Labs for EGN 3375 Electromechanical Energy Systems at University of South Florida

Zhixin Miao, Lingling Fan, Minyue Ma, Yin Li, Zhengyu Wang

Department of Electrical Engineering
University of South Florida
Tampa, Florida 33620

{zmiao, linglingfan}@usf.edu, {minyuema, yin, zhengyuwang}@mail.usf.edu

Abstract—This paper describes the labs designed for University of South Florida (USF)’s undergraduate course EGN 3375 Electromechanical Energy Systems. We employ PSCAD, OPAL-RT’s RT-Lab real-time digital simulator, and National Instruments’ (NI’s) control toolkit: general purpose inverter controller (GPIC), single board RIO (sbRIO) with LabVIEW as GUI. The labs offer students in-depth understanding of Faraday’s Law, the key principle for transformers and rotating machines. The labs also expose students to the state-of-the-art simulation and control tools and offer students hands-on experiences.

Index Terms—PSCAD, RT-LAB, LabVIEW, Real-Time Simulation, Electrical Machines

I. INTRODUCTION

Traditionally, Electric Machinery is the fundamental course for power engineering undergraduate students. The need of this course is obvious that the large-scale synchronous generators at 100 MW or more are the major workhorse for the power industry and the wind energy industry employs both induction machines and synchronous machines to produce power. Moreover, the booming electric vehicle industry makes this course even more appealing to students.

The classic textbook used for teaching is Fitzgerald & Kingsley’s Electric Machinery [1], currently at its 7th version. The book is a classic and offers in-depth knowledge on machines. Even though, there is still a need to design labs for better teaching and suiting the current day industry.

The labs initiated in 2010 when USF joined University of Minnesota’s DOE-sponsored nationwide consortium to revitalize electric power engineering education by laboratories. Through the years, we evolved the labs and integrated RT-Lab and NI’s control toolkits. There are two reasons for carefully designed labs. First, labs lead to in-depth learning. Machines are difficult subjects. To link the abstract concepts of rotating magnetic fields and Faraday’s Law to the physical world, labs are necessary. Second, labs expose students to the state-of-the-art simulation and control tools, and further new subjects. If we show a student how to control an induction motor’s speed through a testbed, then even a student has not taken power electronics and control systems, he/she will have a good picture on how things work and what to pursue as the next step.

The outcomes of the carefully designed curriculum (EGN 3375 and the accompanies labs) make the power program at USF attract more students. Offering training on RT-Lab and NI’s control toolkit also makes our graduates favorites of the industry.

In this paper, the philosophy of the lab design and the details of the labs are presented. The sections followed will present Lab 1: PSCAD labs for transformer B-H curve plotting, Lab 2: PSCAD and RT-Lab modeling of 3-phase transformers, Lab 3: GPIC and sbRIO enabled synchronous machine Faraday’s Law check and Lab 4: GPIC and sbRIO enabled induction machine volt/Hz control and torque-speed curve plotting.

The dominant law in this course is Faraday’s Law and the two applications are transformers and electric machines. In transformers, varying magnetic field induces electromotive force (EMF). In rotating machines, rotating magnetic field is formed in air gap, which causes varying flux linkages in windings and further EMF. In lab designs, our emphasis is Faraday’s Law. Faraday’s Law is expressed as

\[ v = \frac{d\lambda}{dt} \]

where \( v \) is the induced EMF in a circuit and \( \lambda \) is the flux linkage linked to the circuit.

When we deal with a single frequency AC system, we will use phasors to express the Faraday’s Law:

\[ V = j\omega \bar{\lambda}, \]  \hspace{1cm} (1)

where \( \omega \) is the frequency of the flux linkage. Hence it is obvious that volt/Hz should keep constant for a constant flux.

With the first two labs focusing on software training, magnetic circuits, and three-phase system connections, the next two labs focus on hardware setup and control implementation. In both labs, GPIC, sbRIO with LabVIEW as GUI are employed together with DC motor and AC machines. Lab 3 examines Faraday’s Law explicitly through observing the relationship of speed of a synchronous generator and the induced EMF magnitude. In Lab 4, Faraday’s Law is examined through volt/Hz control of an induction machine. Lab 4 exposes students to power electronic converter control and motor drives.

II. LAB 1: B-H CURVE PLOTTING USING PSCAD

This lab helps students understand the electromagnetic circuits. The objective is to plot B-H curves. However, flux density \( B \) and field strength \( H \) cannot be directly measured.
In order to make plots, students have to find the corresponding measurements and develop a good understanding of their relationship.

**A. Lab setup**

A circuit with a transformer needs to be setup. The circuit is shown in Fig. 1. To compare the effect of the resistance at the secondary side, two circuits with different secondary side resistance $R_2$ are built in PSCAD. Note that this is an AC circuit and the measurements are all instantaneous values. The upper circuit has a small resistance ($1\Omega$) while the lower one has a large resistance ($1\,\text{M}\Omega$).

B-H curve is plotted using the primary side current measurement $I_{pp}$ as the x-axis and the secondary side capacitor voltage $V_c$ as the y-axis. Based on Ampere’s Law, we know that the total magnetomotive force (MMF) is proportional to currents and the magnetic field strength is related to the current.

The underlying assumptions are:
- The primary side current can be treated as the magnetizing current. The magnetizing current sets up the magnetic field. That is, the secondary side current $I_{ss}$, after referring to the primary side, is insignificant. The secondary side is almost open-circuited. Apparently, the lower circuit is suitable for B-H curve plotting.
- The capacitor voltage is in phase and proportional to the flux been setup in the transformer.

In the following analysis, we will validate the aforementioned assumptions. We will use PSCAD transformer’s internal variables, such as flux, to validate our points. Note that in real-world, voltage and current measurements are easy to obtain. The flux is for analysis only.

**B. Analysis of the circuit**

In the transformer, there are two windings so MMF can also be expressed by the sum of the ampere-turns of two windings.

$$ F = N_p I_{pp} + N_s I_{ss} \quad (2) $$

To eliminate the effect of $I_{ss}$, the secondary side is open-circuited by connecting a very large impedance in series. Then, $I_{pp}$ is considered as the magnetizing current $I_m$.

$$ F = N_p I_{pp} = H l, \quad H = \frac{N_p I_{pp}}{l} \quad (3) $$

With that, the first assumption is validated. Fig. 2 presents the PSCAD simulation results to show $I_{pp}$ and $I_m$ are the same if $R$ is large. Also note that a transformer’s magnetizing current is distorted due to non-ideal magnetic field characteristics, e.g., saturation and hysteresis.

In the circuit, the selected $R_2$ is much larger than $1/j\omega C$, so $-\bar{I}_{ss}$ and $\bar{E}_s$ are in phase.

$$ -\bar{I}_{ss} = -\frac{\bar{E}_s}{R + 1/(j\omega C)}, \Rightarrow, \bar{I}_{ss} \approx -\frac{\bar{E}_s}{R} \quad (4) $$

The voltage across the capacitor $\bar{V}_c$ and the current $\bar{I}_{ss}$ have the following relationship:

$$ \bar{V}_c = -\frac{1}{j\omega C} \bar{I}_{ss} = -j\frac{\bar{E}_s}{\omega RC} \quad (5) $$

Note that based on Faraday’s Law presented in (1), $\bar{E}_s$ and the flux setup in the transformer has the following relationship:

$$ \bar{E}_s = j\omega N_s \bar{\phi} \quad (6) $$

where $\bar{\phi}$ is the phasor of the mutual flux in the transformer magnetic field.

Substituting (6) into (5), we find that $\bar{V}_c$ is in phase with $\bar{\phi}$:

$$ \bar{V}_c = \frac{N_s}{RC} \bar{\phi}. \quad (7) $$

With that, the second assumption is validated. Hence, $V_c$ is proportional to $B$ and we can represent $B$ by $V_c$ in B-H curve shown in Fig. 4. Fig. 3 validates this assumption. When $R$ is large, $V_c$ and $\phi$ are in phase.

**III. Lab2: Three-phase transformer simulation in PSCAD and RT-Lab**

In Lab 2, a three-phase transformer is built and analyzed. It can help students understand three-phase circuits and the specific characteristics in three-phase transformers. Students are introduced to RT-Lab in Lab 2 after getting familiar with PSCAD.
Fig. 3: Upper: $V_c$ and $\phi$ are not in phase when $R$ is small; lower: $V_c$ and $\phi$ are in phase when $R$ is large.

Fig. 4: B-H curve is generated by plotting $V_c$ versus $I_{pp}$.

A. PSCAD Lab setup

The three-phase transformer consists of three single-phase transformers. They are connected in Y-Y connection shown in Fig. 5. The parameters of the single-phase transformer is listed in Table I.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power level</td>
<td>50 kVA</td>
</tr>
<tr>
<td>Turns Ratio</td>
<td>2400:240 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>60 Hz</td>
</tr>
<tr>
<td>$R_p + jX_p$</td>
<td>0.72 + j0.92\Omega</td>
</tr>
<tr>
<td>$R_s + jX_s$</td>
<td>1 + j3\Omega</td>
</tr>
<tr>
<td>$R_c + jX_m$</td>
<td>6.32 + j43.7\Omega</td>
</tr>
</tbody>
</table>

The relation between the line-to-line voltage and the line-to-neutral voltage is demonstrated by the plot shown in Fig. 6. One voltage meter is placed between two phases and another is placed between the line and the neutral point. Based on Fig. 6, it is found that $E_{p,an}$ is lagging $E_{p,ab}$ by 30 degree. Students can relate the relationship in time-domain to that in phasor: $E_{p,ab} = \sqrt{3}E_{p,an} \angle 30^\circ$.

B. RT-LAB Simulation Lab

RT-LAB provides real-time simulation based on MATLAB/Simulink models and digital/analog I/O interface. Measurements from MATLAB/Simulink models can be output as analog signals to an oscilloscope.

To run simulation in RT-LAB, a Simulink model is required to be built in advance with SimPowerSystem Toolbox components. In the experiment, a three-phase circuit in Y-$\Delta$ connection is modeled.

To generate necessary measurements of the circuit, meters (scopes) are placed in the circuit in Simulink. Next, the Simulink model is converted to RT-LAB model format and imported to RT-LAB software. After compiling and loading model to RT-LAB Simulator, real-time simulation is executable. This experiment setup is shown in Fig. 8.

The source side (Y-connection) phase voltage and line-line voltage, and the load side ($\Delta$-connection) line current and phase current are measured and displayed in an oscilloscope. The measurements are shown in Fig. 9.

From measurement comparison shown in Fig. 9, the results verify the relationships usually presented in phasor domain: in Y-connection, the line to line voltage is $\sqrt{3}$ times of the line to neutral voltage; in $\Delta$-connection, the line current is $\sqrt{3}$ times of the leg current of the $\Delta$ connection.
AC (PMAC) synchronous generator. The mechanical speeds of both machines are the same, notated as $N_m$, in revolutions per minute (rpm), due to the physical connection between their rotors. The DC motor is connected to a DC/DC converter to have an adjustable input DC voltage. Closed-loop speed control is applied on a DC/DC converter to adjust the applied DC voltage in the field winding, in turn to adjust the flux and the mechanical torque. The synchronous generator’s open-circuit output voltage is measured via an oscilloscope. Fig. 7 is the block diagram of lab setup. The experiment setup photo is shown in the Fig. 10.

Students will vary the reference speed of the DC motor and observe the PMAC’s output voltage magnitude. This experiment is to understand rotating magnetic field formation and Faraday’s Law. A rotating magnetic field will be generated in the airgap with a rotating speed same as the mechanical speed. This rotating magnetic field will generate a flux linkage at a frequency of $\frac{Poles \times N_m}{2}$ in a static circuit. Based on Faraday’s Law, the induced voltage is proportional to $N_m$. In short, for sinusoidally distributed airgap flux with a constant magnitude due to permanent magnet, the open-circuit voltage induced is proportional to the rotating speed of the rotor.

The DC/DC converter control is realized through NI’s sbRIO
with LabVIEW as the GUI interface.

From the motor measurement in LabVIEW, mechanical speed \( N_m \) in revolutions per minute (rpm) is collected. The relationship between the open-circuit voltage and the mechanical speed relationship can be simplified as \( E_m = K_e N_m \).

Based on given machine speed references, corresponding line-line output voltage measurements of PMAC are collected as shown in the Fig. 11.

![Figure 11: Measurement output line-line RMS voltage vs. speed reference plot.](image)

The experiment setup block diagram is shown in Fig.12 and the photo of the testbed is presented in Fig. 13.

**Fig. 13: Physical equipment for Lab 4.**

![Figure 14: Line-line RMS Output Voltage Measurement](image)

**V. LAB 4: INDUCTION MOTOR VOLT/Hz CONTROL AND TORQUE-SPEED CURVE**

The objective of Lab 4 is to plot torque-speed curves for various stator frequencies. In undergraduate classes, usually single torque-speed or torque/slip curve appears to show torque and speed relationship under certain frequency and given stator voltage. On the other hand, in AC motor drives [2], multiple torque-speed curves corresponding to different stator frequencies are usually presented.

The various stator frequency is realized through dc/ac converter. Lab 3 already introduces DC/DC converter to students. Lab 4 further introduces dc/ac converter to students. Lab 4 further introduces vol/Hertz control to students. To keep a constant flux, the ratio of voltage and frequency should keep constant based on Faraday’s Law.

In the lab setup, the induction motor’s stator will be connected through a dc/ac converter to a DC source. Its rotor is coupled with a DC motor’s rotor. We change DC motor’s DC voltage to change DC motor’s torque. This in turn changes the AC motor’s load torque. The DC motor’s input voltage is adjusted through a DC/DC converter using open-loop control.

In Lab 4, students will first decide the stator frequency. Under this frequency, they then change the DC voltage of the DC motor. They measure the induction motor’s speed and DC motor voltage. The armature current of the DC motor will be computed and the armature current-speed curves will be plotted. For a DC motor with permanent magnet, its armature current is proportionally related to the torque with a constant coefficient. This torque can also be viewed as the torque of the induction machine. Thus, the plot of DC motor armature current versus speed is equivalent to the torque-speed curves of an induction motor.

![Figure 14: Three sets of data measured when different frequencies are selected for the induction machine’s stator voltage.](image)
Fig. 12: Setup block diagram of Lab 4. By changing the value of \( k \), the stator frequency is changed. By changing the value of \( V_{\text{ref}} \), voltage applied on DC motor is changed, and the torque is changed.

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Vdc (V)</th>
<th>Nm (RPM)</th>
<th>Voltage (V)</th>
<th>Current (A)</th>
<th>Vdc (V)</th>
<th>Nm (RPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.36</td>
<td>829</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.47</td>
<td>834</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.57</td>
<td>839</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.67</td>
<td>845</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.77</td>
<td>851</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.87</td>
<td>857</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>7.97</td>
<td>863</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>8.07</td>
<td>869</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
<tr>
<td>20</td>
<td>0.05</td>
<td>8.17</td>
<td>875</td>
<td>20</td>
<td>0.06</td>
<td>6.675</td>
<td>24</td>
</tr>
</tbody>
</table>

where \( P_{ag} \) is the airgap power, \( \omega_c \) is the stator frequency in rad/s, \( \omega_{sl} \) is the slip frequency (\( \omega_{sl} = \omega_c \)), and \( L_m \) is the RMS value of the flux linkage. The above analysis shows that when slip is very small and the flux is constant, torque is proportional to the slip frequency. This is indeed the foundation of adjustable frequency motor speed control in motor drive. With a constant load torque, if we aim to obtain a different speed of the motor, we change the stator frequency through a dc/ac converter.

Fig. 15: Equivalent torque-speed curves. Torque is substituted by armature current of the DC motor.

VI. CONCLUSION

Four labs were designed for an undergraduate course on Electric Machinery. The labs not only offer a hands-on experience to students to better understand the concepts taught in the class (e.g., Faraday’s Law, rotating magnetic field), but also employ state-of-the-art simulation and power electronic control toolkits and expose students to the tools and various applications.

REFERENCES