

Design and Development of a Wind Turbine Emulator for Analyzing the Performance of Stand-alone Wind Energy Conversion System

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ABSTRACT

This paper describes the design and development of a Wind Turbine Emulator (WTE), which can be used to analyze and assess the performance of Wind Energy Conversion System (WECS). The mathematical modeling of the WTE has been done using MATLAB/Simulink platform. A separately excited DC motor is deployed in order to reproduce the speed/torque, replacing the real wind turbine rotor. The half-bridge DC-DC power converter is developed to run the DC motor in a controlled fashion. Two PI controllers viz speed and current controller are employed which guarantee that the DC motor is following the theoretical (reference) rotational speed of the turbine rotor. A user interface is created in ControlDesk Next Generation, through which the input parameters of the WTE can be altered in real time and the instantaneous effect can be observed by analyzing the output parameters. The designed system offers wide range flexibility and provides a friendly environment in which wind speed and turbine parameters can be altered easily. Hence, offering user to conduct research on variable wind speeds. The DS1104 R&D controller board is employed for implementation of the developed Simulink model. The system design, the model used, and obtained results are presented in this paper.

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1. INTRODUCTION

The wind- input to the Wind Energy Conversion System (WECS), being intermittent in nature, having random variation, being uncontrollable, yields variable mechanical power delivered by the wind turbine and hence the coupled generator may deliver variable power. Therefore, it is essential to analyze the performance of real WECS before installing at the site. Hence, for the purpose of analyzing performance of the WECS before installing at the site, design of Wind Turbine Emulator (WTE) becomes inevitable [1]. WTE also plays a vital role in designing control strategies as well as for validating the control algorithms. It is also used for developing power electronic circuits of the wind energy conversion system. Moreover, it is also employed for testing the generator's control techniques. Above all, it is vital for analyzing the performance of WECS.

A WTE, essentially designed and developed in the laboratory, is an artificial, controllable and flexible test bench which imitates the real WECS, thus provides a platform for researchers, designers and engineers to conduct the research, observe and analyze the operation and control of WECS, in a controlled environment without relying on the natural source and real wind turbine. The fundamental requirement for

developing a WTE is to generate reference signal based on wind turbine characteristics. There are two ways of developing a reference signal, i.e. first, a reference speed is generated based on the mathematical equations and the motor is forced to track this reference speed by using a control system. Another approach is to develop reference torque and based on this reference torque, the motor should track it by using some appropriate control system. While designing wind turbine emulation system, the wind, turbine rotor and gearbox (if applicable) are replaced with a motor driven by controlled power source, which will serve the purpose of generating reference speed and/or torque.

Some publications can be found where other researchers have proposed and developed wind turbine emulators [2]-[15]. Different researchers have used different types of motors in order to replace the real wind turbine. The authors of [2]-[4],[16]-[20] have used DC motor which replaces the wind turbine rotor. The authors of [21] deployed permanent magnet DC motor. In [22] permanent magnet synchronous motor is employed in order to mimic the actual wind turbine. The authors of [23] have chosen Permanent Magnet Synchronous Machine (PMSM) as the driving motor for simulating the wind turbines. In [24] Induction Motor (IM) and in literature [6] Induction Motor is used in conjunction with PMSG. The literature review reveals that for the first time the authors of [25],[26] used inverter controlled IM. The researchers choose an AC motor because of the larger power capacity and lower price, on the contrary, the control method is relatively difficult, and speed or torque regulation and emulation accuracy are not pleasant [27],[28]. On the other hand, from a control point of view, the DC motor presents a simple control approach, i.e. through armature current and voltage, the torque and speed are easily controllable [5]. It has been observed that WTEs based on DC drives, are usually controlled by the armature current, whereas, some researchers preferred to control the armature voltage of a DC drive [15],[20]. Although both armature voltage and current control methods have their own effects into the field of emulation system, however, armature voltage control method is preferred due to the fact that it does not change the speed regulation and from zero to maximum, speed can be controlled quite easily. Most importantly, a DC motor works more accurately at low speeds, which ensures accuracy in imitating the low wind speeds. Therefore, it is worth notable that an AC motor is not appropriate to operate below 33.33% of its base speed, i.e. it will not replicate properly the real turbine characteristics below 33.33% of its based speed [3]. Since the emulator presented in this paper is designed to analyze the performance of the low speed wind turbine and from literature it has been witnessed that for low speed emulation, DC motor would be ideal therefore DC motor is preferred to be used. In designing WTE, control system plays a vital role, because, the machine used in the emulator is supposed to follow the reference value, which means, it should be effective so that by changing any input parameters, the command signal should be generated in order to run the machine accordingly. In the aforementioned WTEs [2],[3],[16],[20], the user interface is not described, which means the real time changing of input parameters is not possible. In this paper, a WTE is presented, which is able to mimic the performance of the stand-alone WECS under varying wind profile and the variation in wind speed is made possible through the user interface developed in ControlDesk Next Generation.

There are some available wind turbine emulators, but the description of each and every component is not provided. This paper aims at presenting the complete design and development of a WTE. The step by step description of every part is given. Starting from the mathematical modelling of the wind turbine based on fundamental equations, design of half bridge DC-DC power converter, the technique of generating & controlling the PWM signal for controlling the output voltage, implementation of the Simulink model onto DS1104 R&D controller board and development of user interface for adjusting the controlling parameters, monitoring the output values etc. are highlighted in depth. Thus, researchers can conduct their studies on WECS in a controllable test environment in replacement of an uncontrollable real system. Above all, the paper presents an extended exposition on design and development of a complete wind turbine emulation system.

The remaining paper is organized as follows. Mathematical modelling of the wind turbine and its characteristics are presented in the section 2. The design and development details of the WTE are presented in section 3. The subsections of 3, i.e. 3.1, 3.2 & 3.3 provide description of modelling and software simulation, control system structure and Half-bridge DC-DC power converter, respectively. The section 4 contains experimental results. Finally, the paper is concluded as presented in the section 5.

2. WIND TURBINE CHARACTERISTICS AND MODELLING

Wind turbine is mechanical device which is used to convert the kinetic energy of the wind into mechanical energy, followed by the generator, for converting the mechanical energy into electrical energy. Wind turbine is one of the most important components of any WECS. Hence, while designing and developing a wind turbine emulator, the mathematical modelling of the wind turbine is considered as one of the basic requirements. So called aerodynamic modelling of the wind turbine, describes the effects of wind

on the wind turbine. The mathematical modelling of the wind turbine yields the output speed of the turbine depending upon the input parameters of the wind turbine, i.e. wind speed, rotor specifications, air density and power co-efficient. The fundamentals of the mathematical modelling can be found in literature [2]-[4],[15]. The mechanical output power of the wind turbine, according to its aerodynamic characteristics, is given by,

$$P_m = 0.5\rho\pi R^2 C_p(\lambda, \beta)v^3 \quad (1)$$

Here, ρ represents air density (kg/m^3) and πR^2 is the rotor swept area; therefore, equation (1) can be rewritten as, the power coefficient represents the conversion efficiency of the wind turbine, also known as Betz's constant, $C_p = f(\beta, \lambda)$. Ideally, upto of 59.30%, maximally, of the available wind power can be converted into mechanical power [21]. However, real turbines can convert around 35-45%, which describes the power coefficient of the turbine known as C_p , as mentioned above. Usually, for small and medium wind turbines, the pitch angle β is kept constant; consequently, the C_p depends only on the Tip Speed Ratio (TSR), commonly denoted by λ . The mathematical model of the C_p obtained from the [3],[28] is as given by the equation (3), and the corresponding curve is depicted in Figure 1.

$$P_m = 0.5\rho AC_p(\lambda, \beta)v^3 \quad (2)$$

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

Here, λ is Tip Speed Ratio (TSR) and is given by,

$$\lambda = \frac{\omega R}{v} \quad (4)$$

The mechanical torque of the wind turbine is expressed as,

$$T = \frac{P_m}{\omega} \quad (5)$$

Therefore, the theoretical rotational speed of the wind turbine can be expressed as,

$$\omega = \frac{0.5\rho AC_p(\lambda)v^3}{T} \quad (6)$$

i.e., equation (6) describing the rotor speed is implemented in the simulation as a reference speed.

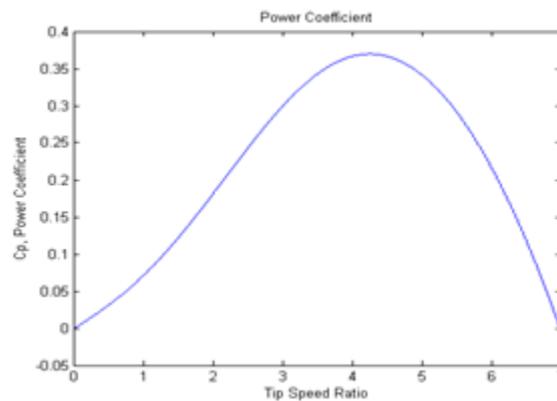


Figure 1. Power co-efficient (C_p) vs Tip Speed Ratio (λ)

3. PROPOSED AND DEVELOPED WIND TURBINE EMULATOR

The proposed and developed WTE consists of PC (with installed MATLAB/Simulink, dSPACE software, Control Desk Next Generation), DS1104 R&D controller board (inserted into PC) for real time implementation of the developed simulink model, CLP1104 I/O board, half-bridge DC-DC power converter associated with gate driver boards, DC power supply as input to the DC-DC power converter, DC low

voltage power supply for gate drivers and supplying power to the different boards, the DC motor-generator set, current transducer and incremental encoder. The developed WTE is shown in Figure 2. Based on the wind turbine characteristics, mathematical model is developed in MATLAB/Simulink, which yields reference signal. As described in the section 2, in addition to wind speed, rotor radius and air density, the reference speed also depends upon the feedback values, i.e. armature current and rotor speed. The calculated rotor speed plays the role of reference speed for the outer controller. Besides the wind turbine characteristics, two PI controllers viz, outer (speed controller) and inner (current controller) are also developed on MATLAB/Simulink platform. More details on control system structure can be found in section 3.2.

The output of the DC-DC power converter is connected with the armature terminals of the DC motor. The details of developing the DC-DC converter are given in section 3.3. Depending upon the commanded values, duty cycle of the PWM signal is calculated and based on the command, dSPACE system generates PWM signals. The generated PWM signals are further sent to gate driver board where they are amplified to a level (15V) suitable for triggering the gates of the IGBTs. Consequently, the output of the DC-DC power converter is such that it runs the DC motor in such a fashion to reproduce the behavior of real wind turbine.

The current transducer is used for obtaining the motor current, the output of the current transducer is sent to CLP1104 I/O board, where analog value is converted into digital. After A/D conversion, using dSPACE system, this current is fed to the simulink model, thus constituting feedback mechanism, in other words this measured current is sent to the inner control loop. In the same way, an Incremental Encoder is mounted on the DC motor for obtaining the speed of the DC motor. The output of the Incremental Encoder is connected to CLP1104 I/O board, and it is observable inside the PC using ControlDesk Next Generation.

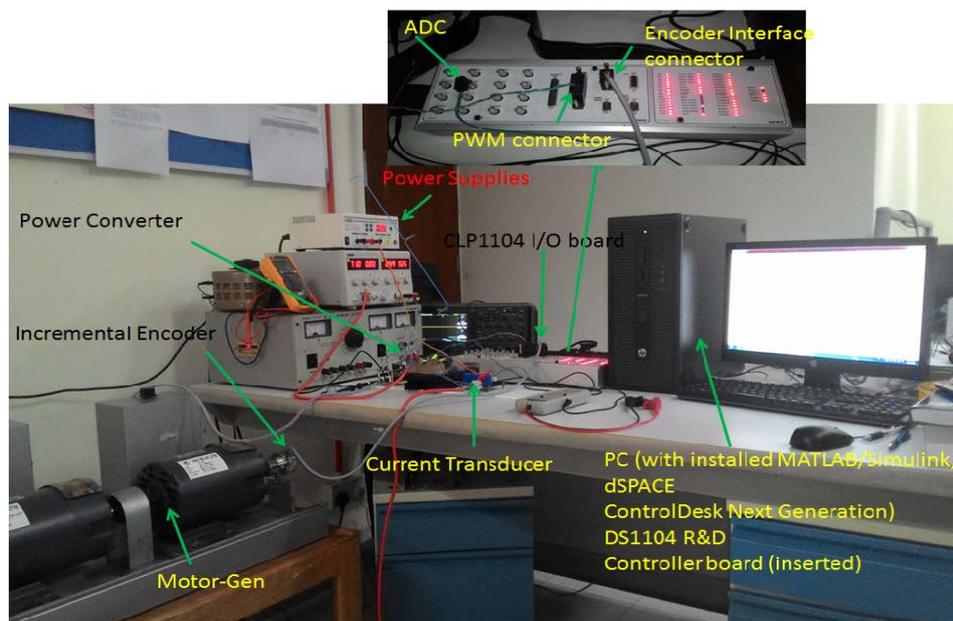


Figure 2. Developed wind turbine emulator

It is important to mention here that ± 10 V DC is used to supply power to the current transducer and +5V is supplied to the gate driver board. It is also necessary to mention here that a separate DC supply is needed as an excitation for field winding of the DC motor, which is 50V constant. Two DC machines- each 1/3hp, 115V, 3.2Amp, 1750rpm -were back to back connected, one working as a motor and other as a DC generator.

3.1. Modeling and software simulation

The modeling of wind turbine characteristics and the digital controllers has been done using MATLAB/Simulink platform, because of simplicity, easy access and modifications. The purpose of developing mathematical model and software simulation is to compute the reference speed of the wind turbine, taking into consideration the input variables, eg. the wind speed, the turbine size, air density, C_p model, and the real time values to complete these calculations. The real time values are the armature current

and speed of the DC motor. One of the prime purposes of software simulation is generating control signals (PWM) for the driver circuit. The inputs to the mathematical model i.e, the wind speed, rotor radius and air density are changeable through user interface developed in ControlDesk Next Generation. Also, the output parameters, the rotor speed and armature current are observable from the developed user interface. For the purposes, i.e, to generate PWM signal, Analog to Digital Conversion (ADC) of armature current and for obtaining the measured speed of the DC motor through incremental encoder, dSPACE system (DS1104 R&D controller board) is employed. Whereas, CLP1104 I/O board, is used as the interface between the DS1104 R&D controller and the external components as depicted in Figure 3. Once the MATLAB/Simulink model is developed, then by building the model (Ctrl+B), .sdf file is generated which is then exported to ControlDesk Next Generation. Over there, a layout is created in order to vary the input parameters as well as to monitor the output parameters.

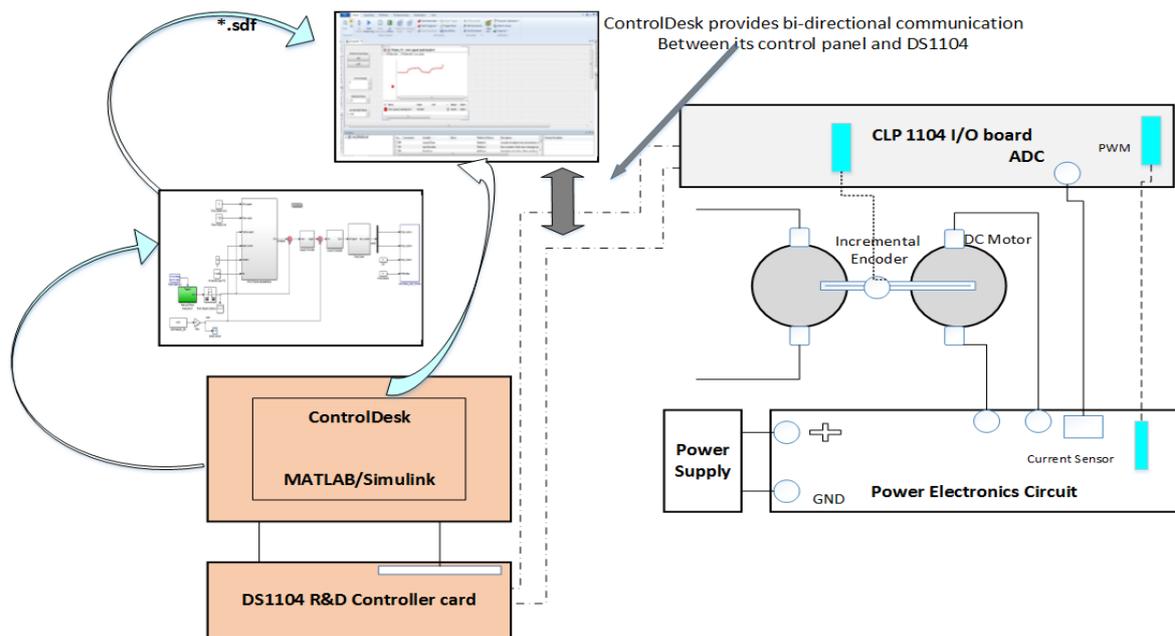


Figure 3. Setup for wind turbine emulator

3.2. Control system structure

The control system structure of the WTE is depicted in Figure 4. As shown in the Figure 4 two PI controllers, i.e. the outer controller (speed controller) and inner controller (current controller) are designed and integrated in to the system. These two controllers are closed loop cascaded connected. The inputs to the outer controller are the reference speed (based on wind turbine characteristics) and the measured speed of the motor. The error is sent to the controller, based on comparison between the reference one and the measured one, controller sends signal to the inner controller. Inner controller- also considered here as the current controller, depending upon the measured current and the reference signal, sends appropriate control signal to the next stage and duty cycle is calculated, based on the duty cycle the dSPACE system (DS1104) generates PWM signals, through CLP1104 I/O board PWM signals are sent to the gate drivers where these signals are amplified to a value suitable for triggering the gate of the IGBT. Hence, the half-bridge DC-DC power converter runs the DC motor in a way that it replicates the behavior of the real wind turbine. The details on DC-DC power converter can be found in subsequent section. As shown in the Figure 4 outer controller requires measured speed of the DC motor and the inner controller needs measured armature current. Hence, for sensing the armature current of the DC motor a current transducer is used, whereas, commercially available Incremental Encoder is deployed for measuring the actual speed of the DC motor.

3.3. Half bridge DC-DC converter

The half-bridge DC-DC power converter was designed. It comprised of two IGBT switches, connected in a fashion, forming half-bridge. The input to the power converter was 75V DC supply. The output of the half-bridge power converter was connected to the armature terminals of the DC motor. It would

be worth to mention here that, separately excited DC motor is deployed, therefore; the field system of the DC motor was supplied by a separate DC source, which in this case was 50V. The IGBT gate signals (PWM) were generated by DS1104 R&D controller board then through CLP1104 I/O board these signals were sent to gate driver board and finally the pulses were applied to the IGBTs for gate triggering. Consequently, the DC-DC converter produced controlled DC output voltage. The duty cycles were controlled in a way that the upper switch of the DC-DC converter received pulses and its compliment (not signal) was connected to the lower switch of the converter.

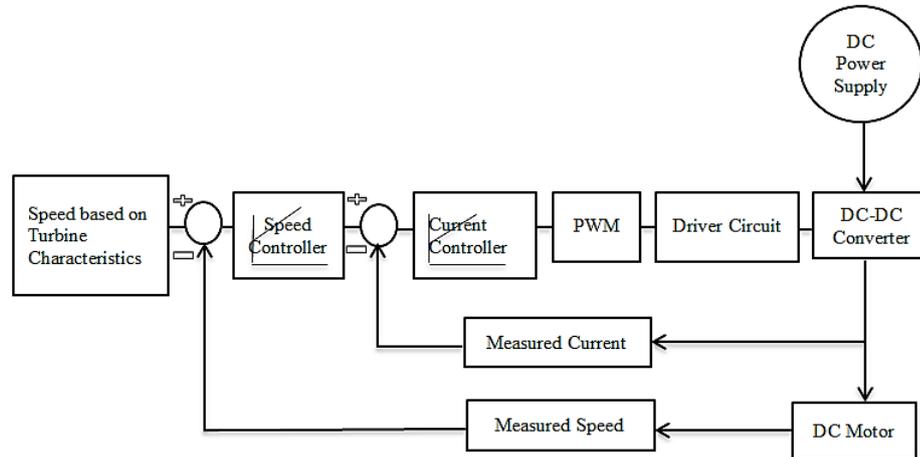


Figure 1. Control system structure

4. EXPERIMENTAL RESULTS

The performance of the developed WTE was analyzed under different wind speeds. In the model wind turbine characteristics, initially 5m/s wind speed was applied, followed by step variation, to 6 m/s, done using user interface created in ControlDesk Next Generation. The air density, considering the real world value, was taken as 1.225 kg/m^3 , the rotor radius was employed as 1.5 m, and approximate mathematical model for the power co-efficient C_p was taken as explained in section 2. Corresponding results are shown in Figure 5. The Figure 5(a) depicts the reference speed, which was calculated based on the turbine characteristics and Figure 5(b) depicts the measured speed of the DC motor. The results show the effectiveness of the control system, which means the DC motor tracks well the reference speed. The user interface was developed in ControlDesk Next Generation. In addition, in order to switch the PWM signals ON and OFF, a switch was inserted into the user interface, i.e., start/stop of the DC motor was made possible.

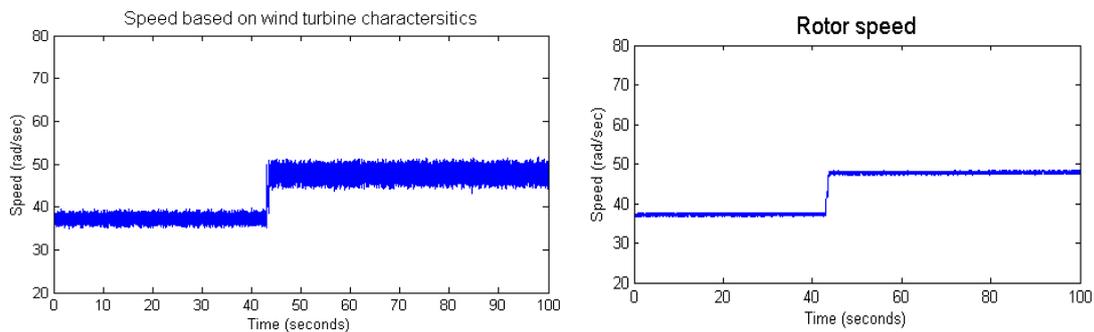


Figure 2. The performance of the developed WTE, (a) speed based on turbine characteristics (b) motor speed (rad/sec)

5. CONCLUSION

A wind turbine emulator based on DC motor driven by controlled half-bridge DC-DC power converter has been designed and developed. Stand-alone wind energy conversion system employing a fixed-pitch three-bladed Horizontal Axis Wind Turbine (HAWT) was selected for the modelling and performance

analysis of the wind turbine emulator. The wind turbine model and digital PI controllers were developed on MATLAB/Simulink platform. The complete Simulink model was implemented onto DS1104 R&D controller board. In addition, user interface was developed in ControlDesk Next Generation for monitoring, controlling and altering the parameters. In the developed user interface, the input parameters eg, wind speed and turbine rotor radius could be modified online. The resulting speed of the DC motor replicating the wind turbine could be monitored in real time.

The developed emulator will be helpful for designers, engineers, scientists and researchers in order to analyze the performance of wind energy conversion system. The paper also aimed at presenting the description of the developing and implementing mathematical model in MATLAB/Simulink, designing technique and development of the wind turbine emulator as well as the performance assessment of the emulator under varying wind conditions. After developing mathematical model, designing DC-DC power converter, generating PWM signals, they all were connected in such a fashion so that it could mimic the real wind energy conversion system. The results obtained confirm the effectiveness of the designed and developed model.

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