AC 2012-3351: DESIGN AND IMPLEMENTATION OF A FUNDAMENTAL ELECTRIC MACHINE LABORATORY USING INDUSTRIAL DEVICES

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Design and Implementation of a Fundamental Electric Machine Laboratory using Industrial Devices

Abstract

The design and implementation of the instructional electric machine laboratory is described in this paper. The objectives of this project are to upgrade 50-year old laboratory equipment and to provide students with hands-on experience on up-to-date electric machines, drives and instruments, as well as to improve their understanding of the theory learned from lectures. Instead of the systems especially designed for educational purpose, off-the-shelf industrial devices have been selected for the experiments to make them more realistic and thus closer to work situations, as well as more cost effective. Experiments, hardware components, instruments and student feedback about the laboratory course offered are presented.

1. Introduction

The importance of power engineering education has recently been recognized and many improvements have been suggested [1-19]. Among the suggestions, offering contemporary laboratory courses is critical because laboratory experience is the only way for undergraduate students to understand the application of theory through active experience using practical equipment. As well as the new courses including power electronics and machine drives, laboratories developed with new technologies, such as software-based virtual laboratories and web-based remote laboratories, have recently been proposed [11-14, 16, 17]. However, despite the benefits of virtual and remote laboratories, the hands-on experience in a physical on-site laboratory is still indispensable [1-4, 13, 15, 16].

The electric machine laboratory is a fundamental course for all electrical engineering students and it has been offered in electrical engineering programs in many institutions. As well as the implementation of new courses and laboratories, the renovation of the existing courses such as introductory electric machine laboratory is also inevitably required because it often has obsolete and out-of-date equipment that makes it difficult to offer a proper contemporary laboratory experience and to accommodate the advanced laboratory courses. Moreover, it often gives negative impressions, e.g. old-fashioned, obsolete, and dangerous, about power engineering to students.

While electric machines have not changed much in their structures and materials, drive technologies for machines and instruments have made tremendous advances, which is why many suggestions for improvement have focused on that part. However, given the fact that the machines, drives and instruments can be shared with the electric drives laboratory, the introductory electric machine laboratory can be readily renovated at the same time with the drives laboratory. It will be a legitimate opportunity to revamp the experiments for the introductory machine laboratory using up-to-date technologies and to improve the cost-effectiveness of the program.

The power and energy engineering program at the University of Colorado Denver has been drawing students steadily, which shows stable student interests and local industry's needs. However, the equipment in the instructional power laboratory was old and the laboratory greatly needed a renovation to accommodate the latest technologies and to offer students appropriate practical experience. The College of Engineering and the Department of Electrical Engineering are committed to renewing the power and energy engineering program by recruiting new faculty members, offering new courses, and upgrading laboratory facility in order to provide up-to-date engineering education and fulfill the institution's mission. This paper presents the design and implementation of renovated electric machine laboratory as one of the efforts. Detailed experiment setup and output sample will also be described. The old power laboratory equipment is shown in Figure 1.

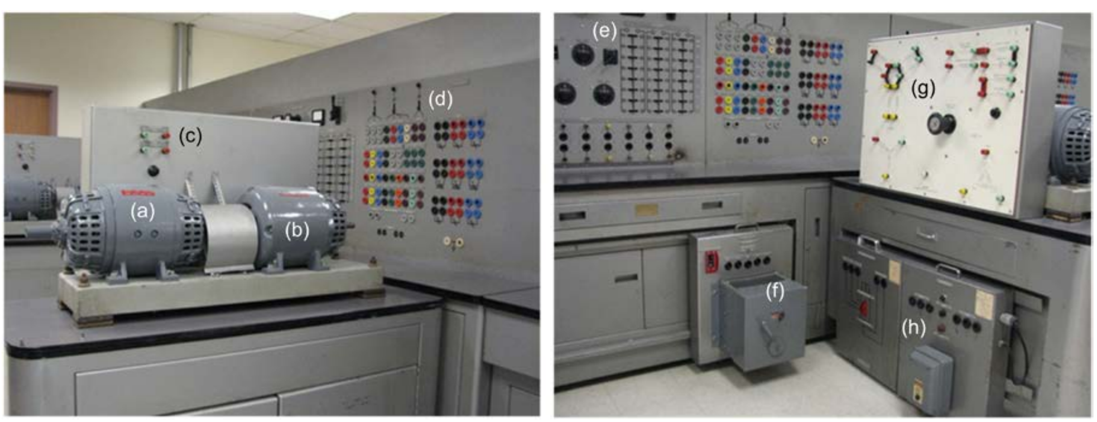


Figure 1. Old laboratory equipment. (a) DC machine (b) Wound rotor AC machine (c) DC machine field control circuit (d) RLC load panel (e) resistor bank (f) DC machine starter (g) AC machine configuration panel (h) AC machine starter

2. Hardware Design

The hardware design of the new laboratory has focused on cost-effectiveness while maintaining reasonably high performance. Furthermore, ability to offer a "real-world" experience has been taken into consideration as an important factor. Most experiments in conventional introductory power and energy laboratory courses have been performed using equipment dedicated to education or training, which has easy-to-use and tailored interfaces specially designed for education. However, there are significant differences between educational equipment and professional equipment in the field and the educational equipment is difficult to expand for additional experiments or modify to accommodate changes, which makes adequate upgrades of the hardware and the program costly.

Instead, industrial-grade systems have been utilized to take advantage of high-performance and cost-effectiveness of commercial systems. Current industrial drives are technically advanced, functionally versatile, and significantly inexpensive compared to the educational counterparts. Furthermore, experiments developed using the industrial devices can offer students experience on actual equipment that they will use almost immediately after graduation, as well as improvement on theoretical understanding. Compared to the laboratories with pre-wired and centrally controlled systems, the proposed scheme can enhance experience on system integration because students actually build an experiment setup using components. This approach has not been investigated extensively, especially for classical electric machine courses, in spite of the functional, economical, and educational advantages. Industrial devices are flexible and provide numerous ways for interconnection, control, and instrumentation, which enable the laboratory course to offer very practical and effective experiments.

2.1 Machines and Drives

For the new laboratory experiments, one horsepower (Hp) DC machine and induction machine have been selected to replace the old bulky machines. The new machines have been mounted on an aluminum plate and connected using shaft couplings. The machines in this size are small enough to be placed on tabletop, but still give more practical characteristics and realistic feel than smaller fractional horsepower machines. Any standard DC and induction machine can be used for the developed experiments. The DC machine selected is Baldor

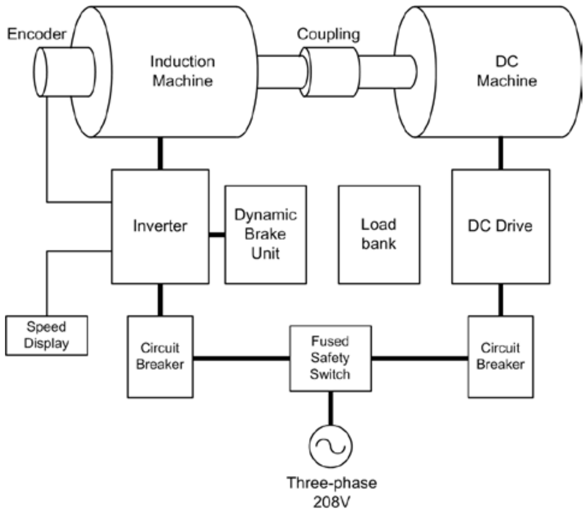


Figure 2. Connection diagram of machines and drives.

CD5319, which is rated 1 Hp, armature voltage 90 Vdc, full load armature current 10A, field voltage 100 Vdc, full load field current 0.6A, and rated speed 1750 rpm. The machine ratings of AC induction machine, Baldor ZDNM3581T, are as follows: 1 Hp, 230/460V, 3-phase, 1725rpm, full load current 3.2/1.6A, and no-load current 1.8A. The induction machine has a built-in rotary encoder, which is utilized for rpm display. The power connection diagram of the new laboratory station can be seen in Figure 2 and the complete laboratory equipment utilized in this laboratory is shown in Figure 3. A polycarbonate cover is used on machines for safety.

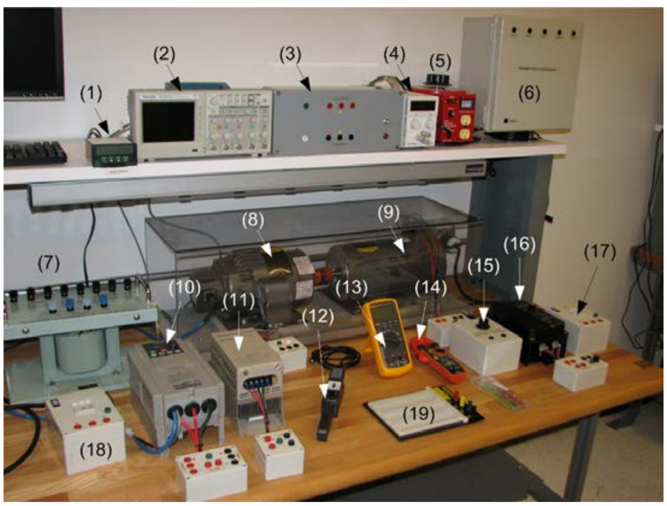


Figure 3. Laboratory station. (1) Speed display (2) Oscilloscope (3) Step-down transformers (4) DC power supply (5) Variac (6) Loadbank (7) Transformer (8) Induction machine (9) DC machine (10) Inverter (11) Dynamic brake unit (12) Current probe (13) Digital multimeter (14) Digital clamp meter (15) Rheostat (16) DC drive (17, 18) Circuit breaker (19) Breadboard.

An AC inverter and a DC drive with same power capacity, Baldor BC254FBR regenerative DC drive and Hitachi SJ-300 AC inverter, have been selected to drive the machines. The DC drive has a built-in regenerative unit and a dynamic braking unit is added for AC inverter. For DC machine's field control, a separate DC power supply can be used as well as a rheostat. Currently there are many companies competing in the AC drive market, which makes high-performance inverters reasonably inexpensive. Due to the advance of microprocessors and switching power devices, advanced control algorithms, sizable numbers of configurable parameters and I/Os are no longer exclusive for expensive high-end drives. On the other hand, as the usage of DC machines have been declining over last decade, choice of DC drive is limited and their control functions and I/Os are rather fundamental in inexpensive drives. Nevertheless, the AC and DC drives that have enough capability to perform experiments for introductory electric machine laboratory and expandability for electric drive laboratory do not cost much.

If a torque meter is installed between the machines in conjunction with speed and current measurement, the line starting transient can be shown to students to allow them to understand how severe the transient is in terms of the high current peak and torque fluctuation. The torque-speed curve for whole speed range can also be plotted. However, torque measurement system including sensor, shaft coupling and signal conditioning circuitry is costly, and steady-state machine torque can be easily calculated using other measurable data, such as power and speed. The torque sensor has not been included in this development.

Addition of a wound-rotor synchronous machine has been investigated, but not included in this laboratory because a small-size, off-the-shelf wound-rotor synchronous machine is very difficult to find. Permanent magnet synchronous machines are easily available, but they may not be appropriate for the introductory electric machine laboratory considering contents of the corresponding theory course. Custom-made machines are possible, although they are quite expensive.

Most of the AC and DC drives in the market commonly have a standard set of features and functions for speed, current and voltage control so that they can be compatible for general field applications. The proposed laboratory experiments have been developed using these standard functions, hence drives from any manufacturer can be utilized to implement the

	Description	Model	Manufacturer
1	DC machine	CD5319	Baldor
2	DC drive	BC254-FBR	Baldor
3	Induction machine	ZDNM3581T	Baldor
4	Inverter	SJ300-007LFU	Hitachi
5	Brake unit	HBU-2015	Hitachi
6	DC power supply	XT120-05	Xantrex

Table 1. Major equipment list.

laboratory. The machines and drives utilized in the developed laboratory station can be seen in Table 1.

2.2 Instruments

Controlling the pre-wired laboratory station with integrated computer interface using data acquisition and I/O cards has advantages such as zero possibility of connection problem, better controllability with centralized control panel, graphic waveform display and data logging using virtual oscilloscopes and meters, and possible expansion to remote laboratory. However, this approach may have following issues. 1) The system is customized, which means it is costly and same system can hardly be found elsewhere. 2) Virtual environment based on computer software is basically for "laboratory" environment, not for field circumstances for the issues such as complexity, reliability, cost, portability, and ruggedness. So experience on a virtual system may not be helpful for field engineers as much as expected.

Therefore, generic industrial instruments, including digital multimeter, digital clamp meter, current probe, oscilloscope, are used in this laboratory. Students build an experimental setup including instrumentation with discrete devices. Instantaneous and root-mean-square (RMS) DC/AC voltage and current can be measured. Compared to the computer-based virtual instrumentation system, these inexpensive basic instruments are widely used in the field and make the experiments similar to work situations that students will encounter. As well as machines and drives, instruments from any manufacturer can be used because the way they operate is practically the same. The instruments utilized in the laboratory are shown in Table

	Description	Model	Manufacturer
1	Oscilloscope	TDS2014B	Tektronics
2	Digital multimeter	Fluke 87-5	Fluke
3	Digital clamp meter	EX730	Extech
4	Current probe	A622	Tektronics
5	Speed display	L70000QD	Laurels

Table 2. Major instrument list.

2. The 5-digit speed display shows machine shaft speed using the rotary encoder signals from the induction machine.

2.3 Wiring and Connection

Although pre-wired and computer-controlled experiment setup can offer fail-proof experiments, practical experience, such as actual wiring between devices, placing instruments on circuits, troubleshooting misconnections or bad contacts, is critical elements of an electrical engineering laboratory experiments. Therefore, a connection system using banana cables has been developed for the proposed laboratory. Two kinds of banana cables and jacks have been used: sheathed banana cables without any conductor exposure and stackable banana cables for voltage measurement and for stacked connection. Experiment setup is easy, fast, and safe with the proposed wiring system. The cables and jacks on a connector box are shown in Figure 4.

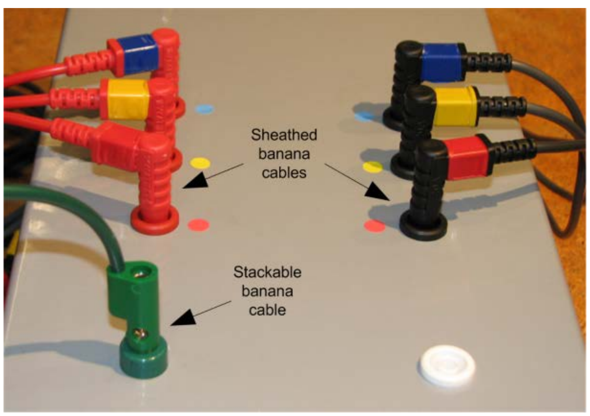


Figure 4. Wiring using banana cables.

Figure 5. Connection boxes for drives.

Connector boxes for all devices including machines and drives are built by in-house machine shop using off-the-shelf polycarbonate boxes and banana jacks. The banana jacks on the connector box are pre-wired to devices' terminals and color-coded so that students can easily build a setup for experiments using banana cables without having to open the devices. This connection boxes can reduce wear on device terminals and possibility of connection error. The connections can also be easily disassembled after experiments, and the devices and cables can be stored separately. However, even with color-coded cables and jacks, care should be taken to make connections. A fused disconnect switch, circuit breakers and the built-in protection system of drives are used as safety measures for possible faults such as over current and over voltage. The connector boxes for drives can be seen in Figure 5.

2.4 Safety and Protection

Because the wiring between devices is done by students, the safety and protection is very important. The lab equipped with several protection devices, such as circuit breakers, fuses and protective functions of the devices. The mechanically moving part is covered with a transparent poly carbonate cover that is permanently-mounted so students cannot touch the mechanical and electrical connections. All of the electrical connections ensure good contact and do not expose any bare copper. Two circuit breakers are on the distribution panel and the bench circuit. And the individual lab bench has a fused disconnect switch. Although all the connectors are color-coded, wiring errors should be expected. Some wiring errors can be

(a) (b) (c) (d)

Figure 6. (a) Circuit breakers in distribution panel (b) Bench-top circuit breaker.
(c) Fused disconnect switch. (d) Emergency shut-off switch.

identified by check-up procedures in the lab manual, such as rotating direction and voltage polarity. A fuse protects the DC drive from the erroneous connection between DC field source and armature circuit. Operational faults such as over voltage and over current are protected by the protective functions of the DC and AC drives. And an emergency switch that shuts off the power to lab stations has been placed on the easily accessible position of the wall. The protective devices in the laboratory are shown in Figure 6.

3. Experiments

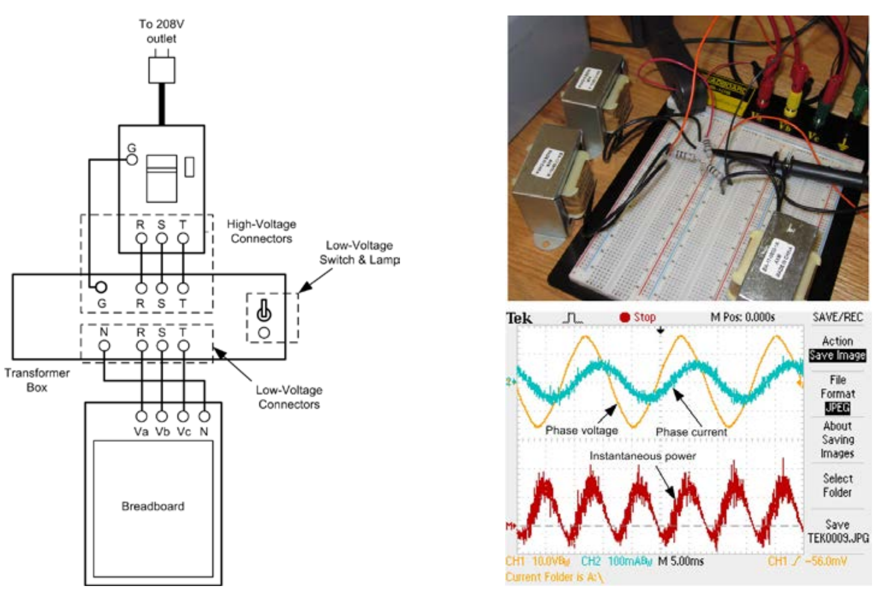
The proposed Energy Conversion Laboratory comprises the following seven experiments. Each experiment session includes experiment setup building for practical experience, data measurements to understand physical phenomena, and analysis questions for data interpretation and application of the concept. Theory review sessions are accompanied with experiments except the Intro Lab.

3.1 Intro Lab

The objective of this experiment session is to have students familiarized with the equipment and instrument used in the course. Cable connections, AC voltage and frequency measurements, instantaneous and RMS current measurement, rheostat test, and oscilloscope features such as probe compensation, trigger setup, screenshot savings are performed. Most students in this level of laboratory course do not have prior experience on the equipment and instruments; especially if they are industrial grade devices. Hence, it is important to have students to spend enough time exploring their features and functions by doing simple tasks.

3.2 Three-phase AC Circuits

Three-phase AC voltage, current, power measurements using current/voltage probes are performed in this experiment. Generally, a three-phase power circuit is difficult to handle because of the high voltage and current level. In this proposed experiment, students can actually build a three-phase circuit on breadboard safely using the 10:1 step down transformers and a circuit breaker. Furthermore, three-phase quantities such as AC voltages, currents and power can be easily visualized on oscilloscope. For example, instantaneous power can be easily shown to explain the relationships between active and reactive power, and students can actually measure power factor angle using oscilloscope’s cursor as well as calculating it from active and reactive power. Three-phase Wye-Wye, Wye-Delta connected resistive and resistive/inductive (RL) load is analyzed. The proposed experiment can improve students’ understanding with intuitive visualization and realistic experience of the AC power



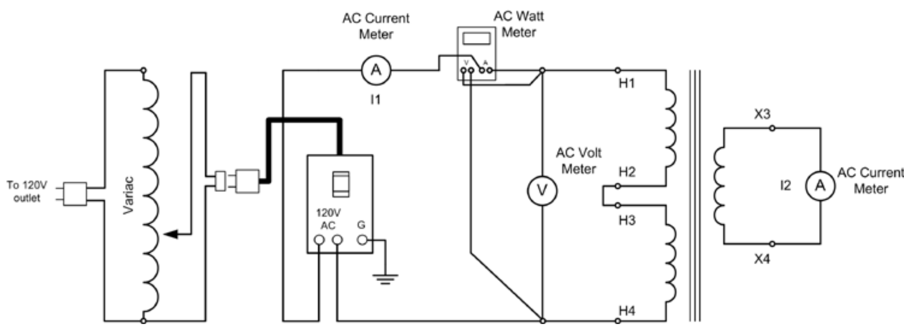
(a) (b)

Figure 7. (a) Three-phase circuit experiment setup.
(b) Phase voltage, current, and instantaneous power of RL load.

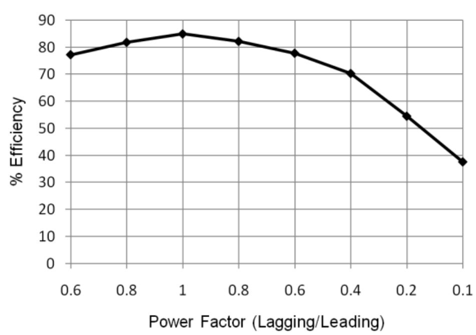
and three-phase circuit theory. The experiment setup and oscilloscope screenshot of a single-phase instantaneous power on RL load is shown in Figure 7 (a) and (b).

3.3 Single-phase Transformer

In this experiment, the transformer equivalent circuit model, the voltage regulation, efficiency and polarity of single phase transformer are determined. A variac is required to control the AC voltage. Using the equivalent circuit parameters, students can calculate and plot the voltage regulation and efficiency. The experiment setup for transformer short circuit test and calculated efficiency versus power factor is shown in Figure 8 (a) and (b), respectively.



(a)

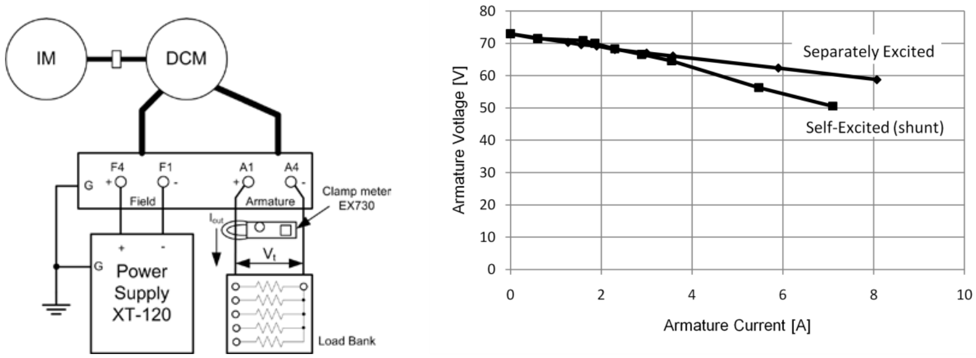


(b)

Figure 8. (a) Transformer short-circuit test experiment setup. (b) Efficiency vs. power factor plot.

3.4 DC Generator

Open circuit characteristics (OCC) and the load characteristics of a DC generator for various modes of operation are obtained in this experiment. The inverter-controlled induction machine works as a prime mover. An experiment setup to determine the voltage characteristic



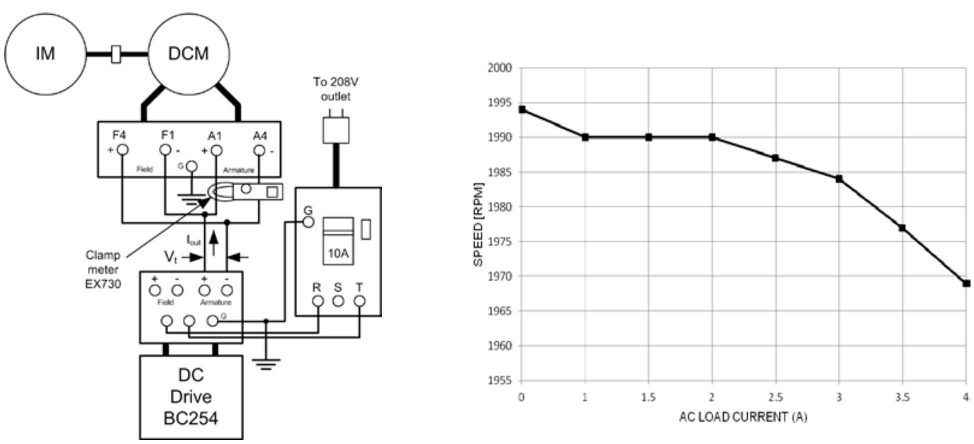
(a) (b)

Figure 9. (a) Separately-excited DC generator experiment setup.
(b) Load characteristic of the DC machine under test.

for a separately-excited DC generator is shown in Figure 9 (a). The field current is easily controlled using a DC power supply with a voltage/current display instead of rheostat and constant voltage source. Generator output is controlled by resistive loadbank, which consists of five power resistors. Possible equivalent resistances range from 8.3 Ω to 200 Ω. The load characteristic can be seen in Figure 9 (b).

3.5 DC Motor

The objective of this experiment is to verify the starting, speed control, speed regulation, and load-speed characteristics of a DC motor. Self- and separately-excited DC motor



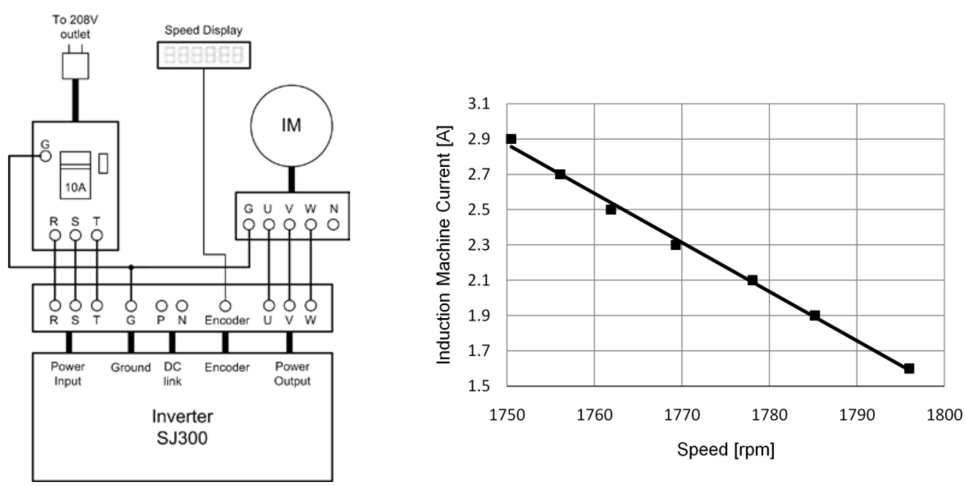
(a) (b)

Figure 10. (a) Self-excited shunt DC motor experiment setup.
(b) Load-speed characteristic of the Self-excited shunt DC machine under test.

configuration are investigated. Also DC motor speed control techniques using terminal voltage and field current are explored. The induction machine is operating as a mechanical load for DC motor. AC side load current can be easily monitored by the current display on the inverter. The setup and load characteristic for self-excited shunt DC motor experiment can be seen in Figure 10 (a) and (b).

3.6 Induction Motor

In this experiment, students find the induction motor equivalent circuit parameters by no-load test and verify the load-speed characteristics. Locked rotor test can be added if a mechanical shaft brake is installed. As the induction machine drives the DC machine, DC power is generated to the resistive loadbank. The load to the induction machine is controlled by DC machine field current similarly with DC generator experiment in Figure 8 (a). The inverter controls the synchronous frequency and monitors the current. The speed display shows the shaft speed for slip calculation. Students can plot the load/speed characteristic in linear range using inverter current, which shows the motor current and slip, which can be seen in Figure 11 (b). Machine torque can be calculated from the power and speed measurement. The experiment setup for induction machine is shown in Figure 11 (a).

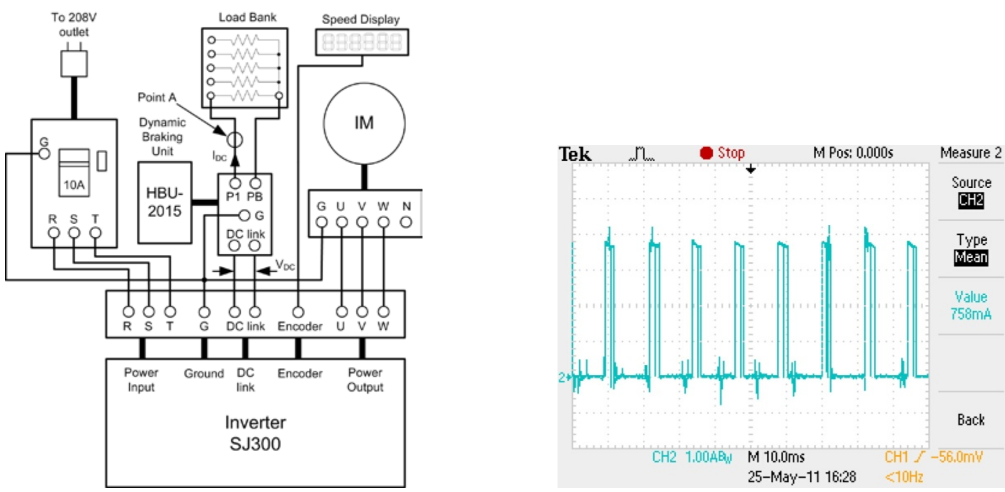


(a) (b)

Figure 11. (a) Induction motor experiment setup.
(b) Load-speed characteristic of the induction machine under test.

3.7 Induction Generator

The objective of this experiment is to verify the operation of an induction machine as a generator. The DC and induction machine needs to be rotating in same speed to start the experiment with zero slip. The slip can be controlled by DC machine's terminal voltage and the induction machine regenerates power to the DC link of the inverter when slip becomes negative. The dynamic breaking unit holds the DC link voltage at a certain level (380V for HBU-2015) by dumping power to resistors in the loadbank. Students can calculate the generated power by DC voltage and current flowing through the resistor at point A with current probe and oscilloscope. Although the current is not continuous due to the switching of dynamic braking unit, average can be easily obtained using the oscilloscope as can be seen in Figure 12 (b). The experiment setup for induction machine is shown in Figure 12 (a).



(a) (b)

Figure 12. (a) Induction generator experiment setup. (b) Current on dynamic braking resistor.

4. Discussion

The new Energy Conversion Laboratory has been offered since Fall 2010. Number of the students enrolled so far was 72. At the end of the course of Fall 2010 and Fall 2011, students were asked to fill out the exit survey and total of 41 surveys were returned. The questionnaire and the results are shown in Tables 3 and 4.

	Question	Score*
1	Overall, the course was satisfactory.	4.44
2	The object of the experiments was clearly explained.	4.53
3	Experiments supplement the lecture well.	4.46
4	Time allocated to experiments (3 hr) was enough.	4.73
5	I understood well how experiment was set up (e.g. wiring, safety devices, and instrumentation).	4.28
6	I think three people per station were acceptable.	4.44
7	Equipment is easy to operate.	4.39
8	I was able to learn how to use the instruments.	4.57
9	I think the course contents helped me to build skills I expected.	4.24
10	I think this course experience will be helpful for my future career.	4.13

* 5-Strongly agree, 4-Agree, 3-Neutral, 2-Disagree, 1-Strongly disagree

Table 3. Exit Survey part I.

		Intro Lab	XFR	3ph cir-cuit	DC Gen.	DC M	Ind. M	Ind. Gen.
1	I like the following session(s).	17	25	21	25	29	20	20
2	I think the following session(s) needs improvement.	1	6	3	5	8	7	9
3	I was able to understand the theory in lectures better by doing the experiments.	N/A	22	25	17	20	15	14
4	Especially the following experiment(s) was helpful to understand the theory.	N/A	17	20	21	18	14	13
5	Especially the following experiment(s) seemed NOT related well to the theory.	N/A	4	0	0	3	5	3

* Students can choose multiple items.

Table 4. Exit Survey part II.

Overall, the course and experiments received very good ratings. Students liked their experience on the new equipment and instruments, and much interest for the course was expressed. Compared to the old equipment, new ones are smaller and modern, and show contemporary technologies and high performance. The visualization of the variables, such as three-phase voltages and AC power on oscilloscope, helps students understand the concepts very much. However, it has been also revealed that some more background knowledge and theory need to be reviewed before complex experiments such as induction motor and generator experiments. Operating industrial devices such as the inverter and the oscilloscope took some time for students to get familiarized because the interface and the functions of the devices are not straightforward and students have little prior experience.

5. Conclusion

In this paper, a design and implementation of the instructional electric machine laboratory has been presented. Latest electric machines, drives and instruments have been utilized in the newly renovated laboratory and the laboratory is providing students with practical experience on up-to-date systems as well as improving their understanding of the theory learned from lectures. Off-the-shelf industrial devices have made the experiments more realistic and closer to practical work situations and at the same time more cost effective. The renovated system, including experiments, hardware components, and instruments, has been received positive feedback from students.

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