AC 2008-310: AN INTRODUCTORY ELECTRIC MOTORS AND GENERATORS EXPERIMENT FOR A SOPHOMORE-LEVEL CIRCUITS COURSE

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An Introductory Electric Motors and Generators Experiment for a Sophomore-Level Circuits Course

Abstract

The design, implementation, and assessment of an introductory electric motors and generators experiment in sophomore-level electric circuits courses are described. Two separate courses were enhanced by the addition of a common motors experiment for both students in the electrical engineering program (e.g., as student preparation for an electric power class) and those in other engineering majors (e.g., as student preparation for mechanical engineering lab experiences). The experiential foundation in the motors lab was designed to solidify concepts on efficiency of energy conversion and on motor performance. Topics included modeling of electric motors, predicting motor performance, and experimentally obtaining relevant motor constants. The experiment used a simple sub-fractional horsepower (Fischertechnik™ #32293: ~1.5 Watt) electric motor together with a unique small-scale dynamometer. In the experiment, students were required to experimentally determine the rotational speed of a motor using an optoswitch-based tachometer to find the motor voltage constant, k_E; to determine motor torque constant, k_T; to explore the use of a dynamometer to measure the conversion of electrical energy into mechanical energy; and to investigate the use of a motor as a generator. Despite the low-cost equipment, experimental results proved to be reliable, accurate, and repeatable. For example, the motor $k_E - k_T$ match was typically found to be within 5%. Student learning was assessed through questionnaires at the beginning and end of the laboratory period. The questionnaires addressed both student knowledge and student confidence levels. The assessment showed a significant overall increase of both student knowledge and confidence scores as well as significant incremental increases. The data also showed that each incremental increase could approximately be represented as a normal distribution. Detailed analysis of the assessment data revealed strengths in student preparation for the experiment as well as certain course topics, such as the operating principles of a dynamometer, which will require more in-depth coverage in subsequent offerings of the course.

I. Introduction

Responding to a recent resurgence in interest concerning basic electric machines and their control[1] has been a challenge for many electrical engineering programs that, either through retirement of elderly equipment or the failure to acquire equipment, have been caught without proper resources for laboratory exploration of electric machines, in particular in introductory electrical circuits courses. The University of San Diego (USD) falls into the latter category with an electrical engineering (EE) curriculum focused on the electronics and communications industries rather than on electrical machines. Recent additions of a mechanical engineering (ME) program and an industrial & systems engineering program to the existing electrical engineering (EE) program have altered the student population balance and, necessarily, have shifted the focus of many lower division courses. In response to these changes, the one-semester, sophomore-level electric circuits curriculum was changed. Prior to the change, all engineering students enrolled in a single course designed primarily to meet the needs of EE students. After the change, a second course was added with a more diversified content to meet the needs of other engineering majors. The first course continued to focus entirely on electric circuits. The basics of electronics and electric motors became the major focus for the last 40% of the new second course with electric machines occupying, at most, the last six lectures and a single lab period.

While laboratory experiments covering electronics are easily adapted from the EE electronics core, neither experiments covering the basics of electric motors nor any appropriate equipment existed at USD. The upper division curriculum of EE at USD does include a course, Principles of Electric Power, that has a large component covering electric machines, but this course does not have an associated laboratory or significant demonstration equipment. The ME program does have a few instrumentation laboratory exercises using the National Instruments ELVIS system including one concerning DC motor speed[2], but those exercises are limited to a very few lab stations.

A faculty team was formed to create a single motor experiment that could easily and simultaneously be performed by approximately twenty students working in groups of two or three within a single three-hour laboratory period. In order to cover a wide diversity of concepts, the often-used approach of building a simple DC motor, such as the construction of Beakman's motor[3], was eliminated in favor of an approach based more on the testing and modeling of an existing DC machine. This approach allows the introduction of mechanical concepts such as force, torque, and power, in the treatment of an electrical system. Among the reasons for choosing a DC motor over an AC motor are: the operating principles governing the control of a DC motor are significantly simpler than those for an AC motor and therefore more suitable for a sophomore-level course, there are a large number of DC motors currently in use and their absolute number keeps increasing, and the control of an AC motor drive emulates the operating principles of a DC motor and its drive[4].

The team's working budget was US$200 to outfit ten (10) lab stations. Such a small budget immediately eliminated the possibility of purchasing a significant number of fractional-horsepower (~150W) motors. Since the department had previously purchased a large number of Fischertechnik™ motors for another project[5], these subfractional-horsepower (~1.5W) motors were chosen as the basis for this experiment. While many upper-division power electronics[6, 7] or electrical machinery[1, 8] labs have explored electric machines and their control, the approach used here is substantially simpler. The laboratory experiences described are primarily focused on the modeling of a simple motor and the fundamentals of energy conversion using electric motors and generators.

II. The Experiment and Experimental Observations

The basic goals for the laboratory experiences were:

- to develop a meaningful electric motor laboratory experience for (primarily) sophomore students who have minimal knowledge of the subject,
- to improve student knowledge concerning the basics of motor operation, performance, and modeling,
- to give the student increased confidence in applying the knowledge obtained, and
- to develop an experiment that could be easily scaled up without prohibitive costs.

The experiments were designed to explore several basic concepts concerning simple electric motors. Specifically, students would collect experimental evidence to verify that:

- motors can be modeled with a few basic circuit elements,
- motor torque is proportional to current,
- motor speed is proportional to voltage,
- the torque and speed proportionality constants are related,
- motor performance can be accurately predicted once the motor model parameters are known,
- output mechanical power is proportional to input electrical power, and
- an electric motor can be used as an electric generator – output power is proportional to input power.

At USD, an upper-division ME laboratory had previously explored the relationship between input voltage and speed with an ELVIS experiment. This procedure used a slotted disk and a transmissive optoswitch to count the revolutions of the motor shaft. While no previous work at USD had explored the relationship between torque and current, a simple measurement of stall (zero rotational speed) torque seemed the most appropriate choice. Relating the proportionality constants and predicting performance are direct outcomes of the modeling process.

Measuring output mechanical power and relating it to input electrical power proved to be an intellectual challenge, because none of the involved faculty had experience with a dynamometer built to such a small scale. The team was well aware of dynamometers constructed with magnetic breaks (e.g., GDJ Inc. Powertek, Single-Cylinder Dynamometer), slipping bands (e.g., Armfield F1-25 Demonstration Pelton Turbine), and similar devices. After brainstorming a few possibilities, it was decided to use a clothespin, slipping on the motor output shaft, coupled to a linear spring scale (sometimes called a fish scale) as the major, torque-measurement components of the dynamometer.

The greatest concern of the team centered on working with toy motors and primitive laboratory equipment. Some of the questions facing the design team were: Will the students be able to measure and model the motors as theory predicted? Will the efforts to keep the cost down and have high student throughput jeopardize the educational value of the experimental experience? Frankly, these concerns could not be addressed adequately until the students had completed the laboratory experiment and the team had evaluated the student reports.

A. Modeling the Electric Motor

Students were given minimal background concerning electrical motors. A simple first-order electromechanical model of a motor[4, 9] was presented (Figure 1) and Kirchhoff's voltage law applied to the loop:

$$V_S = I_a R_a + L_a \frac{dI_a}{dt} + e_a$$

Students were reminded that the model parameters, R_a and L_a, describe the resistance and inductance of the motor armature windings, that the quantity, e_a, is the back emf of the motor, and that, under steady-state operation (constant motor speed), the armature inductance can be ignored.

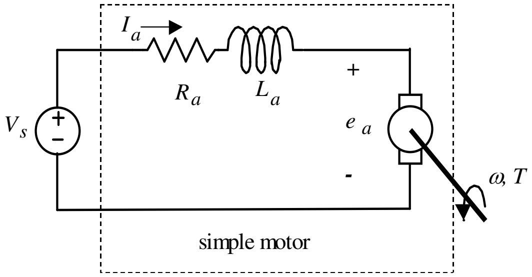

Figure 1. Electromechanical model of a motor.

The relationships of the motor's electrical descriptors, e_a and I_a, and the mechanical outputs, ω and T, were then postulated:

$$e_a = k_E\,\omega \quad \text{and} \quad T = k_T\,I_a$$

It was further postulated that the motor voltage constant, k_E, and the motor torque constant, k_T, have the same numerical value (though different units) if one is working in SI units.

The experimental procedure devoted a separate section to the modeling of the parameters R_a, k_E, and k_T, as well as having as two sections on energy conversion. A list of all components and laboratory equipment necessary for this experiment is given in Table I and the components are shown in Figure 2. Those interested in duplicating this experiment should be reminded that Fischertechnik™ motors and components were used because of their availability at USD. Generic equivalents will typically produce similar results at somewhat lower cost.

TABLE I. Components used (per station)

Quantity	Item
2	Fischertechnik motor (#32293)
1	slotted cardboard disk (~3.8 cm diameter)
1	10-24 machine screw (cut to ~ 1 cm of threaded length)
2	plastic tubing (¼" diameter x 1.5 cm and ¼" x 2 cm)
1	transmissive optoswitch (VTL11D1H or similar)
1	spring scale – 10g full scale
1	wooden spring clothespin ~ 7.5 cm
1	Fischertechnik baseplate (#31002)
2	Fischertechnik spline (#31060)
1	protoboard (Jameco JE25, JE26, or similar)
2	small machine screws
1	spring clip, large (2")
1	standard lab station (2 multimeters, dual output DC power supply, oscilloscope, decade resistor, wires, etc.)

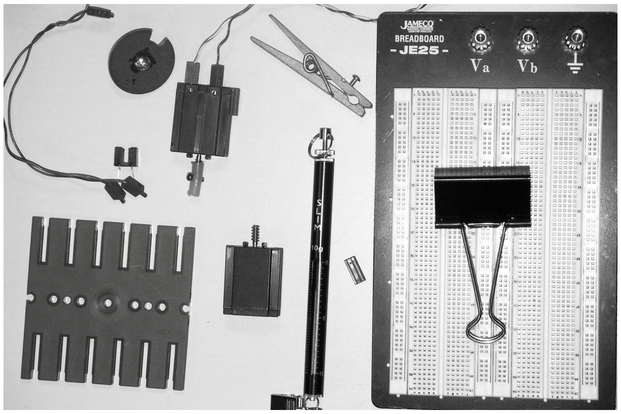

Figure 2. Experimental components

The armature winding resistance, R_a, was measured with a multimeter, searching for the minimum value as the motor shaft was rotated, and that value was used as a first-order approximation for R_a. Students were told that the value should lie below 40Ω for the motor used. This measurement initially proved to be problematic. Multimeter readings of the armature winding resistance were quite sensitive to shaft rotational angle, with readings varying from about 10-400Ω (the true value is ~20Ω). As a consequence, some student groups missed the lowest value and chose a value for R_a that was significantly too large. Those groups that installed the slotted disk on the motor shaft prior to making the resistance measurement were observed to have a much greater control on the shaft angle and, as a consequence, were able to find the minimum value more accurately. Changing the procedure so that the disk was installed before the resistance measurement has eliminated the difficulties.

The relationship between motor rotational speed and voltage was explored with a simple tachometer constructed using a slotted disk, transmissive optoswitch, and oscilloscope. The slotted disk was fabricated with a laser cutter, ensuring a concentric center hole and outer diameter. In order to couple the disk to the motor's worm gear output shaft, the disk was glued to the head of a short (~ 1 cm) machine screw, thereby ensuring perpendicularity to the shaft, and used a short (~ 1.5 cm) segment of plastic tubing to connect the screw, with the disk attached, to the shaft.

The students constructed a detector using a transmissive optoswitch (Figures 3 and 4) and tested its operation. Typical problems were encountered in placing the DIP-packaged optoswitch into the protoboard correctly (operational amplifiers were the only previously-used components in DIP packages), but there were no other significant electrical problems.

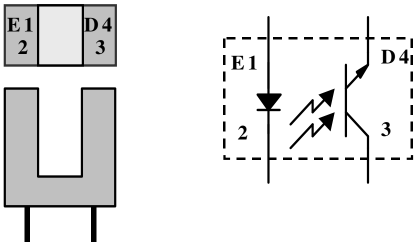

Figure 3. Transmissive optoswitch layout

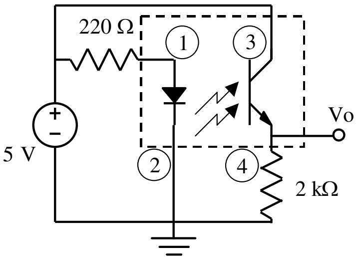

Figure 4. Optoswitch sensor connections.

With the motor running, several measurements of the input voltage and motor current and speed were taken (Figure 5). From the experimental data, the voltage constant, k_E, was determined from a plot of the equation:

$$e_a = V_s - I_a R_a = k_E \omega$$

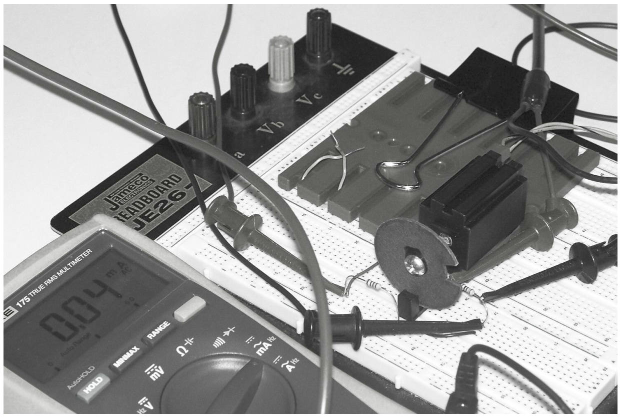

Figure 5. Speed measurement

All students plotted back emf, e_a, as a function of speed using Excel and inserted a linear trend line to determine the voltage constant, k_E. The plots were remarkably linear (Figure 6) and, for those groups who had chosen R_a properly, essentially passed through the origin. In the first revision of the laboratory procedures, students were asked to vary the value of R_a in their spreadsheet in order to make the speed-emf plot pass through the origin, compare this new value to that of the simple measurement of the previous section, and make a decision as to which value to use in modeling the motor. That change improved experimental results for many groups.

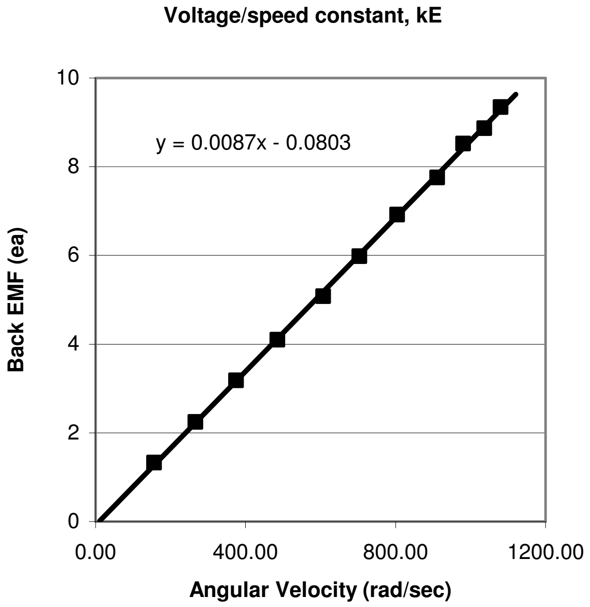

Fig. 6. Sample student data: determination of k_E.

The relationship between the motor stall (zero speed) torque and the input current was explored through the use of a lever arm and linear spring scale. Since the motor used produce a maximum torque that does not exceed 20mNm, 10g (full scale) linear spring scales proved most useful. A spring clothespin was used as the lever arm: its spring tension, when applied to the plastic tubing on the slotted disk, was sufficient to provide a non-slip connection to the motor shaft (Figure 7). Several measurements were taken at different input currents and the results plotted to determine the torque constant, k_T (a reminder to subtract out zero-force spring scale readings was made).

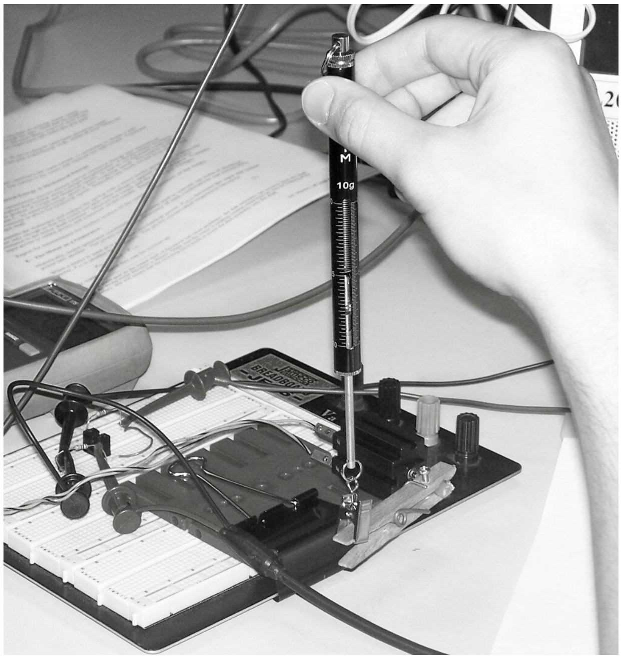

Figure 7. Torque measurement

Plots of torque as a function of current were again remarkably linear (Figure 8). The zero-input force measurement proved somewhat inaccurate for some groups. The next revision of the laboratory procedures notes that the current-torque plot should pass through the origin and asks students to make the appropriate correction to zero-input force.

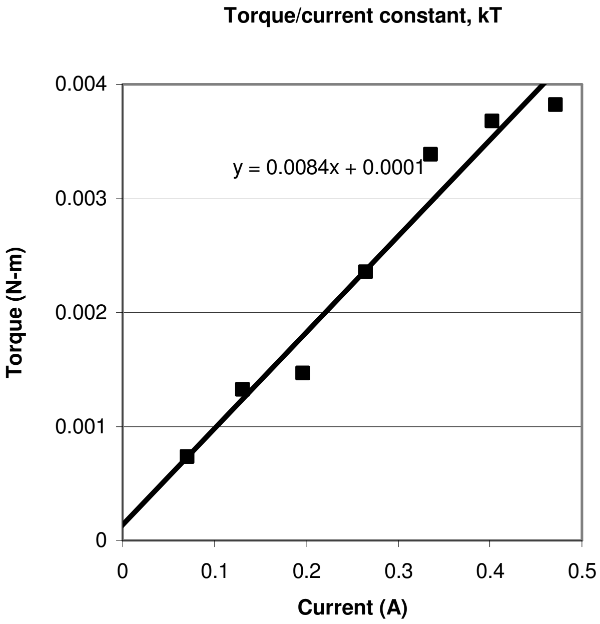

Figure 8. Sample student data – determination of k_T.

At this point the students were asked to compare their experimental values of k_E and k_T and decide which was more likely to be an accurate determination. For those groups who were careful with experimental technique, especially in measuring the lever arm length, the voltage constant, k_E, and the torque constant, k_T, typically matched to within 2-5%. For the student data shown in Figures 6 and 8 (a single team's efforts), the calculated $k_E - k_T$ variation is 2.7%.

In the speed and torque procedure sections, students were asked to predict an electrical input in order to achieve a desired mechanical output and to compare experimental results to predictions. In all cases, student predictions proved to be reasonably accurate.

B. Energy Conversion

In order to measure motor output mechanical power, a small-scale dynamometer was created by slightly modifying the stall torque measurement and using the optoswitch tachometer from the earlier sections (Figure 9). The spring from the clothespin was removed and replaced by a screw holding the two wooden parts together. Adjusting the screw so that the clothespin could spin on the plastic tubing allowed for a varying load to be applied to the motor shaft. Students were asked to compare input electrical and output mechanical power and to account for power losses.

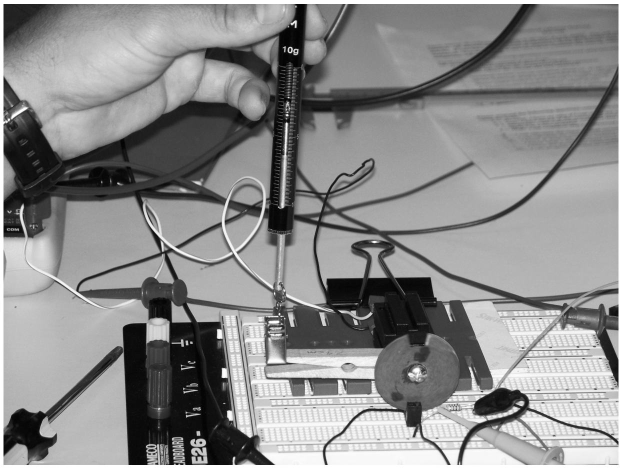

Figure 9. Small-scale dynamometer.

This clothespin dynamometer worked well. Motor power-conversion efficiency was typically measured to be in the 80% range (Table II). The only problem encountered by a few groups was caused by the worm gear output shaft of the motor. If students chose the wrong motor rotation direction, the disk unscrewed from the shaft. A warning was placed in the first revision of the laboratory procedures and the problem eliminated.

Table II. Electrical-mechanical energy conversion

Output Mechanical Power					Input Electrical Power			Efficiency
Δ mass (g)	f (Hz)	T (mNm)	ω (rad/s)	P_{out} (W)	V (V)	I (A)	P_{in} (W)	η (%)
2	35.1	1.2152	220.54	0.27	4.07	0.102	0.42	64.56
2.25	47.3	1.3671	297.19	0.41	5.3	0.109	0.58	70.33
3	65.8	1.8228	413.43	0.75	6.2	0.136	0.84	89.37
3.25	110	1.9747	691.15	1.36	9.33	0.155	1.45	94.38

Motor operation as a generator was explored through coupling two motor shafts together with another short (~2 cm) segment of plastic tubing (Figure 10) and loading the output motor (generator) with a decade resistor. Again, students were asked to compare input electrical power to output electrical power. While not all groups in the initial running of the experiment made it to the motor-generator set, those who did complete it were successful. Power conversion efficiency was only in the 10% range (Table III). While the Fischertechnik™ base plate ensured shaft alignment of the motor-generator pair, the worm gear output shaft again created some difficulties. The plastic tubing migrated toward one motor (later corrected by a screw through the middle of the tubing) and the motors tended to move away from each other, eventually uncoupling unless tethered together.

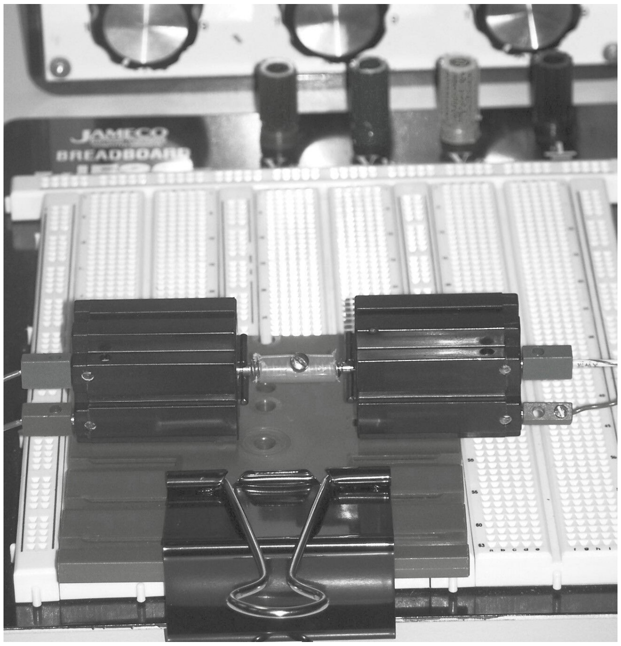

Figure 10. Motor generator set

The laboratory procedures achieved all design objectives. Within a standard three-hour laboratory period essentially all students completed determining the motor model parameters, testing theoretical predictions of motor performance, and observing motor mechanical output with the simple dynamometer. Initially, time allotted to assessment activities kept a significant portion of the lab groups from completing the motor-generator segment of the lab. Moving the assessment activities out of the laboratory period has remedied that problem.

Table III. Electrical-electrical energy conversion

Input electrical power			Output electrical power			Efficiency
V (V)	I (A)	P_{in} (W)	V (V)	R (Ω)	P_{out} (W)	η (%)
8	0.219	1.752	1.2	10	0.144	8.2
9.04	0.238	2.152	1.4	10	0.196	9.1
10	0.253	2.530	1.57	10	0.246	9.7
11.06	0.269	2.975	1.77	10	0.313	10.5
12.04	0.286	3.443	1.94	10	0.376	10.9
12.98	0.305	3.959	2.06	10	0.424	10.7
14.95	0.343	5.128	2.31	10	0.534	10.4

III. Assessment of Student Learning

Student learning of the laboratory material was assessed in both versions of the sophomore-level electrical circuits courses. The assessment was based upon a questionnaire evaluation scale and general format originally designed by Rose-Hulman's Office of Institutional Research, Planning, and Assessment. A similar approach was taken by Throne[10, 11] and Burchett[12] to assess student learning in a control system laboratory. The questionnaires were designed to provide insight into both the level of subject knowledge and the confidence to apply the material. In the sophomore-level courses, the questionnaires were completed by the students at the beginning of the lab period before the experiment and at the end of the lab period after completion of the experiment. A total of thirty-seven survey pairs were completed by students in two separate laboratory sections of the sophomore-level course. One survey pair was excluded from the data analysis since only the "post laboratory" survey was completed by that student and analysis was performed on the aggregate group of thirty-six remaining survey pairs.

The following semester, in order to evaluate changes made to the laboratory procedures, the experiment was offered to students in the upper-division Principles of Electric Power course as an optional extra credit assignment. The questionnaires were distributed by e-mail before the experiment and collected after completion. Limited enrollment in the course and the fact that the experiment and the assessment activities (as mandated by USD Institutional Review Board policies) were optional, limited the assessment response to only three survey pairs. While this small number precludes any conclusions, the data is included for completeness. In spring 2008, the experiment will again be performed in the sophomore-level courses along with the assessment activities.

A. Assessment of Student Knowledge

The following questions were asked before and after the experiment was performed in order to assess the students' knowledge of the subject matter of the lab material:

- Electrical motors convert electrical power (V, I) into mechanical power (T, ω).

- Motor rotational speed is proportional to input voltage
- Motor output torque is proportional to input current
- A dynamometer measures motor output power
- An electrical motor can also operate as a generator
- I know the basic components of an optoswitch
- LEDs emit light
- A phototransistor can be used to detect light

The knowledge score was based on the following scale:
Pre lab:
1 = No clue, this concept is new to me
2 = Low, I had only heard about the concept
3 = Moderate, I knew the concept but had not applied it
4 = High, I knew the concept and had applied it
Post lab:
1 = No Clue, I do not know the concept
2 = Low, I have only heard about the concept, but can't apply it.
3 = Moderate, I know the concept but do not know it well enough to apply it
4 = High, I know the concept and have applied it in this course.

The distribution of the students' knowledge of the lab material before and after the experiment is shown in Table IV.

Table IV. Student knowledge distribution

Knowledge Level		Spring '07 – Soph.		fall '07 – Senior	
		Before	After	Before	After
1 = No clue		95	3	5	1
2 = Low		73	48	3	0
3 = Moderate		72	105	4	2
4 = High		48	132	12	21
Statistics	$\overline{X}$	2.25	3.27	2.96	3.79
	σ	1.09	0.77	1.21	0.64

For the sophomore-level electrical circuits class the following observations can be made. Before the experiment, about twice as many answers are rated "1 = No clue, this concept is new to me" than "4 = High, I knew the concept and had applied it." At the end of the experiment, almost no students answered "1 = No Clue, I do not know the concept" but the largest number answered "4 = High, I know the concept and have applied it in this course." Note that before the experiment, students' knowledge decreased approximately linearly with knowledge score, while after the experiment, students' knowledge approximately linearly increased with knowledge score. The average students' knowledge score increased from 2.25 before the experiment to 3.27 after the experiment. For the senior-level electrical power course, students showed similar gains in knowledge starting from a higher level of initial knowledge and ending with essentially all responses (87.5%) at the level of “4 = High, I know the concept and have applied it in this course.” The incremental change of students’ knowledge scores is shown in Table V:

Table V. Incremental change in knowledge

Change in Knowledge	Incremental Change							Statistics	
	-3	-2	-1	0	1	2	3	$\overline{X}$	σ
Spring ’07 — Sophomore		1	10	90	93	70	24	1.02	1.03
Fall ‘07 — Senior				14	3	4	3	0.83	1.11

For the sophomore-level course, a decrease of knowledge scores is observed only rarely and an average increase of 1.02 score points for students’ knowledge was obtained. For the senior-level course, knowledge gain was limited to only a few topics, but significant in those areas. Particularly strong average incremental gains were obtained in the primary objectives of the laboratory exercises: speed is proportional to voltage (+1.44), torque is proportional to current (+1.61), and a dynamometer measures output mechanical power (+1.17), however the greatest incremental gain in knowledge concerned the optoswitch (+1.69).

B. Assessment of Student Confidence in Applying Concepts

The following questions were asked before and after the experiment was performed in order to assess the students’ confidence in applying the concepts of the lab material:

- I can calculate the input voltage necessary to make a motor rotate at a fixed speed.
- I can calculate the current necessary to achieve a fixed motor torque
- I know at least one way to measure motor speed without touching the motor
- I know what a dynamometer must measure to determine output power
- I know the theoretical relationship between an electrical motor’s torque and voltage constants
- I can properly connect an optoswitch and use it to detect motion.

The Confidence score was based on the following scale:
Pre lab:
1 = No Clue, I have no idea if I can apply the concept
2 = Low, I had heard of the concept but had little confidence that I could apply it
3 = Moderate, I am somewhat confident that I understood the concept and am fairly sure I could apply it to a new problem
4 = High, I am confident that I understood and could apply it to a new problem
Post lab:
1 = No Clue, I am not confident that I can apply the concept
2 = Low, I have heard of the concept but am not sure if I can apply it
3 = Moderate, I am somewhat confident that I understand the concept and I can apply it to a new problem
4 = High, I am confident that I understand and can apply the concept to problems.

The distribution of the students’ confidence in applying the concepts of the course material is shown in Table VI:

Table VI. Student confidence level distribution

Confidence Level		Spring ’07 – Soph.		Fall ’07 – Senior	
		Before	After	Before	After
1 = No clue		121	3	9	3
2 = Low		57	55	2	0
3 = Moderate		31	93	1	2
4 = High		7	65	6	13
Statistics	$\overline{X}$	1.65	3.02	2.22	3.39
	σ	0.84	0.78	1.36	1.11

For the sophomore-level electrical circuits course the following observations can be made. Before the experiment, the majority of students answered “1 = No Clue, I have no idea if I can apply the concept” and almost no students answered “4 = High, I was confident that I understand and apply it to a new problem.” Again, an approximately linear decrease of students’ confidence is observed with confidence score. After the experiment, almost no students answered “1 = No Clue, I am not confident that I can apply the concept” and the largest group answered “3 = Moderate, I am somewhat confident that I understand the concept and I can apply it to a new problem.” The average students’ confidence score was 1.65 before the experiment. This value is significantly smaller than the students’ knowledge score of 2.25 before the experiment. The average students’ confidence score increased to 3.02 after the experiment. This is again a somewhat smaller value compared to the students’ knowledge score of 3.27 after the experiment.

A distribution of the incremental change of students’ confidence scores is shown in Table VII. For the sophomore-level course, a decrease of application confidence scores is again observed in only a few instances. An average increase of 1.37 score points was observed for students’ application confidence with all topics having and increase of at least 1.17 score points. This average increase is somewhat higher than the increase observed in students’ knowledge. Particularly strong average incremental gains in student confidence were obtained in the primary objectives of the laboratory exercises: measuring speed (+1.56), determining the inputs necessary to achieve a desired speed (+1.33) or torque (+1.42), and the relationship between modeling constants (+1.39). The results suggest that a further improvement of students’ confidence to apply the concepts of the course is possible. It may, however, require an additional lab period to reinforce the material to the point that a majority of the students is confident enough to indicate “4 = High, I am confident that I understand and can apply the concept to problems.”

For the senior-level electrical power course, confidence started out somewhat higher than for the sophomore-level course and experienced a significant gain. Although the number of students is small, just as in the case of the sophomore-level course, student confidence seems to lag behind knowledge.

Table VII. Incremental change in confidence

Change in Confidence	Incremental Change							Statistics	
	-3	-2	-1	0	1	2	3	$\overline{X}$	σ
Spring ’07 — Sophomore			3	42	72	70	29	1.37	0.99
Fall ‘07 — Senior				10	1	1	6	1.17	1.38

On the final examination for the more-diversified content sophomore-level circuits course, students showed significant confidence and ability in the material covered in this experiment. The final was a comprehensive test on the all the material covered during the semester. There were seven equally-weighted problems of which the student was required to submit solutions to five. A single problem related to electric motors: it required students to determine model parameters from data and then predict motor performance. Fourteen of the eighteen (77.8%) students choose to submit a solution for the motors problem making the problem the third most frequently chosen. The problem received the highest average score with all but three students achieving a score of 70% or better and half achieving a score of 90% or better.

IV. Summary

The development of a meaningful electric motors laboratory experience met all its goals. The experiment explored several new concepts concerning motor modeling and the measurement of the model parameters. Techniques for measuring motor speed, torque, and output power were successfully explored. A new electronic device, the transmissive optoswitch, was presented and successfully used. Students reported significant gains in knowledge and confidence in using that knowledge. The department was fortunate to have a large supply of Fischertechnik™ motors available and therefore was able to limit its purchases for this experiment to the linear spring scales (~US$8 each). Even if all items needed for this experiment were to be purchased, it is estimated that an equivalent experiment could be accomplished for a per-station cost of less than US$20 (assuming that typical laboratory equipment is available).

Data collection, analysis, and verification on subfractional-horsepower motors exceeded the expectations of the authors. The data collected was reliable, accurate, and repeatable: the models constructed from the data accurately predicted motor performance. At no time did the mechanical power generated by these motors exceed 1.5 W.

An assessment of student learning showed a significant increase in both student knowledge and student confidence in the application of that knowledge. Student knowledge was initially quite varied. Knowledge improved considerably to the point where the students reported knowledge in the highest category most frequently. Student confidence was initially at a much lower level, increased more strongly than student knowledge, but did not achieve the same high final level.

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