

## **AC 2009-443: DEVELOPING WIND-POWER SIMULATIONS AND LABORATORY EXPERIMENTS FOR COURSES IN RENEWABLE-ENERGY SYSTEMS**

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# Developing Wind Power Simulations and Laboratory Experiments for Renewable Energy Systems Courses

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## 1 Introduction

In recent years wind turbine technologies have made significant advances, and more than 30 U.S. states have implemented aggressive renewable portfolio standards. These standards require that electric utilities obtain 10% to 30% of their energy from renewable sources, with target dates between 2020 and 2030.<sup>1</sup> In support of this effort the U.S. Department of Energy is considering the viability of wind energy to supply up to 20% of nation's electricity by 2030.<sup>2</sup> In addition to the technical challenge of integrating wind power into the national grids, another critical challenge in the 20% wind power scenario involves preparing the science and engineering workforce for the changing electric power and emerging wind industries. Unfortunately, engineering courses have not kept pace over the years. There are only a few universities that regularly offer renewable energy and wind power courses, and a lack of appropriate learning materials and faculty expertise in this emerging area.<sup>2</sup>

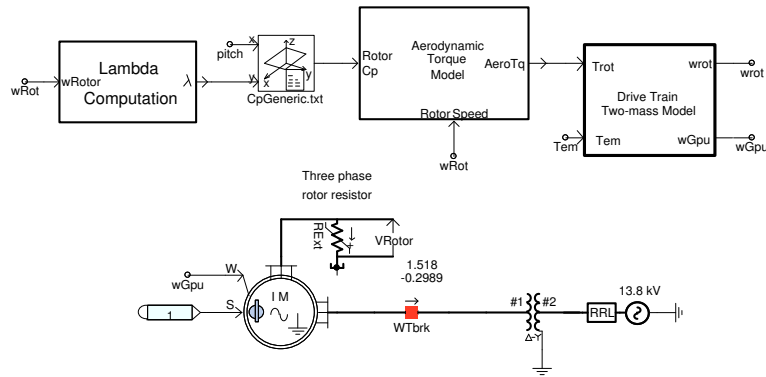
Our primary focus and contribution in this project is the development of learning materials on wind turbine technologies and wind power experiments for undergraduate-level engineering courses. These experiments cover wind turbine technologies and wind power integration issues with both computer simulations and hardware implementations. Technologies covered include fixed speed wind turbine with induction generators and variable speed wind turbines with rotor resistor control and doubly-fed induction generators. Wind power integration experiments include wind farm operations under varying wind speeds, reactive power requirements, islanded operation, and power control. The experiments are divided into basic, intermediate, and advanced levels. The basic and intermediate experiments are integrated into relevant electrical engineering and non-electrical engineering courses.<sup>3</sup> Advanced level experiments are integrated into a stand-alone course dedicated to wind energy and power systems.

This paper describes the first year's work and how the learning materials and experiments are developed and constructed. The basic experiments are described in detail. Topics include the fixed-speed direct connect wind turbine, operation and reactive power requirements of wind turbines, and self-excited and islanded operation of a wind turbine. The computer simulations make use of PSCAD/EMTDC, a time-domain electromechanical simulation tool available in student and educational versions.<sup>4</sup> The hardware-based experiments are initially developed for a Lab-Volt electromechanical laboratory system at the University of Texas at Austin (UT Austin), and we address the issue of their transferability and portability to a similar Hamden laboratory system at the University of Texas - Pan American (UTPA) in Edinburg, TX.<sup>5-6</sup> The experiments are evaluated independently with the assistance of undergraduate students at both institutions. The evaluation is ongoing, and will continue in the second year's work.

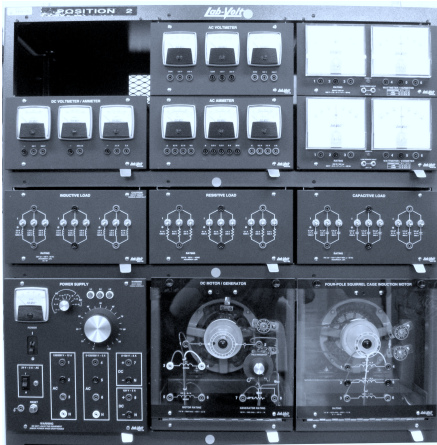
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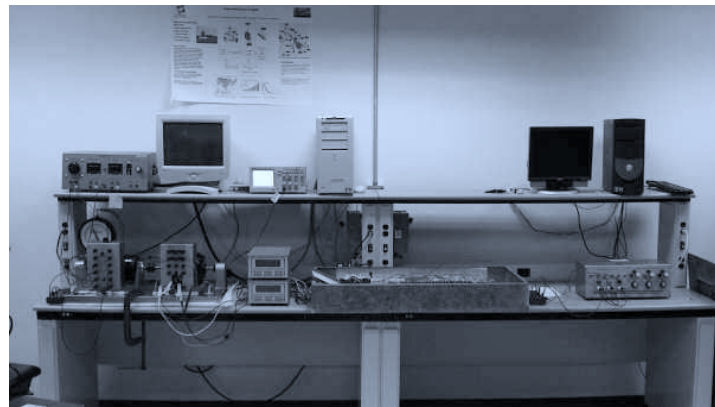
\*\* The University of Texas-Pan American, Edinburg, TX



**Figure 1: Sample PSCAD Model**



**Figure 2: Lab-Volt Equipment**



**Figure 3: Hampden Equipment**

## 2 Resources and Facilities

The materials are designed to use software and hardware available at UT Austin and UTPA. The software package PSCAD/EMTDC is used for the computer simulation experiments. PSCAD solves the differential equations representing an electrical network in the time domain, and offers a graphical user interface for creating models and viewing results.<sup>7</sup> A sample PSCAD model is shown in Figure 1. PSCAD provides standard models for most electrical and mechanical components used in power systems, as well as primitive blocks that can be used to build additional components. Students already familiar with the SimPowerSystems package for MATLAB/Simulink should find PSCAD to be easy to learn. The student version of PSCAD is freely available, but limited to a maximum of 15 electrical nodes. All of the experiments are designed to live within this limit.

The platform for the hardware based experiments will be determined by the equipment already available at a particular university. In this case, UT Austin uses Lab-Volt electromechanical laboratory systems, models 8001 and 8055, while UTPA owns Hampden Engineering laboratory systems, series 100. Sample experiments using these systems are shown in Figures 2 and 3. Each system includes a collection of meters, loads, and electric machines rated to approximately

**Table 1: Typical Equipment**

Module	Ratings
AC Voltmeter	0 - 208 V
AC Ammeter	0 - 2.5/5 A
Power Supply	208 V / 20 A
DC Shunt Motor	120 V, 2.8 A, Shunt potentiometer for speed control
Squirrel Cage Induction Machine	208 V, 200 W
Wound-Rotor Induction Machine	208 V, 200 W
3 $\phi$ Watt-Var Meter	$\pm 300$ W, $\pm 300$ Var

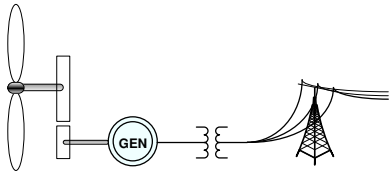
**Table 2: List of Basic, Intermediate, and Advanced Experiments**

Experiment Number		Topic	Level
Simulation	Hardware		
0	0	Introductions to software/hardware	Basic
1	1	Fixed speed wind turbine, real power	Basic
2	2	Fixed speed wind turbine, reactive power	Basic
3		Turbine design, pitch control	Basic
4	3	Rotor resistor control, real power control	Int.
5	4	Self-excited wind turbines	Int.
6		Doubly-fed induction generators	Adv.

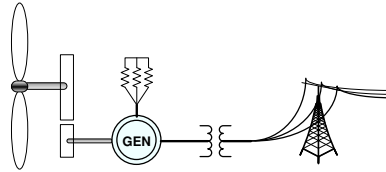
200 W, but the systems are not identical.<sup>5-6</sup> A sample list of equipment is given in Table 1. Most universities offering laboratory courses in electrical machines will have similar equipment available. Thus, the experience gained by transferring laboratory experiments from UT Austin to UTPA will be beneficial to other universities adapting the materials to their own systems.

### 3 Overview of Wind Turbine Technologies

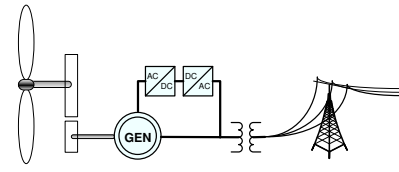
The total aerodynamic power captured by a wind turbine is determined by the wind speed, air density, blade length, and the coefficient of performance  $C_p$ . The coefficient takes into account the blade shape, pitch angle, and linear velocity of the blade tip relative to the wind speed. It typically ranges from a few percent to around 45%.<sup>8</sup> The blades and hub, turning at a low speed, are connected to the generator via a gearbox, the modelling of which is simplified by considering only the masses of the generator and the blades with the spring and damping coefficients of the shafts.<sup>9</sup> The generator is usually an induction machine. A squirrel cage machine connected directly to the power grid will operate within a few percent of the synchronous speed, thus this configuration is considered a fixed speed wind turbine. Figure 4 shows a simple illustration of this arrangement. With a wound-rotor induction machine the rotor circuit is accessible to the user and may be modified to allow the speed to vary, either with an additional resistance or by controlling the rotor currents with power electronics. These technologies, shown in Figures 5 and 6, are capable of controlling the real power output of the turbine. DFIG technology also provides reactive power control. For the other configurations the reactive power requirements of the



**Figure 4: Direct-Connect Fixed-Speed Wind Turbine**



**Figure 5: Variable Speed Wind Turbine, Rotor Resistor Control**



**Figure 6: Wind Turbine With Doubly-Fed Induction Generator (DFIG)**

induction machine must be met with the installation of power factor correction capacitors at the grid connection. All of these characteristics can be modelled in software, and many can be illustrated with laboratory equipment as well.<sup>10–11</sup>

## 4 Experiments

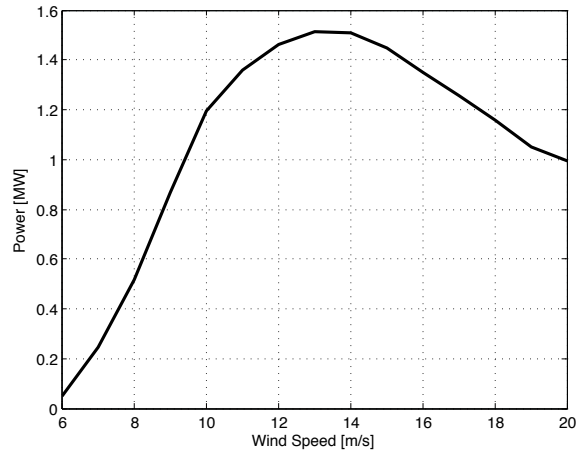
The experiments are designed to be completed in a two-hour time frame by teams of students working pairs on the hardware experiments or individually on the computer simulations.

The documents for the simulations and laboratories contain three main sections. The first section describes the theory behind the experiment. It is intended to be paired with appropriate lecture material, but is written such that it can stand alone. The second section is the procedure for the experiment or simulation, which includes a number of short questions to check students' understanding *during* the experiment. These questions are multiple choice, true/false, or can be answered in a short sentence. After completing the procedure, students report and analyze their work by answering questions in the final section. Questions are both qualitative, to check students' understanding of the subject, as well as quantitative questions requiring mathematical analysis and graphing.

As shown in Table 2, most of the software experiments are paired with hardware experiments. Ideally, both would be used, but if appropriate hardware is not available the software experiments can stand alone. The theory discussions in the first sections of the laboratory documents are similar for both the hardware and software materials, differing only when explaining the particular implementation of the experiment or simulation.

### 4.1 Getting Started

We expect that some students may lack prior exposure to the PSCAD software, laboratory hardware, or both, and provide introductory experiments for each system. Wind power topics are omitted from these experiments. Instead, they provide students with the background needed to construct experiments and make measurements using the hardware and software. With the PSCAD software in particular, it is important that students learn to identify steady state values and disregard startup transients. The PSCAD simulation assumes a knowledge of per-unit electrical systems, and shows how this can be extended to per-unit mechanical systems.<sup>12</sup> Following industry standard practice, equipment parameters are per-unit, while measured quantities are in real units, such as kV or kA. Both experiments also provide a brief introduction



**Figure 7: Power Curve for Fixed Speed Wind Turbine**

to electric machines, though further instruction is highly recommended.

#### 4.2 Fixed Speed, Direct Connect Wind Turbines

Students are introduced to wind turbine technologies in a series of experiments using models for a fixed speed wind turbine connected directly to the power grid. This type of turbine has much in common with modern variable speed turbines and allows many characteristics and components to be studied without the complications of control systems and power electronics. The simulations use a model for a generic 1.5 MW turbine, shown in Figure 1, which includes all the major components described in Section 3.

The hardware experiments use a squirrel cage induction generator with a DC motor as the prime mover. The induction generator terminals are connected to deliver power to the system through the variable three-phase power supply. In a typical hardware experiment, the DC motor is adjusted to drive the induction machine at sub-synchronous speeds. Voltage is then applied to the stator terminals of the induction machine by turning up the variable AC supply. Finally, the speed of the DC motor is increased to drive the induction machine as a generator. It is difficult to simulate the effects of the drivetrain or  $C_p$  characteristic in the lab, so the hardware experiments focus mostly on the performance of the induction machine.

The first pair of experiments focus on the real power delivered by a fixed speed wind turbine with a fixed blade pitch in response to variations in wind speed or driving torque. In the simulations, students determine the wind turbine power curve shown in Figure 7 and study changes in generator speed and  $C_p$ . In the hardware experiments, the DC motor is used to operate the induction machine at a range of speeds covering both motoring and generating modes, and students observe the changes in power and speed. The speed variation observed in the experiments is often much greater than found in real wind turbines, since small laboratory induction machines often have a relatively high rotor resistance.

Continuing with the fixed speed wind turbine models, the second pair of experiments focus on the reactive power consumption of the induction generators, and the need for power factor correction

capacitors. Both procedures are similar to the real power experiments, and students record the reactive power drawn from the grid with and without capacitors at the generator terminals.

In an additional computer simulations, students adjust the blade pitch angle to create a 1.7 MW wind turbine, characterize the new turbine, and compare it to the one studied in the previous labs. This allows students to study the aerodynamic characteristics of the turbine, and observe how blade pitch can be used for power control.

### **4.3 Rotor Resistor Control**

When a wound-rotor induction machine is used in wind turbine, an external resistance can be added to the rotor circuit to modify the generator torque-speed curve.<sup>13</sup> This allows for a wider variation in rotational speed, and allows the power output to be controlled at certain wind speeds. This type of control is covered by both software and hardware experiments. The simulation requires the students to perform the function of a controller, adjusting the external resistance to maintain a constant power output in response to changes in the wind speed. This type of control depends on the aerodynamic torque increasing with rotational speed. Thus the hardware experiment requires students to adjust both the rotor resistance and the driving torque. In both cases, students estimate the additional power losses in the rotor resistance and observe the lack of reactive power control.

### **4.4 Self-Excited Wind Turbine**

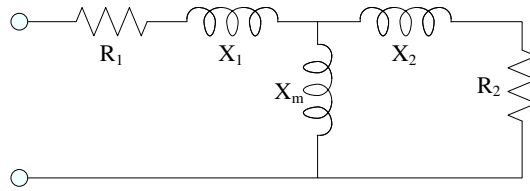
In the previous experiments, the grid provided the load and the source of reactive power for the wind turbine induction generator. With sufficient capacitance at the stator terminals it is possible to magnetize the generator and supply power to an isolated load. This is known as a self-excited or islanded configuration.<sup>14</sup> Both the software and hardware procedures investigate the effect of the exciting capacitance, resistive load, and inductive load on the power output and speed of the wind turbine.

### **4.5 DFIG**

Today the most common variable speed wind turbines use doubly-fed induction generators (DFIGs), with a typical configuration shown in Figure 6. The power electronics and control systems required for a DFIG are too complex for the hardware laboratory system, but can be simulated. The principle advantage to a DFIG is independent control of active and reactive power. The laboratory illustrates how the  $d$  and  $q$  components of the rotor current affect the  $P$  and  $Q$  components of the complex power.

## **5 Integration into curriculum**

A basic knowledge of electric power topics, including voltage, current, active and reactive power, three-phases systems, and one-line diagrams, is required for all experiments. Students will benefit from previous work with electric machines, especially induction machines. It is, however, possible to compensate for a lack of study in this area with sufficient instruction, and the materials provide brief reviews of the relevant electric machine topics for students in need of a refresher.



**Figure 8: Induction Machine Electrical Model**

Since the pre-requisites are fairly basic, many of the experiments are suitable for integration into a first course in electric power. In particular, the fixed-speed direct-connect wind turbine experiments can offer students exposure to wind power quite early in their studies. These experiments are also suitable for electric power courses offered to other engineering majors, such as mechanical engineers.

The materials covering variable speed technologies and the self-excited wind turbine require a somewhat deeper understanding of induction machines including the per-phase electrical model in Figure 8 and, for the DFIG turbine, the dq model.<sup>14</sup> These experiments may not be appropriate for entry level classes but could be integrated into later courses in electric machines and apparatus.

All of the experiments could be considered for upper-level undergraduate classes in renewable energy or wind power. UT Austin already offers an annual course in wind power and will take this approach. UTPA will integrate the experiments into several courses in the electrical engineering curriculum.

We intend to develop additional advanced experiments covering such topics as wind power variability at the system level and additional wind turbine technologies.

## **6 Student Evaluations and Technology Transfer**

During the spring semester of 2009, the laboratory experiments will be evaluated by undergraduate students at UT Austin and UTPA. The labs have yet to be integrated into the curriculum, so the evaluation will take place under the supervision of graduate teaching assistants at both institutions. Evaluation of the materials separately from any courses will ensure that they are truly stand-alone documents. We will also be able to evaluate areas in which further instruction is required, and use this information to adjust course syllabi when integrating the experiments. Students will complete evaluations for each experiment.

The hardware experiments, originally designed for Lab-Volt equipment at UT Austin are being ported to UTPA's Hampden system and modified as necessary. Modifications include changing the recommended values of voltages, currents, and loads to be appropriate for the system. Specifically, the Hampden system inductive load is actually represented with a general reactive load that uses a single knob to adjust the power to lagging or leading, and the actual value of inductance must be estimate by measuring the power and voltage.

Where the controls are likely to differ between systems it is important to give the instructions in



terms of the desired effect on a specific parameter of the experimental setup, such as voltage, current, or speed. For example, while both the Lab-Volt and Hampden systems have a shunt-connected DC motor, the statement “turn the field rheostat knob to its full clockwise position” will result in the minimum speed for the Lab-Volt motor, but the maximum speed for the Hampden motor. The instruction is instead phrased as “turn the field rheostat knob to its minimum-resistance position, making the DC motor operate at its minimum speed,” so that the desired effect is clear.

The differing physical arrangements of the systems also present difficulties. The Lab-Volt components are contained in a grounded enclosure while the Hampden components must be arranged on a work bench, as shown in Figures 2 and 3. We have found that students using the Hampden system are more aware of the grid connection and the resulting safety issues than students using the Lab-Volt system. This may be due to nature of the grid connection on the different systems. In the Lab-Volt system the generator is connected to the grid through the variable AC power supply, while the Hampden system uses a separate variable autotransformer, making the grid connection more obvious.

## **7 Conclusion**

Given the current interest in utility-scale wind power and lack of modern teaching materials in this area, UT Austin and UT-Pan American have developed seven laboratory experiments on wind power topics. The experiments have both software and hardware implementations, using the freely-available PSCAD simulation software and common hardware laboratory systems. The experiments are designed to be completed by pairs of students in two hour laboratory sessions, and solutions are provided. Each document includes sections on theory, the laboratory procedure with questions to check student comprehension, and an analysis section to be completed at the end of the experiment.

Currently the materials are under evaluation by undergraduate students at UT Austin and UTPA. UTPA has successfully performed the first three laboratory experiments on their system. This experience will be used to revise the documents and support the portability to additional platforms. We will continue to revise these lab documents and plan to incorporate them into courses at UT Austin and UTPA in the 2009-2010 school year. We also intend to develop additional experiments on advanced topics.

## **Acknowledgments**

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