The Present and Future Energy Conversion Course and Laboratory at the University of Alaska Fairbanks

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ABSTRACT: All undergraduate electrical engineering (EE) students are required to complete an energy conversion course at the University of Alaska Fairbanks (UAF). It is a 4-credit, one-semester course with a weekly three-hour laboratory which encourages a strong hands-on experimental component. This somewhat unique degree requirement exists because a graduate may find that she or he is the only electrical engineer within several hundred miles of a remote job site and may be expected to solve unanticipated problems outside normal areas of expertise. This paper describes the present configuration of the UAF energy conversion course and plans for future modifications. Future changes include replacing drives and motors used in laboratory exercises with more modern units, introducing Finite Element Analysis as a flux path, flux density, and saturation visualization tool, and offering an introduction to the analysis of ac machines driven by non-sinusoidal excitation. This will provide students with the background needed to understand machine performance when inverter drives are utilized.

1. INTRODUCTION

The four-year undergraduate electrical engineering program at UAF continues to satisfy the Accreditation Board for Engineering and Technology (ABET) accreditation requirements. Electrical engineering courses begin in the second semester of the program with an introduction to circuit analysis and characteristics of primarily passive devices. The third and fourth semesters each include a four-credit course with a weekly three-hour laboratory covering network analysis, analog and digital electronics, and an introduction to energy conversion. The fifth and sixth semesters include, as required courses, three-credit courses in circuit theory and signal analysis, two four-credit courses in physical electronics and electronic circuit design, each of which includes a weekly three-hour laboratory, and a four-credit automatic control systems course. Electric power option students enroll in the energy conversion course described in this paper in their fifth semester. Communications option and computer engineering option students take the energy conversion course during their seventh semester in the BS degree program.

2. THE PRESENT ENERGY CONVERSION COURSE AT UAF

The present energy conversion course, required of all undergraduate EE students, is a four-credit, one-semester course with a weekly three-hour laboratory which encourages a strong hands-on experimental component. This is particularly important because many students, particularly those in the non-power options (communications and computer engineering), are initially uneasy working with high voltage/high current equipment. There is a broad spectrum of laboratory machines ranging from small Faraday's Law Machine Laboratory and Feedback, Inc. dissectable machines, to 25 horsepower units. The course encompasses magnetic circuits, transformers, introductory power electronics, dc machines, three-phase synchronous machines, three-phase induction machines, single-phase induction motors, and special machines such as universal, reluctance, hysteresis, and stepper motors. There are currently twelve three-hour laboratory exercises: (1) magnetic flux measurements in magnetic circuits using a Gaussmeter, (2) qualitative measurements of transformer excitation current and its magnetizing component, and magnetizing flux, (3) determination of transformer parameters using open circuit and short circuit tests, (4) measurement and calculation of all voltage and current magnitudes and phase angles associated with an open-Y open-delta transformer, (5) use of wattmeters to measure real power and reactive volt-amperes supplied to a balanced three-phase, three-wire load, (6) dc generators, (7) dc motors, (8) three-phase synchronous generator, (9) determination of synchronous generator model parameters, (10) synchronous motor V-curves, (11) synchronous generator synchronization to a large power system, and (12) measurement of a complete induction motor torque/speed characteristic. Laboratory reports are required from each student for each laboratory exercise and are graded on English grammar and style as well as on technical content.

2.a. Laboratory exercise details

Laboratory 1: Air core coils are available for measurement of axial magnetic flux density using a Gaussmeter probe inserted between windings. Inductance is also measured using a RLC impedance meter and this measurement is compared with empirical formulas for calculating inductance. Inductances of toroidal windings with plastic and ferrite cores having the same dimensions are measured and calculated. Students are asked to determine relative permeability of the ferrite material from inductance measurements. A three-legged transformer core with a removable I-shaped part and removable coils is used to allow students to measure flux density in the air gaps between the E- and I-shaped parts of the core. Inductance of the coil and core combination is measured and estimated. Finally, the magnetic flux density of a large U-shaped permanent magnet is measured at several different points relative to the magnet.

Laboratory 2: One winding of a multi-winding single phase transformer is supplied by an adjustable magnitude 60 Hz ac source. Excitation voltage and current are viewed on an oscilloscope. A second winding is used with the first to provide a voltage proportional to the magnetizing component of the excitation current. An RC integrator is used with a third winding to provide a voltage proportional to magnetizing flux.

Laboratory 3: Single phase transformer equivalent circuit parameters are measured by use of standard short-circuit and open-circuit tests. In each test, current, voltage and real power are the measured quantities. Students then must determine the impedance magnitude and angle and real and imaginary components and relate them to the equivalent circuit. This laboratory is also valuable in showing the need for and appropriateness of ignoring shunt impedances for the short circuit test and ignoring series impedances for the open circuit test. It gives students a much clearer picture of transformers than just providing an equivalent circuit on paper.

Laboratory 4: All voltage and current magnitudes and phase angles are measured and compared with calculated values for an open-Y, open-delta transformer bank using either a resistive-capacitive or a resistive-inductive load. This exercise shows that developing three-phase voltages and currents are possible from two existing phases without the need for the third phase in the primary side of the transformers. It also shows that a significant neutral return current will flow in the primary (open-Y) side of this configuration. An accurate phase meter is essential for obtaining data that correspond well to calculated quantities. This laboratory exercise also shows the validity of balancing ampere-turns of magnetically coupled pairs of windings and relating primary and secondary voltages of those windings through turns ratios and dot conventions.

Laboratory 5: Three wattmeters are used to measure total real power and reactive volt-amperes in a balanced three-phase three-wire resistive-inductive load. This is an interesting and practical application of the use of wattmeters because it is not immediately obvious to students that a wattmeter is able to determine reactive volt-amperes with the proper connection. Wattmeter 1 has phase A to phase B voltage and phase A line current as inputs. Wattmeter 2 has phase C to phase B voltage and phase C line current as inputs. Wattmeter 3 has phase C to phase A voltage and phase B line current as inputs. The sum of the readings of wattmeters 1 and 2 is the total three phase power. The total three phase reactive volt-ampere load is the square root of 3 multiplied by the reading of wattmeter 3. Students are required to measure the magnitudes and phase angles of all voltages and calculate these quantities using measured values of R, L, and line to line voltages. Students are also asked to measure the floating neutral voltage of the load with respect to the four-wire power source neutral and explain the result of their measurement. This laboratory requires an accurate phase meter and impedance meter.

Laboratory 6: The properties of a dc generator, its magnetization curve, and the effects of a shunt (main) field and a series field on generator volt-ampere characteristics are studied. Separately excited, separately excited cumulative compound, separately excited differential compound, and self excited or “long-shunt” cumulative compound connections are experimentally investigated.

Laboratory 7: A dc motor is directly coupled to a dc generator which is used to load the motor. A starting box separates the dc motor from the dc voltage source. Two sets of data are taken; the first at 1250 revolutions/minute (rpm) at no load, and the second at 1650 rpm at no load. In the first case, the motor is operated as a simple shunt machine and then as a cumulative compound and finally as a differential compound machine. Shaft speeds as functions of loading are plotted. At the higher speed case, the same data are taken. However, the differential compound configuration is now unstable, and the students experience what happens when a dc motor begins to accelerate uncontrollably. Ammeters are protected with shunt switches for this case and the motor is shut off before the speed becomes too high. Finally, a resistance is placed in parallel with the differential compound winding to make this case stable. Students seem to really remember the unstable aspect of this laboratory. It makes the possibility of dc motor runaway much more real to them.

Laboratory 8: A three-phase synchronous generator has six coils and 12 coil terminals brought to a terminal board. Students are asked to determine the pairs of terminals which correspond to individual windings using an ohmmeter. Secondly, they are asked to provide enough dc current excitation to the rotor field winding so that approximately 10 V appears across each coil. A phasemeter is then used to find the relative phase angles of all coil voltages. The students determine how the coils are to be connected to provide a 208 V (line to line) Y-connected, three-phase, four-wire output. Finally, a resistive load is attached to the generator and load voltage is measured as a function of load current.

Laboratory 9: Synchronous generator model parameters are determined by open circuit and short circuit tests, and by direct measurement of armature winding resistance and field inductance. The short circuit ratio is calculated.

Laboratory 10: Synchronous motor V-curves are determined for no-load, one-half load, and full-load conditions. A dc generator is used as a load. It is particularly interesting for the students to observe the angle between phase voltage and phase current of the armature of the synchronous motor as field dc excitation current is changed. A strobe light is used to observe the change in rotor angle as mechanical load is modified.

Laboratory 11: A synchronous generator driven by a dc motor is synchronized and connected to the local power system. It is instructive to note what happens to the synchronizing lights if the phase sequence of the generator is not the same as that of the power system. Data are taken for the following cases: (1) current, real power, and reactive volt-amperes (vars) to the generator load (power system) are zero, (2) real power from the generator is non-zero and vars are zero, and (3) the generator is underexcited and overexcited so that the phase angle between generator output line to neutral voltage and line current ranges between approximately $+45^{o}$ and -45^{o}. This laboratory shows the effects of changing synchronous generator shaft torque and excitation on its output.

Laboratory 12: An induction motor torque-speed characteristic is experimentally determined using dissectable machines laboratory components. Using feedback, a motor load unit allows the complete torque-speed characteristic to be determined, including the positive slope region that is normally unstable. This laboratory not only enhances student acceptance of induction motor characteristics, but is also an instructive application of feedback whereby load torque can be made proportional to shaft speed, independent of shaft speed, or a composite of these two characteristics. It further shows that if a load torque-speed characteristic has a greater positive slope than the motor torque-speed characteristic at the point of intersection of the two characteristics, the resulting system is stable, even though the motor would be in an unstable operating range if it were running under no-load conditions.

3. FUTURE PLANNED MODIFICATIONS

The department is currently purchasing modern solid-state soft ac motor starters, variable torque/variable speed ac motor/drive/load packages, and permanent magnet dc motors with speed controllers and loads to upgrade those areas of the laboratory experience. We are also considering the following course modifications: (a) introduction of Finite Element Analysis (FEA) to visualize flux paths, flux density and saturation, and (b) analysis of ac motors with non-sinusoidal excitation (six step and pulse width-modulated inverters). A discussion of these additions follows.

a). The use of a finite element analysis program allows students to view flux densities, flux paths and saturation within an electric machine. Since most students have been introduced to field theory by their junior year, the concept of viewing an electric machine as a distributed parameter system should be a logical extension of material previously studied. The focus of this exercise is on visualization as opposed to problem formulation. Due to the mathematical nature of the problem, it would be inappropriate to concentrate on the solution of the two-dimensional Poisson equation since most students have not taken a formal course in partial differential equations. The proposed exercise would be constructed from problems previously solved by the instructor so that students would adjust values of input variables and graphically view the results. The devices examined could be as primitive as a horseshoe magnet or as complicated as a switched reluctance machine. Since most departments do not own FEA software for magnetic analysis and most commercial software of this type costs several thousand dollars, the initial expense may be prohibitive. To circumvent this problem, freely available software named MagSolve, developed at the University of Dublin, is expected to be used and is available for the Sun SPARC and the Linux-INTEL platforms. The authors have found MagSolve to be reasonably accurate and easy to use. This software may be retrieved from http://elecmag3.ucd.ie .

b). An introduction to the analysis of ac machines driven by non-sinusoidal excitation provides students with the background to understand machine performance when inverter drives are utilized. With the market share of adjustable speed ac drives increasing annually, the need to educate students about the effects of such drives on power systems and motors becomes increasingly important. The single frequency performance of ac induction machines appears in most undergraduate textbooks but little attention is given to multi-frequency excitation. The standard presentation of ac induction machines begins with the mathematical development of the rotating magnetic field which leads to the presentation of the equivalent circuit from which expressions for motor performance are derived. By including a discussion of effects of harmonics on air gap magnetomotive force and the resultant harmonic equivalent circuits, the student will be exposed to a generalized case which can be easily reduced to the single frequency model.

4. CONCLUSIONS

The energy conversion course at UAF emphasizes practical hands-on instruction while maintaining the mathematical foundation of electric machine theory. Modern motors and drives are currently being purchased to upgrade the laboratory experience in these important areas. The introduction of FEA not only allows the visualization of magnetic fields, but provides an example of the relationship between field theory and electric machines. Finally, introducing the analysis of ac machines excited by non-sinusoidal inputs will provide an understanding of machine performance when inverter drives are used. This will also give an excellent opportunity to emphasize the importance of harmonics in describing periodic non-sinusoidal waveforms as well as power quality issues.

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