



LABORATORY EMULATION OF WIND TURBINE OPERATIONS

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Abstract: This study aims to introduce renewable energy sources with a focus on wind power and presents a horizontal-axis wind turbine emulation experiment by using frequently used electric drives laboratory components, including Matlab, dSpace, Permanent Magnet DC machines, as well as associated pre-lab analysis and post-lab report evaluations. The pre-lab assignment motivated the participating students to conduct research on various renewable energy sources and contemporary wind turbine operations, to perform theoretical wind energy operations, and to develop partial software code for the wind turbine emulation. Traditional DC motors were used to simulate as well as capture the wind power while safe voltage and speed levels in a laboratory environment were utilized. The experiment provided a step-by-step procedure and subject verification questions of the wind turbine emulation for the student teams.

The participating student pre-lab and hands-on laboratory performances as well as report content presentation and data interpretation qualities indicated a successful implementation of wind turbine operations, effectively removing the mostly infeasible laboratory resource constraints.

Introduction: Wind turbines offer exciting potential benefits as part of renewable energy mechanisms since fossil fuel based power generation techniques cause major economical and environmental problems. However, practical wind turbine research and technology development activities typically require large components and field implementations, resulting in mostly infeasible requirements in terms of laboratory resources such as space, setup and maintenance costs for many educational and industrial institutions. For example, a 1.5 Megawatts land-based wind turbine has been reported to require \$2098/kilowatt capital installation costs with 68% of the project cost coming from the turbine tower, drive-train, and rotor while the same size offshore wind turbine is expected to cost significantly higher amount of funds with about 32% of the project cost coming from the turbine components¹. Even the small wind turbines, up to 100 kilowatt power generation capacity, may become infeasible for many academic institutions as a 1.8 kilowatt wind turbine was commissioned in an academic institution wind turbine laboratory with the installation cost of \$10K². As real wind turbines, even the smaller types, seem to be too large and very dangerous for typical laboratory implementation, setting a make-shift lab at wind turbine facilities may also become very impractical and unsafe, with a number of logistical issues and associated liabilities.

Wind energy laboratory development efforts have ranged from hobby types to major industrial research laboratories³. A virtual, i.e., online, wind energy laboratory has been developed to simulate wind turbine design concepts for different turbine-blade, turbine geographic location specifications with the final goal of developing a turbine large enough to capture energy for 400 homes with highest efficiency⁴. Another wind energy laboratory development, WindLab⁵, utilized an aerospace-grade wind tunnel with a programmable variable speed wind source and a custom on-board instrumentation. Affordable wind energy experimentation kits have also been developed for K-12 students⁶, with a classroom pack basic wind experiment set costing up to \$244. Since many engineering schools provide electric machine or drive system laboratories, a feasible and practical solution to introduce wind energy generation can be proposed by utilizing an existing experimental motor-generator set to emulate

a wind turbine operation in terms of power generation principles and associated output characteristics.

This paper describes the development of a laboratory experiment closely related to energy conversion to emulate typical wind energy operations in a college level electric drives and machine course laboratory, offered every Fall semester, at Electrical Engineering and Computer Science Department of Texas A&M University-Kingsville (TAMUK), a minority serving institution. The electric drives and machines course is a 4-credit senior-level core course, having 3-Hour/week lecture and 3-Hour/week laboratory components. The objectives of the experiment include that the participating students will be able to describe contemporary wind turbine power generation principles and that the students will successfully be utilizing major design and analysis software tools during the simulation and testing of real world applications. As the wind energy emulation experiment was based on existing and common laboratory components, the final experiment integration was achieved without any capital investments for the host institution. Also, the laboratory students, mostly Hispanics, were exposed to an important renewable energy concept as part of the electric drive system course.

Experiment Overview: The experiment development focuses on horizontal-axis wind turbine emulation by using commonly available electric drives laboratory components, including Matlab⁷, dSPACE⁸ ControlDesk, Permanent Magnet DC machines, as well as associated pre-lab analysis and post-lab technical report with evaluations. Once the electric drives course covered satisfactory theoretical subjects for successful laboratory activities, pre-lab analysis and experiments took place each week, in addition to traditional two-student homework sets and individual exams. Since the wind energy emulation experiment was covered in the latter portion of the semester, the laboratory students were already exposed to and were experienced on fundamental Matlab and dSPACE ControlDesk real-time implementation procedures in the early laboratories of the semester. The laboratory students were assigned to 2-3 student teams who performed the pre-lab analysis as well as conducted the experiment as a group. The teams investigated different wind turbine structures in terms of both electrical and mechanical perspectives, studied wind turbine implementations around the world, and developed the theoretical analysis of a wind power source and relevant software code during the pre-lab analysis.

The laboratory DC motor first-order model was used to simulate and to study the wind power characteristics. The controlled Permanent Magnet DC (PMDC) motor generated the simulated wind power on the coupled PMDC Generator. Due to the facility limitations, actual wind turbine operations have been modified for practical laboratory experiments. For example, the laboratory DC motors can handle up to 42V and 4000 rpm with MOSFET-based electric drive circuitry while the real turbines likely use Insulated Gate Bipolar Transistor (IGBT)-based drive circuitries and synchronous/induction generators to handle very high power levels¹². The experimental procedure was enhanced with many strategically-positioned subject content verification questions to monitor and enforce superior student educational experience.

Pre-lab Development: Pre-lab assignments are expected to prepare the students for the upcoming labs in terms of necessary theoretical analysis, basic research on practical systems, mathematical derivations, possible controller designs, and possible program developments, likely

resulting in meaningful hands-on laboratory experiences. The wind turbine emulation pre-lab set was assigned one week prior to the actual experimentation, along with the actual experiment handout. The teams were given specific instructions to follow and a number of questions to answer as a team. Although the teams could divide the pre-lab tasks to each team member, all team members were responsible about all pre-lab tasks and were to receive the same grade. Since the focus of the pre-lab was to motivate students in informal academic setting, the pre-lab sets did not require typed and formal reports, i.e., hand-written and simply answering questions were sufficient. As the teams had a week to handle the pre-lab requirements, several research questions and open-ended design perspectives were also covered.

The specific pre-lab instructions included the items, listed as,

- All pre-lab problems should be attempted and the answers **MUST** be clear and easy to follow.
- Different parts/problems may have different point values at the pre-lab sets.
- Problems involving Matlab&Simulink should include the code, possible block diagrams, clearly defined figures (when applicable) to get full credit.
- Although one pre-lab analysis per group is sufficient, individual pop-quizzes may be given at the beginning of the lab session to test the pre-lab problems.
- Staple this cover page to your solution set.
- Study the problems with your group members and turn in your group work!...

The pre-lab technical questions and open-ended research assignments included the items, listed as,

1. Conduct research on renewable energy resources and
 - List all alternative sources and write a short article about one of them in a very creative existing application (Points will be assigned according to the originality of the application),
 - Explain different wind turbine structures, implementations, and efficiency ratings,
 - Determine the existing power capacity of wind turbine generators for a number of countries, the estimated cost of deployment, and possible incentives for wider wind turbine implementations,
 - Propose an innovative wind turbine energy system for the year-2050.
2. Briefly explain the theoretical wind turbine operation and associated mathematical model.
3. Develop a Matlab code to implement the wind characteristics shown in Fig. 3 of the handout. (You need to bring the code to the lab for implementation purposes)
4. Study and explain the block diagrams in Figs. 2 and 4 of the lab handout.
5. Elaborate on the effects of a Proportional-Integral (PI) controller during the wind turbine emulation.
6. Calculate the implied power for the wind characteristics given in Fig. 3.
7. Compare the similarities and differences of the laboratory and real-life wind turbine systems.
8. Explain the major experimental steps for the lab procedures. You need to be general enough to convey the idea but, at the same time, you need to be specific enough to refer to the experiment, equipments, etc.

Experiment Development: Basic wind turbine theoretical principles were introduced. Out of several available wind power plant configurations, a horizontal axis fixed speed wind turbine, shown in Fig. 1, is utilized in this experiment. This particular configuration provides high efficiency only at a particular wind speed while generating low efficiency for other speeds. The nonlinear model of the wind turbine⁹ uses the Tip Speed Ratio (TSR), defined as the ratio between the speed of the tip of a blade and the actual velocity of the wind. The TSR value depends on the physical characteristics of the blade and quantifies the efficiency by

$$\lambda = \frac{\omega R}{v} \quad (1)$$

where λ denotes TSR, ω denotes the rotational speed of the turbine (rad/sec), R represents the radius of the turbine blade (m) and v indicates the velocity of wind (m/sec). For the same wind speed, the power extracted by the wind turbine is expressed as

$$P_m = \frac{1}{2} \pi \rho R^2 v^3 C_p \quad (2)$$

where ρ indicates the air density (m^3/sec) and C_p represents the associated power coefficient, defined as

$$C_p = C_1 \left(\frac{C_2}{\lambda_i} - C_3 \beta - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6 \lambda \quad (3)$$

where C_1 through C_6 , β , and λ_i are constants. Typical parameters for a practical wind turbine system are given in Table 1.

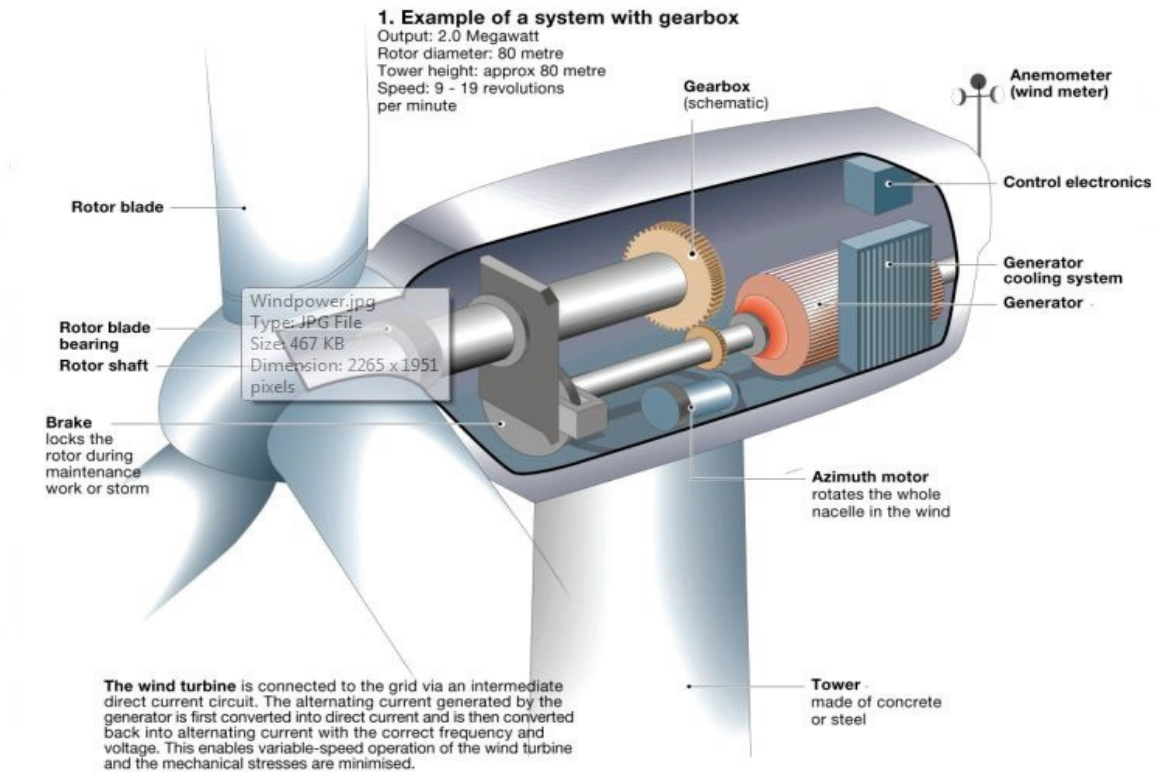


Figure 1. A Wind Turbine Structure¹⁰

Table 1. A Horizontal Axis Fixed-Speed Practical Wind Turbine Parameters¹¹

Number Of Blades	3
Rotor Diameter	22m
Cut In Speed (Lowest Operating Speed of Turbine)	9.068 m/s
Cut Off Speed (Highest Operating Speed of Turbine)	25m/s
Atomic Density (Air Density Higher Density will result in wind exerting more force on blade)	1.225 kg/m ³
Inertia time Constant	4s
Gear Box Ratio (Shaft does not rotate with same speed as Blade)	1:34
C ₁	.5176
C ₂	116
C ₃	0.4
C ₄	5
C ₅	21
C ₆	0.0068
This fixed speed setup optimizes the wind turbine for 15 m/s wind speed	

The experimental design allows selection of particular real wind speed values at which the wind turbine motor shaft rotates. The given wind speed will be the reference speed to the motor system, i.e., the presumed wind speed will be converted to a reference voltage to drive the motor. The presumed wind turbine PMDC generator is connected to the presumed wind turbine motor, rotating at the same speed and generating corresponding voltage values. The teams were given the following concept questions during the actual laboratory and were asked to include the corresponding answers in their technical laboratory report:

- Q) Investigate the wind turbine mathematical equations, explain the variables affecting the power & voltage generation, and introduce another parameter to reflect real-life concerns with full justification.*
- Q) Study different types of motors and fully justify why PMDC motors are more suitable for wind turbine emulation.*
- Q) What is PWM? What device is used to implement in the Lab?*

The experimental wind turbine emulation system block diagram and major components, shown in Fig. 2, were utilized for the wind speed characteristic given in Fig. 3, where the samples of a typical wind characteristic for a region are shown¹¹. The corresponding wind shaft speed characteristics were implemented as a speed-control system.

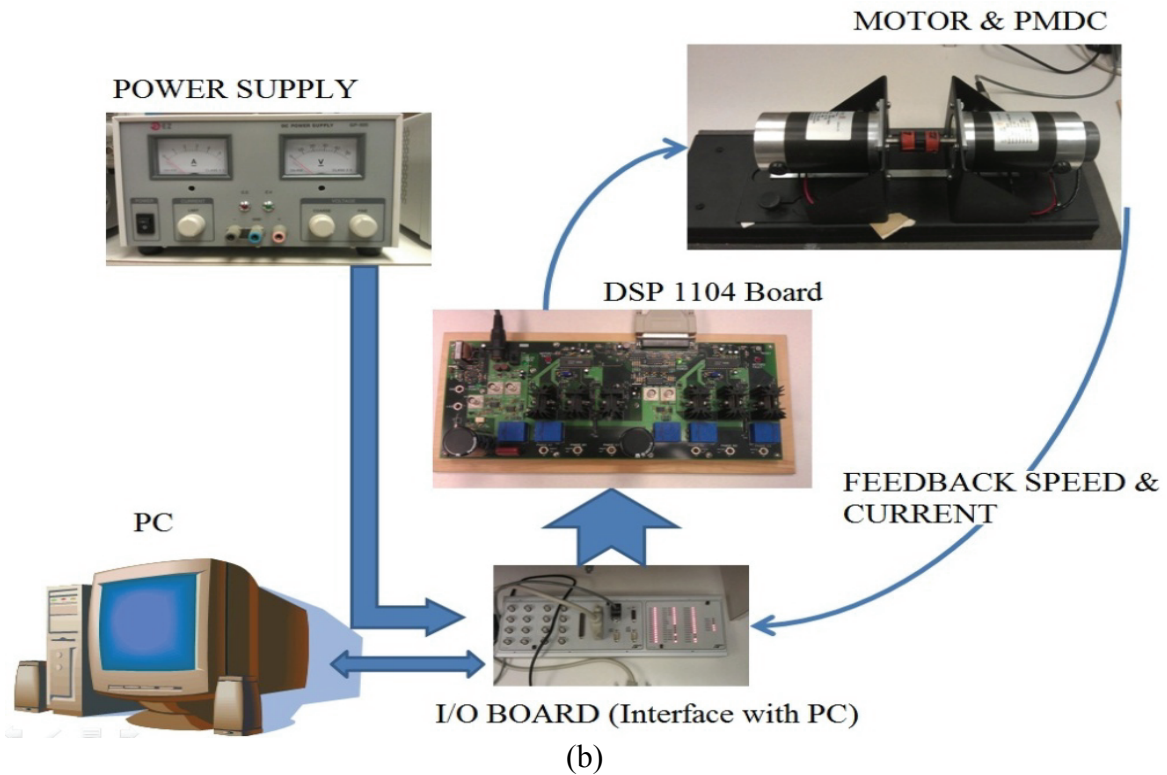
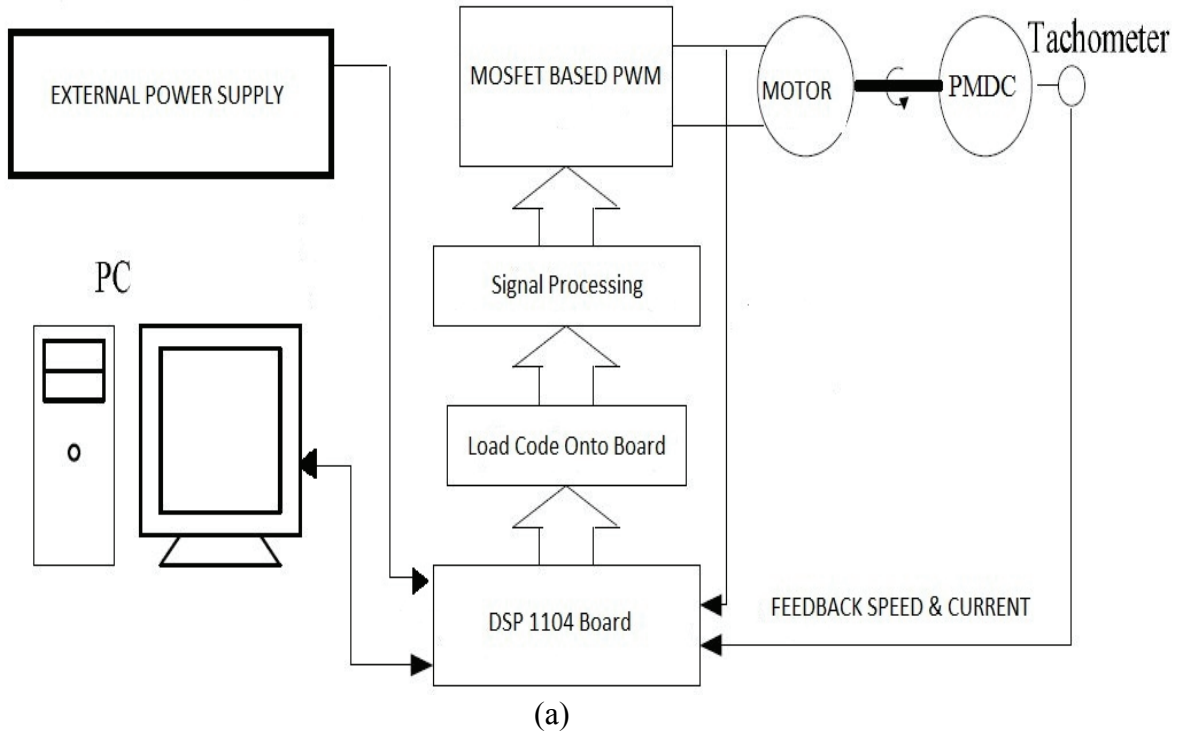


Figure 2. The Experimental Wind Turbine Emulation System a) Block Diagram, and b) Major Components

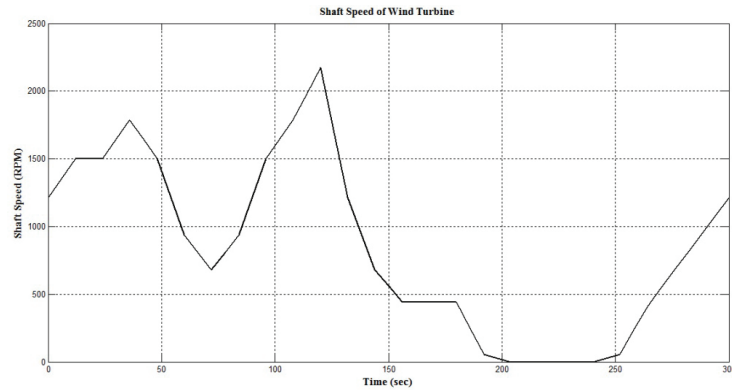


Figure 3. The Wind Turbine Shaft Speed Characteristics

By using the bold font for the important experimental and software execution as well as safety options, the teams were asked to implement the following steps to obtain the wind turbine emulation experimental setup:

- Make sure to bring the Matlab code (from the pre-lab analysis) to satisfactorily implement the wind turbine characteristics of Fig. 3,
- Start **Matlab** and change its workspace directory path to **C:\EEEN4422\Exp11**.

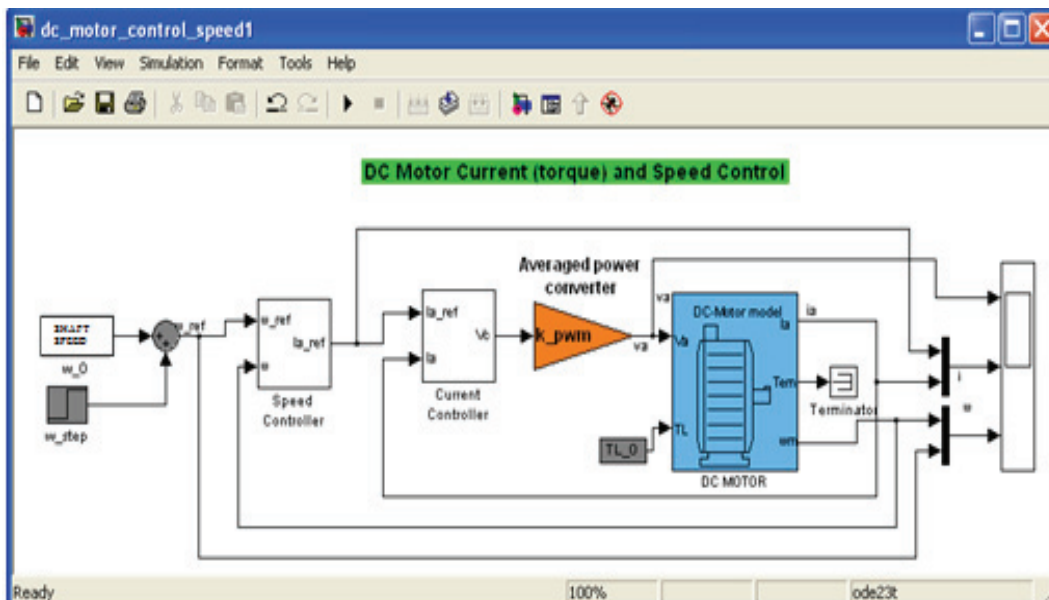


Figure 4. The Simulink DC Motor Model With the Speed/Current PI Controllers

- Open the previously-built DC motor model, shown in Fig. 4, and save as “**windturbinesystem**“. Note that any previous PI control design parameters with overdamped system outputs can be used. Moreover, enter the motor and controller system constants, i.e., R_a , k_E , B , $T_{friction}$, L_a , J , and controller coefficients in the “**windturbinesystem**” model. If the symbolic variables are entered, the associated file containing the constants should be executed in the Matlab command window to achieve the variable assignments in the current window. Verify that the speed- and current-loop controllers are adjusted for proper real-time starting conditions by double-clicking on the

integrator blocks and changing **external reset** to **either**, modifying the variable names, and adding **Reset** to each **integrator** in each controller.

- The reference speed to the system indicates the time varying shaft speed. Use the pre-lab analysis to generate the desired input. (Before the real time implementation, you may want the TA verify the proper shaft speed characteristics). The teams were given the following concept questions during the actual laboratory and were asked to include the corresponding answers in their technical laboratory report:

Q) Obtain and submit snapshots of the complete system and its subsystems, with full justification.

Q) Simulate the system in Fig.4 and submit several snapshots to illustrate its correct operation, with full justification.

- The real-time system should now be obtained by removing the motor/generator blocks and inserting the necessary Simulink and ControlDesk components for pulse-width-modulation real-time operation and proper system interface, as shown in Fig. 5.
- Use the **Real Time Builder** from the Simulink Tools Menu and choose the **Build** option: Matlab command window indicates the execution codes and creates several files in the current workspace.
- Examine the generated files in the current Matlab workspace and identify the particular one with an “**sdf**” extension that contains variables for the dSPACE ControlDesk implementations.
- The dSPACE ControlDesk interface to control the motor creates a layout with virtual instruments and gauges to record values of desired variables.

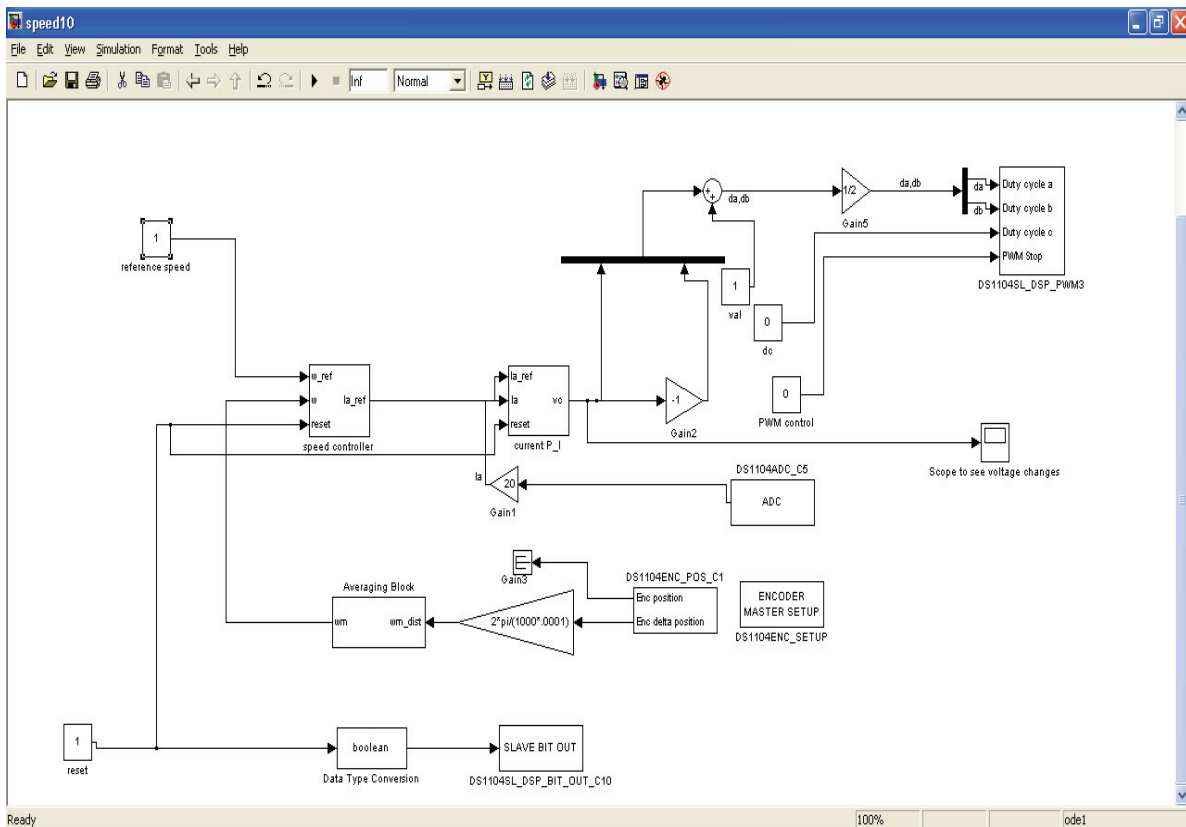


Figure 5. The Wind Turbine Emulation System Real-time Simulink Implementation

- Verify the system physical connections to the motor for the real-time operation; connect the armature jacks of the DC motor to **Phase A1 (to the red terminal)** and **Phase B1 (to the gray terminal)** terminals on the power board. Also, connect the PMDC generator output to a proper terminal on the system interface to save the generated voltage values.
- Start **ControlDesk** and obtain the layout as shown in Fig. 6.

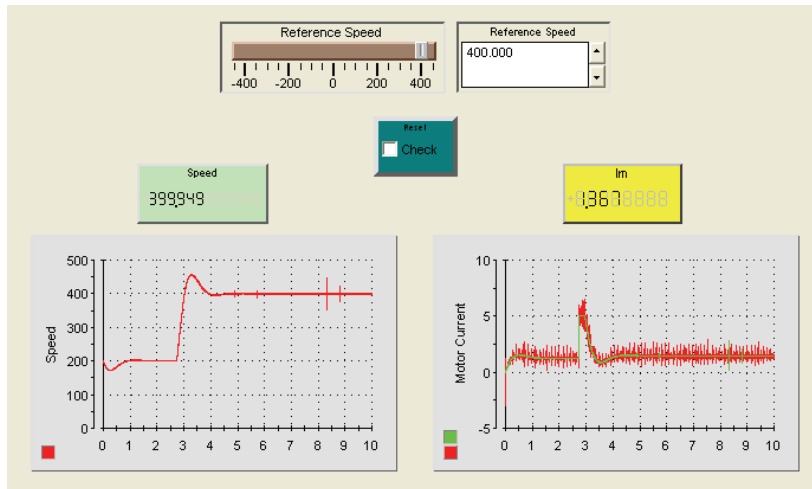


Figure 6. The ControlDesk Interface Snapshot for the Wind Turbine Emulation System

- The teams were also reminded about the final experimental setup verification by the Teaching Assistants before starting the operation: **BEFORE turning on the final system, have the laboratory TA check the system connections, the model in Matlab, the layout in Dspace, and the auxiliary system connections.** Since the initial wind speed is nonzero in Fig. 3, the system shaft rotates at high speeds immediately after turning it on! The teams were given the following concept questions during the actual laboratory and were asked to include the corresponding answers in their technical laboratory report:
 - Q) Obtain and submit several screenshots of the Simulink model and dSPACE layout (at least to show different voltage values are generated by different speeds of the shaft)*
 - Q) Compare and justify the motor speed and reference wind speed outputs and possible discrepancies.*

The teams were asked to present the major experimental outcomes, measurements, and concept question responses in a technical report that was supposed to follow the standard IEEE technical writing principles. As there were many different laboratory report formats, the students were given a choice to follow their most favorite format or to follow the experiment handout pattern. Also, the teams were reminded about the major laboratory report issues, as listed below:

The lab report should follow the handout pattern in terms of procedure steps, figure locations, etc. and should, at least, include the following:

- Well-written and briefly explained steps (In your own words, main steps only, no spelling errors, no broken sentences or definitely no copies of the handout, etc.)

- Measurement tables and figures of experimental results (clearly marked, placed in the right place, referred in the report, etc.)
- Comparison of results and justification of possible discrepancies between theoretical and experimental results (meaning one-on-one comparison, overall comparison should be given in the conclusions)
- Answers to questions, procedure, etc. if any. These answers should be placed according to their locations in the handout.
- Conclusions. Your conclusions should be stating the main observations and results of the experiment.

Evaluation: The participating student team pre-lab performances and laboratory report content presentations as well as data interpretation qualities indicated a successful implementation and illustration of wind turbine emulation operations by utilizing the existing electric drives laboratory components. The pre-lab assignment focused on theoretical and practical wind as well as renewable energy research and preparations for the experiment, and asked the student teams to present their informal handwritten answers while focusing on the content. The corresponding class average for the pre-lab assignment was 95.9, indicating a high level of student research and preparation performances. The comprehensive laboratory report strictly enforced the technical writing principles and subject as well as experimental comprehension and data interpretation evaluation. The corresponding class average for the laboratory reports was 88, indicating a satisfactory level of student performances. The student conceptual understanding was also examined in the final exam, as one response was shown in Fig. 7.

The explicit electrical component structure and operation principles of a one-pole, switch-mode power converter in a wind turbine can be explained as

the mechanical energy from the wind produces a torque that will induce a current, this is just like regenerative braking, the energy produced by the wind through a set of mechanical system is then stored at V_d

$\lambda = \frac{\omega R}{V}$

$P_m = \frac{1}{2} \rho A V^3 C_p$

$C_p = C_1 \left(\frac{C_2}{\lambda} - C_3 \right) \beta - C_4 \quad e^{-\frac{C_5}{\lambda}}$

Figure 7. The Wind Turbine Conceptual Test Question and a Sample Response

Conclusions: A wind turbine emulation experiment in a laboratory with common electric drives components was successfully developed and tested by the students. As the students were exposed to the important wind energy concepts and the experiment was implemented without any additional funds, the experiment can provide a relief for comparable academic institutions that target hands-on wind energy experiences for their students.

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Bibliography:

- [1] 2011 Cost of Wind Energy Review, www.nrel.gov/docs/fy13osti/56266.pdf, Last Accessed on January 3, 2014.
- [2] Wind Turbine Brochure, www.wmich.edu/mfe/energy/wind/pdf/windturbinebrochure.pdf, Last Accessed on January 4, 2014.
- [3] National Renewable Energy Lab: National Wind Technology Center, www.nrel.gov/nwtc/, Last Accessed on January 4, 2014.
- [4] Science of Everyday Life, scienceofeverydaylife.com/innovation/labs/wind-energy/wind.swf, Last Accessed on January 4, 2014.
- [5] WindLab Electrical Generation System, www.turbinetechologies.com/EducationalLabProducts/WindTurbineLab.aspx, Last Accessed on January 4, 2014.
- [6] KidWind, store.kidwind.org/wind-energy-kits/complete-kits/basic-wind-experiment-kit, Last Accessed on January 4, 2014.
- [7] Matlab and Simulink for Technical Computing, www.mathworks.com, Last Accessed on January 4, 2014.
- [8] dSPACE-Home, www.dspace.com/en/pub/home.cfm, Last Accessed on January 4, 2014.
- [9] A. Pinteá, D. Popescu, P. Borne, “Robust Control for Wind Power Systems”, 18th Mediterranean Conference on Control & Automation, Congress Palace Hotel, Marrakech, Morocco, June 23-25, 2010.
- [10] German Renewable Energy Agency, “Functioning Principles of Wind Turbine”, <http://www.unendlich-viel-energie.de/en/details/article/226/functioning-principles-of-a-wind-turbine.html>, Last Accessed on 2013.
- [11] R. G. de Almeida, E. D. Castronuovo, “Optimum Generation Control in Wind Parks When Carrying Out System Operator Requests”, IEEE Transactions on Power Systems, Vol. 21, No.2, May 2006.
- [12] J. F Mushi, G. Chen, J. Daozhu, “Design and Implementation of Wind turbine Imitation System for Direct Drive Permanent Magnet Synchronous Generator Using DC motor”, SUPERGEN 2009 Conference, Nanjing, China, April 6-9, 2009.