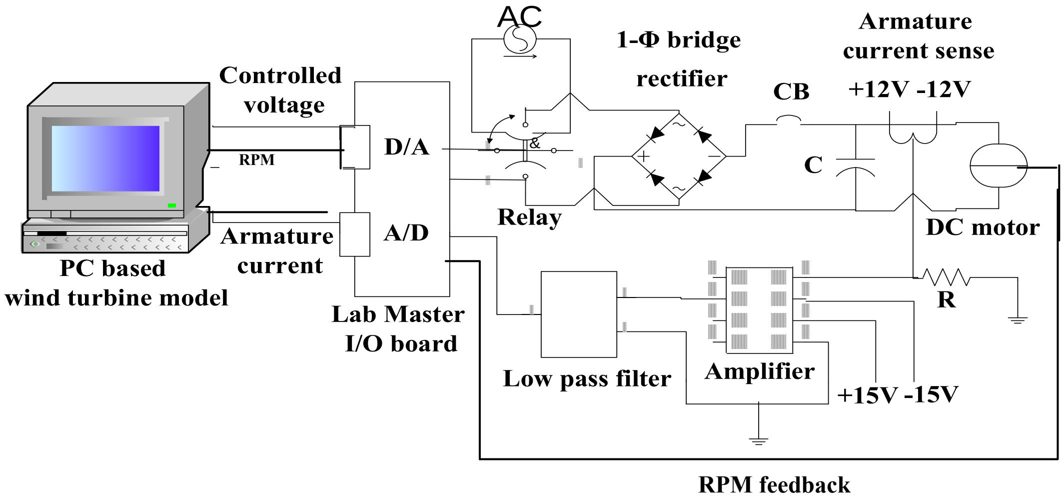

Fig. 5: Schematic of the wind turbine section of the emulator

turbine rotor. The disk is made of cast steel C10/20. Two bearings are used to support the system and a spider coupling is used to couple the disk with the synchronous generator and the shaft of the disk.

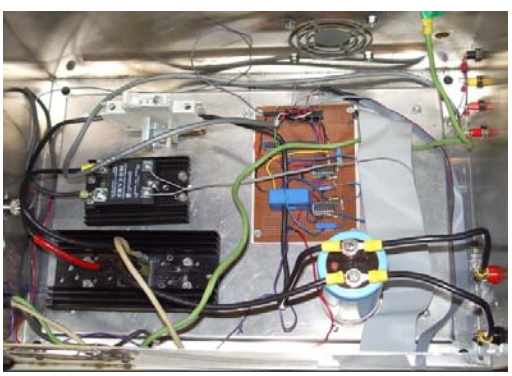

Fig. 6: Photograph of the WTE power electronics

3. MOTOR PARAMETER CALCULATION

The separately excited DC motor used in this research is rated at 3 hp and the parameters of the motor are determined through experimentation rather than assuming the value from the manufacturer. The following procedure was used to obtain the parameters.

The armature resistance of the motor was determined by applying a DC voltage at the armature terminal and measuring the corresponding current.

Several methods exist to determine the inertia of a DC drive. A review of the existing methods by I. H. Lin [22] found that most methods lead to uncertainty in the parameters. In this paper a general approach is considered which is based on the following equation [22]:

$$J = \frac{T_m * K_t * K_e}{R_a} \tag{12}$$

where, J is the moment of inertia of the motor,
T_m is the mechanical time constant of the motor,
K_t is the torque co-efficient of the motor,
K_e is the back emf constant of the motor,
R_a is the armature resistance of the motor.

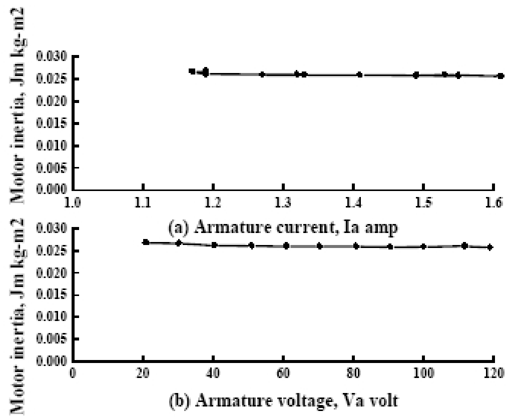

Fig. 7: Variation of motor inertia with armature (a) current and (b) voltage

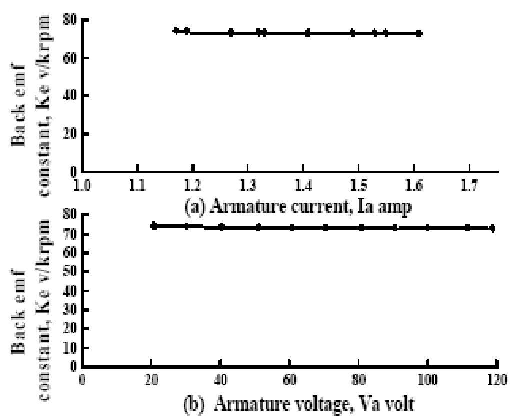

Fig. 8: Variation of back emf constant with armature (a) current and (b) voltage

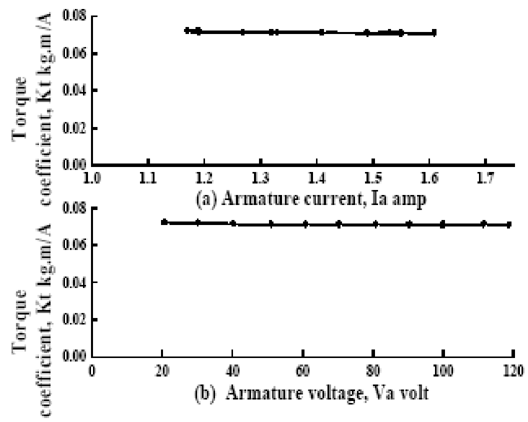

Fig. 9: Variation of torque coefficient with armature (a) current and (b) voltage

The mechanical time constant of the motor is determined by rotating the motor to its base speed and than shut down the power and recording the time it takes to reach 36.3% of its base speed [22]. It was found that the inertia of the motor is almost constant regardless of the variations in the motor armature current and voltage. Finally a mean value has been used and corresponding curve is shown in Figure 7 (a) and (b).

The back emf constant and torque co-efficient are calculated as follows [23]

$$K_e = \frac{V_0}{\omega_0} \qquad (13)$$

where, V_0 is the no load voltage of the armature and ω_0 is the no load speed of the motor [23]

$$K_t = 9.5439e-3 * K_e \qquad (14)$$

where, K_e is the back emf constant in V/krpm.

In order to reduce the error several readings have been taken for emf constant and torque coefficient, and a mean value has been taken and the variation with armature current and voltage are presented in Figure 8. (a) and (b), and Figure 9. (a) and (b) respectively.

The inertia of the wind turbine is a critical part of the research. It largely depends on the rotor radius, blade length and material. An extensive review indicates that the information available regarding the moment of inertia of the wind turbine rotor is not adequate. An assumed value based on the practical experimentation is considered here. The inertia disk is designed using the following approach.

For a solid cylinder, the inertia is given by [24]

$$J_w = \frac{1}{2} * M * \left(R_{disk}\right)^2 \qquad (15)$$

where, M is the mass of the solid disk and R_{disk} is the radius of the disk

Mass = Volume * Density

Cast steel C10/20 is considered for the disk. From eqn (15) the thickness is calculated by choosing suitable radius and it is found that a disk of around 46 kg adequately represents the inertia of such small wind turbines.

4. RESULTS

The small wind turbine emulator described above was implemented and tested in the laboratory environment. A simple gain scheduled digital PI controller was designed to make the speed of the separately-excited DC motor same as the required rotation of the wind turbine rotor and to operate the WTE in a wide

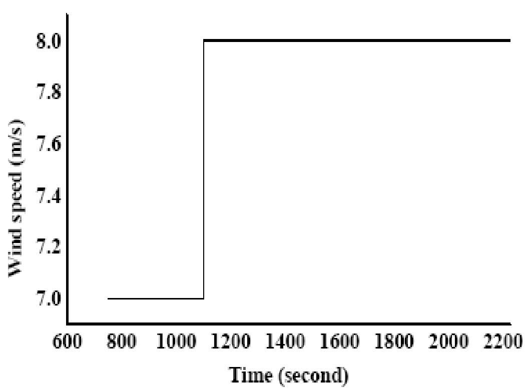

Fig. 10: Wind speed profile applied to the wind turbine emulator

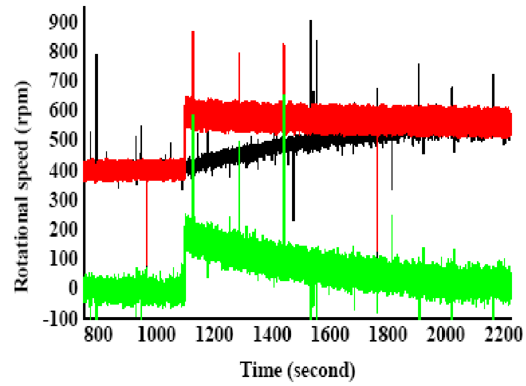

Fig. 11: Variation of rotational speed with wind speed

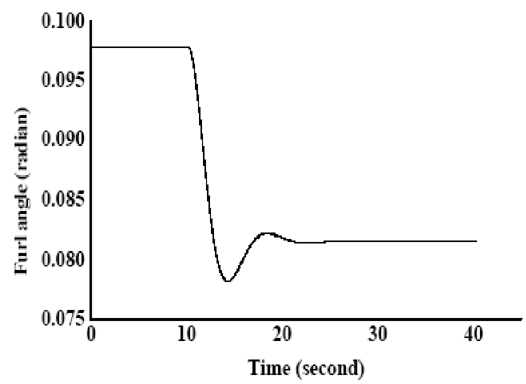

Fig. 12: Representation of expected furl dynamics

coding which decreases the necessity of any extra circuitry. The motor field supply was fixed at 76V. A step increase in wind speed (from 7 to 8 m/s) was applied to the emulator model as shown in Figure 10. The corresponding

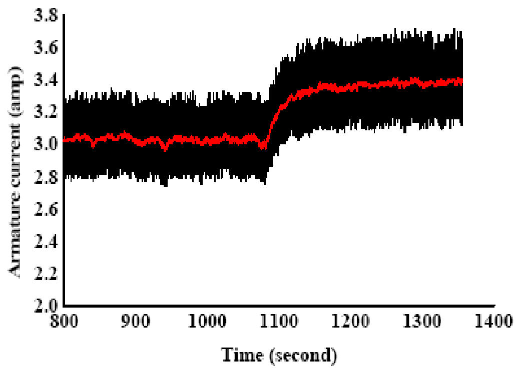

Fig. 13: Variation of armature current with step load

reference rotor speed (upper trace), actual rotational speed (middle trace) of the motor and error (lower trace) are presented in Figure 11. It is shown that after a step, within 3 minutes the speed follows the reference rotor speed and the error term becomes more or less zero. Figure 12 represents the expected furling dynamics of the wind turbine. After a step input, within an acceptable time the rotor comes to a stable state. Figure 13 represents the variation of armature current with a step change in load. As long as the load changes, the armature current settle down to a new higher value. The measured current has been smoothed by averaging. For an initial guess of the PI controller parameter values, the Ziegler-Nichols method was applied and finally after several trial and errors a suitable set of parameters was determined.

5. CONCLUSIONS

A wind turbine emulator is a strong platform for testing and observing the wind turbine behavior. This paper proposes a novel emulator for small wind turbine system where aerodynamic power is controlled through furling action and the resulting dynamics are also incorporated in the small wind turbine model. To reflect the inertia of the wind turbine rotor an inertia disk is incorporated. Preliminary system test results show acceptable performance. This emulator could be used for the design and development of small wind turbine power electronics and evaluate their performance.

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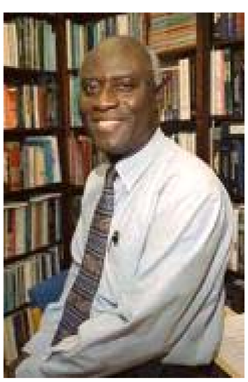
Md. ARIFUJJAMAN received his M.Eng. degree in Electrical and Computer Engineering from Memorial University of Newfoundland (MUN), Canada on September 2006. Prior to that, he fulfilled his B.Sc. degree in Electrical and Electronic Engineering from the Khulna University of Engineering and Technology (KUET), Bangladesh. Afterwards he joined as a lecturer at the same university and consequently held the position of a Consultant and Research Testing Officer for about 2 years before starting his M. Eng. at MUN. He is currently working on a Ph.D. on dynamic control of small DFIG based wind turbines at the High Voltage Engineering Laboratory of MUN. His research involves simulation, control and innovative design approach of renewable energy systems with an intense to small wind energy conversion systems.

M. T. IQBAL received the B.Sc.(EE) degree from the University of Engineering and Technology, Lahore in 1986, the M. Sc. Nuclear Engineering degree from the Quaid-e-Azam University, Islamabad in 1988 and the Ph.D. degree in Electrical Engineering from the Imperial College London in 1994. From 1988 to 1991 and from 1995 to 1999 he worked at the Pakistan Institute of Engineering and Applied Science (www.pieas.edu.pk), Islamabad, Pakistan as an Assistant Engineer and later as a Senior Engineer. From 1999 to 2000 he worked as an Associate Professor at, Riphah International University (www.riphah.edu.pk). Since 2001 he is working at Faculty of Engineering and Applied Science, Memorial University of Newfoundland. His teaching activities cover a range of electrical engineering topics including control systems, power electronics and renewable energy systems. His research focuses on modeling and control of renewable energy systems.



John E. QUAICOE received the B.Sc. degree from the University of Science and Technology, Kumasi, Ghana in 1973, and the M.A.Sc. and Ph.D. degrees from the University of Toronto, Canada in 1977 and 1982 respectively. In 1982 he joined the Faculty of Engineering and Applied Science at Memorial University of Newfoundland, where he is presently a Professor and Associate Dean (Undergraduate Studies) with teaching and research activities in power electronics and related areas. His undergraduate and graduate teaching activities are in the areas of electric circuit analysis, electronic circuit analysis and design, energy systems, power electronics and power electronics systems, including modeling, analysis, control and design of power converters for various applications. Dr. Quaicoe was the recipient of the President's Award for Distinguished Teaching at Memorial University of Newfoundland for 2001 and the IEEE Canada Outstanding Educator Medal for 2002. His research activities include inverter modulation and control techniques, utility interface systems and power quality, and uninterruptible power supplies. Recent researches focus on the development of power electronic systems and control strategies for fuel cells and wind generation systems. He is a member of the Association of Professional Engineers and Geoscientists of Newfoundland and Labrador.