Incorporating Electronic Motor Drives into the Existing Undergraduate Electric Energy Conversion Curriculum

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Abstract

Adjustable speed drives offer an opportunity to increase student interest and extend educational opportunities in undergraduate electromechanical energy conversion instruction. Industry is adopting drive systems for energy conservation, but there is a need for better understanding of drive behavior. In an electromechanical conversion course, opportunities to incorporate drive systems exist in the introductory portion, as individual machines are introduced, in the laboratory, and in the course closure. Capstone design is a feasible place for realistic machine-drive projects. Methods of incorporating topics are presented and tradeoffs are discussed.

Introduction

Not many years ago, the Adjustable Speed Drive (ASD) was just a specialized electronic system associated with direct current machinery. Now it seems that induction motors in many places have sprouted an ASD. The primary reason is the energy saving advantages, which are well documented.[1, 29] Since electric motors consume more than two-thirds of all electrical energy, [2] the market for ASDs will probably continue to expand.

The proliferation of the ASD in industry is a strong argument for introducing it to engineering students. If the student learns of the machine, then its increasingly common means of obtaining energy should be included. An energy conversion course is a logical place to learn both the machine and its drive system. Considering the drive system without the machine is difficult and awkward; on the other hand, considering the machine without the common industrial drive systems, considering the industrial landscape, is rather incomplete.

Teaching What Industry Uses

Electromechanical energy conversion has developed another important dimension with the advent of the (ASD) for alternating current machines. These drive systems have become ubiquitous in several local industries affecting students and graduates of the University of Idaho (UI): processing of dairy products[3], potatoes, sugar, lumber[4], specialized building construction, and semiconductor devices.[5] Of UI engineering students graduating in 1994 and entering industrial employment, fully 80% were required within six months to specify an ASD for their employer.[5] Most of these graduates told of colleagues and even competitors from a wide range of industries who had asked them for help in specifying ASD systems. The fact that ASD systems are still more expensive than the motors they drive makes this request of such junior people all the more significant.

Also of note is the lack of expertise in the utility industry. Many other utilities are playing a catch-up game to understand the ASD and its effects on the grid. Programs to teach field engineers are being developed in several utilities and short courses on ASDs are in demand in the field.[5]

Something New and Wonderful

There is a mistaken perception among students that there is nothing new in this field. This makes attracting students difficult. From perspective of one who teaches energy conversion, the advent of the ASD is a new and exciting opportunity. The ASD provides flexibility in teaching energy conversion that was heretofore difficult to obtain. It provides new challenges that require understanding of concepts and new developments from a range of disciplines, as will be explained in detail later in this paper.

In teaching energy conversion, fixed frequency ac sources have typically been the norm in most texts [6-14] and with most educational equipment manufacturers. Because nearly any reasonable combination of torque and speed is now available from the ASD-driven machine, a whole new range of teaching and experimental possibilities open up. Discussing machine behavior models under variable frequency and variable flux conditions is now reasonable and demonstrating this is quite feasible. Employing machines safely in student projects is no longer little more than an analog drive with a small dc motor; now analog and digital microelectronics, power electronic circuits and switching devices, control theory and practice, circuit protection, programming (assembly language or higher level languages), and signal processing complement a realistic ac machine project that students can tackle successfully.

Practical Ideas to Incorporate Drives

Philosophical arguments presented in the preceding discussion may encourage the use of electronic motor drive systems in electromechanical energy conversion instruction. But when an instructor considers the practical aspects of doing so, a number of difficulties become evident. Enrollment does not support adding a new course in drives, even as a special topics subject. Faculty and student resources for such a course, particularly time, are already committed. Such a course may be too specialized for most undergraduate curricula anyway. Therefore, this paper will not address developing a new course in electronic drive systems. For those wishing to do so, this author can provide the name and location of several who have developed successful electronic motor drives courses, at both undergraduate and graduate levels.

Nonetheless, within an existing curriculum that contains an electromechanical energy conversion course, a practical opportunity to incorporate electronic drives does exist. A twofold strategy presented in next few sections of this paper introduces electronic drive systems, both dc and ac, into the practical confines of an existing undergraduate program of instruction. First, drives are incorporated into the traditional machines or electromechanical energy conversion course. Second, adjustable speed drive systems make a rich senior design experience, drawing on a wide range of design issues and from such topics as machines, analog and digital microelectronics, power electronic circuits and devices, control theory and practice, circuit protection, programming (assembly language or higher level languages), and signal processing. The discussion begins with the energy conversion course, of which 72 existed in the United States at last count.[15]

Modifying the Energy Conversion Course

In an energy conversion course, at least four opportunities exist to incorporate adjustable speed motor drives: in the course introduction, in the study of individual machine types, in the laboratory exercises, and in the course finale.

At the UI's Boise Engineering Program, the energy conversion course begins with an overview of energy conversion applications. Interactive demonstrations include transformers, electromagnetic actuators, and various machines performing interesting tasks. For example, stepper motors give precise positioning, a synchronous machine generates electrical power, a series motor drives a hand drill on either dc or ac, an actuator staples papers, and an induction machine drives a variable speed fan. Here, the variable speed drive adds a dimension previously not practical. The convenience and energy savings of a variable speed induction motor driving a fan become quickly evident to engineering students, many of whom have recently finished their mandatory thermodynamics course. The purpose here is arouse curiosity about the adjustable speed drive (and the other machines, for that matter) in a simple demonstration using something familiar. The fact that the drive is relatively new technology with a host of interesting possibilities gets emphasized.

In the course introduction, sound and motion in the laboratory dominate the demonstrations. Videotape makes a nice supplement, showing such systems as a 250MW hydroelectric generator or a demonstration of a senior design project from the previous year or two.

In the study of dc machines, the relationship between voltage and speed appears in the fundamental relations and, therefore, in the problem sets. Often the student is asked to find a new steady state speed for a machine that has experiences a change in terminal voltage. The dc drive can be introduced here as one response to the question: how does voltage get reduced? Though the instructor may do it with a Variac and a few diodes, someone in industry uses a dc drive. With modern drive systems, the instructor can do so also. A variable voltage provided by a chopper circuit is a relatively simple introduction to converters. The concept of an ideal switch, the advantages of low losses from the chopper circuit (vice a linear voltage regulator), and the idea of an average (dc) voltage controllable through pulse width modulation are all apparent in this context. The behavior of the dc drive is close enough to ideal that an oscilloscope and voltmeter readily give very credible and demonstrable results. With a current probe, the filtering action that smoothes the armature current becomes readily apparent. The dc machine can be considered as a single pole filter (and the armature circuit has a much greater bandwidth than the field circuit). A simple transfer function and frequency response curve that follows nearly by inspection make a nice concurrent review of some signal processing concepts. (That, by the way, is the secret of teaching drives in an energy conversion course--introducing and using them concurrently with other instruction.)

Using a dc drive does not significantly extend the range of steady state dc machine concepts that can be taught, but it does make the instruction more credible because the equipment is obviously new and programmable. In the time typically allotted to an introductory dc machines coverage, this is about all the depth obtainable. To make some time for this presentation, this author reduces coverage of the shunt machine. The student will encounter far more separately excited machines with a dc drives than shunt machines. Hence, the shunt machine appears as a special case of the separately excited machine, usually in a homework problem.

At UI, ac drives appear concurrently in the induction machine instruction. Because most texts present synchronous machines as generators and induction machine as motors, teaching drives with induction motors is the more convenient means.

The six switch voltage source inverter, with ideal switches, follows nicely from the chopper presentation for the dc machine. Each switch connects the dc bus to either the high or low voltage. Students quickly trace through a standard switching sequence to derive a six-step waveform. Seeing this waveform, after having just seen three phase voltages applied to induction machines, efficiently reveals the first concepts of how an ac drive works. It is then an easy step to bring in Pulse Width Modulation (PWM), as an extension of duty cycle modulation, to reduce the low-order harmonic content. Mohan presents a nice introductory discussion of PWM generation, particularly the most popular method, sine-triangle modulation.[29]

The real advantage of the ac drive is the greatly enhanced variable speed capacity it gives to the machine. Textbook induction motor instruction is locked to line frequency. Machine analysis occurs within a narrow speed range. Speed control, if discussed at all, consists of varying either terminal voltage or rotor resistance. However, speed control by variable frequency input opens a whole new dimension. Now the machine can be operated at full flux at every speed. By generating families of curves (torque, speed, efficiency, etc.), the flexibility of even an open loop adjustable speed drive becomes obvious. Reprising the example of the variable speed fan application from the course introduction, with attendant energy savings, strongly reinforces the operation and advantages of the ASD.

Induction machine concepts can also be taught (or reviewed) using some common features of an adjustable speed drive. For example, slip compensation reinforces the notion of how small the slip usually is, showing how accurate a speed estimate can be, computed from current readings available on many open-loop ASDs. A discussion of starting behavior introduces the benefits of setting the acceleration rate, a feature common on most ASDs, and its effect on current amplitude. Finally, a shift in the equivalent circuit, explained by Lipo and Novotny in [22] separates torque and flux components of the current, showing how controlling each separately gives performance understandable in dc drive terms. By covering induction machines last in the course, this treatment provides a nice closure.

There is rarely time to cover such advanced topics as field orientation in an introductory course, but everything else discussed above can be introduced in a couple lessons. Most texts are dropping coverage of salient machines, so some room appears there. The drive is a more convenient means of explaining speed control, particularly if adjusting the Volts/Hertz is considered an option. (Voltage control of speed can be presented as a special case of Volts/Hertz control, saving valuable course time.) Using the drive to help explain starting behavior, rather than such methods as line start, successive removal of series impedance, or an autotransformer-based starter, still gives a realistic treatment of the topic within the same time allotted. (The line start and autotransformer start are special cases of the controlled acceleration, controlled Volts/Hertz start.) Another place to find additional time is to eliminate duplication in the course prerequisite topics. An example of this is the treatment of transformers in the prerequisite circuits course: a whole lesson may be freed by a decision to start from the ideal transformer model already covered in a circuits course, rather than from scratch.

Having a drive and a small machine in class makes it easier to introduce these concepts. Small drives are readily available from manufacturers and easy to use in class. Many manufacturers will donate a small drive to a university upon request. Both our drives, ac and dc, and their attendant machines were a generous donation arranged through an alumnus at Baldor Electric Company.

Laboratory Exercise Modification

In the laboratory, the ac drive complements an induction motor investigation nicely, opening a new dimension for experiments. Typical induction motor experiments include taking a torque-speed curve and observing efficiency, power factor, and slip behavior. If the drive supplies the motor throughout the experiment, observing the same quantities, but at a reduced frequency requires merely a software input, not a circuit rebuild. In other words, the student observes behavior at full voltage and frequency, than at reduced voltage and frequency (constant Volts/Hertz case), and finally at reduced voltage but full frequency (reduced flux case), all with the same circuit. Most drives have an LCD display menu, so these experiments are easy to set up, but do requires some time invested to understand the menu organization.

Many dc drives do have a controlled torque mode, which is useful as a load. In other words, a controlled torque load can be realized by building the M-G set of the 90s: an induction motor and its drive in controlled speed mode coupled at the motor shaft to a dc generator and its drive in controlled torque mode.

Speed control by rotor resistance variation may also be done for comparison. The superiority of a drive to resistance variation for speed control becomes obvious in this experiment, both in terms of how the system behaves and in what we can demonstrate conveniently by experiment.

Mathematical simulation accompanies the laboratory experiments. By looping about the operating frequency, but keeping constant Volts/Hertz, a family of torque, efficiency, and power factor curves can be generated as a function of speed in little more time than it takes to find the nominal frequency case of each. Varying only voltage leads to curves for the reduced flux case. Details of this are presented in [24].

Capstone Design Project

In recent years, power electronic drive systems have changed the application environment for electric machines radically. Design is no solely longer the domain of the machine designer, who works exclusively in iron and copper. Rather, a machine-drive system draws from the resources of several disciplines, for example: the circuit designer, the builder using silicon, the digital control expert, and the circuit protection specialist. Requiring teamwork from people having such a range of expertise makes a variable speed drive system a useful candidate for an undergraduate capstone design project: This project has elements of several disciplines and it fits nicely into the demands of industry for team design work experience for anyone they hire. A variable speed drive project is well within the capability of a typical group of undergraduate electrical engineering students.

A reasonable request for proposal specifies that the drive system should have a simple topology, it should exhibit variable speed, open loop control, it should drive a 2 hp induction motor, it should have negligible harmonic motor current content, and, for simple laboratory safety reasons, it should have galvanic isolation. The student design team ordinarily chooses a conventional DC link Voltage Source Inverter topology for the host of reasons that make it the commercial topology of choice for a drive of this size. The rectifier is the common six-diode bridge circuit and the inverter is the well-known six-switch inverter bridge. These simple, common circuits appear in most of this paper's references and there is a nice explanation in several of them, including [16] and [29].

The Intel 80C196MD microcontroller determines the appropriate switching state of the inverter. This microcontroller has important on-board resources that significantly reduce the time and expertise necessary to design and program an ac motor drive system. These include a PWM generator, several analog-to-digital input channels, analog and digital outputs, on-board memory including a half period sine table, and programmable timers. The design team incorporates these features into microcontroller-based control scheme that achieves successful operation of the ac motor drive.

Extensive circuit protection is not part of the request for proposal.   In a student project, this could be reduced for time and cost reasons. Nonetheless, one student on the design team may have an interest in investigating circuit protection and incorporated this into the design proposal. The existence of this option in the project gives insight into the inherent flexibility of building an ac drive as an open-ended design project.

Equipment donations from industry covers the lion's share of the cost. Purchased parts amount to less than $600 and included for switching devices (Insulated Gate Bipolar Transistors (IGBTs) and diodes), contactors, an isolation transformer, and optoisolators.   Many of these parts would be in stock in established schools; our school is but three years old.

The project is quite flexible, with a wide range of options. For an initial project, the simple goal of getting the motor to turn safely may be sufficient. Ideas for subsequent projects are given in [35], as is a more complete report on an ASD design project completed at UI. Due to the wide range of disciplines necessary to complete the design, it makes a nice team project, one that generates a lot of excitement.

Reference List

To aid in preparation, a reference list is provided at the end of this paper. The first group includes machines texts with a portion devoted to drives issues [6-14]. Of these, Slemon's text [7] has the most extensive presentation; others have a chapter or less. From the publication dates, it is obvious that writing a machines text with a drives chapter is a relatively new thing. At the UI-Boise, we use Sarma's text.[10] The second group are drives texts [16-23], which provide depth of discussion on drives topics alone. Of these, Murphy and Turnbull's book[19] provides a nice reference to the classical professional literature in the field. The final group [25-34] are power electronics texts that address drives in varying depth, normally a chapter or less.

Conclusion

An energy conversion curriculum should address electronic motor drive systems. Drive systems have become an increasingly familiar item in industry and offer a flexibility in teaching machines that was previously difficult to obtain. Adjustable speed drives provide opportunities for review and application of concepts from a host of disciplines, an exciting opportunity to attract students and dispel the myth that nothing new is happening in the field of energy conversion.

Practical methods to incorporate electronic drive systems into the existing energy conversion curriculum include the following: an interest-builder at the beginning of the course, a practical means of introducing high-performance dc machines and servo systems, improved understanding of the induction machine through practical speed control, and more flexible laboratory investigation opportunities. Emphasis in this paper is on working within the existing curriculum; suggestions are presented about how to modify the curriculum to accommodate these ideas. Capstone design projects also present an expanded opportunity for marrying a variety of subjects to energy conversion in a group setting. The advent of the adjustable speed drive presents a wonderful opportunity for increased excitement in the teaching of electromechanical energy conversion.

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