Motor Designs for Instruction in Drives

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Abstract - **We have designed kits of flexibly configurable components that students use to quickly wind and construct dc motors, permanent-magnet (pm) machines, and induction motors. They can use these machines to verify design calculations, test their understanding of the machine operating principles, and to test power electronic drives that they also design and construct. In class, the properties of different motor designs and sizing can be related to commercial products, and commercial products can be used as an inspiration for motor design contests in the teaching laboratory. This paper reviews some of the designs and design features we have explored and employed.**

I. ELECTRIC MACHINES: A WINDOW TO THE ENGINEERING DESIGN PROCESS

Undergraduate instruction in electric machinery diminished substantially in many electrical engineering curricula in the last half of the twentieth century. This change occurred as part of a larger response to rapid changes in technology. A rush to “update” instruction and a laudable and generally successful focus on engineering science has had an unfortunate collision with a marked change in the typical pre-college preparation of our students. As “hacking the web” has supplanted “working on the Ford,” many engineering students are increasingly unprepared to relate analytical material under study to the physical systems for which these tools were developed. These trends may account for our informal observation that many students are increasingly disenfranchised with physics-related courses. A balanced educational experience that combines a good appreciation of exciting, “information age" methods with the essential ability to manipulate and understand the physical world enables a student to design real systems [2]-[7]. This combination should be the hallmark of a first-rate engineering education. The ability to design and understand new electromagnetic energy conversion systems will be of paramount importance in an energy-constrained future.

We believe that the electric machine was in many instances “discarded with the bathwater” from our engineering curricula. Drives remain of the highest industrial relevance, and motors consume a substantial fraction of generated electric power. Electric machines and drives offer important, interdisciplinary design problems that challenge an engineer to think about electric circuits and electromagnetic, thermal, mechanical, and material design problems. Motors and drives are exciting systems to think about. With appropriate constraints, we have used machine and drive examples as engaging hands-on design problems at every level from pre-college students to graduate students.

We have been experimenting with the application of some unusual motor designs for instruction in electric machinery and drive design. These designs permit immediate hands-on access to the machine, easy observation while operating, and the possibility for the student to customize and design. These machines are unconventional compared, for example, to the radial-magnetic flux machines most common in industrial and commercial environments. However, they give undergraduate students a “hands-on,” immediate feel for simple motor sizing rules, electrical terminal models, drive efficiency, and the interaction between a motor and a power electronic drive. We have designed special kits of parts that can permit students to quickly wind and construct dc motors, pm machines, and induction motors, and then to use these motors in power electronic drives that the students also design and construct. In class, the properties of different motor designs and sizing can be related to commercial products, and commercial products can be used as an inspiration for motor design contests in the teaching laboratory. The designs lend themselves to contests, e.g., for maximum rpm, with groups of students. We have found that “design and build” competitions generate enormous enthusiasm and excitement for learning and experimentation with students in our classrooms.

In the next section, we review some of the basic brushed dc motor designs and design considerations that we employ in classes for widely varying age groups and engineering topics. In the following sections, we discuss reconfigurable ac machine designs that we use to teach induction and synchronous machines. These machines are all suitable for use with power electronic drives that can be constructed by students in the teaching laboratory.

II. BRUSH DC MACHINES

The dc motor is a superb example for introducing basic conservation laws, rudimentary circuit analysis, and basic electromechanical energy conversion. It is commercially and industrially relevant. Subtle aspects of dc machine construction and design, e.g., pole-face compensation and long-life brush design, can often be ignored in a first introduction. For this reason, with varying degrees of sophistication in the level of initial modeling, the dc motor has historically been a great introduction to rotating machines for students from K-12 through the graduate level. A basic commutator machine can be used to introduce and explain the right-hand rule and the basics of electromagnetic torque production to students at almost any level.

A. Commercial Examples

We have employed the dc machine as a relevant example and source of design problems in a wide range of classes, including introductory network theory, classical feedback control, introductory embedded control, field theory, freshmen and pre-freshmen seminars, and graduate and undergraduate machines classes. We often begin with a review of a relevant commercial or industrial product or products, and use this review to pose a design problem. This design problem might be part of a longer problem set, e.g., with several different network or circuit-solving problems related to the machine. It could also lead directly to a focused “design-and-build” activity. We have even used the dc motor as an example to teach machine shop skills. Students can learn about the lathe, milling machine, water-jet cutting machine, and other tools while building components for a machine of their design.

Typical commercial machine examples that we might use to motivate a “learn-design-build” activity are shown in Figs. 1 and 2.

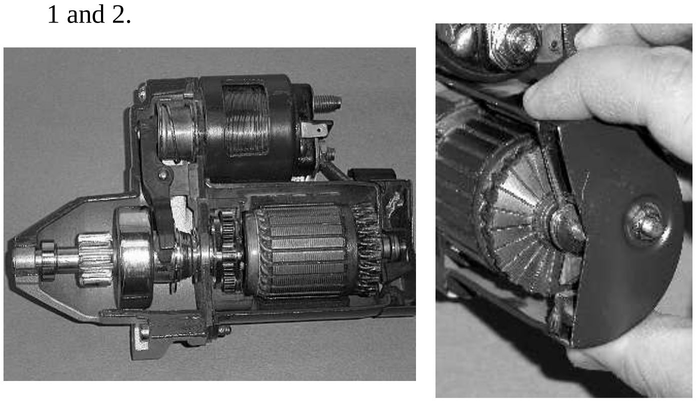

Figure 1: Starter motor.

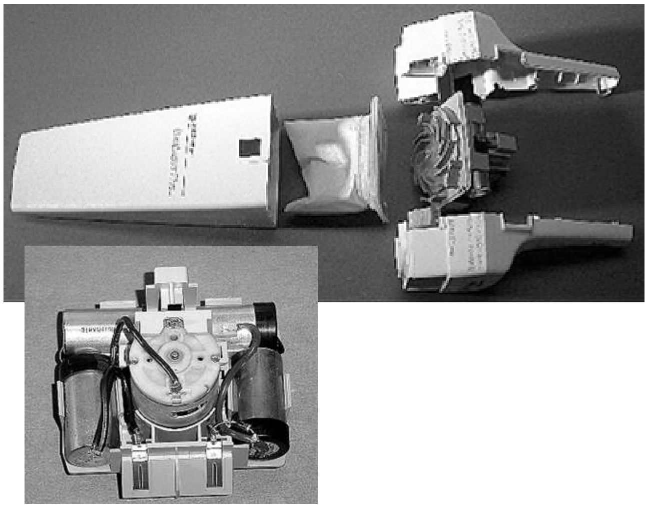

Figure 2: Hand-held vacuum cleaner.

Figure 1 shows a 12-volt starter motor for an automobile. This particular machine has been cut open for display and examination in class. It normally has an almost completely sealed metal enclosure for protection from the environment. It includes a solenoid that throws a gear forward during starting to engage the internal combustion engine, a planetary reduction gear, and a dc motor with an interesting commutator arranged as “pie wedges” on an axial disk at the back of the machine. Figure 2 shows a hand-held vacuum cleaner with a dc motor powered by rechargeable NiCd batteries. This motor spins at a much higher speed than the dc motor in the automotive starter, and employs more typical, radially distributed commutator segments inside the machine. The similarities and differences between these two example dc machines are often an excellent point and counterpoint for students beginning to wrestle with the design considerations associated with making a motor. The mechanical differences between the two motors, e.g., the differences in the commutators, bearing mounts, and winding arrangements, are quickly discerned and lead to enthusiastic discussions about electrical and material differences between the machines.

B. Machine Models

In class, we examine these and other motors and develop “cartoons” of the dc machine like the cross-section of a machine with active length L shown in Fig. 3.

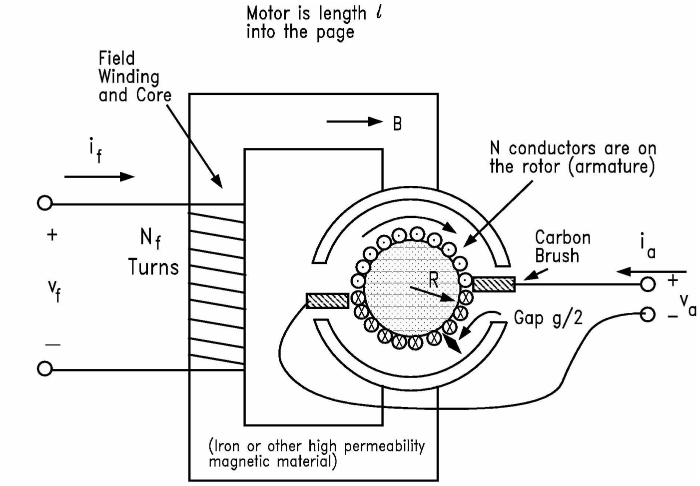

Figure 3: Motor cross-section cartoon.

The details of the commutator are not fully illustrated in Fig. 3, although the effects of the commutator are shown in the current reference directions of the N wires on the surface of a rotor cylinder of radius R and moment of inertia J. The field yoke on the stator is illustrated as a wound-field electromagnet producing a magnetic field of strength B.

We use schematics like those shown in Fig. 3 to motivate a variety of interesting problems for the students to consider. For example, the field winding can be used as an early problem for learning about magnetic circuits. We have used magnetic circuits to motivate the study of circuit-solving techniques in general. Magnetic circuit analysis can also be used to discuss and compare a wound electromagnet with a permanent magnet, e.g., to understand the enormous energy density or effective "amp-turns-per-meter" provided by a contemporary neodymium high-performance magnet. These studies can lead to more detailed and subtle analysis of the results of the material properties. For example, a magnet can experience eddy currents due to the conductivity of magnetic material, and these losses can be compared to the eddy currents and hysteresis losses in a laminated wound-field yoke.

The windings are shown on the surface of the rotor cylinder in Fig. 3. For new audiences, this configuration illustrates a practical example where the right-hand rule can predict the Lorentz force on the wires and therefore the torque of electromagnetic origin on the rotor. For more sophisticated students, we compare and contrast the wire configuration shown in Fig. 3 with the buried rotor wires similar to those on the starter motor in Fig. 1. For the "buried" wires, we have students solve or measure for the shielding effects of the rotor iron. This leads to an appreciation for the utility of the Maxwell stress tensor in computing traction on the rotor surface.

Using Fig. 3 and the right-hand rule, students can solve for the motor constant,

$$K = RNLB,$$

which, multiplied by the armature current $i_a = i$, is equal to the shaft torque of electromagnetic origin. Students also explore the generator constant, which is also equal to K, through a number of different possible experiments and calculations depending on their sophistication and the course material at hand. They may use field theory to solve Faraday's law and find the generator constant. They may also conduct experiments with an actual machine, measuring torque with a torque bar and weights, and comparing their motor constant to a generator constant measured by spinning the electrically unloaded machine and studying the change of the dependent back-EMF source with shaft speed. They may also learn about the equivalence of the motor and generator constant by balancing the mechanical shaft power and electrical port power for a permanent-magnet dc machine assuming that the machine is lossless (analytically) or by accounting for the losses (in the lab).

With the motor constant K in hand, students can begin to understand how the motor performance is affected by changes in key physical design variables like the rotor radius, number of active turns of wire, and the active length of the machine. This leads to a beginning understanding of rudimentary machine-sizing rules for different applications. They can learn that doubling the active length of the machine can approximately double the shaft horsepower, assuming that the machine can spin smoothly and continue to function with its given rotor material and bearing system. They see, for example, the equivalence in some respects between doubling machine length and having two identical machines with front and rear shaft connections joined together. They begin to understand the importance of mechanical and thermal details in the machine, e.g., that it is not sufficient to simply double the length or radius of a rotor to increase shaft torque. They learn that it is also necessary to be able to remove heat from a mechanically expanded system, and to support the system with smooth running bearings and a minimum of mechanical vibration.

A beginning understanding of the motor constant leads to many exciting lab and classroom experiments and demonstrations. For example, we challenge the students to develop a circuit model for a permanent-magnet brushed machine, and to use this model to understand the behavior of the machine driven by a voltage source versus a current source. Ignoring armature inductance, students at an early exposure to this material will begin to develop circuits like those shown in Figs. 4 and 5. The shafts in the machines illustrated in Figs. 4 and 5 can experience a load torque proportional to the product of shaft speed ω and a linear friction constant β.

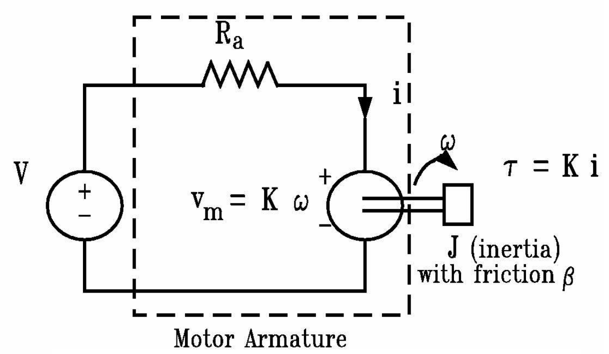

Figure 4: PM dc machine with voltage drive.

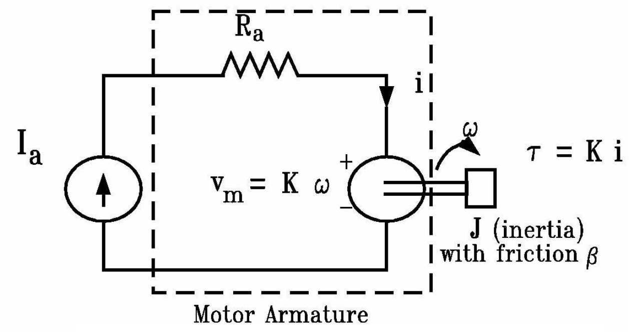

Figure 5: PM dc machine with current drive.

These circuits in Figs. 4 and 5 provide wonderful opportunities for understanding the limits of engineering approximation and for appreciating electromagnetic force and torque production. For example, we ask our students to energize a small dc machine in the laboratory with a fixed current of perhaps a quarter of an amp using a power supply configured as a current source (essentially Fig. 5). The power supply settles to whatever voltage is needed to drive the

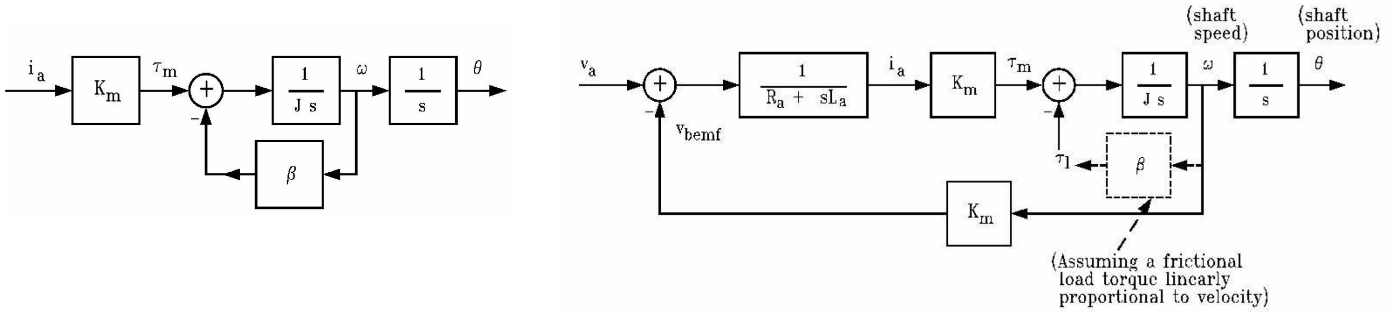

Figure 6: PM dc machine block diagrams: current drive (left), voltage drive (right).

machine with a quarter of an amp, e.g., 12 volts for a typical small gear-head motor in our lab. They learn that current "programs" shaft torque, which they can check with a shaft bar and weight, or by grabbing the shaft with their fingers at different current levels. Then, we ask them to energize the machine with a voltage-source power supply running at 12 volts, allowing the machine to settle to steady operation at a quarter of an amp (essentially Fig. 4, at the same nominal operating conditions as for the previous experiment with Fig. 5). Now, the students discover the inherent "feedback" loop present in the voltage-driven machine. When they grab the shaft, the machine slows fractionally. The back-emf drops, and the machine draws more current, "fighting" the student in a manner very different from the fixed torque felt in the Fig. 5 configuration.

In our introductory feedback class, we use this experience to motivate modeling the machine with block diagrams. Figure 6 shows typical student results. The block diagram on the left in Fig. 6 shows the model for a pm dc motor driven with a current source. There is no inherent feedback loop that regulates the shaft speed based on the input current. Specifically, a change in the friction constant β, e.g.., grabbing the shaft, perturbs the shaft speed. The block diagram on the right in Fig. 6, on the other hand, shows the model for the pm dc motor driven by a voltage source v_a (in this case, with armature inductance included). Changes in the friction constant are "buried" in a minor loop in the forward path of the machine model. The shaft speed is relatively insensitive to such changes if the motor is a "good" machine with relatively low armature impedance and, therefore, high "gain" in the forward path. This modeling reinforces the students' tactile experience with the machine in the lab, and motivates students by demonstrating the practical value of circuit solution and block diagram modeling.

We use this analysis and modeling to motivate "design and build" competitions at varying age levels and in varying courses and pedagogical venues. A friendly competition can be used to promote understanding by highlighting design "paradoxes" at various intellectual stages in the development of understanding about the dc machine. For example, in several classes, we challenge students to build a machine to match the specifications in the hand-held vacuum cleaner – a very difficult challenge rarely met in practice by students in the lab.

This machine spins at approximately 12,000 RPM (no load) from a 4.8 volt voltage source. At first, students attempting to design for high speed typically assume that they should design a motor with a **large** value for the motor constant, K. They reach this conclusion by assuming that "more K means more torque," and more torque should push the shaft to higher speeds. This assumption is flawed in our vacuum-cleaner-based competition, where the input to the motor is a voltage source. Students then typically "rediscover" the voltage source model, but often apply it hastily, assuming that the armature impedance is negligible and that the machine is essentially a shaft-dependent back-emf source. In this case, students may reach the conclusion that, since the armature voltage and back-emf should approximately equilibrate, K should be as **small** as possible to maximize speed. At this point, they may be thoroughly confused and they have the opportunity to carefully revisit the machine model in Figure 4, with realistic loss mechanisms in place, i.e., a finite armature resistance and a linear shaft friction. In this case, students can solve for the steady-state shaft speed, finding that, in steady state:

$$\omega = \frac{K\,V}{K^2 + R_a\,\beta}$$

This is an interesting equation that illustrates an "optimum" point typical for many simple engineering "trade-off" problems. For a given set of losses (electrical resistance and mechanical friction), there is a "sweet spot" that maximizes kinetic energy stored in the rotor with respect to loss mechanisms in steady state. This can be seen in a typical plot of steady-state speed versus K (for V = 4.8 volts, and an $R_a\beta$ product arbitrarily chosen to be unity for illustration) as shown in Fig. 7.

Figure 7 summarizes the pedagogical essence of a number of very exciting design competitions for students studying motors and other energy conversion systems. For any given challenge application, students must understand the meaning of the motor constant K and how the physical parameters of the machine affect K. The key parameters - rotor radius, active machine length, field strength, and number of active conductors - are not completely independent variables. The magnetic circuit of the machine is affected by the machine dimensions and the craft or skill that the students bring to assembling the machines. Many surprising and exciting competitions can occur when elements of craft and skill are mixed with a complete understanding of the basic physical principles behind the machine.

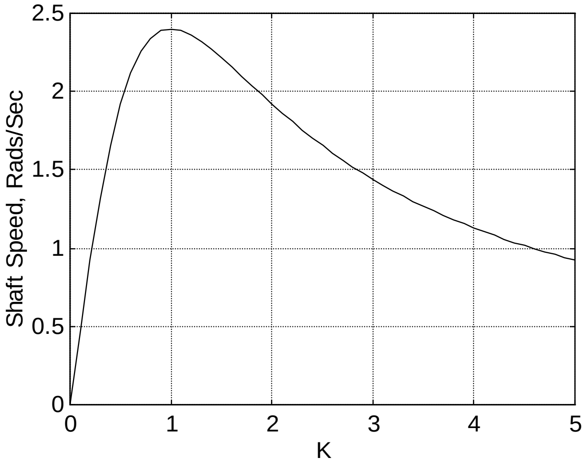

Figure 7: Steady-state speed versus machine constant K.

These design trade-offs vis-à-vis the machine constant K are not limited to competitions in which the students are actually designing the machine. We have used this analysis with students in other courses and majors, for example, in mechanical engineering. These students may be involved in classes where a fixed, known motor is bought for every student for some application under consideration in the course. Intriguingly, gear ratio, r, between the motor shaft and a wheel or other mechanical load affects K directly. That is, students can work with a new variable, $K_{mod} = rK$, and produce a plot just like Fig. 7 for steady-state speed versus K_{mod}.

In either case – motor design competitions, or product design competitions using a motor – students can be challenged to estimate the loss mechanisms in their systems based on experiments and intuition about what they plan to build mechanically and electrically. Given estimates of losses, they can select a wise choice of machine variables to produce a certain K, or a particular gear ratio, or both, to find the "sweet spot" or peak steady-state speed illustrated in a graph like that shown in Fig. 7.

We have used these ideas to develop teaching modules and engineering design competitions for students at almost every age level. Different student-built machines are shown, for example, in Figs. 8, 9, and 10. Figure 8 shows our local implementation of a commonly built "rotating dipole" machine design, popular in education kits and toys. The commutator is fashioned directly on the wire of the dipole by "half-stripping" the insulation on one of the wire pigtails. Figure 9 shows a more mechanically sophisticated machine, with a plexiglass rotor built by students in a two-day competition using a campus machine shop. For quicker exposures that still involve design variability and touching real tools, we have built a motor "erector set" kit, with a variety of different blocks and rotors, that students can use to assemble a motor of their choice within some design limitations. A typical example is shown in Figure 10.

The wire dipole motor is simple enough to make with children of almost all ages. We have taught a small introduction to motor building for 4 year olds, albeit with relatively little discussion of Maxwell's equations. The more sophisticated "shop-based" and "erector set" designs in Figs. 9 and 10 work very well with college students and graduate students studying a variety of different engineering disciplines. The analytical "pitch" and the instrumentation used to measure and compare experiments with design results varies depending on the level of student sophistication.

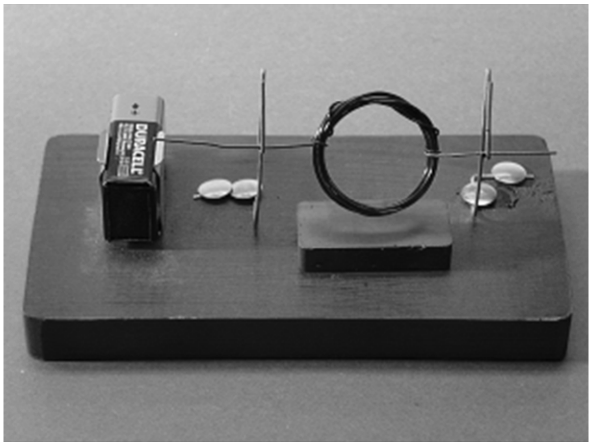

Figure 8: Wire dipole motor.

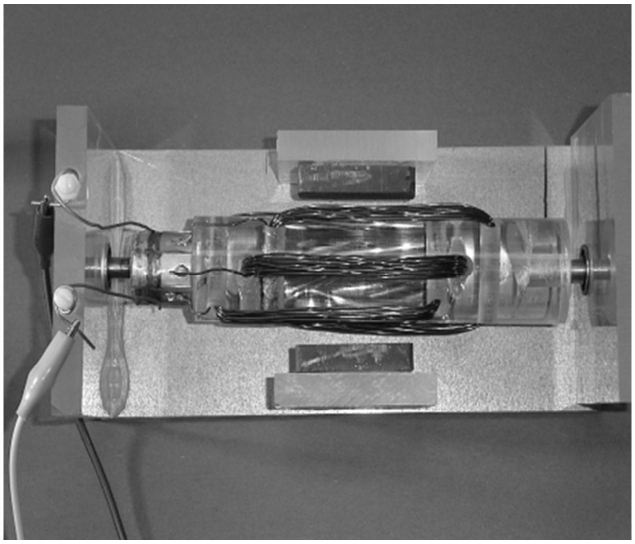

Figure 9: Plexiglass "shop day" motor.

Similar design competitions and the "hunt for the sweet spot" can be conducted even when the laboratory activity is not specifically a motor design problem. For example, we have conducted student seminars that challenged students to build an electric go-cart or small robot. In these cases, the choice of gear selection and the estimation of realistic loss mechanisms for the system at hand become paramount. Such problems still provide a strong introduction to engineering design and making trade-offs. An example of a go-cart for a competitive race built by one of our student teams is shown in Fig. 11.

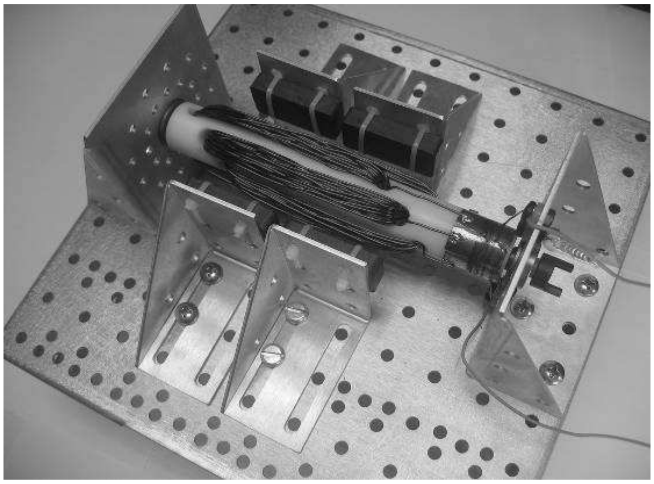

Figure 10: Motor "erector set".

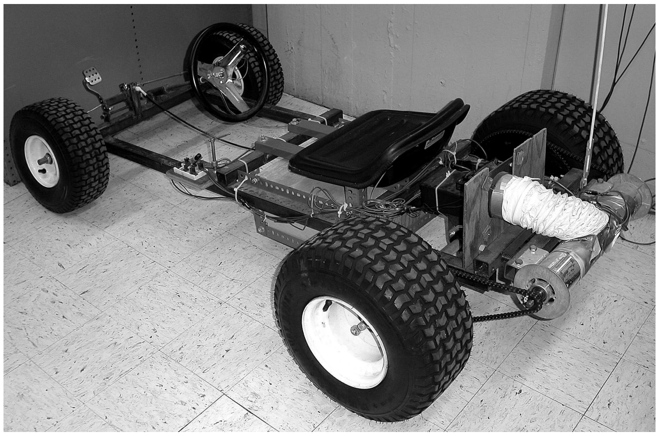

Figure 11: Electric go-cart built by a student team.

III. AC MACHINES

We have also developed a flexible, multi-use, 3-phase axial-flux machine suitable for laboratory instruction [1]. This machine permits many of the same kinds of design challenges, pedagogical opportunities, and possibilities for friendly student competitions described in the previous section. This machine is configurable as a permanent magnet (brushless dc) motor or as an induction machine. It would typically be used with a three-phase inverter built by our students as part of a power electronics laboratory. In some cases, e.g., an embedded control laboratory, we might provide part of the inverter, such as the three-MOSFET totem poles and gate drivers, while the students would provide the drive logic and control signals.

A desire for quick re-configurability led us to an axial-flux design, shown in the wire-frame diagram in Fig. 12. For example, one of the desired experimental setups for the induction machine involved the possibility of varying the thickness of the rotor conductor and also the machine air gap. With an axial-flux design, these quantities can be changed quickly by substituting rotor disks and altering the axial position of the rotors. The sides of the motor provide space to mount other electromechanical devices for interacting with the machine. For example, an encoder and a prime mover (a dc motor) can be added to the machine, permitting use as a controlled drive or as a generator. The rotors are double-sided, with a copper disk (for an induction machine) on one side and magnets (for a permanent magnet machine) on the other side. There is substantial space in the frame for additional expansion, e.g., a multi-rotor machine. Spacers can be inserted between the rotor disks and the Gramme-ring stator in order to control the air-gap dimension.

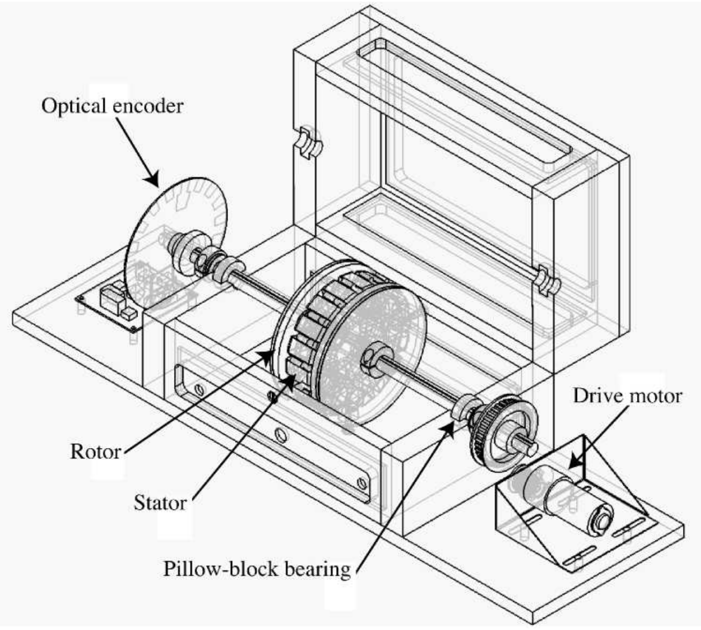

Figure 12: Experimental axial flux ac machine.

Figure 13 shows the ac machine in use in the laboratory. The Gramme ring in the center of the motor box is secured to the base of the motor. The steel disks are mechanically keyed to the shaft, which can turn freely on the bearings mounted in the box walls on the left and right sides of the picture. The machine is shown configured as an induction machine, with copper disks secured to the steel rotor backing. The steel disks can also be "flipped" to bring magnets and a steel magnetic circuit facing the Gramme-ring stator. Students may use the dc motor shown on the far right of Figure 13 to measure machine torque. We also give them a torque bar and spring scale in the laboratory to measure the static torque produced by the machine.

There are innumerable experiments that can be performed with the induction and pm machines that can be constructed using the experimental ac machine. We have challenged

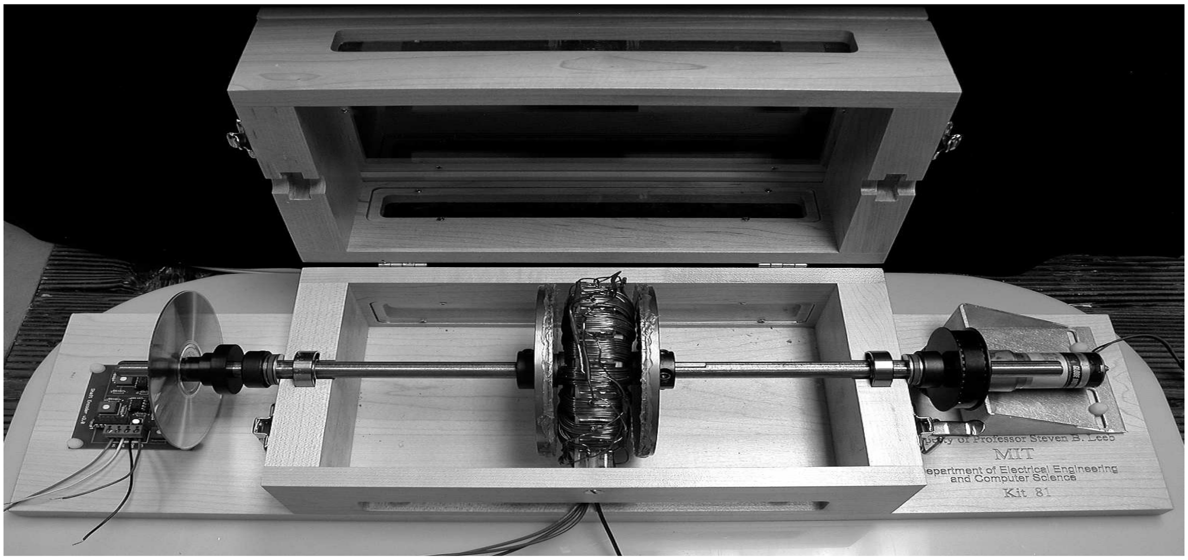

Figure 13: Experimental ac machine in the laboratory. A brushed dc prime mover can be connected on the right. A position encoder constructed by the students is shown on the left.

students to characterize the induction machine, for example, and to develop analytical and experimental torque-speed curves. We have posed lab experiments where we ask the students to lock the machine rotor and drive the machine with a variable-frequency, three-phase ac power supply. They measure the phase currents and line-to-neutral voltages applied to the machine in order to characterize a circuit model for the motor. For example, they might model the machine with a locked rotor and three-phase electrical excitation with the single-phase model shown in Figure 14.

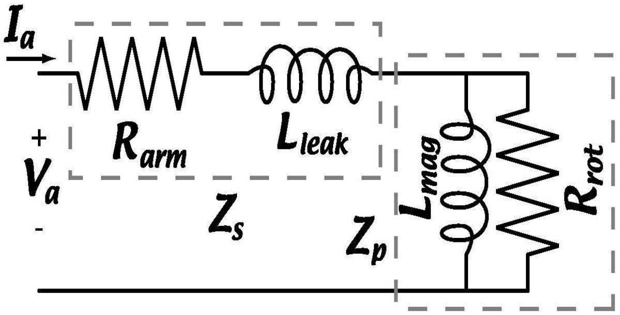

Figure 14: Induction machine phase model.

The circuit model shown in Fig. 14 has an input impedance

$$Z_{phase}(j\omega) = Z_s + Z_p = R_{arm} + j\omega L_{leak} + \frac{j\omega L_{mag} R_{rot}}{j\omega L_{mag} + R_{rot}}$$

With measurements of the phase current and line-to-neutral voltages at different electrical frequencies under locked rotor conditions, the students collect sufficient data from the experimental machine to use Matlab and this equation for input impedance to identify the machine parameters. With the empirically determined machine parameters in hand, they can compute a torque-speed curve for the machine and compare it against torque measurements made in the lab. They can also compare their empirically determined machine parameters against analytical predictions, opening the door to many interesting problem set problems on field theory associated with the machine geometry.

We have also challenged students to construct drives for the machine and operate it as either a pm or induction motor. A typical student-built, finite-state machine-based drive circuit for the motor is shown in Figure 15. In the case of the induction machine, the “speed clock” signal comes from a signal generator that effectively sets the synchronous speed. For the brushless pm configuration, the speed clock signal comes from the encoder on the ac machine. This effectively slaves the count of the finite state machine to the rotor position, creating a solid-state commutator for the motor. The counter (74LS163) and selector (74LS138) provide signals that are combined by appropriate logic circuitry to create a desired drive pattern. The 74LS00 NAND gates create a 120 degree conduction pattern in the circuit shown in Fig. 15. The 74LS08 AND gates add a PWM modulation to each phase voltage, thus providing amplitude control of the waveforms in addition to the frequency control offered by the speed clock signal. The output lines labeled G1, G2, and G3 drive the inputs drivers for the top three switches in a three-phase totem pole. The lines connected to the G4, G5, and G6 signals drive the complementary bottom switch in each totem leg, respectively.

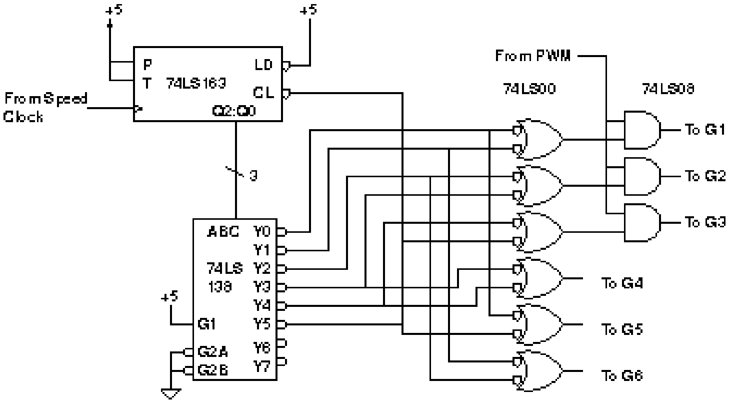

Figure 15: Finite state machine controller.

A partial schematic of a typical student-built inverter circuit for use with the ac machine is shown in Fig. 16. Each of the six MOSFETs in a three-phase inverter board built by the students is controlled or driven by an IR2125 gate driver from International Rectifier. The input lines for these gate drivers are provided by the G1 through G6 lines of the finite state machine shown in Fig. 15.

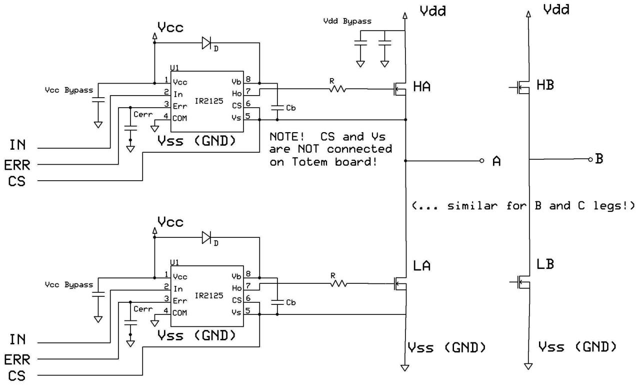

Figure 16: Partial schematic, three-phase inverter.

IV. CONCLUSION

We have found that electric machines offer tremendous hands-on teaching opportunities in our engineering courses. Of course, electric machines of all types are exciting examples for instruction in drives. They are also wonderful opportunities for providing hands-on examples for a large range of other important topics, including field theory, circuit analysis, feedback control, and embedded control design. The designs presented in this paper represent a more general approach of finding ways to make electric machinery accessible and easy to play with for students in the laboratory. These teaching machines are quick to use and configure, and they provide immediate and fascinating pedagogical feedback that can be tied directly to a wide variety of course material under study. We have also developed extensions of the ideas presented here for linear machines of all types and also for variable reluctance machines.

By adjusting the type of machine and the material under consideration, we have found motor and generator examples to be excellent teaching aids for almost any age group and for an enormous range of engineering topics.

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