Doubly Fed Induction Machine Drive Distance Learning Laboratory for Wind Power and Electric Ship Propulsion Applications

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Abstract— This paper presents a new remotely controlled hardware laboratory for distance learning education. The hardware includes a doubly fed induction machine with a bi-directional power source on the rotor to emulate the operation of a wind power generation system. The new laboratory is designed to reinforce the theory learned in class and to verify that modeling and simulations of the lab machine are accurate. The power conversion system is controlled by two FPGA based controllers which communicate with a web server PC through a USB interface so that the laboratory can be executed on campus as well as remotely. The remote students only need access to a PC with internet connection and a standard browser, without the need to install any software or modify its security settings.

I. INTRODUCTION

Today wind power generation systems are widespread and as the power level of the wind turbines increases, so does the need to control the power flow through power electronic systems. This technology creates the need to educate engineers to design and operate complex power electronics based systems. As engineering education is now available not only on university campuses but also at the student’s own location, thanks to distance learning (DL) courses, educational material needs to be accessible through the internet and so are the hardware laboratory experiments [1-7]. Providing DL students with hardware laboratory experience is challenging from both logistical and pedagogical points of view. Logistically the hardware needs to be entirely controllable by a computer. The computer must be a web server providing internet access to the hardware and finally the student should not be required to have administrator rights to his/her remote computer in order to access the DL laboratory. From a pedagogical point of view the remote user interface must be easy to understand and operate as well as provide a meaningful learning experience which adds to the theory and modeling that the students learn as part of their regular class work. Although much literature is available on doubly fed induction machine (DFIM) drives [8][9], including hardware simulators for laboratory experiments [10], to the authors’ knowledge a remotely controlled DFIM drive system for DL courses has not been presented to date.

This paper presents a new DL laboratory, which allows the remote student to experimentally verify the operation of a DFIM drive system emulating a wind power turbine connected to the grid or a bidirectional drive for ship propulsion applications. The DL laboratory provides the students with hardware experience including the ability to change the commanded speed and load of the machine, listening in real time to the sounds associated with the different speeds and loading of the DFIM and viewing and acquiring the experimental waveforms from the oscilloscope. The DFIM laboratory remote access is made possible by digital electronics that control the hardware and communicate with the internet via a web server. Field programmable gate arrays (FPGAs) serve as the digital electronic platform to gather sensor data and control the power electronics hardware. The student design center (SDC) introduced in [3] is used as the basis for the drive’s control system, however the new DL laboratory set up presented in this paper utilizes a USB interface for faster and more flexible data processing capabilities. Additionally the web interface software has been simplified with respect to the previous version. The remote operator only needs a standard web browser to access the DL laboratory. No administrator rights are required to change security settings or to install any software.

The paper is organized as follows: Section II presents the hardware set up for the DFIM drive laboratory. The hardware includes the embedded controller, the power conversion system and the interface with the web server. In Section III the web interface is described including the Java
software and tools utilized to create an effective graphic user interface accessible through a standard web browser. Section IV presents the details of the DFIM drive hardware implementation and operation. In Section V the machine model and simulations are presented as they are experienced by the students. The experimental validation of the DFIM model is presented in VI. An example of a remotely controlled laboratory session is shown in Section VII. The students use the experimental measurements to validate the model they study in class and to experience the real machine waveforms and sounds in real time. The conclusions are presented in Section VIII.

II. NEW STUDENT DESIGN CENTER

The student design center (SDC) introduced in [3] was upgraded to include a PCB mounted power converter and a USB interface to communicate with a personal computer (PC) used as a web server. This is a significant improvement because the software package Xilinx Chipscope™ [13] is no longer utilized in this new version, thus reducing the complexity of the communication for the web server. Also the JTAG (Joint Test Action Group or IEEE Standard 1149.1) programming cable is used only to program the FPGA one time, not to communicate with the web server in real time. Data acquisition is accomplished through the USB interface. Fig. 1 shows the SDC version 2 (SDC2) block diagram including an FPGA control board and the new custom interface featuring a USB chip for use with an application programming interface (API). The API allows the user to write programs that communicate directly to the FPGA via the USB connection on a PC used as web server.

![Figure 1. Student Design Center version 2 (SDC2) block diagram.](image1)

The SDC2 block diagram in Fig. 1 shows a Xilinx Virtex IV development board [12] on the left. Xilinx provides the software packages together with the development board to speed up the FPGA programming work. The design is carried out using Simulink [14] and compiled by Xilinx’s software to program the FPGA. Therefore knowledge of VHDL, the hardware description language for VHSCIs (Very High Speed Integrated Circuits), is not required to design the power converter control system. The large Virtex IV FPGA allows flexibility when experimenting with different power conversion systems and control/modulation strategies. Optimization of the FPGA algorithms is not an objective for the purpose of the educational laboratory. The “Interface PCB functionality” in Fig. 1 is realized by two custom printed circuit boards (PCBs), one for the power conversion components and the other for the signal processing components. The photograph in Fig. 2 shows the hardware which comprises the SDC2 as it is assembled in the lab. The PCB with a power converter includes an IGBT (Insulated Gate Bipolar Transistor) integrated power module (IPM), current and voltage sensors, passive components for the DC bus and the output filter, DC power supply. The IGBT IPM includes six diodes and six IGBTs in the standard three phase three legs configuration. The second PCB includes a USB interface chip, USB connector to interface with the web server, analog to digital (A/D) converters, voltage level shifters and several other connectors to interface with the other boards. This PCB is mounted on top of the FPGA board as shown in Fig. 2. The power supply on this board provides power for the power converter board as well. They both can be mounted on top of the PCB with the power converter to create a compact stack. The SDC2 is designed to accommodate several power conversion topologies including DC/DC converters, three phase inverters and rectifiers, for different laboratory set up. For the DFIM drive two SDC2 systems are used, one for the three phase rectifier and one for the three phase inverter as described in Section IV.

![Figure 2. Photo of the SDC2 in the laboratory.](image2)
• Most NPS remote locations have firewalls that leave a few standard ports open, such as the HTML standard and secure sockets layer ports. Therefore the DL laboratory must be accessible through a standard web browser to overcome the user’s security settings.

• Most DL students use computers without system administrator privileges and thus cannot readily download and install client programs or web application plug-ins. Therefore the DL laboratory must require no software installation on the remote user’s PC.

Some popular client programs, such as National Instruments LabVIEW can create a client program to communicate with the server program that directly controls the experiment [1],[6],[7]. However LabVIEW uses ports that are not allowed through the firewalls. In this paper we chose to use a Java server application developed through the Netbeans Integrated Development Environment (IDE) to publish the laboratory interface as a standard web page. In addition the Java server does not require the client machine to install the Java Development Kit (JDK) to locally run a Java application, such as an applet. Instead the Java server renders the page in standard HTML and then sends this code to the client browser. To further help with programming we use the Java Server Faces (JSF) version 2.0 frameworks to connect standard widgets in html enabled web pages with functions written in the Java programming language to read values, process data, update the web page, and wait for student input. These functions are called backing beans. The open source and standardized nature of Java Server Faces programming allows others to create new widgets and functional packages that are added to the project through an IDE such as Netbeans. The standard open source environment centered around the Java language, XML markup, and HTML allow various entities to work together for larger projects. A webpage graphic design team can work in their own environment such as the open source Eclipse IDE to provide a user friendly front end webpage (see the HTML wrapper block in Fig. 3).

Java backing bean functions communicate with the FPGA through the API to perform actions based on the command submitted by the student. We use a Java package create by Pablo Bleyer [18] that aids in calling functions in the API. The API is a dynamic link native Microsoft Windows library provided by Future Technology Devices International Limited (FTDI) [17]. FTDI provides a USB driver and a hardware USB interface to a FPGA development board. This FTDI API has various functions that send and receive instructions and data from the FPGA’s own set of routines and processes that control the DFIM.

Fig. 3 shows a block diagram describing how the DL lab is made available to remote user. The apparatus used for the DL lab web publishing includes an oscilloscope with its own web pages and a live video display of the actual experiment that includes audio. The NPS remote labs are currently published through the Sakai Collaborative Learning Environment (CLE). The CLE provides the login authentication method and the student is already signed up for the class that connects to the experiment web page. We also plan on connecting to the iLab web service architecture for authentication and scheduling of the DFIM lab to remote students [6].

![Block diagram describing the web publishing method.](image)

**IV. DFIM DRIVE LAB ARCHITECTURE**

This section describes the hardware architecture that the students access remotely to run the DFIM drive in real time. Fig. 4 shows a schematic of the laboratory set up including the embedded electronics functionality, power converter topology, machine and measuring tools. The DFIM is rated 0.25 hp and its rotor is controlled by a three phase voltage source inverter as shown in Fig. 5. The stator windings are connected to the grid. This configuration is well known and it is sometimes referred to as Scherbius drive [9]. In this configuration the power converter is only connected to the rotor circuit, therefore the drive power electronics need only manage 25% of the power transferred from the machine to the grid when operating as a generator [8]. External torque can be applied to the DIFM from a DC machine that is connected to the DFIM by a rubber belt. The torque can be adjusted to achieve different modes of operation of the DFIM.

Two SDC2 systems, as described in Section II, are used to implement the double bridge AC-AC power converter shown in Fig. 4. The SDC2 with the inverter is connected to the web server via USB interface for real time communication. Its four current sensors are used to acquire two stator and two rotor currents as shown in Fig. 4. An encoder is also used to measure the DIFM’s speed. The SDC2 with the rectifier, once its FPGA is programmed, does not communicate directly to the web server but it communicates with the inverter’s SDC2, which handles all communications with the web server.
Fig. 4. DFIM drive schematics as implemented in the lab.

Fig. 5 shows a block diagram of the inverter control algorithm. A speed reference, \( \omega^* \), is the controller input which the user can manually schedule. The speed PI (proportional-integral) controller defines a reference current that is proportional to the torque. The current PI controller defines the voltage source inverter output voltage. The voltage source inverter is controlled using space vector modulation as described in [16]. The rectifier, which controls the DC voltage inside the VSI block of Fig. 5, provides a constant DC bus voltage with bidirectional power flow as described in [9]. All control algorithms are programmed inside the FPGAs in the two SDC2 systems.

V. MACHINE MODEL AND SIMULATIONS

The students are provided a Simulink [14] model of the DFIM as part of the class material. The machine model differential equations used are well known and are explained and derived in class [15]. The actual machine parameters of the DFIM used in the laboratory have been identified by measurements and are given to the students. The power electronics are idealized in the simulation which neglects their switching behavior. As part of the laboratory exercise the students are asked to simulate a specific operating condition which matches an operating mode in the laboratory available through the web interface. Then the students download the measured data and compare them to the simulated data. The machine can be controlled remotely as a motor or a generator at super-synchronous or sub-synchronous speed. These operating mode changes will change the rotor current frequency and rotor power flow direction, which the students can measure [8],[11].

Simulations plots are presented in Fig. 6 and Fig. 7 for generation and motoring mode of operation respectively.

Fig. 6 shows the simulated rotor current, voltage and speed when the DFIM runs as a generator and a DC motor is used as a load. This is the case for wind power applications. A step change in speed is introduced in the simulation so that the speed changes from super-synchronous to sub-synchronous in the same plot. Since the DFIM used in the model and in the lab is a 4 poles machine, synchronous speed is 1800 rpm. From the simulations the students learn that when the generator operates at super-synchronous speed...
the rotor current and phase voltage are out of phase (power flows out of the rotor) and they are in phase when the speed changes to sub-synchronous. They also learn that the opposite is true when the machine runs as a motor, as in the ship propulsion application. As shown in Fig. 7, in motoring mode the current and phase voltage in the rotor are in phase at super-synchronous speed and out of phase at sub-synchronous speed.

The relationship between the rotor electrical frequency and the rotor mechanical speed is shown in (1):

\[ f_{\text{rotor mech}} + f_{\text{rotor elec}} = 60 \text{Hz} \]  

Using this equation, the students can measure the mechanical frequency and the electrical frequency from the Matlab plots shown in Fig. 6 and Fig. 7 and then verify the theory for all modes of operations as shown in Table I.

<table>
<thead>
<tr>
<th>TABLE I. DFIM FREQUENCY DATA FROM SIMULATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed [rpm]</td>
</tr>
<tr>
<td>Generator</td>
</tr>
<tr>
<td>1570</td>
</tr>
<tr>
<td>Motor</td>
</tr>
<tr>
<td>1569</td>
</tr>
</tbody>
</table>

VI. EXPERIMENTAL VALIDATION OF THE MODEL

The simulations reinforce the theory that the students learn during class, and in order to have confidence in the simulations they must be validated in the lab. The DFIM model presented in Section V is validated by experimental measurements on the DFIM drive set up in the laboratory as shown in Fig. 4. Fig. 8 and Fig. 9 show some examples of experimental measurements and simulation plots superimposed for visual comparison. The line to line stator voltage and the stator phase current were acquired in the laboratory and compared to the simulated waveforms obtained in the same operating conditions. The experimental data was acquired and post-processed using Matlab.

Fig. 8 shows waveforms of the DFIM stator voltage and current when it is operating as a generator, as in wind power generation applications. Fig. 9 shows the DFIM stator voltage and currents when it is operating as a motor, as in ship propulsion applications. The experimental measurements match the simulations closely as can be seen by the waveforms which lay on top of each others. Other measurements are available to the students for further comparisons. The laboratory measurements reinforce the theory and build confidence in the DFIM model and parameter estimation.

VII. DL LABORATORY SESSION

The real time hardware exercise is the last event in the educational experience where theory and simulations constitute the preliminary steps. The first goal of the hardware laboratory exercise is to validate the physics based model derived in class and used for the simulations as shown in Section VI. Additionally the students learn to operate the laboratory, the oscilloscope and acquire data in different formats for their laboratory report. The real time experience also includes audio and video feedback so that the students can hear the DFIM emitting different sounds at different speeds and loads and see the hardware in the lab. The DL laboratory presented in this paper allows remote students to operate the hardware laboratory from their own internet enabled PCs wherever they are and still enjoying the same experience that their on campus colleagues are exposed to.

**Figure 8.** Simulation and experimental measurements in generating mode: stator line to line voltage (top) and stator phase a current (bottom).

**Figure 9.** Simulation and experimental measurements in motoring mode: stator line to line voltage (top) and stator phase a current (bottom).
the applied torque the student moves the slider to the desired value and then pushes the “Update Hardware” button to send the information to the hardware. Once the data is sent to the FPGA, the “Update Hardware” button changes color. It becomes blue when the slider is moved again. The main power in the laboratory is turned on by a lab technician, upon request by the DL student. This is a safety precaution so that the equipment can only be run when laboratory personnel is present. The power button on the user interface turns on the power converter and the machine. It is red when it is pushed on, otherwise it is gray. Before turning on the machine the students must check that the DC bus voltage is set to show that the experiment’s main power switch has been turned on by a lab technician.

A thorough description of the lab set up complete with block diagrams is included on the DL lab website. The information for writing a laboratory report is also posted on the DL lab website together with instructions on how to operate the hardware, acquire waveforms from the oscilloscope and compare the measured results with the simulations. An introductory video is also available to get started.

On the right hand side of Fig. 10 the oscilloscope webpage is displayed in a miniature version. This allows the student to watch currents and voltages change as he/she controls the hardware. In the example shown in Fig. 10 the machine is run as a motor at super-synchronous speed (1890 rpm).

The oscilloscope is a Tektronix MSO4034 which is a web enabled with its own IP address. The link underneath the oscilloscope display takes the student to the full size oscilloscope page where the oscilloscope can be fully controlled and its waveforms can be acquired in different digital formats. Fig. 11 shows an example of the oscilloscope full screen capture when the DFIM is running as a motor at sub-synchronous speed. The waveforms are displayed with the notation used in Fig. 4. On the top the stator line to line voltage (channel 1) and phase current (channel 4) are displayed. On the bottom the rotor phase current (channel 2) and the voltage at the output of the inverter (channel 3) are plotted. The students can appreciate that the voltage applied to the DFIM rotor is not sinusoidal but it is a switching waveform produced by a three phase inverter. Although the DFIM model discussed in Section V. does not include the power converter, the students study space vector modulation as part of the curriculum and are familiar with the switching waveforms such as the one in Fig. 11. The picture shown in Fig. 11 was acquired by right-clicking on the oscilloscope picture and saving the file in
bitmap format. The individual waveforms can also be acquired as data files for post-processing. This is the case for the measurements shown in Figs. 8 and 9 where the data was acquired from the oscilloscope and post-processed using Matlab.

![Figure 11](Image)

**Figure 11.** Motoring mode at subsynchronous speed: ch1-stator line to line voltage $v_{ab}$, ch2-rotor phase a current $i_m$, ch3-inverter output line to line voltage $v_{dis}$, ch4-stator phase a current $i_n$.

VIII. CONCLUSIONS

A new DL laboratory featuring a DFIM drive has been successfully designed and demonstrated to supply remote students with the hardware experience which is typically only available to resident students. The laboratory is accessible via a standard web browser and the DL students only need internet access. The students do not need administrator rights because the DL lab operation does not require software installation or security setting changes.

The logistic and pedagogical challenges of delivering the lab experience to DL students are addressed and their solutions highlighted. Particularly an innovative system, the SDC2, was designed to include the power conversion elements, sensors, and all necessary components to control the DFIM and effectively communicate with a web server via a USB interface. The DL lab offers a meaningful experience to remote students because they can hear, see and interact with the hardware. They use an oscilloscope to measure currents and voltages and acquire data to build confidence that the simulations are correct.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the Naval Postgraduate School’s Center for Educational Design, Development, and Distribution (CED3) for its support and especially Tom Mastre, the Director, Philip McCullick for programming the graphic user interface and Sherrill Meaney for the website layout.

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