Design and close loop control in the electromechanical energy conversion course

Margaret G. Wismer, Bucknell University, Lewisburg, PA 17837

Abstract

Electromechanical energy conversion is currently a required senior year course at Bucknell University. The course has been revamped over the past several years in order to reinterest students and give them a greater appreciation of power systems, power electronics, machine drives and feedback systems. The course is design and experiment oriented and include several multiweek projects in which students have the opportunity and responsibility to execute a design, evaluation and redesign of a power system. The first third of the course provides students with a formal introduction to the definitions and types of power (active and reactive), three phase circuits and transformers. The final two thirds introduces generators and motors and controllers. The general order of the topics is DC generators, voltage regulators for the generators, DC motor, speed controllers, AC gener a tor, AC voltage regulator, AC motor and AC motor controllers. There is a weekly lab which is closely tied to the lecture material. Specifically the labs include three phase circuit design, transformer characterization, generator voltage controller design, and motor speed controller. In order to complete the labs on generator control, students need to know about pulse width modulation (PWM) circuits and feedback systems. While DC generators may not be the most likely machine a practicing engineer will encounter, it is felt that they provide students with a simpler introduction to machines and controllers as compared to AC or DC motors. The topic of DC generator voltage control leads naturally to DC motor speed control, AC generator voltage control and finally AC motor speed control. Recent student surveys indicate that they are satisfied with the course and that they have a grasp of the material.

1 Introduction

The typical electrical engineering course in electric rotating machinery and energy conversion has been reconsidered over the past 20 years due to waning student interest and the maturation of the subject. While at some schools the course has been squeezed out of the curriculum, at many institutions the course has been overhauled and updated in order to tap into student interests in clean energy, distributed generation, electric vehicles and to satisfy employers' needs for knowledgeable people in power electronics, electric drives and power systems. Examples of how this course has been restructered and "modernized" are given in [1]-[3]. By all accounts students are responding to these new formats and in particular the University of Minnesota has reported noteworthy increases in the numbers of students enrolled in their power engineering electives[3].

At Bucknell University the electromechanical energy course has also changed. Since its the only in depth exposure most students receive in many aspects of electric power it has evolved to include many topics such as definitions of power, three phase circuits, transformer modelling, modelling of generators and motors and control of motors and generators. One course naturally cannot cover all aspects of electric power and electric machinery. At

Bucknell the electric power required course can be viewed as a "focussed survey" course in which two to three weeks are spent discussing applicable topics. The 14 week course is taken by first semester seniors and this allows the instructor to draw on the students' knowledge of electronics, electromagnetics, linear systems, microcontrollers and control systems in introducing topics. The course includes a weekly three hour lab which now is more design–oriented and which is tightly linked to the material presented in lecture. Because of the complexity of the tasks all but the first 2 labs require more than one lab period to complete, and students (in groups of two) are usually allowed 3 to 4 weeks to design, build and test their systems.

Generally the course is split in two halves in which the first half covers basic definitions of power, power factor, etc., as well as three phase circuits, transformers and three phase transformers. Faraday's law is covered briefly to aid with the physical explanation of transformers. Faraday's law is also used to introduce the concepts of electromechanical devices which is the topic for the second half of the course. For transformers, covered in the first half, and motors/generators, covered in the second half, emphasis is placed on developing and using equivalent circuits over energy balance principles. DC generators and voltage regulators for generators are covered then DC motors and motor controllers, followed by AC generators and AC generator regulators. One of the labs requires them to design and build a feedback controller for a 1/4hp DC generator. In short they create an error signal and use this signal to control the voltage across the field winding via a PWM circuit. This is the second to the last lab in the course and while it requires several weeks to cover this topic and complete the lab its been found that once they've completed it, they are better able to understand the follow up topics of speed control and AC machines.

Currently the textbook for this course is "Electrical Machines, Drives and Power Systems" by Theodore Wildi[4]. Although this book includes the broad range of topics covered by the course, it does not cover them to the depth desired by the instructor. It also does not include any information on feedback control. Supplemental material is available via the course URL at *www.eg.bucknell.edu/˜wismer/ee491.* Although students are doing feedback control, system dynamics and transients are not covered in this course. The controller designs are based on steady state characteristics. Students take a concurrent course in control systems in which they discuss issues of stability and response times.

2 Course outcomes

In light of the new ABET criteria, specific course outcomes are designated as follows:

- be able measure electrical power, efficiency, voltage regulation and power factor in circuits which use at least 20W of power.
- be able to determine whether it would be economically advantageous to correct power factor in circuits with low power factor.
- be able to analyze balanced and unbalanced three phase ciruits connected in both delta and wye.

- be able to design and implement a simple 3-phase system with generator, transformers and load.
- be able to simulate, on PSPice, a simple 3-phase circuit.
- be able to determine the equivalent circuit model for a transformer.
- be able to analyze circuits with non-ideal tranformers to determine efficiency and voltage regulation.
- be able to simulate circuits, on PSpice, with non-ideal transformers to determine circuit efficiency and voltage regulation.
- be able to analyze DC generator circuits, determine generator equivalent circuits and use generator equivalent circuits.
- be able to design and build a control circuit for a 100W generator to regulate the output voltage.
- be able to analyze power electronic switching circuits which use PWM signals.
- be able to analyze the equivalent circuit of a DC motor to determine efficiency and speed regulation.
- be able to analyze the equivalent circuit of a synchronous generator to determine operating parameters.
- be able to formulate meaningful answers to open-ended, ill-defined problems in electric power circuits.
- be able to appreciate how relevant the topic of electric power is in an advanced technical society (such as ours.)

Each of these course outcomes is mapped directly into at least one exam question, quiz problem, homework problem or lab assignment. Furthermore the students are asked at the end of the course about whether they felt they have achieved these outcomes.

3 Course outline

Approximately 2 weeks are spent on each topic which are covered in the following order:

- Definitions of power, active and reactive power, power factor, power factor correction.
- Three phase circuits, wye and delta loads, simple unbalanced loads, three phase ideal transformer circuits.
- Faraday's law as it relates to non–ideal transformers, equivalent circuits of non–ideal transformers, voltage regulation and efficiency of transformers.

- Faraday's law as it relates to voltage and torque generation, basic commutator, DC generator equivalent circuits.
- Analysis of DC generator circuit for voltage regulation and efficiency, separate and self excitation.
- Basic PWM switching circuit, field control for automatic voltage regulation of DC generator, derivation of steady state close loop gain, design of feedback controller for the DC generator (based on steady state operation.)
- Analysis of DC motor circuit for speed regulation and efficiency, basics of speed control.
- Analysis of automatic speed controller for a DC motor, derivation of close loop gain.
- AC synchronous generators and equivalent circuit, power factor angle, torque angle, number of poles, voltage regulation, briefly cover feedback control of AC generators based on knowledge of DC generator control.
- AC synchronous motors and speed control of AC motors (as time permits)

4 Lab experiments

There is a weekly 3 hour in which experiments are closely linked to material covered in lecture. There are five lab stations each of which contains, an AC and DC machine, resistor, inductor and capacitor load banks, an assortment of instrumentation and PC's running PSpice, MATLAB, Borland C++ and Benchlink. Students usually work together in teams of 2 although for one of the labs the 4 or 5 groups per section must work together to complete the lab. The lab handouts are purposely sparsely written and do not contain step–by–step procedures. Students are forced to consider what procedures they must do to achieve the lab objective and may even need to consult the textbook. There are 6 labs as follows:

1. Lab 1: Students are given a small black box with 2 input terminals and 2 output terminals. They are instructed to connect a 100V AC voltage across the input and a lightbulb across the output. They must decide what measurements are needed to determine overall efficiency and voltage regulation. To do this they must consider things like power factor, input and output voltage and current. Based on all their measurements and calculations they are then asked to conjecture about what might be in the box. This is a one week lab.

   Lab 1 outcome: In this lab students are required to design an experiment to test a system rather than design the systems. They are forced to think about power factor and how it affects power measurements. With the instruments available they must display on the scope the input voltage and current. They will often question why the input current is so much smaller than the output current and wonder if this actually makes sense. The box contains a transformer.

2. Lab 2: This is a one week lab in which students become acquainted with a DC and an AC rotating machine. They must mechanically couple the two machines and then run the DC machine as a motor to produce a 3 phase AC voltage. They must display all 3 phases on their oscilliscopes. They run the AC machine as a motor to run the DC generator and produce a DC voltage out. They take basic measurements on the generator such as armature voltage and excitation current. They are also asked to determine the Thévenin equivalent for the armature of the DC generator.

   Lab 2 outcome: Students become comfortable running the machines and being energy producers. They inevitably become accustomed to the idea that they must provide an excitation current in order to produce an output voltage. They are always charmed by seeing a three-phase voltage on their scopes and they are introduced to the concepts of a machine equivalent circuits via their existing knowledge of Thévenin equivalents.

3. Lab 3: This is a multi week (usually 3) in which students work with 3 phase circuits. Now that they are power producers they are asked to design a 3 phase circuit to meet certain specifications. There are usually 4 or 5 groups per lab section and each group must do one of the following:

   - Design, build and test a 3–phase circuit with a load which draws 120Watts at 0.895PF lagging.
   - Design, build and test a 3–phase circuit with a load which draws a line current of 0.2A and 33.7° behind the phase current.
   - Design, build and test a 3–phase circuit with a load which draws 1.44Watts at a PF=1.
   - Design, build and test a 3–phase circuit with a load which has line currents of $I_a = 0.3\angle{-45°}$A, $I_b = 1\angle{-120°}$A, and $I_c = 1.114\angle 75°$A and in which the phase currents are given by $\mathbf{I}_{AB} = \mathbf{I}_a 1.92\angle 75°$, $\mathbf{I}_{BC} = \mathbf{I}_b 0.577\angle 30°$ and $\mathbf{I}_{CA} = \mathbf{I}_c 0.518\angle - 15°$

   Each station has a 3-phase inductor, resistor and capacitor load banks with 300:600:1200Ω loads. They are constrained by these loads and the transformers from lab 1 which are either 12.3:1 or 6.1:1. They are expected also to verify their designs using PSPice. Each group must also implement and test the design of another group.

   Lab outcome: This lab forces students to know the difference between line and phase voltages and currents. It is usually a frustrating lab because there are so many possibilities and they often just use trial and error to determine the best solution. But once they go through all the combinations they are pretty adept at analyzing 3-phase transformer circuits and the different Δ–Y combinations.

4. Lab 4: This is also a 3 week lab in which students are charged with determining the equivalent circuit parameters of the transformers from lab 1. They must also use PSPice to model the transformer and determine its efficiency and voltage regulation and then compare PSPice results with experimental results. The actual lab handout includes no procedures with regard to the open circuit or short circuit tests. Students

must figure out for themselves how they would determine the parameters and are directed to consult the textbook and ask plenty of questions as the instructor is always willing to answer questions.

Lab 4 outcome: As with lab 1 students must design the experiment rather than the system. If they do the lab properly they will find that their simulated and experimental results match pretty well. This is always gratifying.

5. Lab 5: This is the lab in which students must design an automatic voltage regulator for their DC generator using field control. The specifications stimulate a minimum output of 65V with 1% regulation with a 150Ω load. The concept of the regulator is introduced in lecture with the basic topology of Figure 1 which is typically analyzed in detail and the close loop steady state gain is derived. The switching circuit for the field and the idea of pulse width modulation would have already been covered in a previous lecture. To complete the lab, students must find the magnetization curve (i.e. the relation between E_o and I_x for their machines), determine suitable values for R_1, R_2, K_P and V_S and complete the detailed circuit design. They are directed to use the SG3524 in order to create the PWM circuit and use this to drive an IRF610 N-channel MOSFET in series with the field winding.

   Extra credit is available based on the following criteria:

   50% for using NO external power supplies (i.e. anything which needs to be plugged into an outlet.) Excludes the power needed to operate the motor.

   20% for using just ONE external supply.

   1% extra for each 1V regulated above 65V within 1% (with 150Ω load.)

   30% for implementing the system in software.

   30% for simulating the entire circuit (i.e. generator with regulator) on PSPice

   10% for reporting on the price of the regulator in batches of 100.

   Lab outcome: Although 4 weeks is designated for it, this lab invariably requires 5 to be completed. The extra time is never begrudged the students because they learn so much by doing it and they always demonstrate great satisfaction at implementing a working system. Every year at least 1 or 2 groups will seek much of the extra credit by implementing a controller for the generator operating in self excited mode. Two years ago a group was able to implement their design in software and use NO external power supplies by controlling a self–excited generator with a microcontroller. They used the generator output to power all the control logic through 3 pin voltage regulators. This year one group implemented the self excited machine and simulated their circuit in PSpice. Students may also achieve software control with GPIB controlled instrumentation available at all the benches or with a Keithley Metrabyte A/D board in each computer.

   An example of a group's regulator simulated in PSPice is shown in Figure 2.

6. Lab 6: For their final lab, groups must design and implement another feedback control system for another machine. They must do one of four options as follows:

Basic topology for automatic voltage regulator Lab 5

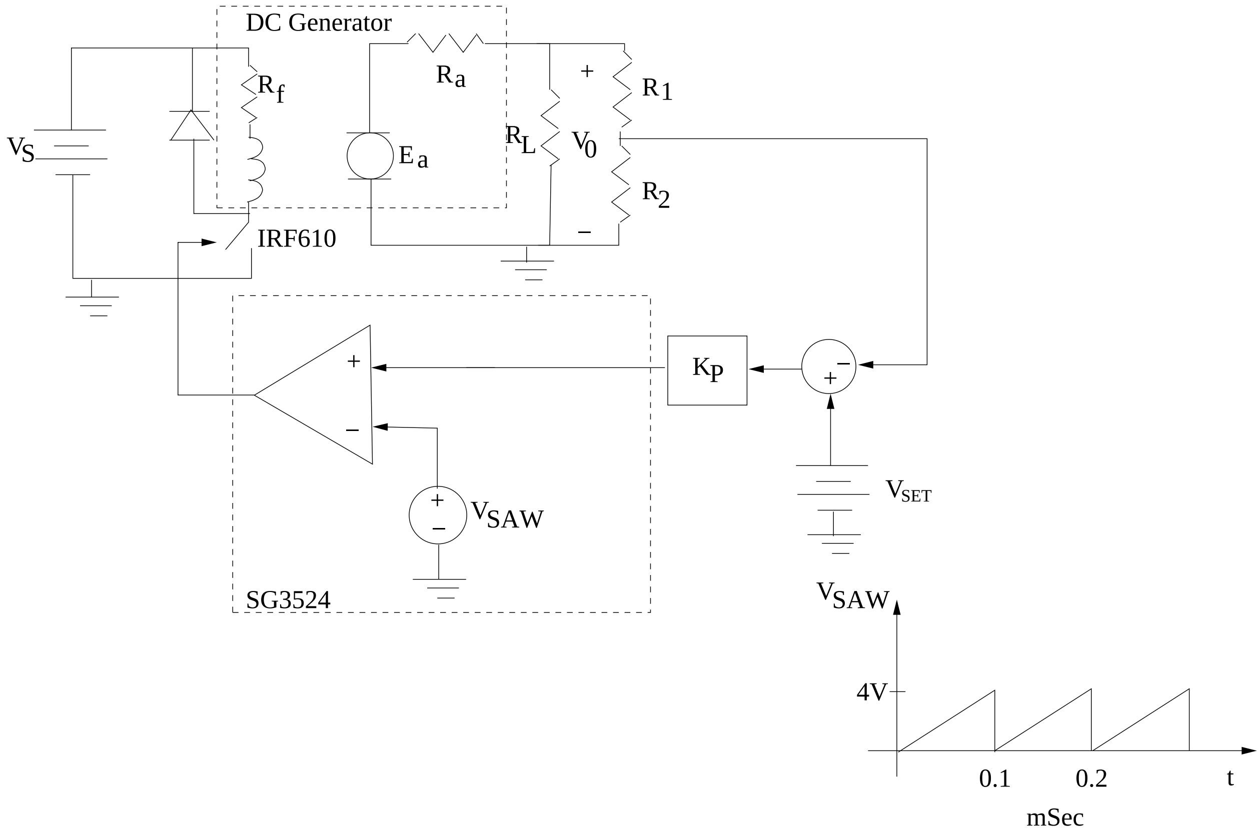

Figure 1: Basic schematic for the DC generator voltage regulator using field control. The steady state, close loop gain, V_O/V_{SET} is derived in class. For lab, students must complete the design by chosing V_S, R_1, R_2, K_P and designing the circuits for K_P and the voltage differencer. If they chose to implement their design in analog they usually use an SG3524 to get the PWM signal. The switch is an IRF610 N–channel MOSFET.

- Control the DC generator voltage by varying shaft speed instead of field current. The generator shaft is spun by a 3 phase motor whose speed can be controlled by a 3 phase, voltage–controlled, variable speed drive available at each of the benches.
- Control the AC generator voltage with field control. Must regulate the output voltage to 100V rms within 4% with 3 phase loads of 300Ω and j300Ω.
- Control the speed of a DC motor with armature control. Must have a minimum speed of 1500rpm with a regulation within 4% with a maximum load of 3lbf–in. Each of the DC motors has a tachometer with a voltage output and dynamometers are used to provide the torque load.
- Control the speed of a 3 phase AC motor with a minimum speed of 1500rpm within 4% with a torque load of 3lbf–in. This is possible with the voltage controlled, variable speed drives.

Lab 6 outcome: Because they've spent so much time on lab 5 there usually is only about 2 weeks left to fully complete lab 6. For most students, however, this is sufficient time. As a consequence of lab 5, they have a pretty good understanding of rotating

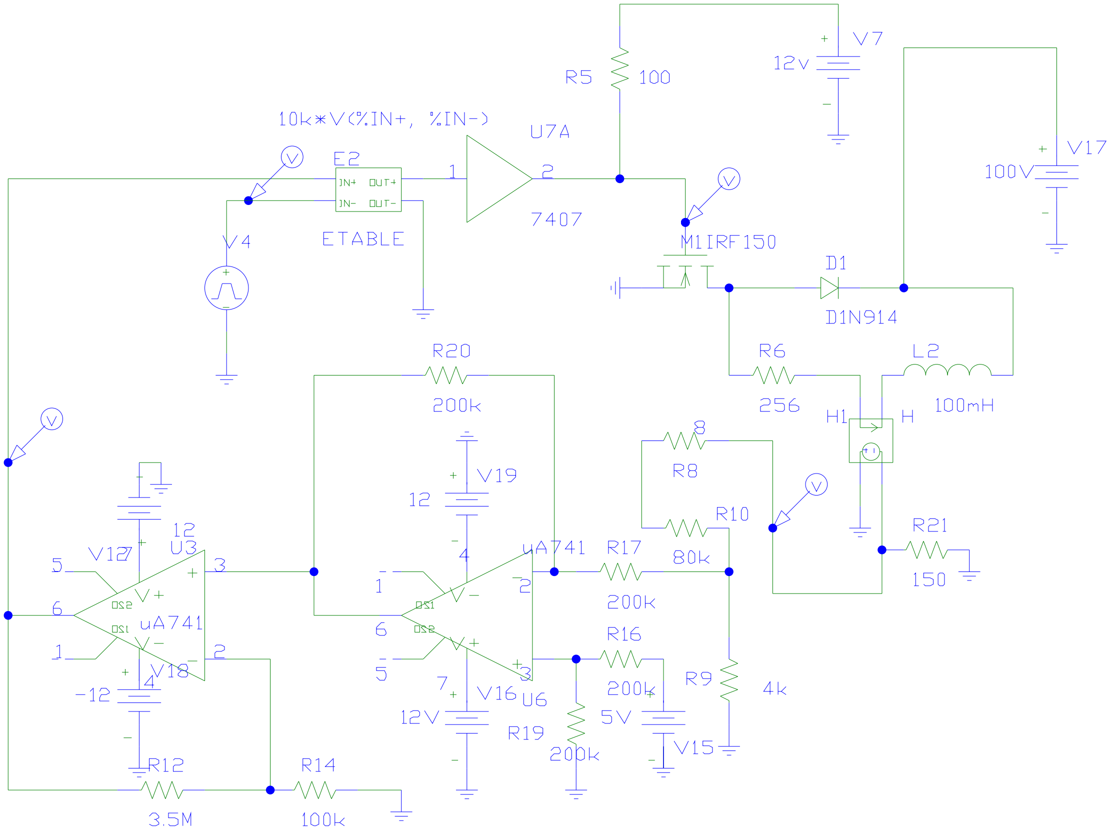

Figure 2: PSPice schematic of the final design of a regulator for the DC generator.

equipment and controllers for them. Lab 6 is viewed as applying the concepts of lab 5 and using parts of the circuit from lab 5 to control another piece of equipment.

5 Conclusions

Naturally everything cannot be covered in one course. The curriculum is already being "squeezed" by the constant inclusion of new technologies. What we hope to do is open the students' minds to the subject, introduce some of the fundamental concepts and try to impress upon them an atitude of lifelong learning in many areas. Its important to provide motivational material early on and this is easily done in this course by discussing the inevitable energy shortages and blackouts that have occurred over the long hot summer. The Thomas Overbye article on "Reegineering the Electric Grid"[5] is assigned as a first reading. Furthermore Bucknell has its own cogeneration power plant capable of producing 6.7MW of power and for the first time this semester the class toured the facility. This was a big boost to the semester just as it started to drag and students were able to observe, big cables, big transformers, big generators, big motors, etc.

Its felt that the course has accomplished its goal of impressing upon graduates the relevance of issues in electric power, power electronics and rotating machinery and how critical the whole area is to other technologies. It has also honed their problem solving skills and allowed them to think deeply about some problems in electric power and control of rotating machinery.

6 Bibliography

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