ECE 469 -- Power Electronics Laboratory

LABORATORY INFORMATION AND GUIDE

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Version 2.5 -- August 2014

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Preface and Acknowledgements

Power electronics studies the application of semiconductor devices to the conversion and control of electrical energy. The field is driving an era of rapid change in all aspects of electrical energy. The Power Electronics Laboratory course -- one of only a few offered at the undergraduate level in the United States -- seeks to enhance general material with practice and hands-on experience. The laboratory course provides instruction in general lab practices, measurement methods, and with the design and operation of several common circuits relevant to the field of power electronics. It also provides experience with common components such as motors, batteries, magnetic devices, and power semiconductors. The course has a significant design component. The final weeks of the term are devoted to a power converter design project.

The equipment and instrumentation for ECE 469 were updated substantially in 2011, and our complete new laboratory is being commissioned in 2014. Many people have helped in a wide variety of ways in the past, and their efforts are appreciated. Past work by Z. Sorchini, J. Kimball, R. Balog, and K. Colravy is acknowledged. The generous support of The Grainger Foundation has been instrumental in developing and improving the laboratory. The efforts of the ECE Electronics Shop and the ECE Machine Shop in preparing the benches and equipment are gratefully acknowledged.

Student feedback is encouraged throughout the semester. Your input will help make the course more interesting and enjoyable, and will increase its value over time. Comments are always appreciated. Experiments and other work can and will be modified quickly if the need arises. The course is designed as an advanced laboratory, primarily for seniors and graduate students. You will find that procedural details are up to the student teams. The requirements for lab reports and procedures reflect the standards of a productive industrial research and development lab more than the relatively routine work in beginning courses.

Expected Schedule

The schedule will be provided during the first week of classes.

Introduction

Power electronics is a broad area. Experts in the field find a need for knowledge in advanced circuit theory, electric power equipment, electromagnetic design, radiation, semiconductor physics and processing, analog and digital circuit design, control systems, and a tremendous range of sub-areas. Major applications addressed by power electronics include:

- Energy conversion for solar, wind, fuel cell, and other alternative resources.
- Advanced high-power low-voltage power supplies for computers and integrated electronics.
- Efficient low-power supplies for networks and portable products.
- Hardware to implement intelligent electricity grids, at all levels.
- Power conversion needs and power controllers for aircraft, spacecraft, and marine use.
- Electronic controllers for motor drives and other industrial equipment.
- Drives and chargers for electric and hybrid vehicles.
- Uninterruptible power supplies for backup power or critical needs.
- High-voltage direct current transmission equipment and other power processing in utility systems.
- Small, highly efficient, switching power supplies for general use.

Such a broad range of topics requires many years of training and experience in electrical engineering. The objectives of the Power Electronics Laboratory course are to provide working experience with the power electronics concepts presented in the power electronics lecture course, while giving students knowledge of the special measurement and design techniques of this subject. The goal is to give students a "running start," that can lead to a useful understanding of the field in one semester. The material allows students to design complete switching power supplies by the end of the semester, and prepares students to interact with power supply builders, designers, and customers in industry. Many of you will be surprised at how pervasive power electronics has become -- and at how few people have a deep understanding of the field.

Power electronics can be defined as the area that deals with application of electronic devices for control and conversion of electric power. In particular, a power electronic circuit is intended to control or convert power at levels far above the device ratings. With this in mind, the situations encountered in the power electronics laboratory course will often be unusual in an electronics setting. Safety rules are important, both for the people involved and for the equipment. Semiconductor devices react very quickly to conditions -- and thus make excellent, expensive, "fuses." Please study and observe the safety rules below.

Safety

The Power Electronics Laboratory deals with power levels much higher than those in most electronics settings. In ECE 469, the voltages will usually be kept low to minimize hazards. Be careful when working with spinning motors, and parts that can become hot. Most of our equipment is rugged, but some delicate instruments are required for our experiments. Even rugged instruments can be damaged when mishandled or driven beyond ratings. Please follow the safety precautions to avoid injury, discomfort, lost lab time, and expensive repairs.

- **GROUND! Be aware of which connections are grounded**, and which are not. The most common cause of equipment damage is unintended shorts to ground. Remember that oscilloscopes are designed to measure voltage relative to ground, not between two arbitrary points.
- **RATINGS!** Before applying power, check that the voltage, current, and power levels you expect to see **do not violate any ratings**. What is the power you expect in a given resistor?
- **HEAT! Small parts can become hot** enough to cause burns with as little as one watt applied to them. Even large resistors will become hot if five watts or so are applied.
- **CAREFUL WORKMANSHIP!** Check and recheck all connections before applying power. Plan ahead: consider the effects of a circuit change before trying it. Use the right wires and connectors for the job, and keep your bench neat.
- **WHEN IN DOUBT, SHUT IT OFF!** *Do not manipulate circuits or make changes with power applied.*
- **LIVE PARTS!** Most semiconductor devices have an electrical connection to the case. Assume that **anything touching the case is part of the circuit** and is connected. Avoid tools and other metallic objects around live circuits. Keep beverage containers away from your bench.
- **Neckties and loose clothing should not be worn when working with motors.** Be sure motors are not free to move about or come in contact with circuitry.
- Remember the effects of inductive circuits -- high voltages can occur if you attempt to disconnect an inductor when current is flowing.
- **EMERGENCY PHONE NUMBER: 9-911**

The laboratory is equipped with an emergency electrical shutoff system. When *any* red button (located throughout the room) is pushed, power is disconnected from *all* room panels. *Room lights and the wall duplex outlets used for instrument power and low-power experiments are not affected.* If the emergency system operates, and you are without power, inform your instructor. It is your instructor's task to restore power when it is safe to do so. Each workbench is connected to power through a set of line cords. The large line cords are connected to two front panel switches labelled "3φ mains" and "dc mains." The standard ac line cord is connected to the switch on the bench outlet column. Your bench can be de-energized by shutting off these three switches.

Equipment and Lab Orientation

Introduction

The Grainger Electrical Machinery Laboratory was funded through a grant from the Grainger Foundation. The equipment and support have been completely renovated, including an entirely new facility. The laboratory rivals many modern industrial research counterparts in terms of safety and instrumentation. The room includes a set of workstation panels to distribute power throughout the room and special lab benches that are the primary tool for all work. The benches hold rotating machines, dedicated power meters, an instrument rack, a cable rack, and connection panels. Extra instrumentation and equipment are stored in cabinets at the bottom of each bench.

Map of the Facility and Electrical Panels

The laboratory is located in room 4024 in the Electrical and Computer Engineering Building, as shown in Figure 1. A storage area is located just east of the laboratory. Motors and extra instruments are kept in that area. The adjacent classroom, 4026 ECEB, will be used at the beginning of lab sessions. Down the hall to the east is the Advanced Power Applications Laboratory, a research facility which shares many of the same features. The main laboratory is supplied by 60 Hz ac power at 208 V three-phase into special panels. A separate dc power supply system delivers ± 120 V at up to 24 kW. Power from the regular building supply is used for instruments and low-power experiments. The room includes an interconnect set for experiments that involve multiple benches. Up to 30 A can be imposed on any of these wires.

The master circuit breakers in the room have what is called a “shunt trip” mechanism. They can be turned off with a short pulse of ac power. When any of the large red “panic buttons” throughout the room is pushed, all master breakers feeding the workstation panels are forced to shut off. When this occurs, power is cut off at all lab station panels throughout the room. This provides an emergency disconnect capability. It does not affect lights or regular wall outlets in the lab.

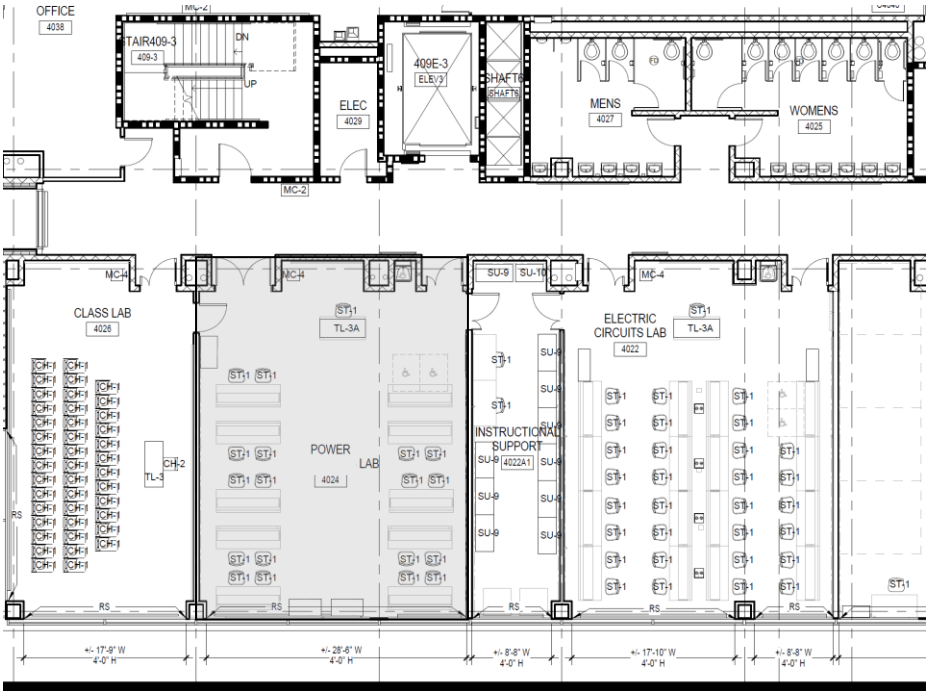


Figure 1. The Grainger Electric Machinery Laboratory and surroundings.

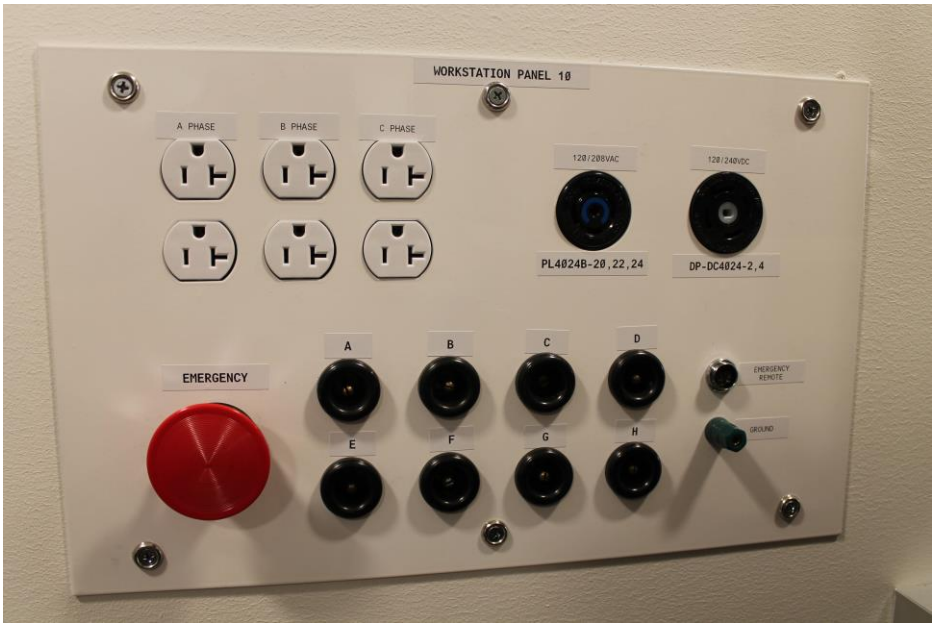


Figure 1. Front view of workstation panel.

A view of one of the workstation panels is provided in Figure 2. The top portion contains two power outlets for convenient access to various high-power supplies. One of these is a 120/208 V three-phase source,

which is also connected to an adjacent set of duplex outlets. The bottom of the panel holds eight "transfer jacks," wired to the interconnect panel. There is a ground jack for access to a solid earth ground.

The Lab Workbenches

Overview

Each power lab bench is designed as a complete test station, with its own safety features and protective mechanisms. The benches have space for instrument operation and for storage, rotating machines, and power connections. A photograph is shown in Figure 3, with a layout in Figure 4. There are two functionally identical bench versions -- a right-hand unit and a left-hand unit.

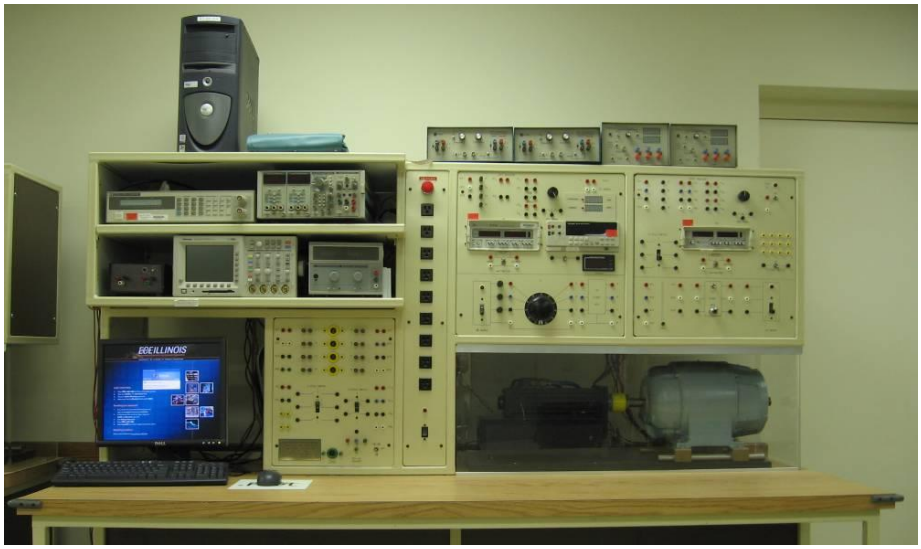


Figure 2. Laboratory bench, "left-hand" version.

The benches plug into the workstation panel outlets with power line cords accessed through the bench "window" behind the computer monitor. Many panel jacks on your bench have been pre-wired internally for your convenience. These jacks have identical labels. They allows short, organized connections. *Please be aware of these labels, and respect them.* The benches are divided into four major sections: input power handling and distribution, rotating machine connection panels, the instrument rack, and the load patch area.

The power line cords have incompatible plugs to prevent errors in power access. They are of the twist-lock style to prevent accidental removal. Three-phase ac power to the bench is from the 120/208 V source. A double-throw center-off switch located beneath the bench must be set to select the proper source. In any case, three-phase ac power is wired to the "3φ mains" switch on the bench front panel. When this switch is off, no three-phase power will appear at the bench panels. Dc power to the bench is routed from the line cord, through a fuse box, and then to the "dc mains" switch on the front panel. As with ac power, turning this switch off will remove all panel access to the dc source.

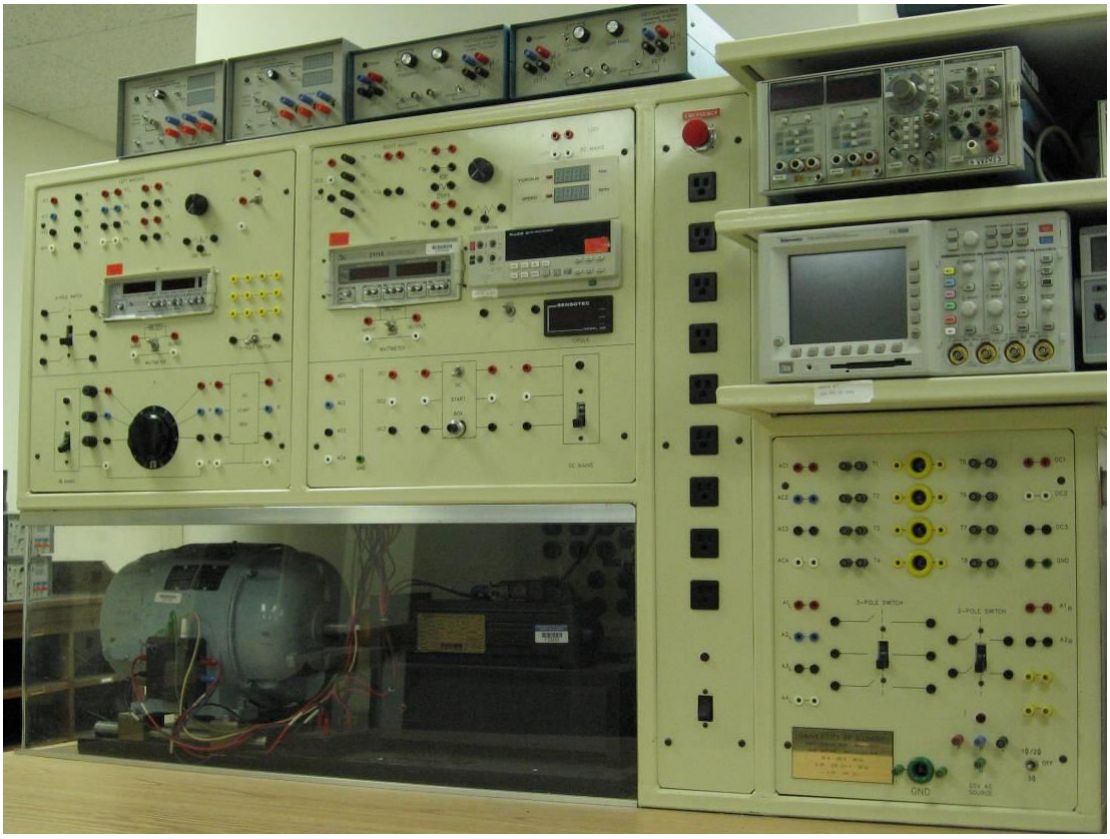


Figure 3. The laboratory workbench.

The single-phase ac instrument power is routed from the familiar 1φ line cord to the outlet column near the center of the bench, to outlets in the instrument rack, and to internal instrument power through a front-panel circuit breaker. The single-phase line cord should be plugged into the wall duplex outlet near the floor so that computers and instruments will not be affected by use of the room panic buttons. The other cords should be plugged in only as necessary for power access. Each bench can be shut off by turning off the 3φ mains switch, the dc mains switch, and the instrument power switch.

Inventory

Each bench is permanently equipped with the following:

- Variable three-phase ac transformer, 0-230 V, 0-10 A.
- Yokogawa WT310 digital power meters.
- Fluke dual-display multimeter.
- Westinghouse Power Miser TRIAC-based ac motor starter.

- Kollmorgan PWM ac servodrive and permanent-magnet motor with encoder.
- One, two, or three-phase transformer set, 120 V/25.2 V, 0-3 A.
- Two 300 Ω power potentiometers, 100 W.
- Power resistor, 100 Ω, 150 W.
- Three switches, 30 A rating.
- One switch rated 6 A.
- Machine set.

In addition, each bench is supplied with the following equipment:

- Tektronix model MSO4034B digital oscilloscope with TCP/IP interface.
- Tektronix model TCP202 current probe and P5205 differential voltage probe.
- Agilent model 34461A multimeter.
- Agilent model 33500B waveform generator.
- Agilent model E3631A triple-output dc power supply.
- Kenwood PD56-10AD power supply, 0-56 V, 0-10 A.
- Hewlett-Packard model 6660B electronic load, 0-30 V, 0-30 A.
- Windows computer.
- Isolated dual power FET control box, 0-300 V or more, 0-15 A or more.
- Isolated one-two-three phase SCR control box, 0-300 V or more, 0-20 A or more.
- PWM audio amplifier, single channel.
- Three power resistor boxes, each with ten 500 Ω resistors.
- Three capacitor boxes, each with eight 6 μF capacitors.
- Three transformer boxes, 1 kVA each.
- Lead rack with banana and BNC leads of various lengths.

Additional power supplies, meters, and small motors are stored in the cabinets. There is an extensive selection of power resistors, inductors, magnetic cores and parts, power semiconductors, heat sinks, tools, protoboards, and other general parts. Special purpose instruments expected to be available for shared use include:

- Hewlett-Packard model 4195A network/spectrum analyzer.
- Tektronix model 371 power semiconductor curve tracer.
- Philips model PM6303 automatic RCL meter.

Please make an effort to keep track of the equipment at your bench, especially portable items such as probes. It is important to take measurements carefully and in an organized fashion. Equipment damage is expensive and can cause time delays or inconvenience for you. Look over your station at the beginning of each lab.

Course Organization and Requirements

The course consists of about fourteen lab sessions and a weekly lecture/discussion session. The hour of lecture/discussion each week will provide specific lab preparation, opportunity for general questions, time for elaboration on practical power electronics topics, and demonstrations. Required efforts are as follows:

- A short pre-lab assignment accompanies each experiment. The purpose of this assignment is to help you prepare for the experiment. The problems apply directly to the procedure or report. *Pre-labs must be completed and turned in before performing the given experiment.* **Late pre-lab assignments will not be accepted**.
- The experiments and reports are semi-formal in nature. Proper lab notebooks must be maintained by all students. Reports are written independently by each individual, and follow the format given below. Correct spelling, grammar, and punctuation are expected. Most reports cover a group of experiments.
- The final class session involves a brief oral presentation. Here, the design project is described and demonstrated.

Care and neatness in the maintenance of lab notebooks and in the preparation of reports is important. Your instructors will be pleased to assist you in generating quality work.

As you know, it is difficult to make up missed laboratory work. Please notify your instructor as soon as possible if illness or similar emergency prevents your attendance. In other cases, arrangements can sometimes be made, given enough advance warning; however, time demands on your instructors are such that **make-up sessions will not be held without acceptable excuse**.

Lab sessions will be divided into two major categories:

Demonstrations are conducted by your instructor, and usually involve complicated laboratory work. They allow experiments which require extensive setup time, unusual equipment, or intricate measurements. In the case of demonstrations, the pre-lab assignments serve to highlight major points. In general, you will be expected to take notes and record data during demonstrations, for use in preparing reports.

Experiments are conducted by students in small teams. For each experiment, one team member serves as leader, another as recorder, and any others as helpers. Teams will be assigned early in the semester, and will generally stay the same throughout the course. Team duties rotate for each experiment.

The Lab Notebook

The laboratory notebook is a crucial tool for work in any experimental environment. A notebook used in a research lab, a development area, or even on the factory floor is probably the most valuable piece of gear in the engineer's arsenal. The purpose of the notebook is to provide a complete *permanent* record of your practical work. Why a notebook? It allows you to reproduce your own work, or to refer to it without having to duplicate the effort. It provides a single place that tracks your work in a consistent way. It provides a permanent physical record for legal purposes. Often, it permits us to "reverse engineer," and find errors of record or procedure.

The notebook is your record, but in most industry practice is the property of your employer. For this reason, many companies have specific rules about notebook format, content, and usage. In the ECE 469 lab, your notebook will eventually become your property (although for the moment you should act as if it belongs to the State of Illinois). It should include:

- Diagrams of all circuits used in the lab. If the circuit is identical or almost identical to one in your procedure or book, you may reference (not copy) it. The important factor is to be able to reproduce your setup in case of errors.
- Procedures and actions. (But do not repeat steps in the lab manual.) The idea is to provide enough information so that you could repeat the experiment.
- Equipment used. (List only your bench number if you used only the standard bench equipment.) The model and serial numbers of special instruments and equipment should be recorded in your notebook. This is mainly for your protection in case a scale is misread or equipment is defective.
- All data generated in the experiment. Be sure to include units and scale settings. For example, oscilloscope data might read “data in display divisions, 50 mA/div,” and then list the numbers read. Use data in its most primitive form. Do not perform scaling or calculations when data is first recorded. The objective is to minimize errors.
- If hard copy plots or prints are generated, write the date on them and tape them into the notebook at the appropriate location.
- Names of the experiment team, with a summary of duties. Each team member should maintain a notebook in each session, although the recorder performs the bulk of this task each week. The recorder should provide copies of the original pages to all team members before leaving each week. Even though the recorder keeps notes for a given week, other team members should summarize their efforts in their own notebooks.
- Dated initials of the recorder on each page used for a given day's work.

- Your instructor's signature and signatures of all team members on the last page of the day's work.

It is entirely permissible to include calculations, observations, and even speculations in your notebook, provided these are clearly marked and kept apart from experimental data and actual bench work.

The notebook must be a bound book with permanent, pre-printed page numbers. Within these requirements, any type is acceptable. Do not use loose sheets for data or other information. It is absolutely not acceptable to recopy information into the notebook at a later time. Notebook errors should be crossed out (not obliterated) and initialed and dated by the recorder. Be sure to initial and date each page of your notebook as it is filled. Remember that paper is cheap: start a new page rather than cramming extra information onto one sheet. *The notebook must be kept in ink!*

Keeping a complete lab notebook sometimes seems inconvenient, but in the long run saves a tremendous amount of time and effort. Some of the uses of an official notebook are:

- A record of your personal efforts for use with your manager or instructor.
- A history of work on a particular project or circuit. This avoids the need for duplicated effort.
- An official record for patent applications. If a patent is challenged in court, the notebook is the key document to be used.
- A complete technical record for use in reports, articles, specification documents, and drawings.
- Identification of points at which errors were made.

The notebook is the "who, what, where, when, how" of the technical world. Billions of dollars are wasted each year duplicating efforts which were not carefully documented or defending patents based on sketchy lab data.

The Lab Report

An experiment is not considered complete until the results have been properly reported. One of the primary tasks of an engineer is to *interpret* results of work, rather than just to gather data. A good report helps you understand the concepts in the experiment, and also helps you when you wish to discuss and communicate those results with others. A high-quality report allows a reader to understand your results and gain the benefits of your insights. Working engineers often mention technical writing as an area in which they could have used better preparation -- because of the need for good engineering reports. To give you some additional practice along these lines, lab reports for ECE 469 are semi-formal in style. They should be prepared with a word processor and laser-quality printer. The computers in room 4024 can be used if necessary. Be sure to take advantage of spell-checking and similar features.

The report has six elements:

1. **The Title Page**. This must show the report title, author, dates, and names and duties of group members.

1a. **Table of Contents**. Required only on the Design Project report. This should show the locations of all headings and major subheadings.

2. **Abstract**. A one paragraph summary of the report, including:

→ A brief but clear summary of the objectives and results.

→ An indication of the system studied, loads used, and the basic work performed.

3. **Discussion**. This is the body of the report, and may contain subheadings as needed. It should report on the laboratory effort, summarize the data and any calculated results, and briefly describe the important theory and concepts. It should compare measured results with those expected, and contrast the various cases studied. It should discuss important sources of error and their relevance to the results. Finally, it should discuss any difficulties encountered and suggest what might have been done differently. Study questions assigned in class or in this manual should be addressed in the Discussion. Figures, tables, and circuit diagrams are encouraged. Laboratory reports in which the discussion merely paraphrases the lab manual are not acceptable. Suggested subheadings include:

→ Theory

Brief overview of theory and the methods used for the experiment and its analysis. This should provide sufficient background for the reader to understand what you did and why. It should help the reader follow along with the rest of your discussion. *Detailed or basic theory should not be repeated from the lab manual or textbook.*

→ Results

This portion provides an organized summary of your data and calculated results, in forms that help you interpret them. Graphs are a powerful tool for this subsection. When you include graphs, be sure to label them properly, and talk about them in your discussion. A good sample graph from a student report appears in Figure 5 below. In most reports, this subsection also will include tables of numerical results. When calculations are involved, you should show one example of each type of calculation (please do not provide extensive numerical calculations). A sample table from a student report appears in Figure 6. Perhaps the most important aspect of your report is the task of analyzing the results, such as comparing expected and actual results. This discussion should be quantitative whenever possible. Be sure to include percent errors or other indication of deviations from expectations. Be aware of significant digits in your data and calculations. Keep in mind that engineering is about *interpretation* of results much more than generation of results. The results subsection is the usual place to address study questions given in the lab manual.

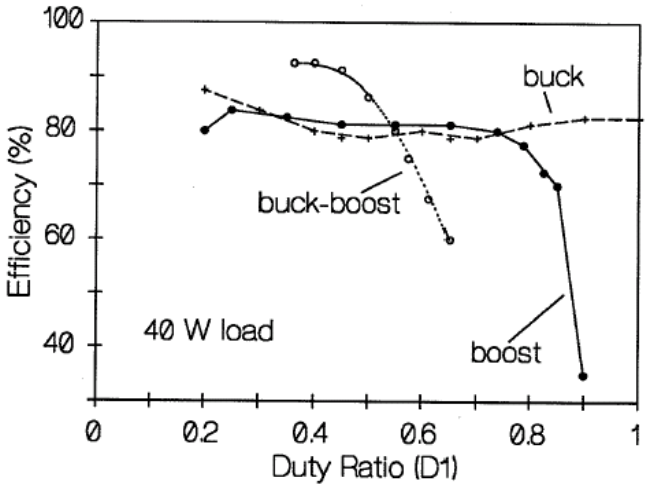


Figure 3: Efficiency vs. Duty Ratio for Dc-Dc Converters

Figure 4. Sample graph from student report.

→ Error Discussion

In most reports, it is important to point out sensitive places in the data. The issue is to determine the level of confidence in the results. Error issues should be discussed in quantitative terms. Consider the following example, from a student report:

TABLE 1.3 Third Test Setup

L = 370 uH
C = 50 uF/ 50 v
R = 16 ohm/55 watts
Period = 30.5 usec
Switching Freq. = 32.79K Hz

Vin	Iin	Pin	Vload	Iload	Pload	Vfet	D2	Ripple	Po/Pin
Vdc	Adc	W	Vdc	Adc	W	Vdc		Vpp	%
15.00	2.83	42.5	24.10	1.572	39.9	14.6	0.367	1.44	94.0
12.00	3.83	46.0	24.00	1.577	39.9	5.8	0.482	1.72	86.8
9.00	7.45	67.1	24.00	1.573	39.1	-10.0	0.649	2.48	58.3
7.20	(Unable to achieve 24 volt output at this level)								

Figure 5. -- **Sample table from student report**

> *"The calculated results depend on the phase measurements in Part I. These were hard to make and may not be very exact. Since the frequency was 50,000 Hz, 1° is only 56 ns. The scope gives up to 3% time error. On the 10 μs scale, this is 300 ns. So the measured phases could be 6° off. Our results are a lot better than this, so maybe the scope has less error."*

4. **Conclusion**. A brief summary of the results and significant problems uncovered by the work. These should represent the actual results as opposed to any expectations you might have had. This is a good place to suggest how you would do it differently if you were to repeat the experiment.

5. **References**. A list of any references used. Please be aware of University regulations involving written work. Quotations or paraphrases from other works, **including the lab manual**, must be properly referenced. If the lab manual is the only source you used, you can just list "ECE 469 lab manual" as the reference. When other references are involved, list them in the order used. Examples of the format (IEEE style):

   [1] I. Rotit, *The Basics of PWM Inverters*. New York: Energy Printers, 2026, p. 142.

   [2] E. Zeedusset, "Phase error effect in bridge converters," *IEEE Transactions on Industrial Electronics*, vol 66, pp. 4231-4236, October 2019.

   In the text, you should use the reference numbers. For example, "... methods for PWM control are described in depth in [1]...," or "... are discussed in detail in the ECE469 lab manual."

6. **Appendix**. *This must include copies of the original data sheets*. Number the sheets if you refer to them in the discussion. The appendix should also include any auxiliary information such as semiconductor manufacturer's data sheets, a summary of the procedures actually used, and an equipment list if it differs from that in the lab handout. It is not necessary to include copies of material from the lab manual.

Lab reports should not be lengthy. Except for the Design Project report (which covers extra information), the total length of a report, except for the Appendix, *should not exceed twelve double-spaced pages*. This includes the title page. Lab report grading will address format as well as each of the six major sections. The discussion is most important. More details about grading will be provided by your instructor. To help you in writing the report, there are several study questions given at the end of each experiment write-up. These questions do not substitute for a complete discussion of results, but provide a starting point. They are not to be taken as homework problems to be answered one by one in the lab report, but rather as important points that should be addressed in the body of the report. The study questions are of two types:

- Specific questions about results. These might request certain plots or calculations. You are expected to provide the expected information completely in your reports.
- Thought questions. These are intended to guide your thinking when evaluating the results. They should be covered in your discussion, but do not answer them one at a time as if they were test problems.

Instrumentation Notes

HP 6060B Electronic Programmable DC Load

The HP Programmable load is basically an inverter that accepts dc power and converts it to ac that is then injected into the power grid. It can be extremely useful since it is a versatile, programmable load.

The ratings on the load appear on the front panel and are as follows:

Voltage: 0-60 V

Current: 0-60 A

Max Power: 300 W (notice that this is not the max current at the max voltage)

Always obey these ratings!

How to use the HP Load:

1. Turn the power on.
2. Select what mode you want. The choices are:
   Current – it behaves as an ideal current sink
   Voltage – it behaves as an ideal voltage source with negative input current
   Resistance – you can set a specific resistance

a. Press [**MODE**]
b. Press either [**CURR**], [**VOLT**], or [**RES**]
c. Press [**ENTER**]

3. Enter the value:

a. Press the button of the mode you are in, for example: [**CURR**]
b. Enter on the numeric keypad the value, for example: [**5]** (for 5 amps)
c. Press [**ENTER**]

4. [**METER**] button toggles the display between volt / current and watts
5. [**INPUT ON/OFF**] can be used to disconnect the load

Advice:

When you are first trying to get your circuit to work, use a power resistor from the lab stock. This removes the variable of the programmable load. It makes trouble shooting easier since we all know how a plain old power resistor should work. One the results make sense, you are encouraged to replace the resistor with the active load.

ECE 469 POWER ELECTRONICS LABORATORY

DEMONSTRATION #1 -- Introduction to the Laboratory

Objective -- This demonstration is intended to introduce some of the special equipment and methods of the Power Electronics Laboratory. Basic laboratory concepts and safety issues will be reviewed.

Pre-lab Assignment -- Take a few minutes to read the safety information in the lab manual introductory pages. Be prepared with any questions. Also, be prepared to be quizzed about safety rules.

Introduction -- In this demonstration, the unusual equipment associated with the Power Electronics Laboratory will be described and operated. For each lab station, basic electronic measurement gear is provided. In addition, four custom circuits have been constructed for your use. These are:

- A low-voltage ac supply, from a transformer bank, built into each bench. This supply provides polyphase output, with ratings of 117 V input to 25.2 V output. The switch allows the bank to draw power either from the bench single-phase source or three-phase source. A circuit diagram is shown in Figure 1.

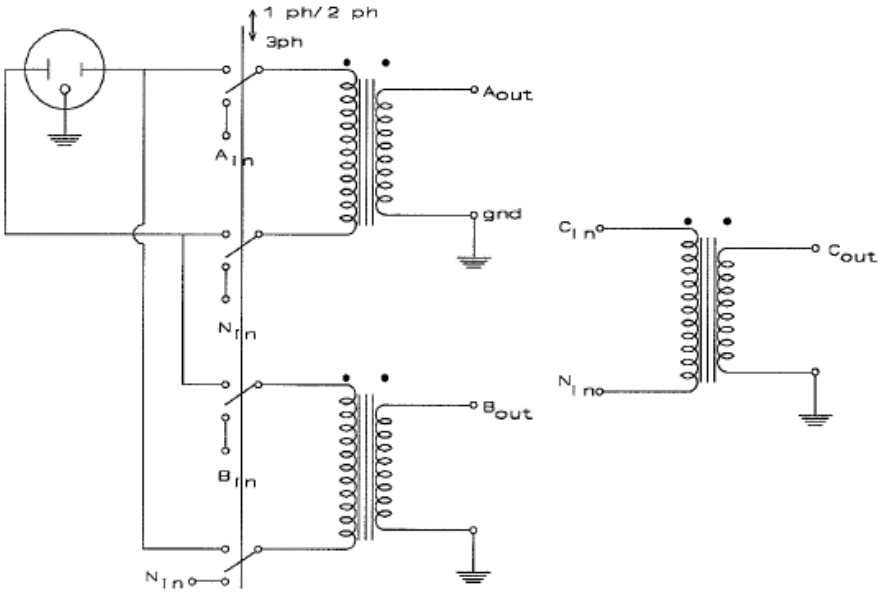


Figure 1. Polyphase transformer bank.

With the panel switch in the "one-phase two-phase" position, A and B outputs are available, with 180° phase shift. The "C" output is indeterminate. With the panel switch in the "three-phase" position, three outputs shifted 120° are available (if 3φ power is suplied to the bench). In both cases, the common neutral point is connected to bench frame ground.

- One-two-three phase SCR control unit. This box contains three silicon controlled rectifiers (SCRs).

Each SCR is controlled by a pulse transformer and is floating with respect to ground. The SCR is similar to a standard diode, except that it does not turn on until a pulse or a switching function is applied to a gate terminal. The three SCRs in the box are operated so that the switching functions are spaced a precise time interval apart, controlled from the front panel.

The "phase" delay value sets the time shift among the three phases. For one-phase or two-phase circuits, it should be set to half the input period -- 8 1/3 ms for a 60 Hz input. For three-phase circuits, it should be set to 1/3 of a cycle, or 5 5/9 ms for a 60 Hz input.

The "master" front panel delay control sets the time delay of the SCR "A" signal relative to the input zero crossing. When the value is set at zero, there is no delay. It can be adjusted in milliseconds up to about 40 ms. A front view of the box appears in Figure 2.

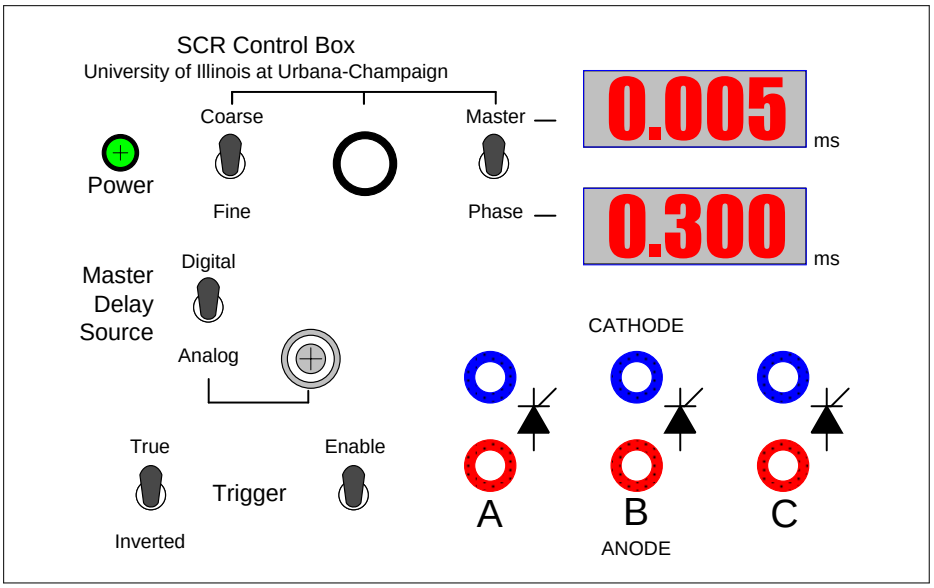
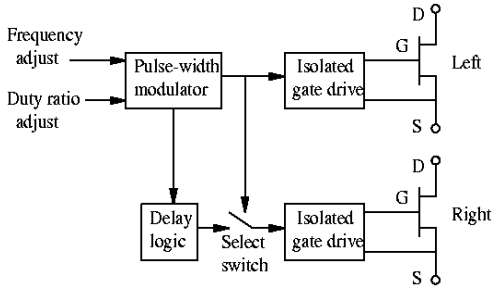


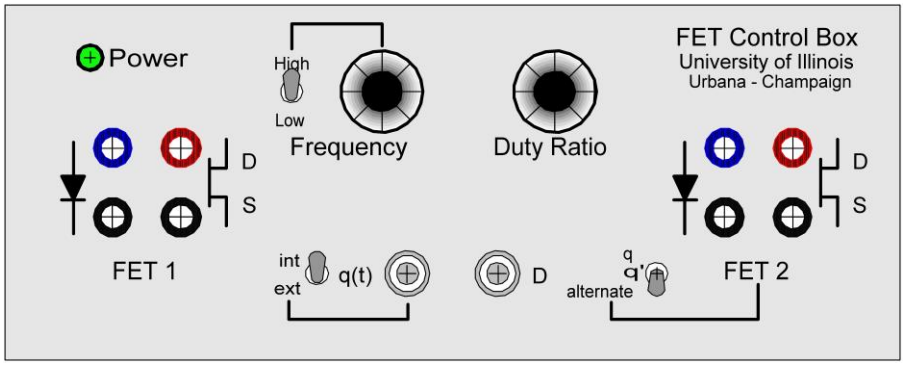
Figure 2. Polyphase SCR control unit

- Isolated dual power FET control box. This box contains two field-effect transistors (FETs), each rated for at least 300 V and 15 A. The FET is used as a switch, with either a small resistance (on state) or a very large resistance (off state). The drain and source terminals are floating, and can be connected to any voltage which does not violate the ratings.

Also contained in the box is a circuit which operates the FET gates to turn the devices on and off. In essence, a square wave is applied to the FET, turning it on when the square wave is high, and off when it is low. Panel controls adjust the frequency of this square wave, the fraction of the time during which the wave is high, and the action of the square wave on the second FET. The operation is useful for dc-dc and dc-ac conversion applications. For convenience, unconnected power diodes are provided inside the box. A block diagram and a view of the front panel appear in Figure 3.



a) Block diagram



b) Front panel

Figure 3. Isolated FET control unit.

- PWM audio amplifier. This small circuit is similar to the FET control box, except that it has been purpose-built for dc-ac conversion in which the ac waveform is an audio signal. Pulse-width modulation (PWM) allows a variable signal to control the power delivered to a load.

Basic Theory -- Power electronics studies electronic circuits for the conversion of electric power. Examples are units which change dc voltage levels, convert ac to dc or dc to ac, or change the frequency of an ac waveform. Since a converter appears between a power source and a load, and because high power levels might be involved, efficiency is critical. Therefore, such circuits are built up from lossless devices or from low-power control electronics. The possible lossless devices include storage elements (capacitors and inductors), and transformers, but the most important lossless device in power electronics is the switch. A perfect switch has no voltage drop when on and no current flow when off: the power is always zero.

Probably the most familiar example of an electronic switch for power conversion is the rectifier diode. A rectifier circuit converts ac waveforms into dc power, with minimal loss. The drawback of simple diode rectifier circuits is the inability to control them. A diode is on whenever current attempts to flow through it in a forward direction, and off otherwise. To improve on this, a family of semiconductor devices known as "thyristors" was invented. The SCR is the most basic thyristor. This device is similar to a diode, except that it need not be on whenever a forward voltage is applied. Instead, turn-on can be delayed until a pulse is applied to a third terminal -- the gate. Once the device is on, it functions like a diode. This ability to delay turn-on means that output can be adjusted. Outputs can range from zero (gate always off) to a full waveform equal to that of a diode (gate always on). The SCR is useful in applications which require ac to dc conversion, and power levels beyond 100 MW can be supported with commercial devices. Alternative power devices which can be turned on or off on command also exist. Both field-effect and insulated-gate transistors are used in power electronics for this purpose, along with various more complicated types of thyristors.

Demonstration Circuits -- For this demonstration, both the SCR and the power FET will be used in converter circuits. The SCR set will be used in a controlled, full-wave rectifier circuit, while the FET unit will be used to form a basic dc-dc converter. These circuits are typical power electronics applications, and many commercial power units are based on them.

There are two major ways to form a full-wave rectifier, shown in Figure 4. One is with a rectifier bridge, which converts a single ac source into a full-wave rectified waveform. The second uses two diodes with a center-tapped transformer as a "two-phase" ac source. As in the figure, SCRs can substitute for diodes in a full-wave rectifier. The SCRs are operated half a cycle apart, with an adjustable phase angle delay.

The full-wave output is applied to a resistor for this demonstration. When the ac voltage at the top node of the transformer is positive, the top rectifier is forward biased. In the case of the diode, the device will turn on. In the case of the SCR, the device will turn on only if commanded to do so. When the bottom node of the transformer is positive, the bottom diode will be forward biased. Again, the SCR will turn on only when commanded to do so. Part 1 will explore this action.

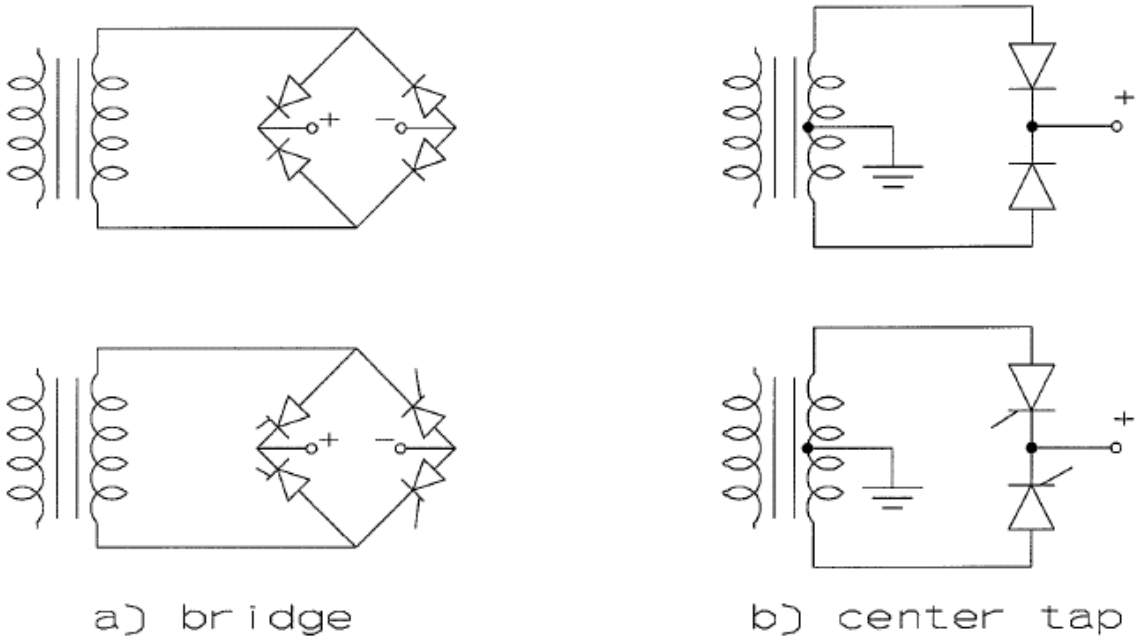


Figure 4. Basic diode and SCR full-wave rectifier circuits

Pulse-width modulation (PWM) is the most popular control tool for dc-dc and dc-ac conversion. When pulse width is adjusted, the average value of a waveform grows larger or smaller, following the width. If a circuit is set up with unipolar dc input, the result is adjustable dc output. If both positive and negative inputs are provided, an ac output is possible when pulse width is adjusted gradually. Parts 2 and 3 examine PWM and its applications.

Procedure

Part 1 -- Rectifiers and the SCR box

1. Connect the 25 V ac supply for two-phase operation. Connect two 1N4004 diodes for full-wave output (anodes to phase A and B output, cathodes in common to load). See the figure below.
2. Connect a load of approximately 50 Ω from the common cathode to ground. What should the resistor power rating be?
3. Observe the resistor voltage waveform. Observe diode current and comment. Measure the resistor RMS voltage, RMS current, power, and average voltage. What is the relevance of each?
4. Repeat the tests with SCRs in place of the diodes. Connect the 25 V ac supply for two-phase operation as in the figure below. Phases A and B should be wired to anodes A and B of the SCR box.

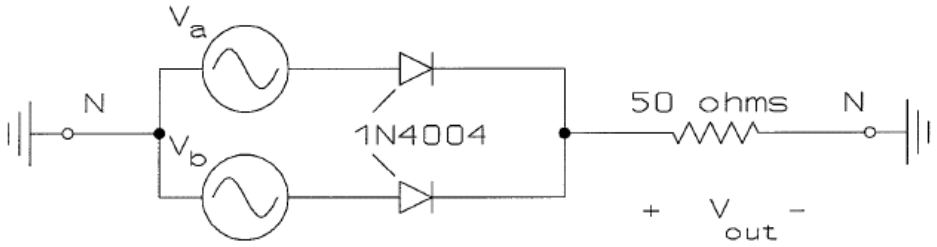


Figure 5. Two-phase diode rectifier test circuit

5. Connect the SCR cathodes in common, and to a power resistor of approximately 25 Ω. The resistor is then connected to supply ground. What power rating must the resistor have?

6. With the output enable of the SCR box off, set the phase delay to 8.33 ms for two-phase operation. Set the master delay to 0, then enable the box. Double check all connections, then turn the power on.

7. Observe the voltage waveform across the resistor. Notice how the waveform changes as the master delay is altered. Again measure RMS voltage, RMS current, power, and average voltage, and consider the relevance of each.

Part 2 -- Dc-dc conversion and the FET box

The FET unit will be used in a simple circuit which converts a dc voltage to a lower level with minimal power loss. The output is presented with a rapid switching of the input. The average output level (the dc portion) is lower than the input since the switch is on less than 100% of the time.

1. Set up the FET control box as shown in the circuit diagram below. Use the left FET in the box.

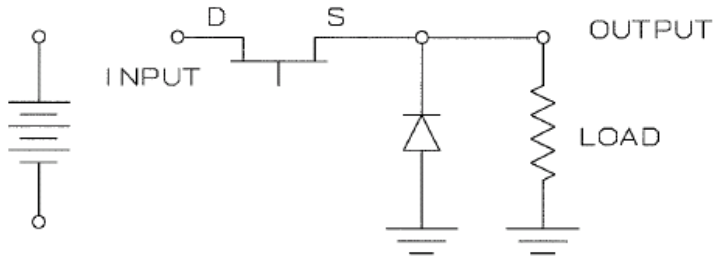


Figure 6. Simple dc-dc converter circuit

2. Observe the drain-to-source voltage. Turn the unit on. Adjust the output for 50 % duty ratio (50 % on time) and about 50 kHz. Disconnect the measuring device.

3. Connect a voltage source of 20 to 30 V to the input. Observe the output waveform and average voltage. Adjust the duty ratio and notice the change. Adjust the frequency and notice the change. Explain the results.

Part 3 -- PWM audio amplifier

1. Set up the PWM audio amplifier board with a 12 V dc input, CD audio or waveform generator input, and loudspeaker output. The volume should be set to the minimum.
2. Connect a voltage probe to the square wave output and a current probe to the loudspeaker. Turn the circuit on.
3. Adjust the volume to a low but audible level. Can you see the variation in the pulse widths?
4. Observe the change in behavior as the volume increases. Explain the behavior.

Discussion and Conclusions -- We have performed some basic experiments with power electronic converters. It is hoped that this introductory demonstration will help you work in the laboratory. The following group of study questions will be useful to consider in future reports:

1. In dc output converters, what is the relevance of RMS output voltage? What about average voltage? (Hint: consider the effects on loads which are purely resistive, and on loads that include low-pass filtering.)
2. Why do we operate the A and B SCRs one-half cycle apart for the full-wave rectifier?
3. For the simple dc-dc converter of Demonstration #1, explain how to predict the average value of output voltage from the input voltage, the switching frequency, and the switch duty ratio (the fraction of the time during which the switch is on).
4. Consider how an audio signal relates to the dc-dc converter case. What if the switch duty ratio is adjusted "slowly" over time?

In preparation for next week's experiment, please obtain a laboratory notebook. This can be any of several types, but *must be bound and must have pre-printed page numbers*.

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #1 -- Basic Rectifier Circuits

Objective -- Measurement techniques of power electronics will be studied in the context of half-wave and full-wave rectifier circuits. Load effects in diode circuits will be explored. The silicon controlled rectifier (SCR) will be introduced, with an R-C delay circuit for gate control.

Pre-Lab Assignment -- Read the discussion below. Study the procedure, and bring any questions to class. This experiment is not a long one, *provided that you are familiar with the procedure before beginning*. Solve the following, on a separate sheet, for submission as you enter the lab. Please note that your instructor may elect to provide a different problem.

1. A four-diode bridge is used with an ac voltage source with a RMS value of 480 V and a frequency of 60 Hz to produce a full-wave rectifier. The rectifier can be attached to any of several loads. **Sketch** the resistor voltage and diode current vs. time for the following three cases. **In these assignments and in the lab procedures, "sketch" means to draw the waveshape and its important features, without much regard for numerical values**. A sketch represents shape information, as opposed to detailed numerical data. You are encouraged to use tools such as *Matlab, Mathematica* or *MathCad* to generate graphs and solutions, but be sure to submit the commands used when you turn in the assignment. The cases are:

    a. A purely resistive load of about 40 Ω.

    b. A constant current source with a dc value of 10 A in series with a 25 Ω resistor.

    b. A 120 mH inductor in series with 30 Ω.

    c. An 800 μF capacitor in parallel with 40 Ω.

Discussion --

Introduction - A bridge rectifier circuit provides an ac-dc conversion function (rectification). But the waveforms and operation of such a circuit depend on the output load. Furthermore, diodes do not permit any control. This ties the dc output level to the ac input voltage. You have studied the properties of simple R-C, R-L, and R-L-C circuits in previous courses. Properties of "D-C" circuits (diode-capacitor circuits), as well as D-L, D-L-C, and various D-R-*x* circuits are nonlinear and cannot be studied with familiar linear methods. The behavior of these circuits provides a practical look at power electronic converters, both from the standpoint of energy conversion applications and from the standpoint of laboratory measurements. This is the focus of Experiment #1. Also, the SCR will be introduced, with an R-C circuit applied to provide a time delay in the action of its gate signal.

Basic Theory -- "Diode" is a general term for an electronic part with two terminals. The most common type of diode is the rectifier diode (or forward-conducting, reverse-blocking switch). Silicon P-N junction devices and metal-semiconductor junction devices known as "Schottky" diodes are used for this function. Modern silicon diodes have impressive ratings -- currents of more than 5000 A can be carried by units which can block reverse voltages of more than 6000 V. Actually, the analysis of diode-based circuits is direct given a single additional consideration. A rectifier diode acts as a switch: It is either on or off. Once this "switch state" is determined, circuit analysis can proceed along conventional lines. The state of a diode -- whether it is on or off -- is determined uniquely and immediately by the terminal conditions. If forward current flow is attempted, the diode will turn on, and will exhibit only a small residual voltage drop. If reverse current flow is attempted, the diode will turn off and only a minuscule residual current will flow. No third "gate" terminal is needed.

In the half-wave rectifier in Figure 1, the state of the diode depends on the input voltage polarity -- and also on the load. With no information about the load, it is *not possible* to predict either the load current or voltage (convince yourself of this; how would one assign the on or off state?). Let us begin with a resistive load, shown in Figure 2. In a resistor, the voltage and current are related by a constant ratio, and the load voltage is zero when the diode is off.

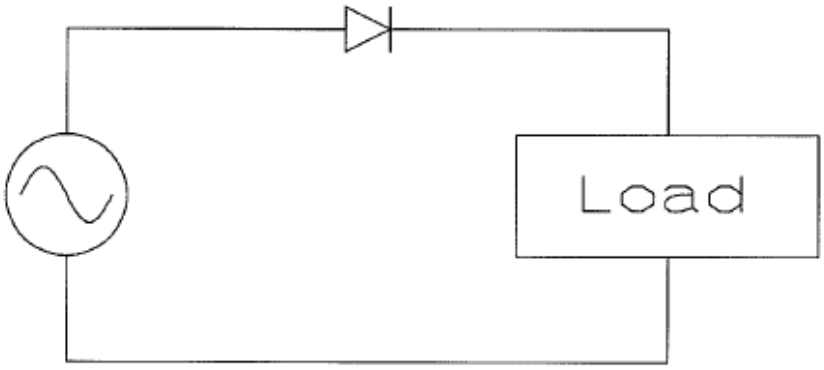


Figure 1. Basic half-wave rectifier diode circuit

One way to find the circuit action (even though we already know what the circuit does), is to take a "trial" approach. For example, consider the case when V_{in} is positive. We might guess that the diode is off. Then the voltage across the diode is just V_{in}, which is positive. But an off diode cannot block forward voltage, so the guess was wrong -- the diode must be on. Similarly, consider the case when V_{in} is negative, and guess that the diode is on. Then diode current must be negative. But the diode can only support forward current, and so again the guess is wrong. In reality, the correct guess can be made most of the time. The important principle is that all

currents and voltages in a diode circuit must be consistent with the restrictions imposed by the diodes. Even a complicated diode circuit combination can be understood quickly with the trial method. The essence of the method is this: Once the diode switch state is determined, the circuits are easy to analyze. If we do not know the switch state, we can just assign it in some assumed manner, then proceed with circuit analysis and check for consistency.

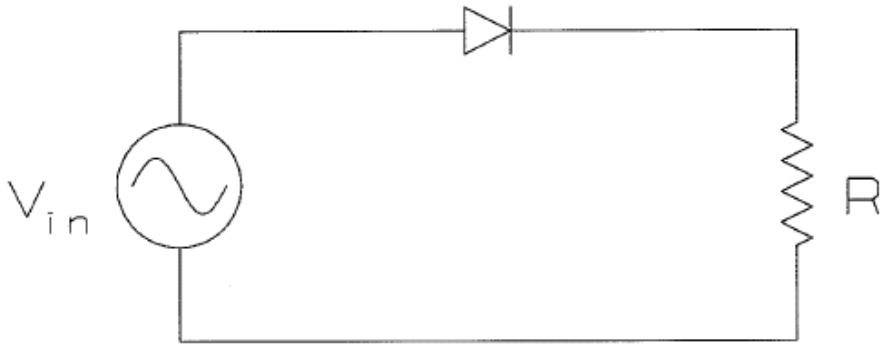


Figure 2. Half-wave rectifier circuit with resistive load

Now, look at the inductive load of Figure 3. Assume that the inductor is large. If current is initially flowing in the inductor, the diode is on. Inductor voltage V_L will be positive or negative, depending on the input voltage and the inductor current. Since there is current flow, the diode will stay on for some time regardless of the V_{in} value. If $v_L = L\frac{di_L}{dt}$ is negative, the inductor current will fall, possibly even to zero. The diode must stay on until the current reaches zero. This time will be delayed relative to the voltage zero-crossing.

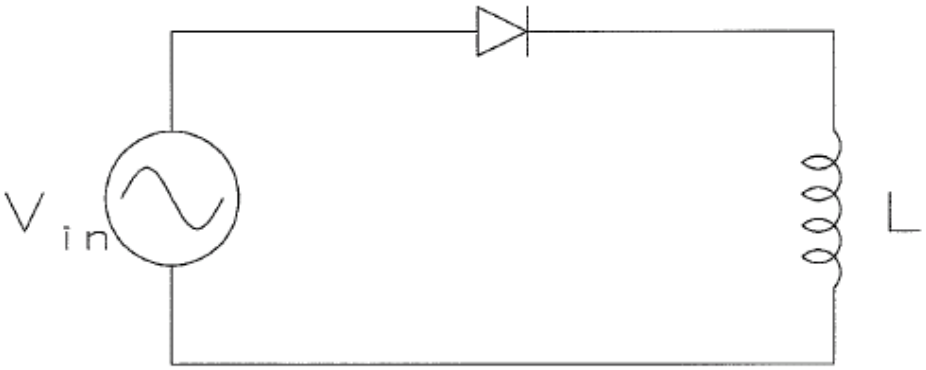


Figure 3. Half-wave circuit with inductive load

Capacitive loads bring about a different problem. Imagine the capacitor of Figure 4, fully charged and supplying energy to the resistor. As long as $V_{in} < V_{out}$, the diode will be off. When V_{in} becomes larger than V_{out},

the diode must turn on. But then a large forward current $i_C = C\frac{dv_c}{dt}$ will flow until V_{in} becomes less than V_{out}. Brief, large current spikes are characteristic of diode-capacitor circuits. Such waveforms are typical of the power supplies in cheap electronic equipment. This is not the best situation, since the large current spikes generate noise.

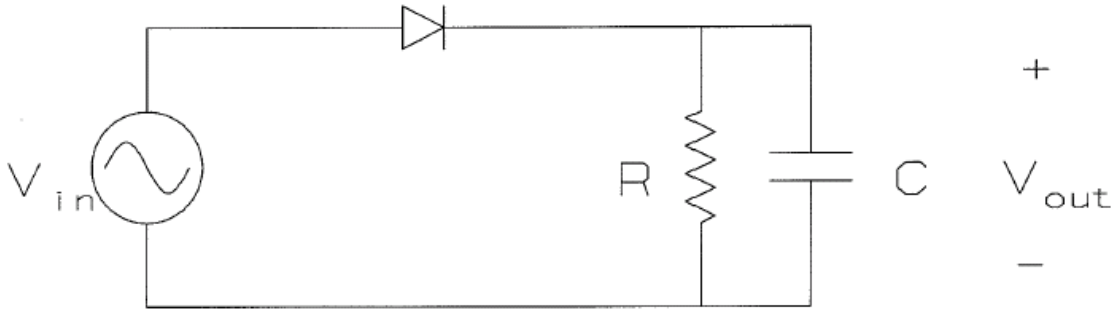


Figure 4. Half-wave circuit with capacitive load

So far, these circuits have no control. The switch necessary to add control still needs to carry current in only one direction, but must be capable of blocking forward voltage when required. The SCR provides this function. The SCR is a triode (three-terminal electronic device), built as a four-layer P-N-P-N configuration. It is called a "latching" device, because the on-state is self-sustaining once it is established. For our purposes, this means that the device is off until commanded to turn on and exactly equivalent to a diode once on. As in Demonstration #1, a set of SCRs can replace the diodes in a simple rectifier to bring about control.

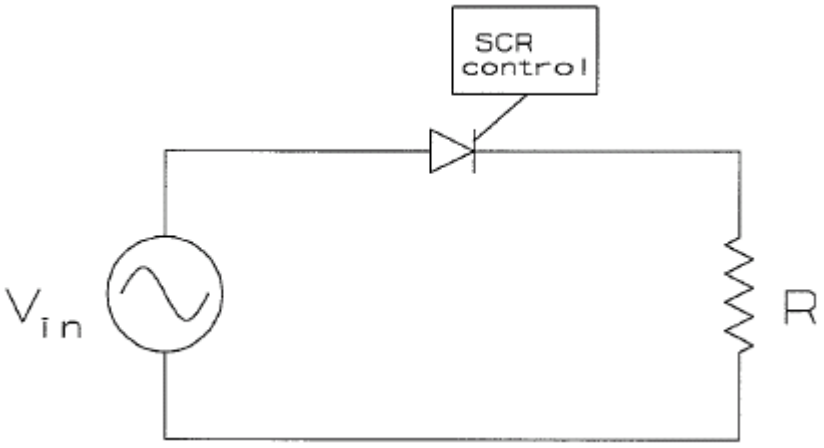


Figure 5. Basic SCR half-wave circuit with resistive load

The basis of rectifier control when SCRs are involved is turn-on delay. Consider the half-wave resistive circuit below. Turn-on of the SCR can be delayed to alter the waveshape. The turn-on delay is

traditionally measured in degrees relative to a full diode waveform. The action of this control is not hard to determine for a known load, since the input waveform is being switched on and off.

Measurement Issues -- In the Power Electronics Laboratory, measurement interpretation is an important ingredient. Many of the waveforms are not sinusoidal, so we will need to supplement conventional measurements with current waveforms, etc.

The input voltages in a rectifier circuit are sinusoidal ac waveforms, while the intended output is dc. Consider the ac input, which has an average value of zero. A root-mean-square (RMS) measurement would be appropriate for magnitude. Consider the rectifier output. The dc portion (the average value) is of interest. Typical laboratory meters provide the necessary capabilities. For example, the Fluke 45 multimeter displays average value whenever it is set for dc. When set to ac, this meter directs the input through a capacitor, and computes the RMS value of this filter output. Some of the important meter specifications are given in the table below.

Table I -- Summary Specifications of the Fluke 45 Multimeter

Quantity	Dc voltage	Ac voltage	Dc current	Ac current	Resistance
Measurement range	0.1 mV - ±1 kV average	0.1 mV - 750 V RMS	1 μA - 10 A average	1 μA - 10 A RMS	0.01 Ω - 300 MΩ
Valid frequencies	0 Hz (rejects ac above 20 Hz)	20 Hz - 100 kHz (rejects dc)	0 Hz (rejects ac above 20 Hz)	20 Hz - 20 kHz (rejects dc)	---
Error	±0.02% of reading, ± 2 digits	±0.2% of reading ± 10 digits	±0.05% of reading, ±2 digits	±2% of reading, ±10 digits	±0.05% of reading, ± 8 digits

Often, a waveform we measure will contain both dc and ac. The "true RMS" value might be useful in this case. Power is also an important quantity. The Yokogawa model 310 power analyzers will be useful for these kinds of measurements. These instruments perform the arithmetic necessary to find actual RMS and P_{ave} values. They have a voltage input, and include a 0.006 Ω series resistor for sensing current. A front view of the 2101 with its panel connections is shown in Figure 6. The voltage to be sensed is applied in parallel with the input. The output connection forces the current to flow through the sensing resistor. The shunt switch should be *off* in operation. Its purpose is to direct current around the meter if needed to avoid short high-current exposure. An input signal at 0 Hz and 0.5 Hz-100 kHz will give a true RMS display, as long as the value is within the meter range. Error is shown in Table II. Current from 5 mA to 20 A, and voltage from less than 1 V to 600 V can be measured.

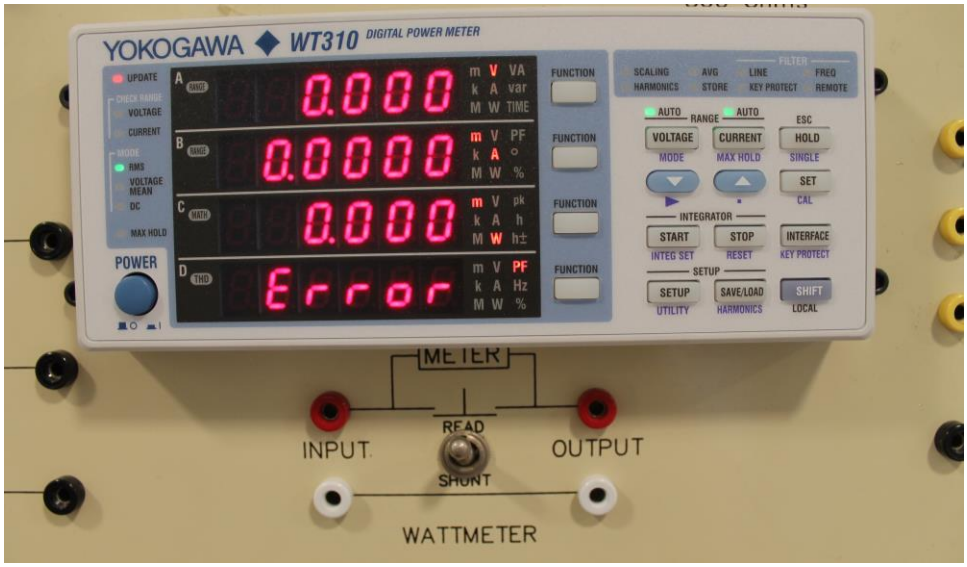


Figure 6. Front panel view of Yokogawa model 310 meter, mount, and connections.

Table II -- Summary Specifications of the Yokogawa 310 Wattmeters

Quantity	Voltage	Current	Power
Measurement Range	Auto ranging, up to 600 V rms, 1000 V peak	Auto ranging, up to 20 A rms, 40 A peak. Withstands 300 A for 20 ms with no damage.	True average power is computed and displayed from voltage and current data.
Valid frequencies	0 Hz, 0.5 Hz to 100 kHz	0 Hz, 0.5 Hz-100 kHz	0 Hz, 0.5 Hz- 100 kHz
Error, 0 & 45-1000 Hz	±0.1% of reading ±0.2% of range	±0.1% of reading ±0.2% of range	±0.2% of reading ±0.2% of range
Error, 1-10 kHz	±0.00007f% of reading ±0.3% of range	±0.00007f% of reading ±0.3% of range	±0.1% of reading ±0.000067(f-1000)% of reading ±0.3% of range
Error 10-100 kHz	±0.5% of reading ±0.5% of range ±0.00004(f-10000)% of reading	±0.5% of reading ±0.5% of range ±0.00004(f-10000)% of reading	±0.5% of reading ±0.0009(f-10000)% of reading ±0.5% of range
Other	Above is for unity power factor. Scale linearly to add 0.2% of S when pf=0.		

Like current magnitudes, current waveforms can be observed by using a low-impedance series sensing resistor. An alternative that does not introduce grounding problems is to sense the magnetic field produced by flowing charges. The laboratory is equipped with Hall-effect current probes for this function. These probes can measure current from 0 to 12 A (peak) at frequencies between 0 and 50 MHz. One drawback is that the probes have an internal dc offset which drifts for about twenty minutes during warm-up. A second is that they are delicate. You will probably find these drawbacks minor compared to the information that can be gained.

Timing is critical in the operation of most power converters. Since switches are the only means of control, the exact moment when a switch operates is a key piece of information. Consider the waveforms in the figure below. A sinusoidal waveform (perhaps the input voltage to a rectifier) serves as a timing reference. It is straightforward to measure the time shift between this wave's zero crossing and the turn-on rise of the switched signal below it. The example in the figure shows two 60 Hz waveforms. The time delay τ_d can be measured directly from the graph as about 1.25 ms. Since a full 360° degree period lasts 16.667 ms, an angle φ_d can be calculated from τ_d as

$$\phi_d = \frac{1.25ms}{16.667ms/cycle} x \frac{360°}{cycle} = 27°$$

One important detail in making this measurement is to make sure both oscilloscope traces are being triggered simultaneously. Make sure the scope is not in an "alternating" waveform mode, and that a single trigger signal (such as the power line) is used.

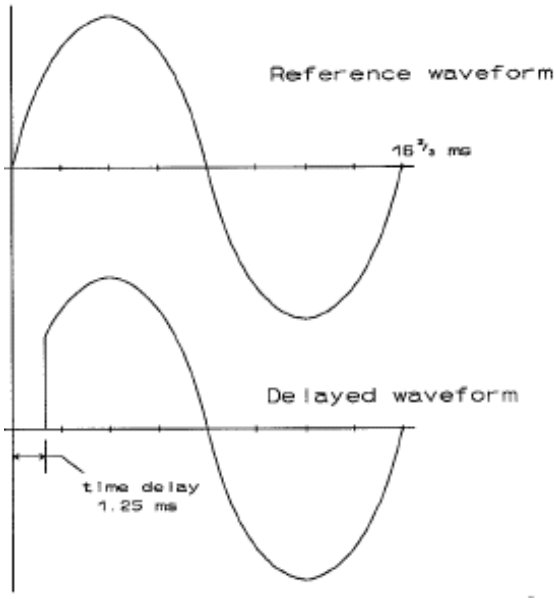


Figure 7. Phase delay measurement example

Procedure --

Part One -- The Diode

To permit testing with small inductors and capacitors, we will use a waveform generator for the early parts of today's experiments. Please use care in connecting and operating this instrument. It is not designed to supply high current.

1. Obtain a toroidal or audio power transformer from the lab selection.

2. Construct the circuit shown in Figure 8. Diodes should be standard 1N4001 or 1N4004 rectifiers, or similar.

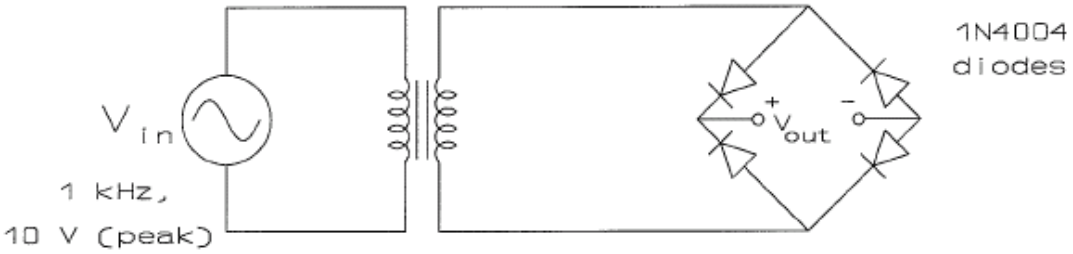


Figure 8. Rectifier test circuit

3. Be careful with ground connections. Set the waveform generator for approximately 1 kHz output at about 10 V peak. Observe V_{out} with the scope.

4. Quickly sketch the output waveform under "no load" conditions (the scope probe gives a slight load).

5. Load the bridge with a 500 Ω resistor (**compute the necessary power rating first!**). Observe and sketch the output waveform. Use the current probe to observe and sketch the current out of the transformer.

6. Connect an inductor, specified by your instructor, in series with the resistor. Observe and sketch the resistor voltage waveform and the current into the bridge. Measure the average resistor voltage with a multimeter.

7. Remove the R-L load. Instead, attach a 47 Ω resistor in series with an 1 μF capacitor. Place a 1 kΩ resistor across the capacitor terminals. Observe and sketch the capacitor voltage waveform and the bridge input current waveform. Also measure the average capacitor voltage.

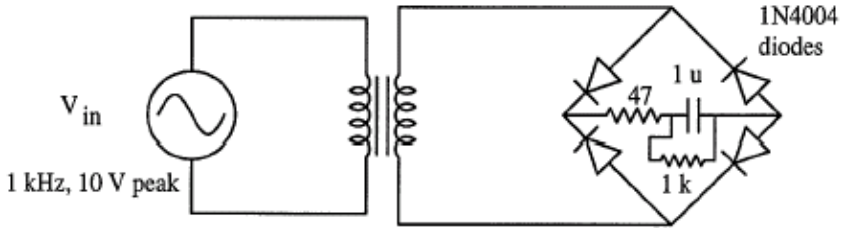


Figure 9. Rectifier test circuit with RC load.

Part 2 -- The SCR

In Demonstration #1, we saw a simple controlled rectifier example, and the waveforms which result. The gate control was described as a pulse, but was not observed or controlled. Today, we will actually operate an SCR with external control, in order to gain some feeling for the gate signals expected.

1. Construct the circuit shown below. The input source should be the 25 V 60 Hz supply.

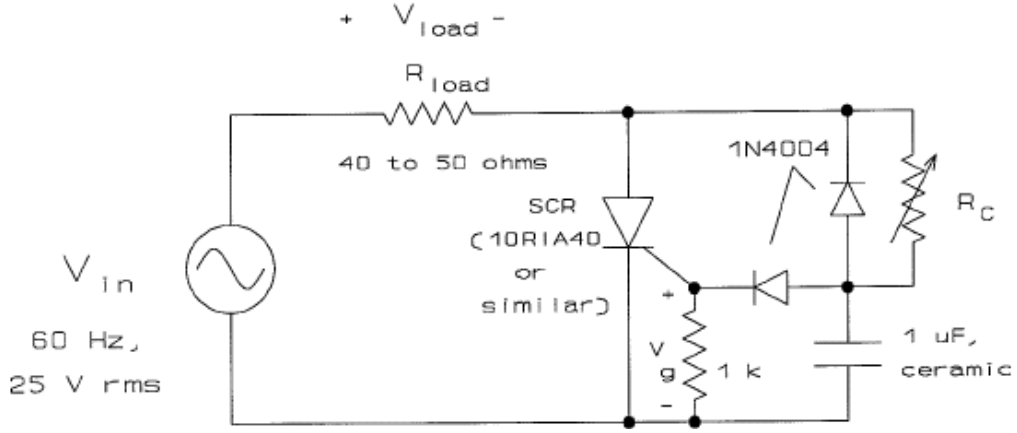


Figure 10. SCR rectifier test circuit

2. Use a 10 kΩ potentiometer or a resistor substitution box for R_c. Observe the V_g and V_{load} waveforms for R_c values of 0, 200, 400, 600, 800, 1000, and 1200 Ω. Sketch the two waveforms for two or three values of R_c. Measure the turn-on delay by comparing V_g or the gate current with V_{load} with the oscilloscope set for line triggering. Also, use the meters to measure the average and RMS values of V_{load} in all cases.

Study Questions:

1. For part 1, what waveforms would you expect for R, R-L, and R-C loads? Hint: think in terms of low-pass or high-pass filtering.
2. Compare the actual waveforms with those expected. Compute the actual circuit time constants, and discuss how they might affect the waveforms.
3. The R-L and R-C cases of part 1 represent different output filter arrangements for a rectifier circuit. Discuss the circumstances under which each of these will be effective for generation of dc output.
4. Comment on how the diode forward voltage drop (about 1V) affects the waveforms.
5. From the part 2 data, tabulate and plot the average load voltage vs. the value of R_c.
6. Compute the SCR gate circuit R-C time constants. Is the turn-on delay governed by RC?
7. The circuit shown in Fig. 10 is similar to that used in incandescent light dimmers. Can you suggest other applications?
8. Could a battery be substituted for the load resistor in Figure 10 to form a controlled charger?

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #2 -- Ac-Dc Conversion, Part I: Single-Phase Conversion

Objective -- This series of two experiments will examine the properties of controlled rectifiers, or ac-dc converters. The first experiment will concentrate on the single-phase (half-wave) circuit, while the second will examine two- and three-phase converters. Converter concepts such as source conversion and switch types will be studied. Popular applications such as battery chargers and dc motor drives will be introduced.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Solve the following on a separate sheet, for submission as you enter the lab. The dc motor can be modeled as a constant voltage proportional to speed. For this particular motor, the constant is 50 V per 1000 RPM. Please neglect any series inductance. Your instructor may elect to provide a different problem.

1. A dc motor control circuit is shown below. It is drawing an average current of 1 A. Study it, and answer the following.

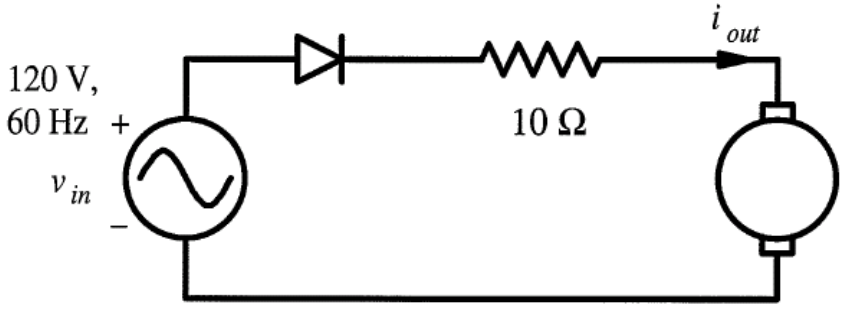


Figure 1. Motor supply circuit for pre-lab assignment

a) Sketch the waveform for the motor current.

b) Find the motor speed.

c) Now, given the motor speed, refine your current waveform to make it an accurate plot.

d) Repeat a), b) and c) using a four-diode bridge instead of a single diode.

Discussion --

Introduction -- In Experiment #1, you had a chance to become familiar with the basic action of the SCR, and also studied a number of non-resistive rectifier load circuits. The SCR was seen to support control, since it can block forward voltage until commanded to turn on. In today's experiment, the lab SCR boxes will be used to study controlled-rectifier action in more depth.

The 120 V ac waveform available to us in the lab (or the 25 V ac waveform at our transformer output) is a good voltage source. It provides a consistent sinusoidal ac voltage at current levels from 0 up to many Amperes. In a switched converter network, KVL will not allow us to connect this ac voltage source directly to a dc voltage source. Thus, if the objective is to obtain a controllable dc voltage, the ac source must be converted into current or buffered with some other part before it can be otherwise processed. Many types of loads act to provide current conversion. The source conversion concept is one subject of today's work.

Basic Theory -- Switching networks allow efficient conversion of electrical energy among various forms, but one disadvantage is that the KVL restriction does not allow direct energy conversion between different voltage sources. Similarly, energy cannot be transferred directly among different current sources by a switch network. To circumvent these drawbacks, it is necessary to provide intermediate conversions. For example, energy from a voltage source can be transferred to a current source, and then on to another voltage source.

A resistive load is a trivial example of current conversion: the incoming voltage produces a proportional resistor current. This is a far cry from a current source, but it is not a voltage source, and it does result in a conversion function. An inductive load is a better conversion example: the inductor voltage $V_L = L(di/dt)$ resists any change in current. If L is very large, any reasonable voltage will not alter the inductor current, and a current source is realized. A capacitive load has the opposite behavior. The capacitor current $i_C = C(dv/dt)$ responds whenever an attempt is made to change the capacitor voltage. If C is very large, no amount of current will change the voltage, and a voltage source is realized.

In Experiment #1, you saw three types of rectifier behavior. With a resistive load, the rectified waveform has a dc component, but has substantial ac components as well. With an inductive load, the current is closer to a fixed dc value. With a capacitive load, current is transferred in large spikes during a fraction of each cycle — a behavior which enhances noise and wear and tear on the electrical parts. The inductive circuit came closest to the desired current source conversion. Many electrical loads, especially motors, are inductive. As a result, most circuits behave in such a way that current does not change much over very short periods of time. In power electronics practice, this behavior, along with the desired source conversion function, means that most loads are treated as “short-term” current sources.

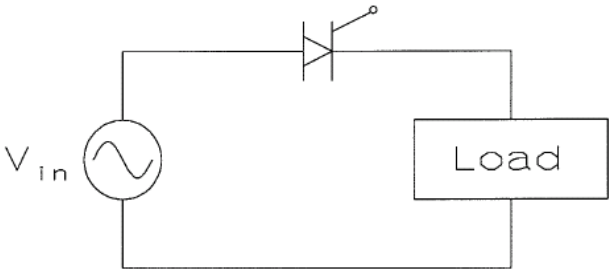


Figure 2. Basic single-phase controlled rectifier

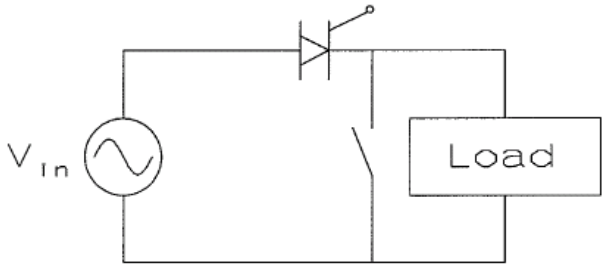


Figure 3. Single-phase converter with second switch for KCL

The basic single-phase controlled rectifier is shown in Figure 2. If the load is inductive, there is no KVL problem. But there is a KCL problem: the switch cannot be turned off if the load is inductive. To see that this is so, observe what happens to L(di/dt) when an attempt is made to turn the switch off. The current must approach zero almost instantaneously. The value of L(di/dt) is a huge negative voltage. In practice, this voltage will likely exceed the blocking capabilities of the switch, which will be damaged. A solution is to provide a second switch across the load, as shown in Figure 3. In simple ac-dc converters, this switch can be a diode, or it can be a second bidirectional-blocking forward-conducting device. Any load which resembles a current source can be taken into account by addition of this second switch.

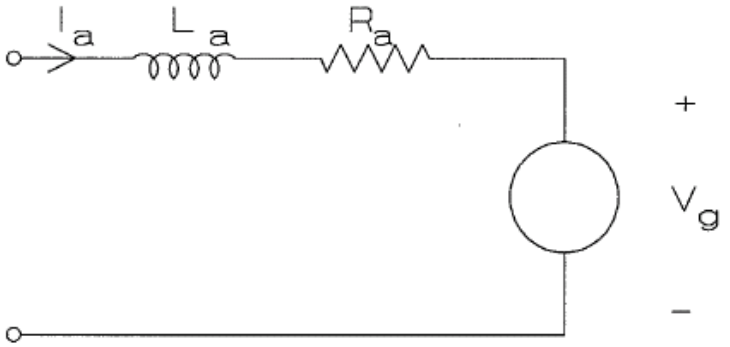


Figure 4. Basic dc motor circuit equivalent

Two popular loads for ac-dc converters are the dc motor and the rechargeable battery. The dc motor has an inductive model, as shown in Figure 4. The motor looks rather like a voltage source, but its windings provide series inductance. This combination has many current-source properties.

A battery provides a good dc voltage source. To support the desired energy conversion function, something must be placed in series with the battery for current conversion. A resistor can be used, as in the Pre-Lab, with a loss in efficiency. Alternatively, an inductor can be used, as in the circuit of Figure 5. Analysis of this circuit is not trivial. The controlled switch is on whenever V_{in} is positive. When it is on, the output current is given by

$$\frac{di_L(t)}{dt} = \frac{V_{in} - Ri_L - V_{battery}}{L}$$

When the controlled switch is off, inductor current is

$$\frac{di_L(t)}{dt} = \frac{-Ri_L + V_{battery}}{L}$$

If L is large, the current is approximately constant. These differential equations can be solved to give actual values of current. Charging current is controlled by the resistor value and also by the phase delay used to operate the SCR.

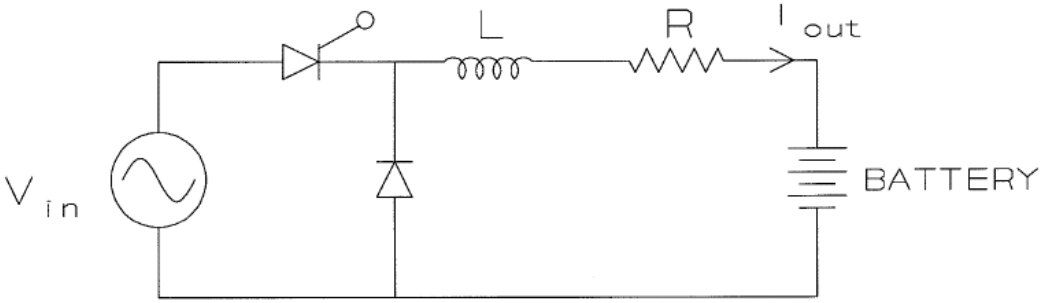


Figure 5. Single-phase battery charger with inductive filter

The form of circuit now expected for single-phase conversion appears in Figure 6. The switches are implemented with an SCR and a diode. In this case, the output voltage is V_{in} whenever the SCR is on, and zero when it is off. The SCR turns off automatically when $V_{in} \le 0$. The voltage waveform is a familiar one: a half-wave rectified waveform, possibly with a delayed turn-on. The voltage has an average value given by

$$V_{out(ave)} = \frac{1}{2\pi}\int_{\alpha}^{\pi} \sqrt{2}V_{ac(RMS)} \sin\theta \, d\theta$$

where α is the angle of delay before the SCR is turned on. This integral can be computed to give

$$V_{out(ave)} = \frac{\sqrt{2}V_{ac(RMS)}}{2\pi}(1 + \cos\ \alpha)$$

Since the output is a dc current source, average power exists only at dc, and is simply $I_{out} \cdot V_{out(ave)}$.

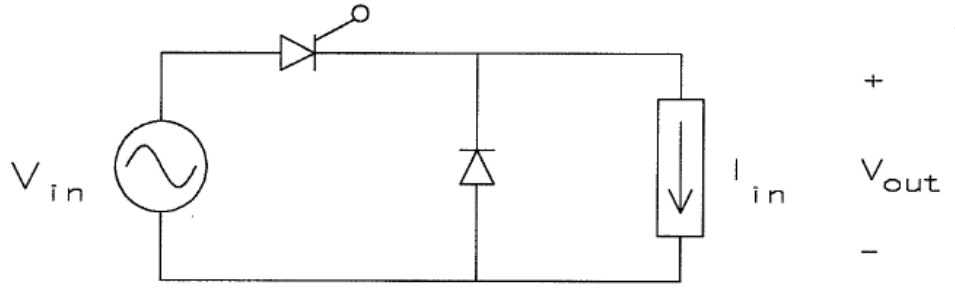


Figure 6. A single-phase ac voltage to dc current converter

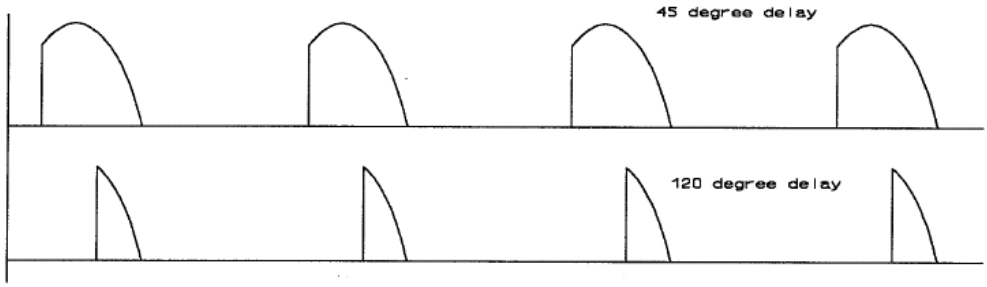


Figure 7. Typical output voltage waveforms

Procedure --

Part 1: Ideal R-L load

1. Connect phase "A" of the nominal 25 V 60 Hz supply, the SCR labelled "A" in the SCR box, and a resistive load, as shown below. Estimate the required resistor power rating, and abide by it. Remember that the source neutral is grounded. Record the actual RMS value of the source voltage.

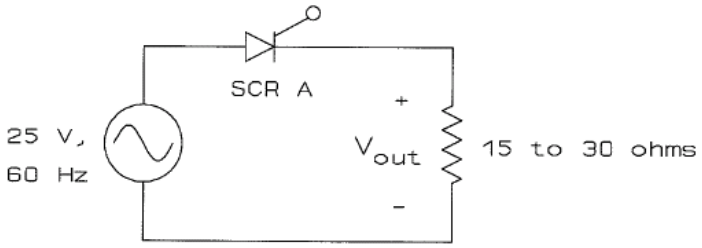


Figure 8. SCR test circuit, resistive load

2. Set the SCR master delay to zero (i.e. set it to act as a diode). Observe the output and load voltage waveforms. Measure the following output parameters and sketch the voltage waveform: $V_{out(ave)}$, $V_{out(rms)}$, $V_{load(rms)}$ (notice that the output and load are the same in Fig. 8). The phase delay setting is not relevant for this experiment.

3. Repeat #2 for time delays corresponding to approximately 45°, 90°, and 135°, respectively. *Sketch* just one or two typical waveforms, rather than the whole series.

4. Place an inductor specified by your instructor in series with the resistor, as shown below. Observe the

resistor voltage waveform. Repeat #2 and #3 above for this new circuit. Record input and output power data so you can compute efficiency.

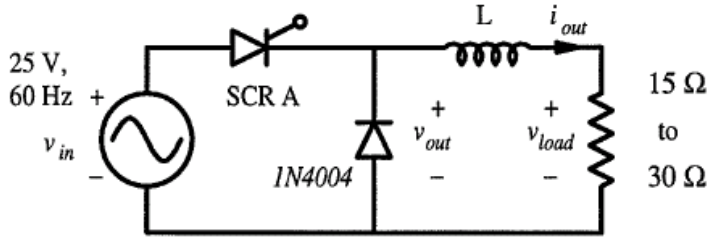


Figure 9. SCR test circuit, series R-L load

Part 2 -- A battery load

1. Connect a rechargeable battery in the circuit of Figure 10.

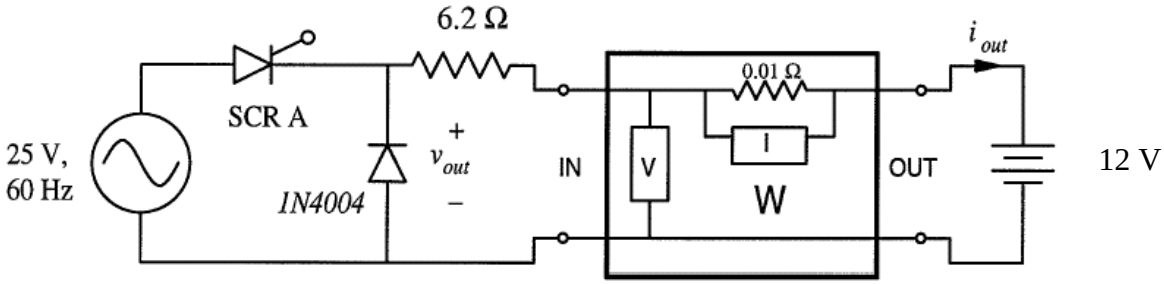


Figure 10. SCR test circuit with battery charger load

2. Measure battery currents $I_{out(ave)}$ with your multimeter and $I_{out(rms)}$ with a wattmeter. Do this and record the master delay time for at least four different SCR delay angles. Observe and sketch the resistor current waveform at one intermediate SCR delay angle. Record information to permit computation of efficiency. What data will be needed?

3. Add an inductor in series with the load and then repeat step 2.

Optional Part 3 -- Dc motor load (to be performed only if extra time is available)

1. Connect a small dc motor in place of the battery in Fig. 10.

2. Observe and measure current and motor voltage for at least four values of SCR phase delay.

Study Questions --

1. For the loads of Part 1, tabulate and plot $V_{out(ave)}$ and $V_{out(rms)}$ vs. the SCR delay, computed in terms of angle. Compute a theoretical result, and compare it to the data. Do these agree?

2. For the battery load in Part 2, tabulate and plot $I_{out(ave)}$ and $I_{out(RMS)}$ vs. the SCR delay angle. Again consider whether your results are consistent with theoretical expectations.

3. Why is the "flyback" diode included in today's circuits?

4. Compute the efficiency of the battery charger studied here.

5. Comment on how the diode and SCR forward voltage drops affect your results.

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #3 -- Ac-Dc Conversion, Part II: Polyphase Conversion

Objective -- This second in a series of two experiments will examine the properties of ac-dc converters with polyphase input sources. The experiment will concentrate on input voltage sources, as these are the mainstay of modern electric power system supplies. The midpoint converter will be the focus of this experiment, and will be tested with inductive loads including a dc motor.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Solve the following on a separate sheet, for submission as you enter the lab session. Your instructor may elect to assign a different problem.

1. An ac-dc conversion circuit for battery charging is shown below. The input voltage V_a is a sinusoidal voltage with an RMS value of 25 V. You may assign a resistor value if you wish.

   a) Plot V_{out} vs. time and the input current from V_a vs. time for this circuit.

   b) Compute the average and RMS values of V_{out}.

   c) How would V_{out}, as well as its average and RMS values, change if the load is made a current source?

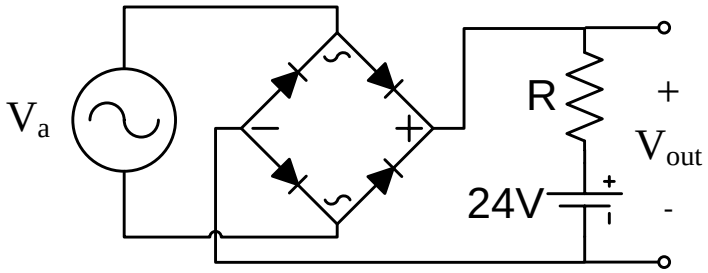


Figure 1. Ac-dc converter for pre-lab assignment.

Discussion --

Introduction -- In Experiment #2, the circuits had a single SCR in a half-wave rectifier configuration. A flyback diode was needed to provide a current path when the SCR turned off. The simple half-wave circuit transferred energy to the load only a small fraction of the time -- at least half the time, the source is unconnected. Since polyphase sources are so common, the half-wave circuit seems ineffective.

A polyphase ac voltage source is a set of *m* sinusoidal ac voltages, each equal in amplitude and frequency, spaced equally in phase through a full 360°. The most common source is three-phase, with three voltages 120° apart. Six-phase sources are also common, and have six voltages at 0°, 60°, 120°, 180°, 240°, and 300°. It turns out that any polyphase set with *m* odd can be converted to a polyphase set with 2*m* phases by means of center-tapped transformers. The even number of phases results from the inverting portion of the transformer winding.

The definition of polyphase sources also applies to the "two-phase" case -- two voltages, each 180° apart. While this is consistent, a confusing historical nomenclature has arisen. In communication systems, a "quadrature" voltage source is a set of two, spaced by 90°-- a sine and a cosine. Quadrature sources were used in many early power systems, and gave rise to an unfortunate use of the term "two-phase" for such a source. The usage continues, even though most "two-phase" equipment is actually constructed as four-phase. We will use the term two-phase to refer to a set of two voltages 180° apart rather than to a quadrature set. In today's experiment, the lab SCR boxes will be used to study controlled-rectifier action with two and three-phase sources.

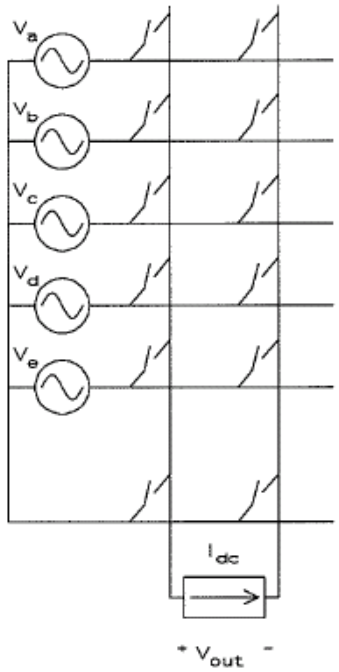


Figure 2. Polyphase ac to dc converter

Basic Theory -- When multiple input sources are available for ac-dc converters, it is natural to use all of them. The circuit below shows the most general such converter -- an *m*-phase to dc converter. Today, we will examine a slightly simplified version of this converter -- the one in which there is a common neutral connection between input and output. This is called a "midpoint" converter, and appears below.

In the midpoint converter, the KVL and KCL restrictions are reasonably clear: no more than one switch may be on at any time, and one switch must be on if the load current is not zero. This implies that $\Sigma\, q_i \leq 1$. If the load is a current source, $\Sigma\, q_i = 1$, and the switching functions are said to form a "complete set." We want to operate the switches so that the dc value is maximized and the unwanted ac components are minimized. It can be proved that if the switching frequency is chosen to equal ω_{in}, the best choice of switching functions is to follow the polyphase input: each switch is on 1/*m* of the time, and switching functions are spaced 360°/*m* apart. The dc

output component can be controlled by adjusting the phase of the switching functions. The output voltage is given by

$$V_{out} = \sum_{i=1}^{m} V_i h_i$$

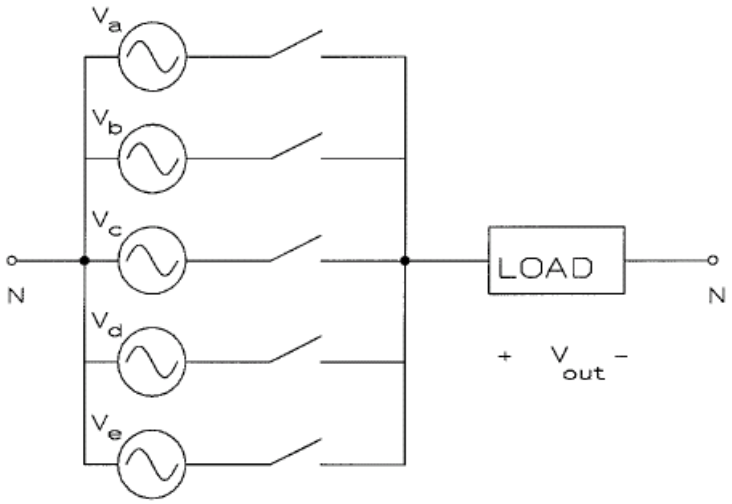


Figure 3. Polyphase midpoint ac-dc converter

This gives a complicated series, in the form

$$V_{out} = \left(\frac{1}{m} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin\left(n\pi/m\right)}{n} \cos\left(n\omega_{in}t + n\phi_0\right) \right) V_0 \cos(\omega_{in}t)$$
$$+ \left(\frac{1}{m} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin\left(n\pi/m\right)}{n} \cos\left(n\omega_{in}t + n\phi_0 - \frac{2\pi n}{m}\right) \right) V_0 \cos\left(\omega_{in}t - \frac{2\pi}{m}\right)$$
$$+ \left(\frac{1}{m} + \frac{2}{\pi} \sum_{n=1}^{\infty} \frac{\sin\left(n\pi/m\right)}{n} \cos\left(n\omega_{in}t + n\phi_0 - \frac{4\pi n}{m}\right) \right) V_0 \cos\left(\omega_{in}t - \frac{4\pi}{m}\right)$$
$$+ \ldots$$

The dc component appears in the n=1 term, and is given by

$$V_{out(ave)} = \frac{2}{\pi} \sin\left(\frac{\pi}{m}\right) \frac{V_0}{2} \cos\left(\phi_0\right) + \frac{2}{\pi} \sin\left(\frac{\pi}{m}\right) \frac{V_0}{2} \cos\left(\phi_0\right) + \ldots$$

This, in turn, can be simplified to give

$$V_{out(ave)} = \frac{m}{\pi} \sin\left(\frac{\pi}{m}\right) \cos\left(\phi_0\right), m \geq 2$$

Notice that $V_{out(ave)}$ depends on φ, where φ is defined as the delay angle between any voltage and the switching function associated with it. The result is a controlled rectifier. Unwanted components appear at frequencies which are multiples of $m\omega_{in}$. This is a better situation than the single-phase case, which had a lower dc

component and large unwanted components at multiples of ω_{in}. The unwanted components can be reduced by increasing *m*. In large power system applications such as high-voltage dc transmission, as many as 48 phases are used at the converter input, to reduce unwanted components.

In this experiment, the two-phase source will be obtained by means of a center tapped transformer (the one-phase/two-phase switch setting on the bench front panel). The standard 120 V ac line is supplied to the transformer, and direct and inverted outputs are provided. The SCR switching functions must be spaced 180° apart (1/2 cycle) in order to best effect conversion. The three-phase source will be stepped down from laboratory power. In this case, the SCR control box will need to be adjusted to provide the necessary 120° delays, based on phase A for a reference.

Procedure --

Part 1: Two-phase converter

1. Set up the 25 V 60 Hz supply for two-phase output. Remember that the output neutral is grounded.

2 Connect the SCRs labelled "A" and "B" in the SCR box with a resistive load, as shown below. Estimate the required resistor power rating, and abide by it. Set the phase delay on the SCR box to 8 1/3 ms to provide for 60 Hz input.

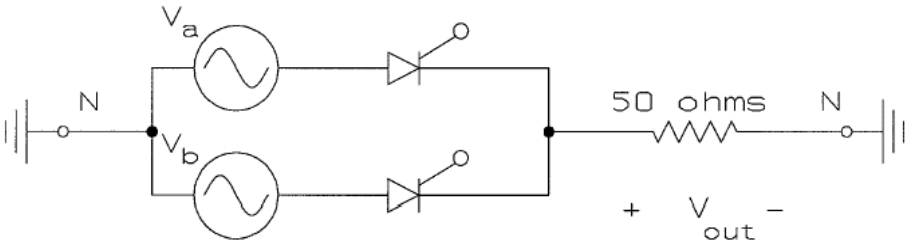


Figure 4. Two-phase SCR test circuit

3. Set the SCR master delay to zero (i.e. set it to act as a diode). Observe the output voltage waveform. Record $V_{out(rms)}$ and $V_{out(ave)}$ and sketch the output voltage waveform.

4. Repeat #3 for time delays corresponding to approximately 30°, 60°, 90°, 120°, and 180°. Sketch just one typical waveform, rather than the whole series.

Part 2 -- Three-phase converter

1. Connect the 25 V 60 Hz supply and SCR box for three-phase operation. Plug the SCR box into the outlet labeled Phase A on the power panel at your bench. Adjust the phase delay for 5.55 ms to reflect the need for 1/3 cycle delay at 60 Hz.

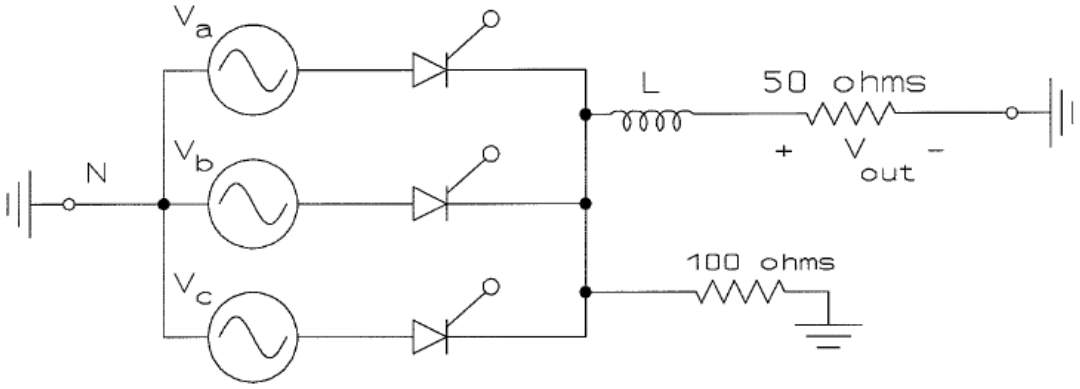


Figure 5. Three-phase SCR converter test circuit

2. Apply 120/208 V 3φ power to the three-phase setup.
3. Set the SCR master delay to zero (i.e. set it to act as a diode). Observe the output voltage waveform. Measure $V_{out(ave)}$ and $V_{out(rms)}$, and sketch the waveform.
4. Repeat #3 for master time delays corresponding to approximately 45°, 90°, and 135°. Sketch just one typical waveform, rather than the whole series.
5. If there is time, repeat #3 with a dc motor as the converter load, except set the master delay at about 120° initially. Observe and sketch the motor current and voltage waveforms with no motor shaft load.
6. Add some shaft load, and observe current and voltage waveform changes. Record your observations.

Study Questions --

1. For each of the load and source combinations, tabulate and plot $V_{out(ave)}$ and $V_{out(rms)}$ vs. the SCR delay angle. What would you expect in theory? How well do your results agree with the theory?
2. For one delay angle (pick 45°, for instance), plot $V_{out(ave)}$ and $V_{out(rms)}$ vs. the number of input phases (you have data for one, two, and three). What do you expect to happen when more phases are used?
3. Why is the flyback diode *not* included in today's circuits?
4. A bridge converter implements the full switch matrix of Fig. 2, as in the pre-lab (Figure 1). How would $V_{out(ave)}$ be affected by the use of a bridge rather than a midpoint converter?

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EXPERIMENT #4 -- Dc-Dc Conversion, Part I: One-Quadrant Converters

Objective -- This series of two experiments will examine dc-dc conversion circuits and their major applications. Pulse width control is the basic technique for operating such converters, and this method will be used. The first experiment in the series examines most of the simple one-quadrant converters (buck, boost, buck-boost, boost-buck). The second examines dc-dc converters for motor drives.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. The procedure is very measurement intensive, so you should be ready to record and organize data quickly. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different problem.

1. A dc-dc buck-boost converter is shown below. It has V_{in} = 20 V, and a value of V_{out} which depends on the choice of duty ratio D_1.

   a) Calculate V_{out} for duty ratios (on switch #1) of 0.25, 0.5, and 0.75.

   b) If the load is 10 Ω, find $I_{in(ave)}$ and $P_{out(ave)}$, for the duty ratio values of (a).

   c) For the duty ratios of part (a) and the 10 Ω load, what are the values of inductor current?

   d) For a duty ratio of 0.75, sketch the current through switch #1.

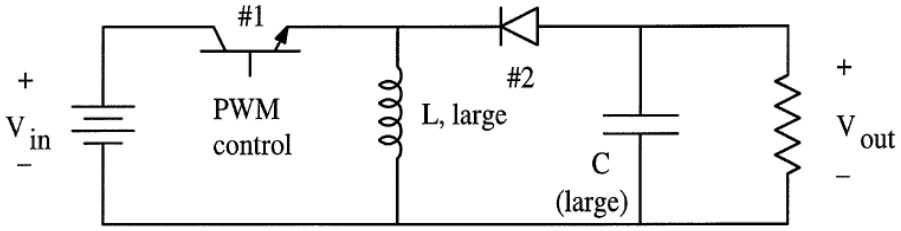


Figure 1. Dc-dc converter for pre-lab assignment.

Discussion --

The general two-input two-output switch network has four switches. It will provide dc-dc conversion if a dc source is used at the input and pulse width control is used to operate the switches. In this experiment, some common one-quadrant converters will be implemented and tested. Most commercial dc switching power supplies use one of these one-quadrant methods as their basis. The main tool of the experiment is our FET switch control unit. This box contains two sets of power switches -- a pair of power metal-oxide-semiconductor field-effect transistors and a pair of diodes -- along with switching function circuitry for the FETs. The circuitry provides direct front-panel control of the switching function frequency and duty ratio. The power devices in the FET control box are fully isolated to permit their use in any switching circuit.

The FET is a bidirectional-conducting forward-blocking switch, and so can be used in place of the simple forward-conducting forward-blocking switch needed for one-quadrant dc-dc conversion. In this experiment, we will set up two one-quadrant circuits and characterize their operation. The converters we will build are actually fairly sophisticated, with fast switching functions and switching frequencies as high as 200 kHz.

Basic Theory -- In theory discussions, dc-dc converters are depicted as providing energy transfer between two ideal sources. In practice, one of the sources is almost always implemented as an electrical energy storage element. For example, the buck converter stores energy in an inductor when the controlling switch is on, and discharges that energy through the load when the controlling switch is off. An objective is to keep energy flow into the load nearly constant as the switches operate. Many converters apply nearly constant voltages or currents to the storage elements.

The general dc-dc converter is shown in Figure 2. The four switches must be operated so as not to violate KVL or KCL. Several one-quadrant dc-dc converters can be built from simplified versions of this matrix. The four major ones are shown in Figure 3. Notice that the combination converters (buck-boost and boost-buck) are really two matrices connected together. As long as the inductors and capacitors maintain voltage and current levels, KVL and KCL requirements must be accounted for in switch operation. When $V_C > 0$ and $I_L > 0$, the two switches must have $q_1 + q_2 = 1$, and $D_1 + D_2 = 1$. In every dc-dc converter, the output waveform represents a scaling of one or more switching functions. Average values are therefore determined by the switching function duty ratios.

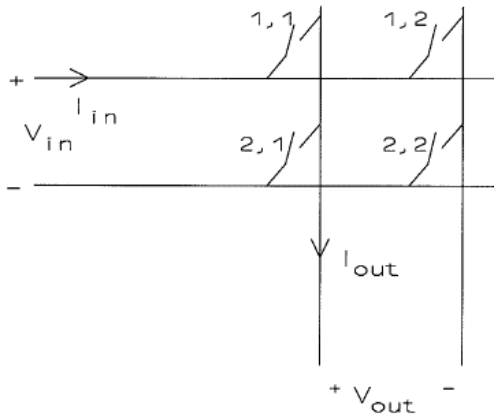


Figure 2. General dc-dc converter matrix

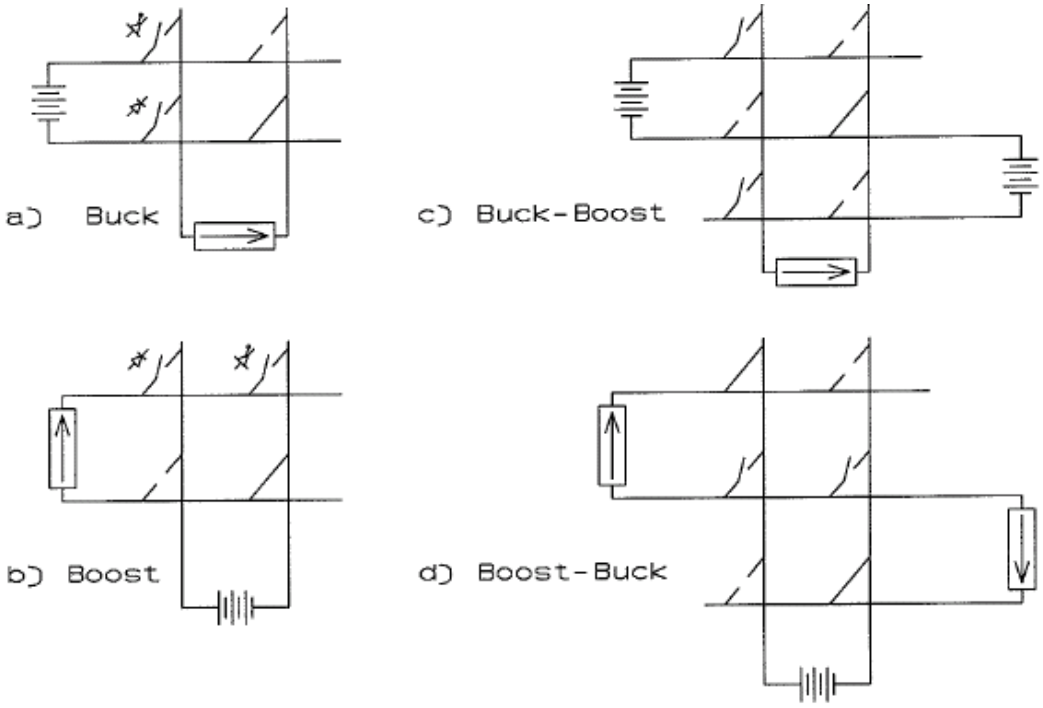


Figure 3. Major one-quadrant dc-dc converters

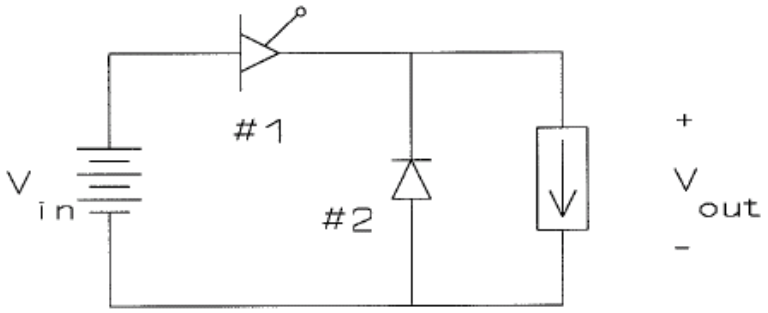


Figure 4. The buck converter

For example, the buck converter has $V_{out} = q_1 V_{in}$, which in Fourier form is

$$V_{out} = V_{in}\left[D_1 + \frac{2}{\pi}\sum_{n=1}^{\infty}\frac{\sin(n\pi D_1)}{n}\cos(n\omega_{switch}t + n\phi_0)\right]$$

The average value of this series is $D_1 V_{in}$. Unwanted Fourier components appear at the switching frequency f_{switch} and its multiples. The largest unwanted component is

$$\frac{2}{\pi}\sin(\pi D_1)\cos(\omega_{switch}t + \phi_0)$$

A special advantage of dc-dc converters is the arbitrary value of f_{switch}. This frequency can be chosen in any manner, as long as the desired duty ratio can be provided. Some common constraints used to select the switching frequency include:

-- The speed of switch transition from on to off or off to on.

-- Allowed size and weight of inductors and capacitors.

-- Sensitivity of the load or source to ripple voltages and currents.

-- Radio-frequency interference caused by high-frequency components.

Modern dc-dc converters are implemented with GTOs and FETs. Each of these has a preferred switching frequency.

-- GTO-based dc-dc converters (used for dc motor drives and very high power conversion): up to several kilohertz.

-- FET-based dc-dc converters: up to 2 MHz or more.

-- FET-based "resonant" dc-dc converters: up to 20 MHz or more.

In general, as switching frequencies increase, the values of *dv/dt* and *di/dt* values also increase, and smaller inductors and capacitors can be used without sacrifice in performance.

Procedure --

Part 1: Buck converter

1. Set up the FET control box as a buck dc-dc converter. Use the left devices. The red jack is the FET drain lead (the "forward" switch terminal). Be sure to provide the capacitor shown across the input power supply. The capacitor should be placed as close to the FET box as possible so that the inductance of the wires to the FET will be very low. The HP 6060 load box can be used as appropriate.

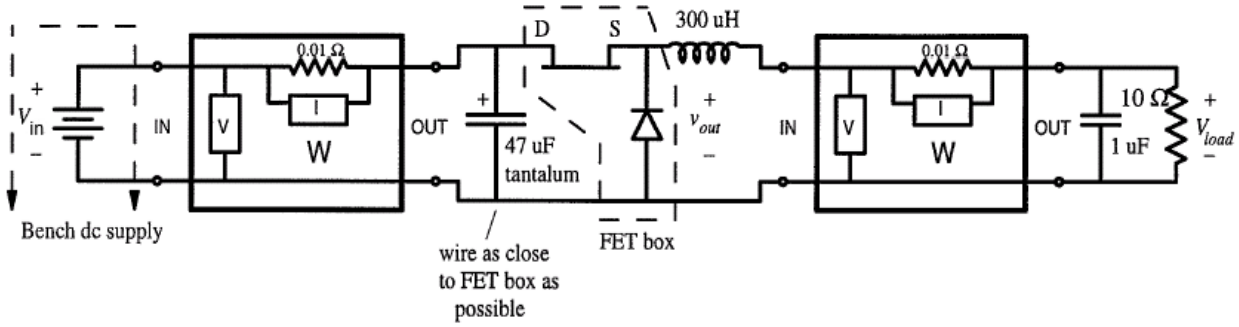


Figure 5. Buck converter test circuit

2. Set the power supply current limit for about 3 A, and the voltage to 12 V. Set the duty ratio dial on the FET box to the center position (5.00). Connect oscilloscope leads across the load, V_{load}, and across the output terminals, V_{out}. The oscilloscope input coupling should be set to "dc."

3. Turn on the FET box and the input power supply.

4. Set f_{switch} to about 100 kHz. Notice that the V_{out} waveform allows easy measurement of f_{switch}.

5. Confirm that the duty ratio is close to 50%. Sketch the V_{out} and V_{load} waveforms.

6. Use the oscilloscope to measure the peak-to-peak ripple on V_{load} at duty ratios of 10%, 50%, and 90%. The ripple measurement can be performed by setting the oscilloscope input coupling to "ac," and expanding the voltage scale. Don't forget to return the coupling to "dc" when you finish the ripple measurement.

7. Measure average values of V_{load} and I_{in} at duty ratios of close to 10%, 30%, 50%, 70%, and 90%. Use your multimeter for $V_{load(ave)}$. The meters on the Kenwood power supply monitor average values. Record the duty ratio, the input and output RMS voltage and current from the wattmeters, and the power.

8. Change f_{switch} to 5 kHz. Observe the output current rise and fall. Note the current value at a few points in the waveform. The objective is to determine di/dt as the basis for estimating the inductance in your report.

Part 2 -- Buck-boost converter

1. Set up the FET control box as a buck-boost dc-dc converter, as shown below. Again, remember that the red jack is the FET drain lead.

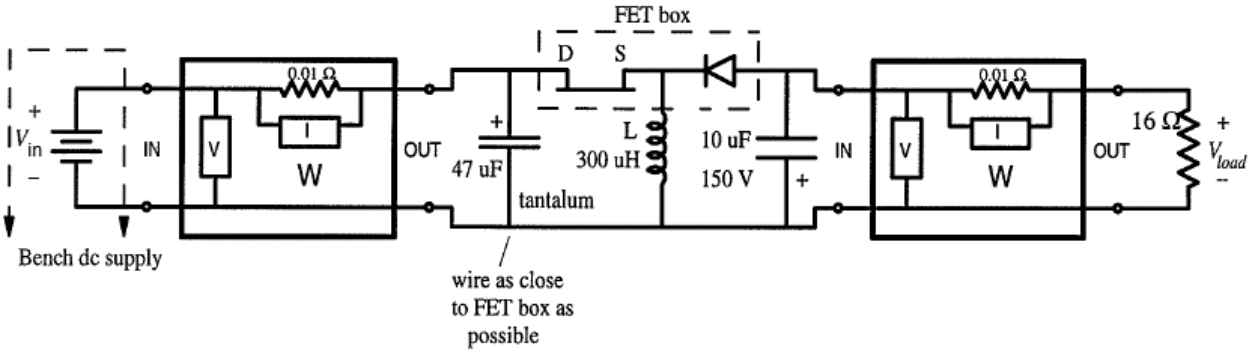


Figure 6. Buck-boost test circuit

2. Set the power supply current limit for about 3 A, and the voltage to 12 V. Set the FET box duty ratio dial to the zero position. Connect oscilloscope leads across the load resistor and across the inductor.

3. Turn on the FET box and the input power supply. Set f_{switch} to about 100 kHz.

4. Set the duty ratio to about 50%, and confirm this. Sketch the inductor voltage waveform. Use the current probe to sketch the inductor current waveform. Observe and sketch the load voltage waveform.

5. Measure average and RMS values of V_{load} and I_{in} at duty ratios of close to 20%, 40%, 50%, 60%, and 70%. Confirm whether or not the output polarity is reversed. Record power readings as well. **The output voltage can become high quickly with $D > 60\%$, so be careful.**

Study Questions --

1. Tabulate your data in an organized fashion. Compare the RMS readings from the wattmeters with the various average readings. Do they agree?

2. Compute and tabulate ratios of $V_{load(ave)}/V_{in}$ for these converters for your data. Are the results consistent with duty ratio settings?

3. Estimate the *average* input and output power from the *average* readings of V_{load} and I_{in} for each operating condition. Compare these results to the wattmeter readings. Calculate efficiency, P_{out}/P_{in}, from the wattmeter readings.

4. Estimate the inductor value from the measurements of the current waveform in the buck converter. Use this value to compute an expected load voltage ripple at 100 kHz. How do your results compare with the data? If the inductor value were to double, how would this affect the behavior of these circuits?

5. What is the impact if a student tries to test a boost or buck-boost circuit under no-load conditions?

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #5 -- Dc-Dc Conversion, Part II: Converters for Motor Drives

Objective -- This second in a series of two experiments will examine the operation of dc-dc converters in the context of motor drives. Motor drives are typical applications of multi-quadrant dc-dc converters. Motors are not true current sources. Some types of switching motor drives take advantage of this fact in their operation. Others are directly equivalent to the dc-dc converters studied so far.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different problem.

1. A dc-dc buck converter has 48 V input. This converter is connected to a dc motor that spins at 2000 RPM for 24 V input, 1000 RPM for 12 V input, and follows a linear speed relation at other voltages. The motor is characterized by a voltage source in series with an inductance and resistance. The resistance is 0.5 Ω. The inductance is 10 mH. The converter switches at 20 kHz. At 2000 RPM with no mechanical load, the motor draws 0.5 A.

   a) What is the no-load motor speed at 10% duty ratio? At 50% duty ratio?

   b) The buck converter has been set to operate the motor at 2500 RPM, when the FET abruptly turns off. Sketch the motor current after this turn-off. Where in the circuit does the current flow? When does it equal zero? (You may assume the motor emf remains constant after the FET turns off)

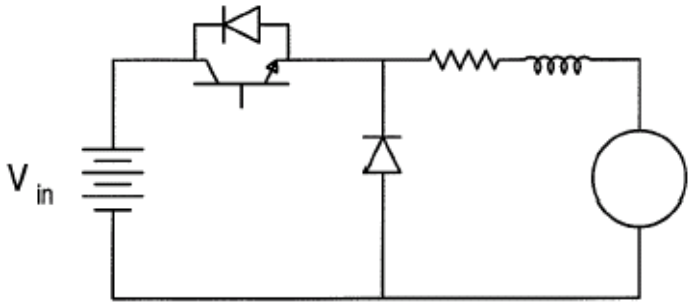


Figure 1. Dc-dc converter for pre-lab assignment.

Discussion --

Introduction -- One common example of the applications of dc-dc converters is the switching power supply, in which a single rectified waveform can be converted with minimal loss into a variety of dc voltages. This makes switching dc supplies common in computer systems, where three or four different dc voltage levels are often needed. Dc power supplies are usually always based on one-quadrant circuits: the output power and current are positive at all times. A second major application of switching dc supplies is the dc motor drive. In this

case, dc power from some source (perhaps a rectifier) is to be controlled in order to achieve a mechanical function. Converters or other electric controllers used for such applications are called "motor drives," and dc-dc converters are often called "chopper drives" in this context. Motor drives range from units rated at a few watts (for motors in printers, computer disk drives, and CD players) to units rated at thousands of horsepower (used in locomotives, ships, and large pumps).

In large dc motor drives, the rotating kinetic energy of a large motor is considerable, and in a braking situation, this energy must be removed. The energy can be converted to heat and lost, as it is in gasoline engine vehicles, or it can be directed back to the energy source for recovery. This "regeneration" energy can be controlled only with multi-quadrant circuits. Multi-quadrant dc-dc converters are the main topic of this experiment.

Basic Theory -- The equivalent circuit of a dc motor is repeated in Figure 2. Rotation of the motor produces a "back EMF," equal to $k\omega i_f$, where k is some constant, ω is the motor shaft speed in rad/s, and i_f is the "field exciting current" or some other variable representing the magnetic field strength inside the motor. The back EMF, symbol V_g, appears in series with the inductance and resistance of the motor windings. If a voltage V_t is applied to the motor terminals, a current $(V_t - V_g)/R_a$ will flow in the steady state. This current sends power into the motor, which is converted to mechanical energy. The input power accelerates the motor until the electrical input power exactly balances any mechanical energy delivered to a shaft load.

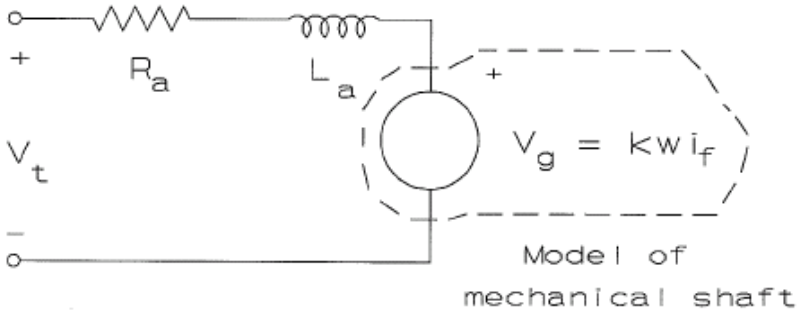


Figure 2. The dc motor equivalent circuit with mechanical model

The power input, and hence the operating speed, of a dc motor can be controlled by altering the value of V_t. Since the actual output power is into some mechanical load, with its associated inertia, ω will not change much over short time periods, and V_g will be nearly constant. This is a good match for a dc-dc converter, since the average electrical power into the motor will be determined by the average value of V_t, even when the inductance is low. For example, a simple buck converter could be used to control V_t, as in Figure 3. The output

could vary from 0 to 100% of some input dc source voltage, and thus speed could be altered from near 0 to near rated speed.

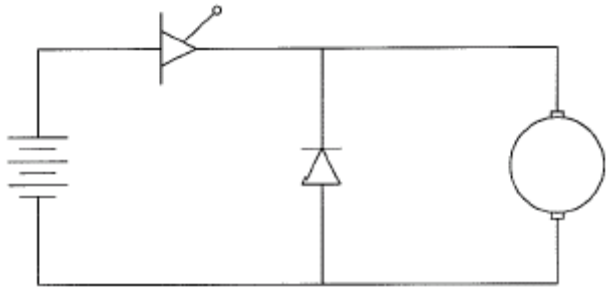


Figure 3. Buck converter in a dc motor drive application

If i_f is held approximately constant, as it is in "separately excited" motors or motors with permanent magnets, the input power is a very direct function of converter duty ratio, and speed control is made easy. In fact, many converters have feedback systems built in for this purpose. Consider the unit of Figure 4, in which the transistor duty ratio depends on a low-power input voltage. This voltage could be generated as shown in the figure, with some reference signal being compared to information from a tachometer. In this unit, the duty ratio automatically increases if the motor speed drops. This results in additional input power and is intended to keep running speed nearly constant. The operating speed can be changed easily by adjusting the reference voltage, and will be held constant at the desired value.

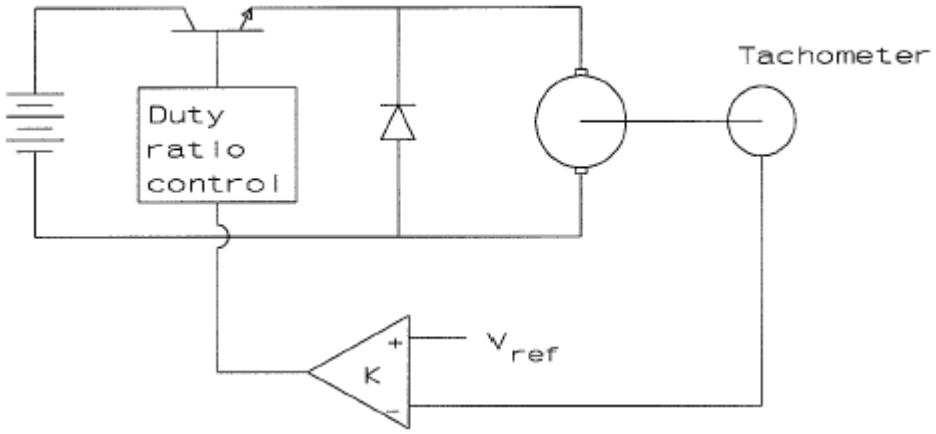


Figure 4. Dc-dc converter set up for speed control

In high power and traction motor drives, a considerable amount of energy is represented during a speed decrease. An example is the braking of an electric vehicle. The energy removed from a motor during deceleration is equal to the energy needed to accelerate the motor, at least in principle. In mechanical systems, this braking energy is converted to heat, dissipated, and lost. This is not an acceptable situation in battery-powered electrical systems. Multi-quadrant dc converters can be used to convert the braking energy back into

electrical form. The energy can be dissipated just as it would be by mechanical brakes, or recovered. The dissipation version is called "dynamic braking" and is often used for very rapid deceleration of electric motors. The recovery version is called "regenerative braking," or just "regeneration," since it uses the motor as a generator during deceleration.

The buck converter is sometimes called a class-A chopper when used as a motor drive [1]. This converter makes a useful, simple motor control. When braking, the controlling switch turns off, and only the diode conducts. If inductance is low, the output current quickly goes to zero, and the motor merely coasts to a stop. If inductance is high, the braking energy is dissipated in R_a. Figure 5 shows some typical waveforms. A boost converter can be used to return generated energy from a motor to a source, provided that the source voltage V_t is less than V_g. Such a converter, shown in Figure 6, can provide regenerative or dissipative braking. It is sometimes referred to as a class-B chopper [1].

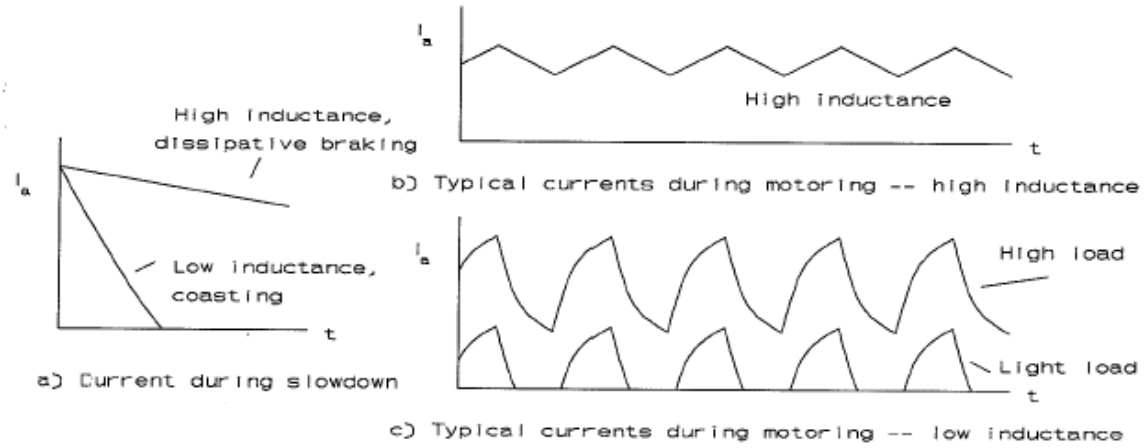


Figure 5. Buck converter current waveforms

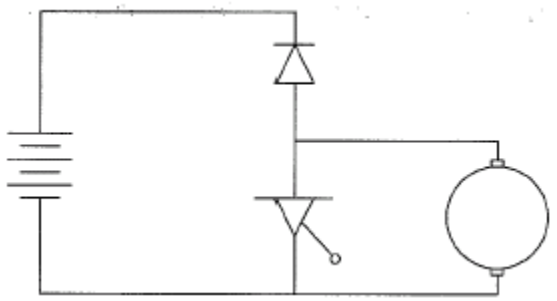


Figure 6. Boost converter for braking energy recovery

A motor could be attached to both a buck and a boost converter, with the buck converter operating (with $I_a > 0$) during "motoring," and the boost converter operating (with $I_a < 0$) during regeneration. Such a unit is

called a class-C chopper, and is widely used for dc motor drives. In a class-C chopper, care must be taken to avoid turning on both active switches simultaneously, since this would short the input source. To operate a class-C chopper, the boost converter active switch is shut off, and the buck converter is used to accelerate and provide running power to the motor. When regeneration is desired, the buck converter is shut off until I_a becomes negative. At that point, the boost converter can begin operating, and will transfer energy from the motor back to the source. In effect, the two converters operate independently.

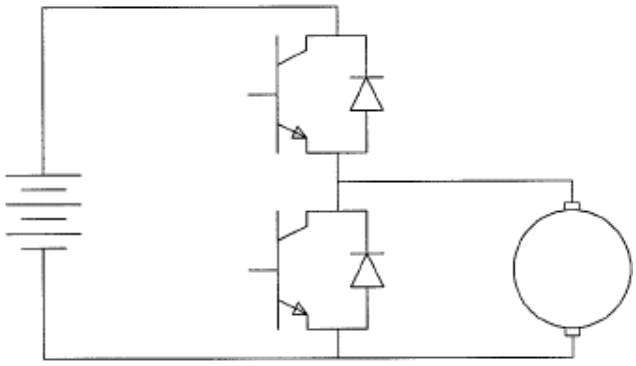


Figure 7. Class-C chopper circuit

The general dc voltage to dc current converter shown in Figure 8 is not especially useful for dc motor control, since the inductance value is usually too low for useful regeneration. If a large inductor is placed in series with the motor, the circuit is capable of regeneration, since V_t can be negative with I_a positive. The converter cannot provide negative steady-state voltage to the motor, and so is no more useful than the class-C chopper above. It is called a class-D chopper.

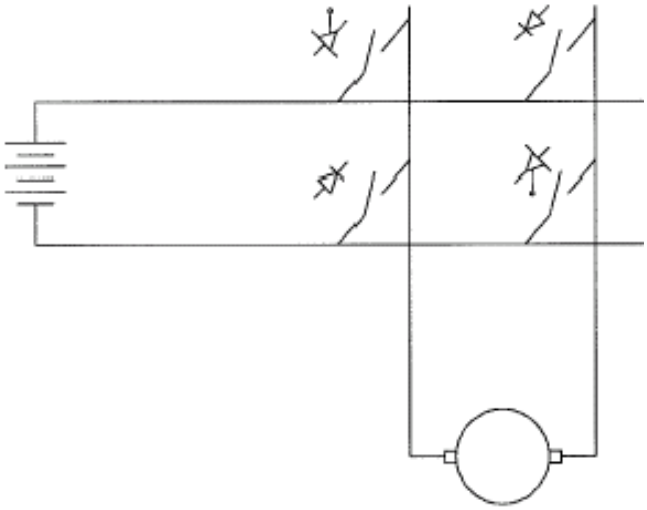


Figure 8. Two-quadrant dc-dc converter

In many applications, it is necessary to reverse the motor direction, while maintaining both motoring and regeneration. Two class-C choppers, one for each motor V_t polarity, can be assembled for this purpose. The resulting class-E chopper consists of four converters, each of which operates in only one quadrant. It is shown below.

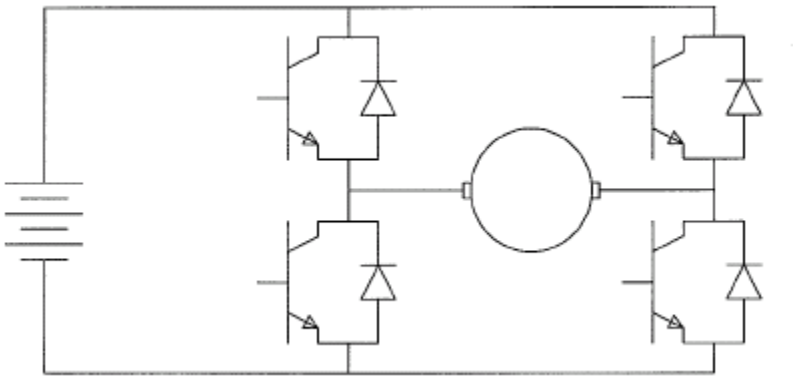


Figure 9. Class-E chopper circuit for bidirectional dc motor drive

The class-E chopper is more often termed an "H-bridge," based on its shape. Low-power IC H-bridge devices are the basis of many computer motor drives. In practice, the most common multi-quadrant converters operate as if they are built up from multiple one-quadrant converters. It is possible to view ac-dc, dc-ac, and ac-ac converters as if they were multi-quadrant dc-dc units. We will carry this idea further in later experiments.

Procedure --

Part 1: Class-A (one quadrant) motor drive

1. Choose a dc motor from the lab selection. Use your multimeter to measure R_a for it.
2. Set up the FET control box as a buck dc-dc converter, with a dc motor as the output load. Remember that the red jack is the FET drain lead (the “forward” switch terminal). Be sure to provide the capacitor and resistor shown across the input power supply. The resistor is intended to take up any regenerated energy.
3. Set the power supply current limit for about 5.0 A, and the voltage to 24 V (depending on the motor ratings). Set the duty ratio dial to zero. Connect an oscilloscope lead across the motor. Set up the current probe to measure the motor armature current.
4. Turn on the FET box and the input power supply. The motor voltage waveform gives you a way to observe switching frequency (how?). Set f_{switch} to about 20 kHz (a period of 50 μs). Monitor and record

the power supply current and voltage levels with the supply panel meters, and shut down if anything unexpected appears.

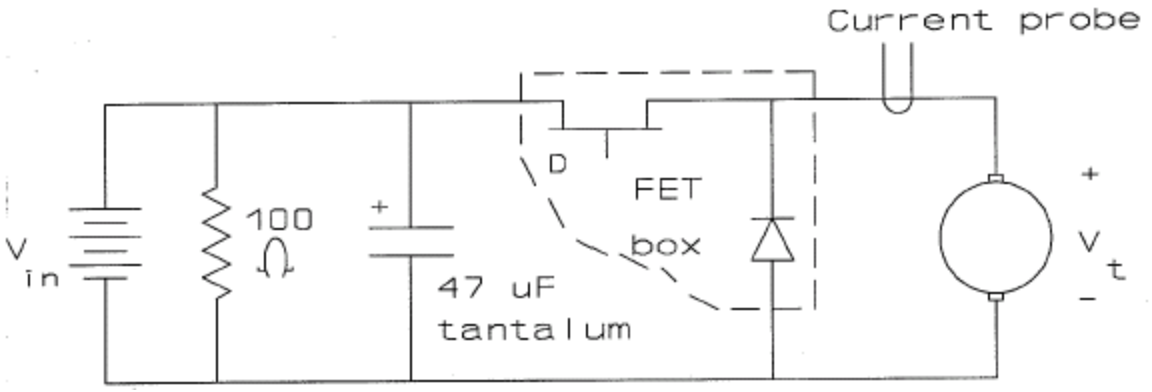


Figure 10. Class-A chopper test circuit

5. Sketch the motor terminal voltage waveform and current waveform with a duty ratio setting of about 50%. If there are intervals during which $I_a = 0$, take special care to record the value of voltage during such intervals. Measure the peak-to-peak ripple on I_a.

6. Observe and sketch the motor voltage and current waveforms, and measure the motor average voltage and current, at: (a) the lowest duty ratio for which the motor runs steadily, and (b) a duty ratio of about 90%. In each case, observe qualitatively the effects of shaft load on the current waveform.

7. Change f_{switch} to 2 kHz. Take current waveform data that will allow you to determine the time constant of I_a during its fall. This will allow you to estimate L_a later.

Part 2 -- Class-C (regenerative) chopper circuit

1. The two active switches of the class-C chopper operate separately. Be aware that either one can be operated only when the other is off. The dual FET box is configured in one setting to provide a "dead time" to avoid any possible overlap. Use both devices in your FET control box to set up the circuit of Figure 11. The switching function setting must be in the *q'* position to add the necessary dead time.

2. Use an input voltage of 12 V or 24 V (depending on motor rating). Turn on the FET box, and observe operation at approximately 50% duty ratio. Sketch the motor voltage and current waveforms, and record the average motor voltage and current. Measure the peak-to-peak ripple on I_a.

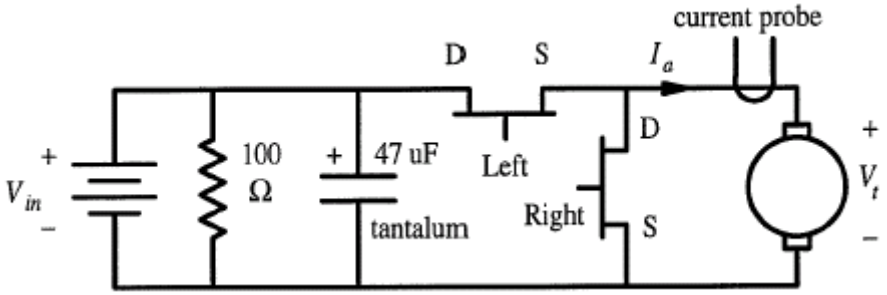


Figure 11. Class-C chopper test circuit

3. Increase the duty ratio to near the maximum amount, then drop the duty ratio abruptly in an attempt to observe converter action during regeneration. You may need to repeat this step, or spin the shaft externally by hand or with another motor to observe regeneration behavior. Make note of your observations. Try to obtain a situation in which I_a reverses, in which case the machine is a generator.

Study Questions --

1. During intervals when $I_a = 0$, the motor voltage is not necessarily zero. Interpret its value during such intervals. (Hint: Since $I_a = 0$, this is an open-circuit voltage.)
2. Compute average power into the motor for each operating condition.
3. Estimate the motor series inductance value from the buck converter data. Use this to estimate the voltage ripple at 20 kHz. Does this match your measurements?
4. Is the average motor voltage determined by the duty ratio?
5. Why is the class-A chopper incapable of regeneration? What will happen in such a converter if V_t is suddenly lowered?
6. What would happen if no dead time were present (i.e. what if the controls for the two switching devices in Part 2 were to overlap for a short time, such as 100 ns)?

[1] S. B. Dewan, G. R. Slemon, A. Straughen, **Power Semiconductor Drives**. New York: John Wiley, 1984.

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #6 -- Dc-Ac Conversion, Part I: Voltage-Sourced Inverters

Objective -- This series of two experiments will examine inverter circuits. Inverters, or dc-ac converters, are used for generation of backup ac power, for ac motor drives, and for switching amplifiers. Commercial inverters are also used in alternative energy applications such as solar power. Uses of inverters are growing rapidly with expanded use of backup power, inverter-based amplifiers, and ac motor controllers.

Square-wave (voltage-sourced) inverters will be studied in this first experiment of the series. Emphasis will be placed on phase control techniques and resonant filtering.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may assign a different problem.

1. The half-bridge converter shown below has a square waveform for V_{out}. To avoid any dc component in V_{out}, the two switches are operated with duty ratio of 50% at a frequency equal to the intended ac output. The capacitor bridge also prevents any dc component from flowing in the output. The intended output frequency is 50 Hz. Select L to make this load resonant at 50 Hz, so just a single harmonic flows.

   a) Sketch the voltage waveform associated with the load resistor.

   b) Sketch the voltage and current waveforms in either of the two large capacitors in the divider network.

   c) Can the output average power be varied by adjusting the phase or duty ratios of the switching functions? Why or why not?

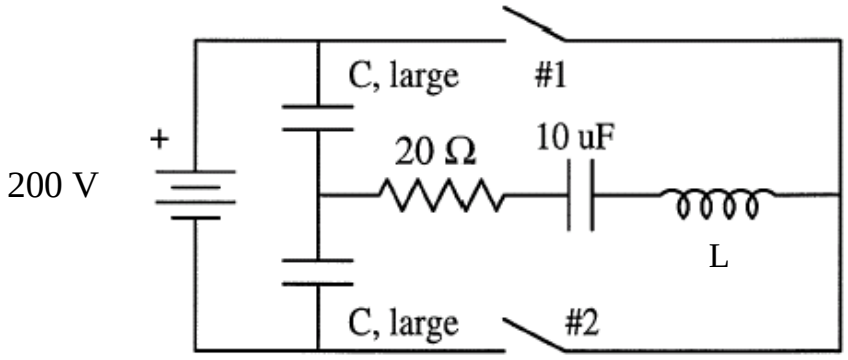


Figure 1. Dc-ac converter circuit for pre-lab assignment.

Discussion --

Introduction -- Dc-ac converters, or inverters, can be classified according to the properties of the dc source. Those with a dc current source are often used for sending energy into an ac power system. Dc

regeneration and HVDC transmission are two examples. Such inverters blur distinctions between rectification and inversion. In practice, the only difference between rectifiers and inverters when dc current sources are involved is the direction of any unidirectional switches used in the circuits and the current flow direction.

Ac-dc/dc-ac converters which involve dc voltage sources are more common, and operate differently from the current-sourced versions. These "voltage-sourced inverters" imply an ideal ac current source load -- rare in practice. Normally, the “ac current source” serves instead as a model for an electrical load such as a motor. In an energy sense, these loads are "passive:" they consume energy delivered to them, and can be represented as an equivalent load impedance under steady-state conditions. A passive load just follows its input waveform, and do not establish a time of reference for phase purposes. The phase just leads or lags the input voltage by a certain amount. Without a phase reference, there is nothing to be gained by adjusting the phase of the switching function set, so that approach to control is not available. An alternative is to use one of the switching functions as a phase reference and then adjust others relative to it. This gives rise to *relative phase control*, which is used in some backup systems. Today's experiment will consider the basic square-wave inverter, widely used for backup power and general ac power needs.

Inversion is important in three general application contexts:

1. Transfer of energy from some dc source into an ac power system. Such uses include alternate energy source conversion and dc motor regeneration. Typical examples are inverters for solar power or fuel cell power.
2. Backup ac power. Since most electrical equipment is intended for ac power from a utility, switching power converters which produce ac from storage batteries are of growing importance.
3. Ac motor drives. Induction motors, synchronous motors, and so-called brushless dc motors require ac power at variable frequency. An inverter with adjustment capability is essential for ac motor drive applications.

The first of these is usually addressed with current-sourced inverters or with voltage-sourced inverters that apply relative phase control. In the current-sourced case, series inductance is added on the dc side, and the ac utility line provides an absolute phase reference. Phase advance or delay is used, and the control is just like that in a rectifier. In the second application, square-wave inverters (perhaps with added filters) often serve the purpose. There are somewhat more sophisticated backup inverters that create better waveforms, but square-wave circuits remain the

most common. In the third case, we must be able to create a good sinusoid, independent of the utility grid, with full control over amplitude and frequency. Next week's experiment will consider PWM methods for this purpose.

Basic Theory -- The most general dc-ac converter (based on single sources) is shown in Figure 2. It has at most four switches. The switching functions are constrained by KVL and KCL, as usual, but also, they must have a Fourier component at the ac source frequency. An important practical consideration is that most ac utility sources involve transformers and cannot tolerate a dc component. This further constrains the functions. An obvious choice is to operate the switches in pairs, in a manner similar to the two-quadrant buck or boost dc-dc converters. The switching functions are given a duty ratio of 50% for symmetry, to avoid any dc component on the ac source.

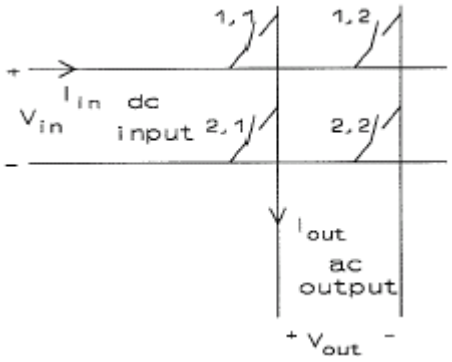


Figure 2. Basic dc-ac converter

The dc current to ac voltage case is shown in Figure 3. As in a two-quadrant buck converter, V_{out} can be either V_{in}, $-V_{in}$, or 0, depending on the switch combination. Notice the switch types to be used in this converter. The devices must support current in either direction, although there is only one voltage polarity.

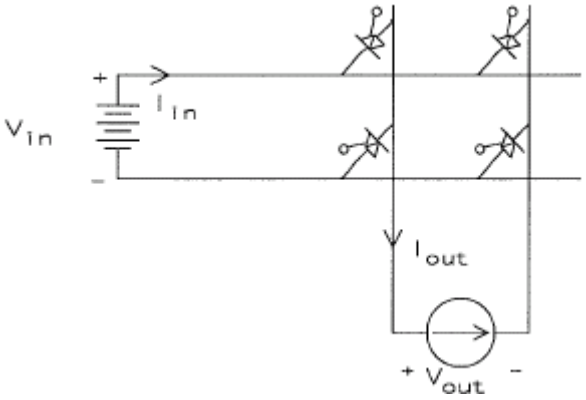


Figure 3. General voltage-sourced dc-ac converter

An induction motor equivalent circuit is shown in Figure 4. This circuit acts as an inductive load. For the purposes of KCL, the current cannot change instantaneously, so a current source is an appropriate model over

short times. Nonetheless, the phase of this current source is linked to the phase of the input voltage. Changing the phase of the input voltage will change the current phase but not alter power. This is a reminder that an absolute phase control approach does not apply to this type of load.

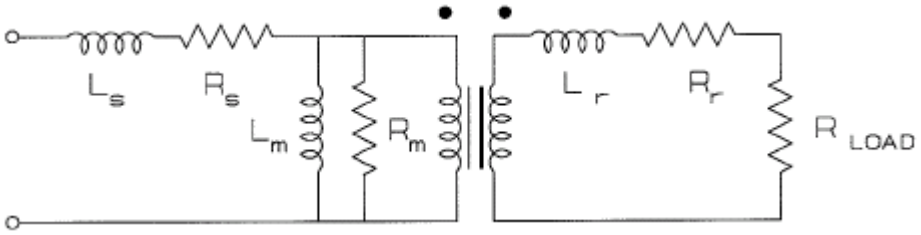


Figure 4. Induction motor equivalent circuit for each phase

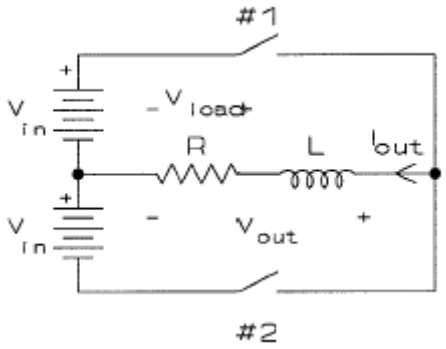


Figure 5. Half-bridge inverter with R-L load

Because of the ac current source phase behavior, properties of the load are important to converter operation. A half-bridge converter with R-L load is shown in Figure 5. KVL and KCL require $q_1 + q_2 = 1$. The practical requirement of no dc component in V_{out} can be met if $D_1 = D_2 = ½$. V_{out} is a square wave at the desired frequency, and has a value of $V_{out} = (2q_1 - 1)V_{in}$. This generates the Fourier series

$$V_{out} = \frac{4V_{in}}{\pi}\sum_{n=1}^{\infty}\frac{\sin\left(n\pi/2\right)}{n}\cos\left(n\omega_{out}t - n\phi_0\right)$$

Output current and power depend on the load, in a manner which can be computed term-by-term based on $V_{out} = RI_{out} + L(dI_{out}/dt)$. In steady state, I_{out} is periodic at the same frequency as V_{out}, and has a Fourier series

$$I_{out} = c_o + \sum_{n=1}^{\infty} c_n \cos\left(n\omega_{out}t + \theta_n\right)$$

This series can be differentiated. Let $X_n = n\omega L$. Then we can solve for I_{out}, with the final result

$$I_{out} = \frac{4V_{in}}{\pi}\sum_{n=1}^{\infty}\frac{\sin\left(n\pi/2\right)}{n\sqrt{R^2 + X_n^2}}\cos\left(n\omega_{out}t - n\phi_0 - \tan^{-1}\left(\frac{X_n}{R}\right)\right)$$

This process can be automated, and the current at any point in time can be found by adding several terms in the series. A sample current waveform is given in Figure 6. Some loads of this type will be tested in this experiment.

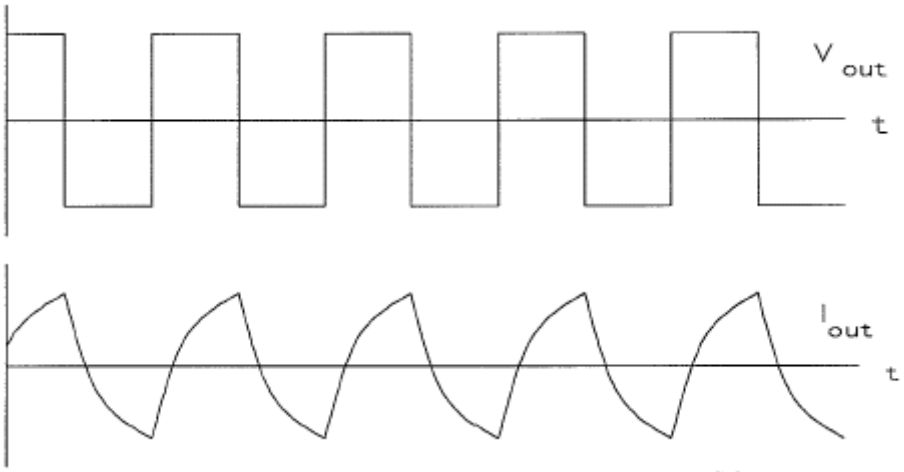


Figure 6. Typical output waveforms of voltage-sourced inverter

Procedure --

Part 1: Voltage-sourced inverter, R-L and R-L-C loads

1. Set up an FET control box with the two devices set for a short dead time between them, to form a half-bridge inverter. Use a single supply with a capacitor bridge, or a bipolar supply as suggested in Figure 7. Do not confuse the FET drain and source leads.

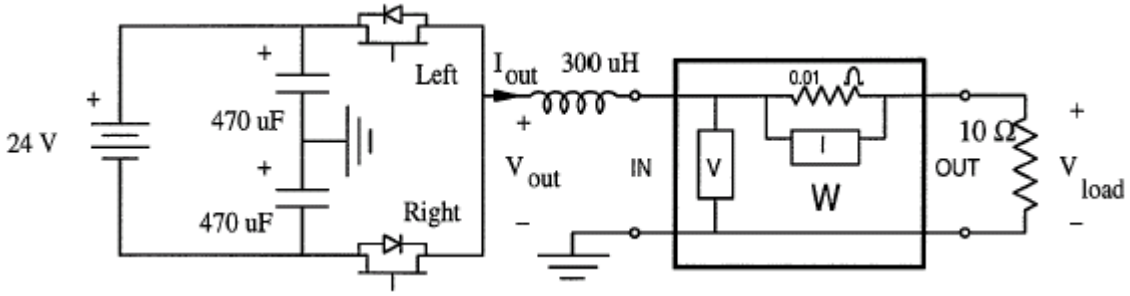


Figure 7. Voltage-sourced inverter test circuit

2. Set the power supply current limit, if there is one, for about 2.0 A, and the voltage to zero. Set the duty ratio dial to 50%. Connect oscilloscope leads and wattmeters across the load resistor and across the converter output, as suggested in Figure 7.

3. Turn on the FET boxes and the input power supply. Set f_{switch} to about 10 kHz. With a bipolar supply, use ±12 V.

4. Measure the output average voltage. Is it zero? For a bipolar supply, adjust the duty ratio and fine-tune the input supplies to get 50% duty and zero average output. *Small average offsets can swing the current to the power supply current limits.* Some supplies must be shut off to reset if current limits are reached.

5. Sketch the load resistor voltage and the output voltage waveforms. Record the RMS voltage, current, and power from the wattmeter. Measure the average input current from either of the two supplies.

6. Compute the series capacitance needed for resonance with the inductor at the switching frequency. Add this capacitor in series with the inductor. Adjust the frequency as needed to obtain near-resonant operation.

7. Sketch the resistor voltage waveform with the R-L-C load. Record the RMS value of the load resistor voltage, the output power, and the average input current from the supplies.

Part 2 -- Isolated converter with ac link (half-bridge forward converter)

1. Set f_{switch} to 50 kHz. Wire a toroidal transformer into the circuit, as shown in Figure 8.

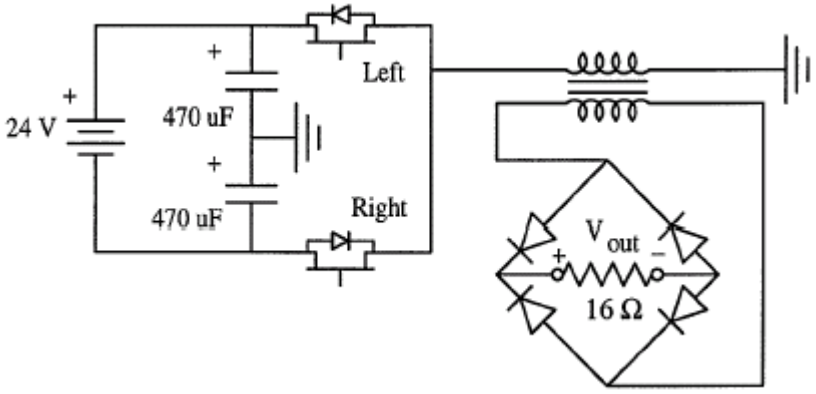


Figure 8. Isolated ac link converter

2. Measure the average output voltage of this circuit. Sketch the waveform.

3. Place a 1 μF capacitor across the output terminals. Again measure the average output voltage. Also measure the average input current.

Study Questions --

1. How do you expect waveforms for an R-L load to change with frequency?

2. An alternate method for control of $V_{out(wanted)}$ is to add a third switch across the output combination. This allows zero as a possible output value. The duty ratios can then be adjusted so that V_{out} changes. Assuming that the dc component remains at zero, find $V_{out(wanted)}$ as a function of D for this control scheme.

3. What is the effect of a resonant load, such as that in Part I?

4. Why is dead time required in these applications?

5. What is the efficiency of the converter circuits tested above?

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #7 -- Dc-Ac Conversion, Part II: Pulse Width Modulation Inverters

Objective -- This second in the series of inverter experiments involves pulse-width modulation circuits. The intent is to gain familiarity with the waveforms and concepts of pulse-width modulation as it applies to power electronics. PWM inverters are quickly becoming the method of choice; their use is likely to expand. The PWM inverter will be examined in the context of an ac motor drive. Basic ac drive concepts will be one feature of this experiment.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different problem.

1. The PWM waveform shown below has a switching frequency of 5000 Hz and a modulating frequency of 200 Hz. It is applied to a series R-L circuit with R = 8 Ω and L = 10 mH. Sketch the expected steady-state current waveform. You are not expected to compute it in detail.

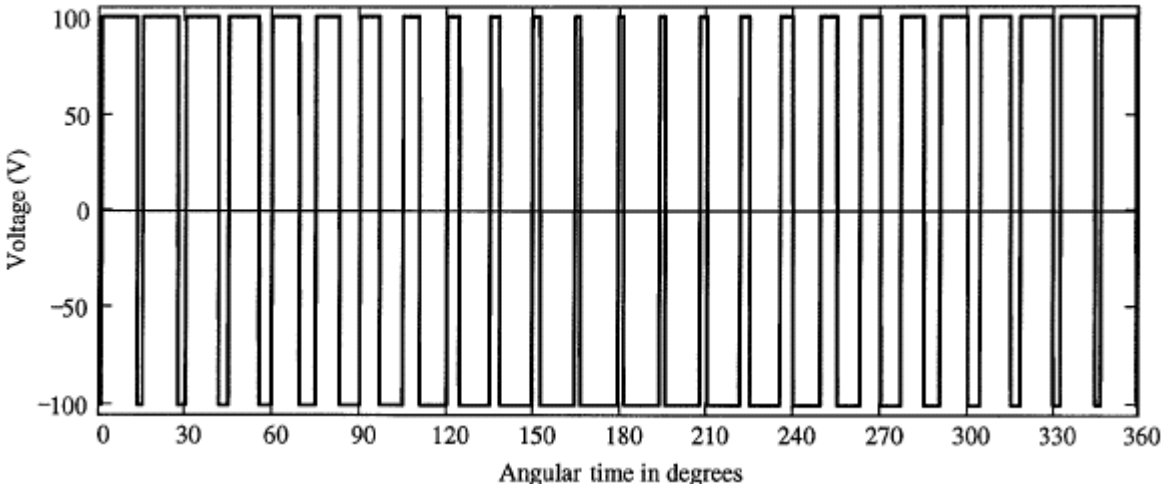


Figure 1. Sample PWM waveform for pre-lab assignment

Discussion --

Introduction -- Control of output voltage in dc-ac converters is critically important in ac motor drives, and is very useful in all inverter applications. With output control, the converter can compensate for input changes or allow the user to set a desired output.

There are two methods in common use for controlling the output voltage (and power) of an inverter. The first is to use "relative phase control," in which the two half-bridges in a full-bridge inverter are adjusted in phase relative to each other. This approach is common in high-power inverters and is also used in low-cost low-power inverters. The drawback is that there are significant unwanted harmonics in the output. In fixed-frequency applications, these can be addressed with resonant filters, as in the previous experiment. Relative phase control

permits slow switches, such as SCRs, to be used in inverters. The switching frequency is the same as the intended output frequency.

The second method, pulse-width modulation (PWM), decouples the switching function frequency and the intended output. This method can provide the desired results if the switches operate much faster than f_{out}. Modern FETs, IGBTs, and GTO thyristors have made PWM possible in nearly all contexts. To understand PWM, consider a very fast square wave. The duty ratio can be varied slowly between 0 and 100%, in a manner similar to pulse width control in dc-dc converters. In a buck converter, for example, this would have the effect of slowly changing $V_{out(ave)}$. This slow change can be sinusoidal. V_{out} can change at the rate of 60 Hz if, for example, a switching frequency of 10000 Hz is used. To allow V_{out} to appear in two quadrants, a full-bridge inverter can be used. This circuit operating under PWM is identical to a two-quadrant buck converter. The pulse width is now intentionally varied, rather than held constant.

The drawbacks of PWM include the relatively high switching rates and power losses which increase with switching rate, the wide range and high magnitude of unwanted components, and radio interference which results from the unwanted components. Advantages include the ease with which $V_{out(wanted)}$ can be varied, the fact that adjusting f_{out} is just as easy as adjusting $|V_{out(wanted)}|$, the simplicity of PWM systems, and the possible wide frequency spread between wanted and unwanted frequency components. This wide frequency spread simplifies filtering -- a low-pass filter is generally all that is used.

We will examine PWM in the context of ac motor control and R-L loads. The ac induction motor, for example, is mechanically simple and rugged, requires no electrical connections between stationary and rotating parts, and is inexpensive. Ac motor speed control in general requires adjustment of the motor input frequency. Unfortunately, ac motors also have frequency-dependent impedance. As the frequency is decreased, input current and internal magnetic flux rise. To counteract these effects, the voltage must change along with frequency. If the voltage is altered in the correct manner as a function of frequency, an ac motor can be made to act almost like a dc motor in terms of speed and torque control. Today, ac motor drives are displacing dc motors in most applications. These drive units are nearly always based on PWM.

Basic Theory -- The half-bridge inverter in Figure 2 has output $V_{out} = (2q_1 - 1)V_{in}$. If the duty ratio is varied with time as some *modulating function M(t)*, V_{out} becomes

$$V_{out} = V_{in}\left[2M(t) + \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{\sin\left(nM(t)\right)}{n}\cos\left(n\omega_{switch}t - n\phi_0\right)\right] - V_{in}$$

Remember that D must be between 0 and 1. Substitute ½[k·cos(ω_{out}t)+1] for M(t). Then V_{out} becomes

$$V_{out} = V_{in} k \cos\left(n\omega_{out} t\right) + \frac{4V_{in}}{\pi} \sum_{n=1}^{\infty} \frac{\sin\left(\frac{n\pi}{2}\left[k\cos\left(n\omega_{out} t\right)+1\right]\right)}{n} \cos\left(n\omega_{switch} t - n\phi_0\right)$$

Notice that this is *not* a Fourier series -- time appears in several places, as does sin[$nk\ cos(\omega_{out}t)$]. It can be decomposed into a Fourier series (by using properties of Bessel functions), and the Fourier components that result appear at frequencies of $n\omega_{switch} \pm m\omega_{out}$. The components drop in amplitude quickly for increasing m, but slowly for increasing n. If the multiple f_{switch}/f_{out} is large, very little of the energy appears between ω_{out} and ω_{switch}.

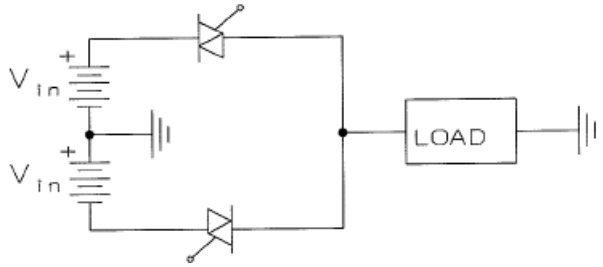


Figure 2. Half-bridge inverter for PWM control

Since the output is a voltage source, a current-sourced interface such as an inductive load is appropriate. Thus a series R-L load will act as a low-pass filter (just as in the dc-dc buck converter) in order to separate f_{out} from the unwanted components. This function can be performed by a deliberate R-L load, or by a motor winding or transformer. The experiment procedure below illustrates both PWM and the filtering process.

Procedure --

Part 1: PWM inverter, R-L load

1. Set up the dual FET control box to form a half-bridge inverter, as in Figure 3. Use a fixed 24 V supply or a dual ±12 V supply as the input energy source. Remember that the red jacks are the FET drain leads. Set the box for dead-time between the two switching functions.

2. Set the power supply current limit, if there is one, for about 1.5 A, and the voltage to zero. Set the duty ratio control knob to 50%.

3. Set up the waveform generator at your bench to produce a sinusoidal voltage, with frequency of about 50 Hz, such that the lowest voltage is 1 V and the highest is 3 V (sine wave with 2 $V_{p\text{-}p}$ and 2 V dc offset). Connect this voltage to the duty ratio input BNC jack on the control box.

4. Observe both the half-bridge output voltage and the (filtered) resistor voltage. Turn on the FET box and the input power supply. Set f_{switch} as low as possible.

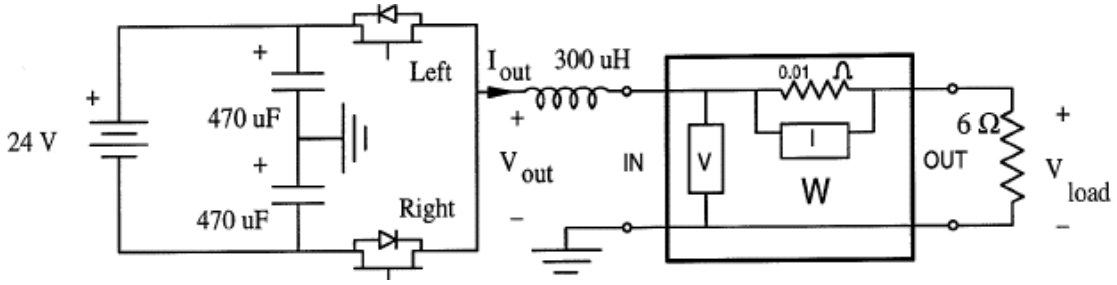


Figure 3. Voltage-sourced inverter test circuit.

5. Monitor the average value of V_{out}, and observe the power supply currents. Adjust the function generator to get near zero average output. The supply currents should be roughly equal. Remember that some supplies must be turned off if their current limit becomes active.

6. Sketch the V_{out} waveform. Can you see the modulation process?

7. Increase f_{switch} to about 50 kHz. Record the RMS voltage current, and power into the load resistor. Measure the average input current.

8. Decrease the amplitude of the function generator modulating waveform by about 50%. Sketch the V_{load} waveform. Record meter data as in steps 6 and 7.

Part 2 -- Induction motor drive

1. Turn off the power supply. Replace the R-L load with a series combination of 5 Ω and a transformer winding of 12.6 V rating.

2. Place a 1000 Ω load across the transformer secondary terminals. Turn on the power supply, and measure the RMS and average voltage across this resistor, and observe and sketch the waveform. **Be aware of the relatively high voltage level.**

3. With the supply off, wire the small quadrature motor into the circuit, as shown in Figure 4. Apply power. Sketch the converter output voltage and resistor voltage waveforms (refer to the Figure).

4. Change the sine wave frequency and amplitude to observe an ac motor control function.

Part 3 – Audio amplifier application

1. Set up the audio amplifier circuit provided in the laboratory. Use a power supply of 9 V, and prepare a 1 kHz sinusoidal modulating signal for input. The load can be a loudspeaker or a 6 to 10 Ω resistor.

2. Based on the amplifier data sheets, observe the modulating function, carrier waveform, and switching function for at least two different amplitudes of modulating signal. Please keep the signal below the saturation limit.

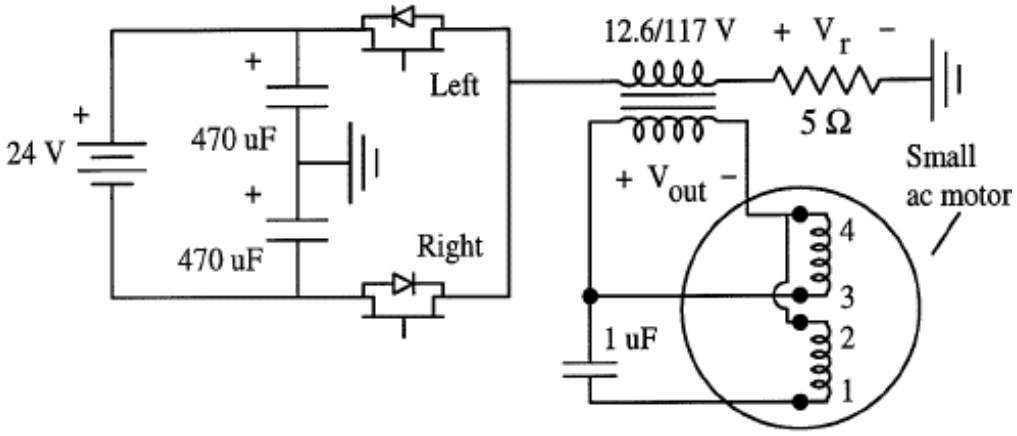


Figure 4. Ac motor drive test circuit.

3. Record your observations.

Part 4 -- Commercial drive demonstration

Your instructor will demonstrate a commercial PWM ac motor drive.

1. Connect a PWM drive to a motor of proper ratings, then to 208 V three-phase power.
2. Observe current and voltage traces. Turn on the drive.
3. Operate the drive at frequencies of approximately 20 Hz, 40 Hz, and 60 Hz. Record your observations.

Study Questions --

1. For this type of converter, how do you expect waveforms for an R-L load to change with switching frequency? With modulating frequency?
2. Why is PWM advantageous in ac motor control?
3. Draw the full-bridge inverter for PWM. What relationships would you expect among the various switching functions?
4. The three-phase inverter uses six switches. What waveforms do you expect for line-to-line and line-to-neutral voltages?
5. Compute and tabulate the converter's efficiency from your part 1 data.
6. Compare PWM with the simpler inverter scheme of Experiment #6.
7. Compare the PWM inverter from Part 2 to the commercial unit of Part 3.

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #8 -- Passive Components, Part I: Models for Real Capacitors and Inductors

Objective -- This series of experiments will study the behavior of real passive components. In the first experiment, basic operation of realistic capacitors and inductors will be examined, with emphasis on impedance effects. The second experiment explores the nonlinear effects of magnetic saturation.

Pre-Lab Assignment -- Read this experiment. Study the procedure. *There is a considerable amount of data to be taken for this experiment. The recorder should prepare appropriate tables prior to the lab session.* Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different set of problems.

1. A sinusoidal voltage of amplitude V_0 and frequency f_s is applied to the series RC circuit shown.
   a) Find the amplitude and phase of V_c as a function of frequency. Tabulate the values of amplitude and phase for frequencies of 200 Hz, 20 kHz, and 2 MHz.
   b) If the capacitor is really a series-resonant LC pair (as in Figure 5), what is V_c at resonance?

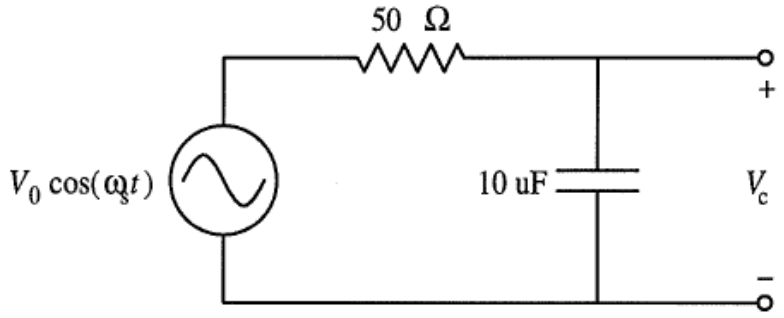


Figure 1 RC voltage divider for pre-lab assignment

2. A sinusoidal voltage of amplitude V_0 and frequency f_s is applied to the series RL circuit shown.
   a) Find the amplitude and phase of V_L as a function of frequency. Tabulate values at 200 Hz, 20 kHz, and 2 MHz.
   b) If the inductor has significant series resistance, can the value be determined knowing V_L and f_s? If so, what is the value in terms of known or measured quantities?

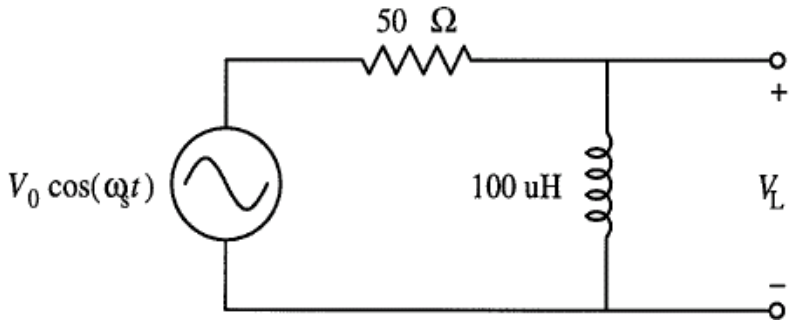


Figure 2. RL voltage divider for pre-lab assignment.

Discussion --

Introduction -- The capacitors, inductors, and resistors used in circuit analysis have ideal properties: $i_c = C\frac{dv_c}{dt}$, $v_L = L\frac{di_L}{dt}$, $v_R = Ri_R$. As in the case of voltage and current sources, real devices are not ideal. In the context of power electronics, these effects are often important. After all, we often seek large values of L and C at high levels of voltage, current, power, and frequency. We often use resistors in high-speed circuits.

Some of the nonideal effects are straightforward: wires have resistance and inductance, coils of wire have capacitance between the turns, and so on. In order to use passive components in power electronic circuits, it is important to understand what the effects are, how they are characterized and measured, and the implications for design. In these experiments, we will examine practical effects in passive devices.

Basic Theory, Capacitors -- When two conductors of any shape are placed in an electric field, a charge develops on each one. The amount of charge changes with voltage on each conductor. In a system which consists only of perfect conductors and perfect insulators, the charge Q depends on voltage in a linear fashion, so that $Q = CV$. The constant of proportionality is **defined** as "capacitance." Since voltages perform work in separating charge, the charge and capacitance represent stored energy, in the well-known form $W = \frac{1}{2}CV^2$. Current is, of course, the time rate of change of charge. If capacitance is constant (e.g. the conductors are stationary), this leads to the simple relationship $i = C\frac{dv}{dt}$.

A real capacitor must provide conductors to hold the charge, wires to allow application of voltage, insulation which physically supports and separates the conductors, and a protective package to prevent damage. There are two major classes of commercial capacitors. The first consists of two flat metal conductors, separated by a dielectric layer. The second type, known as the "electrolytic capacitor," consists of an oxidized metal conductor and a nonmetallic conductor. Each of the two types has all the parts needed, and provides storage of electric charge. An excellent overview of capacitor types can be found in [1].

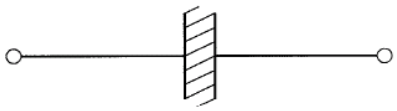


Figure 3. Parallel-plate capacitor

Both types can be modelled with a parallel-plate geometry, shown in Figure 3. The capacitance value depends on the plate spacing d, the plate area A, and the dielectric constant of the insulator, ε, according to the relation $C = \varepsilon A/d$. A large value of capacitance requires large plates, small spacings, and high dielectric constants.

Capacitors possess both current and voltage ratings. The dielectric must not break down. To avoid this, the electric field magnitude E = V/d must be kept sufficiently low. The voltage rating of a capacitor, then, depends on *d*. When the applied voltage changes rapidly, significant currents will flow. The wires and plates must be large enough to handle the applied current without overheating. In general, one wants to place very large plates in a small package, along with a dielectric of high ε. The choices mainly involve plate thickness, wire size, dielectric thickness, and dielectric type. The nonideal effects are also relatively clear: the wires and plates introduce series inductance and resistance, and an imperfect dielectric could allow some current flow between the plates. A candidate circuit model emerges:

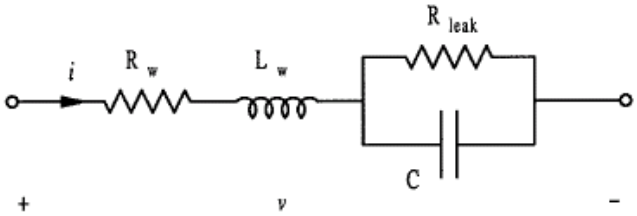


Figure 4. Proposed circuit model for simple dielectric capacitor

This circuit model can be simplified at a specific frequency. Then the parallel portion can be transformed into a series equivalent. This gives the **standard model**:

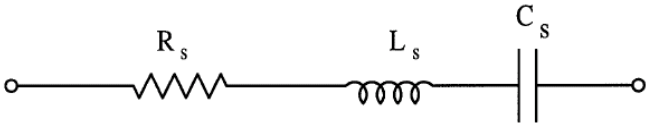


Figure 5. Standard series equivalent circuit of a capacitor.

Many manufacturers use this standard model as a basis for describing their capacitors. The **equivalent series resistance** (ESR, another name for the R_s of the circuit) is often given at a frequency such as 120 Hz. The **equivalent series inductance** (ESL) is often given in the form of a "self-resonant frequency," f_r. The properties of the standard circuit include:

- Voltage drop across the ESR, which reduces the stored charge relative to expected values.
- The resonant effect of the series R-L-C circuit means that a plot of impedance vs. frequency will fall at first (capacitive impedance), reach a minimum, and then rise (inductive impedance).
- Above f_r, the device is an inductor!
- Any current flow produces loss in the ESR. The higher the frequency of the applied voltage, the higher the current and losses.

- The circuit does not model real behavior well at very low frequencies. For instance, the original circuit of Figure 4 shows that some leakage current will flow when a dc voltage is applied. Real capacitors show this effect. The standard model does not predict it.

The ESR mainly represents the dielectric properties. As you might guess, dielectrics are strange materials, and do not act in accordance with Ohm's Law. Because of this, the ESR is generally some kind of nonlinear resistance; for example, it varies with frequency. A traditional way of characterizing such materials is with the so-called "loss tangent." The loss tangent, also called tan δ or "dissipation factor" (*df*), is defined as the ratio of resistance to reactance for a series R-X circuit. For the standard model of the capacitor, tan $\delta = \omega RC$. The loss tangent has a characteristic value for a given capacitor dielectric material, regardless of the plate geometry. It also happens that many good dielectric materials are characterized by a loss tangent which is roughly constant over a wide frequency range. For these reasons, loss tangent or *df* is often given in capacitor specification sheets. The ESL is more closely related to packaging and lead structure, since wire inductance is the most important factor.

In electrolytic capacitors, the insulating layer is formed through an electrochemical reaction between the two conductors. If voltage of the wrong polarity is applied, the reaction reverses, and the insulating layer is destroyed. The device becomes a resistor, and usually overheats and fails catastrophically. When the correct polarity is applied, the electrolytic capacitor shows the same general properties as the simple dielectric version, with two changes: the leakage current levels are much higher, which means ESR is significant; and the effective plate surface area is very high, which allows high values of capacitance per unit volume. Electrolytic capacitors are more nearly characterized by constant ESR than by constant df values.

Basic Theory, Inductors -- Inductors are formed simply by wrapping a coil around a magnetic material. Current in the coil creates magnetic flux in the material. If the material is linear, the flux is proportional to current, so that $\lambda = Li$. The constant of proportionality in this case defines inductance. By Faraday's Law, if this flux varies with time, it gives rise to a voltage v_L. Thus $v_L = L \cdot di/dt$. Magnetic materials in general are *not* linear; these effects will be studied in more detail in a later experiment.

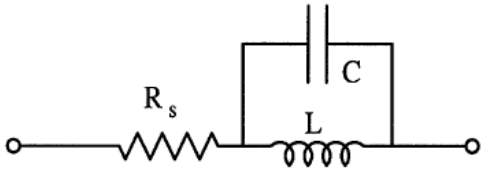


Figure 6. Proposed circuit model for basic inductor.

Even without considering the effects of nonlinearities, some aspects of real inductors are clear. The wire coil has resistance. Incoming and outgoing wires act a bit like parallel plates. A simple circuit model might be the one in Fig. 6. Below resonance, the LC combination can be treated as just an inductor, so an RL series combination is sufficient as a model. Since no computation or "equivalencing" is required to find R, it is usually just called the **series resistance**. In reality, the magnetic material also shows loss, so other resistances appear. As in the capacitive case, the loss tangent is defined as the ratio of resistance to reactance. It is hard to build inductors which handle high power levels and still have very low loss tangents.

Inductor types are defined mainly by the magnetic material. This can be a linear material, such as air, or any magnetic material. Good linearity is a desirable feature, so most practical inductors have an air gap. In this experiment, inductors will be tested for their ESR values and resonant frequencies.

Procedure --

Part 1: Reference measurements. *Do these as time permits rather than first so teams can trade off.*

1. Your instructor will assign a set of capacitors, inductors, and resistors to each team. Use the automatic RLC meter in the lab to obtain 1000 Hz values for C_s, C_p, R_s, R_p, L_s, L_p, and $D = df$ for each of your assigned parts. Special emphasis should be placed on the values relevant to the various models.

Part 2: Frequency sweeps

1. Insert one capacitor in the circuit shown below. If the capacitor is electrolytic, be sure to observe the polarity marks, and add a dc offset to V_{in} so that $V_c > 0$ always. If it is not electrolytic, use an offset of zero. If the capacitor is less than 0.5 μF, substitute a 1 kΩ resistor for R_s.

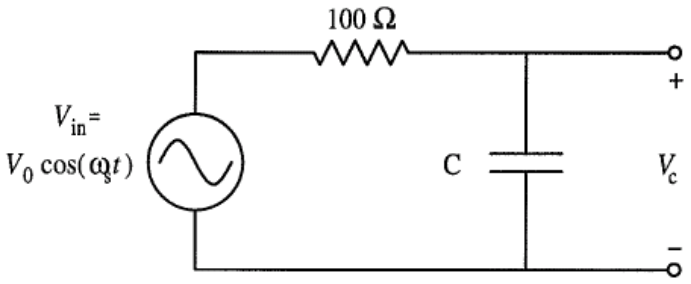


Figure 7. Capacitive impedance test circuit.

2. Set V_{in} at 1000 Hz, and observe V_{in} and V_c on your oscilloscope. Measure the peak-to peak amplitudes and the phase shift between them in degrees. (Hint: Phase measurements can be made more easily by using the oscilloscope cursors to measure time differences.) Use the highest available V_{in} value.

3. Look for the resonant frequency of the part by adjusting f_s until the phase shift is close to zero. The amplitude will be close to minimum for a capacitor. Record amplitudes of V_{in} and V_c at this frequency.

4. Choose at least three frequencies below resonance and three above it; also make a measurement at 1 kHz. The frequencies you choose should cover roughly a factor of 100 in frequency. Record amplitudes of V_{in} and V_c, and the phase shift between them, at each of these frequencies.

5. Repeat parts 1-4 for your other assigned capacitors and inductors. In some cases, you may want to change the resistor value to allow better measurements of V_c. If you do this, be sure to use $R \geq 50\ \Omega$, and be sure to record the R value actually used for each part measured. A value $R = 1000$ is suggested for inductors.

Study Questions --

1. Use data for V_{in}, V_c, and phase to compute the impedance for each tested capacitor and inductor.

2. Plot impedance magnitude and phase vs. frequency for each capacitor and inductor.

3. Plot resistance vs. power for the wirewound resistor.

4. Calculate ESL for each capacitor based on the resonant frequency you measured.

5. Calculate ESR at 1000 Hz and at a frequency near resonance for each capacitor and inductor from your frequency sweep data. Compare the 1000 Hz results to the RLC meter data.

6. Discuss how your data conform to the proposed simple models.

[1] Donald M. Trotter, Jr., "Capacitors," **Scientific American**, vol. 259, no. 1, July, 1988, pp. 86-90B.

Sample table for Experiment #8 Data

Device	Series R	Frequency	V_{in} peak-to-peak	V_{device} peak-to-peak	Time separation, V_{in} to V_{device}
C_1, 2 μF film	100 Ω	5 kHz	16.	2.1	30 μs
C_1	100 Ω	15 kHz	15.9	1.7	15 μs
C_1	100	20 kHz	15.8	1.2	1 μs
C_1	100	23.5 kHz	15.7	0.13	0
C_1	100	30 kHz	15.7	0.9	-1.9 μs
C_1	100	80 kHz	15.7	1.8	-2.8 μs
L_1 pot core	1000 Ω	2 kHz	16.3	1.2	0.22 ms
L_1	1000	10 kHz	16.4	2.2	86 μs
L_1 pot core	1000 Ω	42 kHz	16.4	8.9	0

(* Mathematica evaluation of RC and LC dividers for component tests. July 2009. P. T. Krein *)

(* The data given include frequency, peak-to-peak amplitudes of input and output voltages, and the time separation between input and output. *)

(* The variables are:

freq -- input frequency

vinpp -- input peak-to-peak voltage

voutpp -- output peak-to-peak voltage

dt -- the time difference

rs -- the divider series resistance

zout -- the impedance of the device being tested. *)

(* Computed quantities include:

phiout -- the radian phase angle on vout relative to vin

per -- the period

vout -- the complex output voltage *)

In[4]:=

per=1/freq

Out[5]=

1 / freq

In[6]:=

phiout = 2 Pi dt/per

Out[6]=

2 dt freq Pi

In[7]:=

vout = voutpp*Exp[I*phiout]

Out[7]=

2 I dt freq Pi

E voutpp

In[8]:=

vout == vinpp*(zout/(rs+zout)) (* The voltage divider equation. *)

Out[8]=

2 I dt freq Pi vinpp zout

E voutpp == ----------

rs + zout

In[9]:=

Solve[%,zout]

Out[9]=

2 I dt freq Pi

E rs voutpp

zout -> ----------

2 I dt freq Pi

vinpp - E voutpp

Notice that this can be written

$$Z_{out} = \frac{R_s V_{out(pp)} \angle \varphi}{V_{in(pp)} - V_{out(pp)} \angle \varphi}$$

ECE 469 -- POWER ELECTRONICS LABORATORY

EXPERIMENT #9 -- Passive Components, Part II: Magnetics

Objective -- This experiment provides an overview of many concepts of magnetic component design, based on measurement of the hysteresis loop. It concentrates on inductor and transformer design for high-speed converters.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Read over the magnetics information in your lecture material. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different problem.

1. A certain magnetic core has a magnetic path area of 2 cm², path length of 10 cm, permeability that is about $75\mu_0$, and a saturation flux density of 1.0 T. This coil is wrapped with 50 turns of wire. What is the maximum current that will avoid saturation?

2. The circuit below is intended for use in measurement of hysteresis loops of magnetic materials. Recall that H is equal to Ni/l for the core, and that B is related to flux linkage as $B = \lambda/(NA)$. The flux linkage, λ, can be found as $\lambda = \int v\, dt$. In the circuit, voltage v_i is supposed to be proportional to H, and voltage v_c is supposed to be proportional to λ. In a certain test, the frequency is 1000 Hz, the measured value of v_i is 0.1 V, and the measured value of v_c is 0.6 V. The core being tested has an area of 4.0 cm² and a path length of 24 cm. What are the actual values of magnetic field intensity H and flux density B in this case?

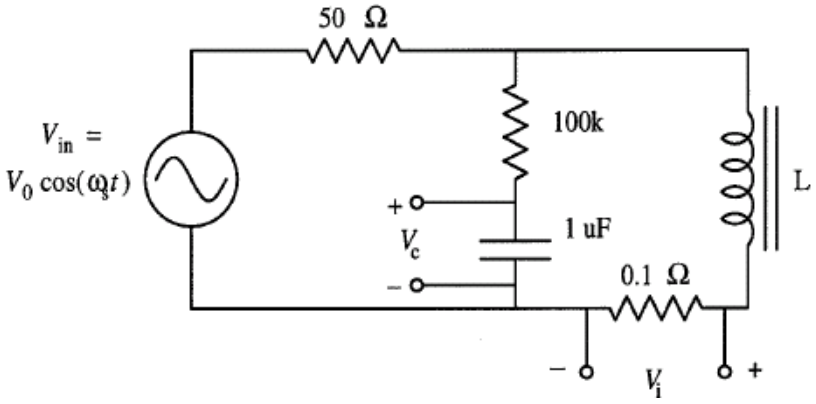


Figure 1. Possible test circuit for magnetic core.

Discussion --

Introduction -- Since the days of Faraday, magnetic devices have been known to provide the inductance function, and to store energy of the form $\frac{1}{2}Li^2$ in a magnetic field. Late in the 19th century, the use of magnetic devices to construct transformers and ac motors had major impact on the development of modern electric power systems. In power electronics, both the energy storage capabilities of inductors and the potential-shifting

properties of transformers are important in converter designs. But the requirements are unusual. For example, high power levels are often an issue at relatively high frequencies. Losses must be as low as possible. The best switching converter designs take full advantage of the latest magnetic materials, such as low-loss powder alloys and metal glasses. Motors can use permanent magnets. High temperature superconductors also have considerable promise.

Material properties are hard to ignore in the design of magnetic components, even more than for capacitors. Two important reasons for this involve the behavior of "magnetic conductors." Highly permeable materials with the ability to direct magnetic flux are only a few orders of magnitude better than air or vacuum. They have limited capacity for carrying magnetic flux. A second difficulty is that the most permeable materials are metals -- they carry magnetic flux, but also carry electric flux, so that a time-changing magnetic flux will create current flow and losses in the materials. The necessary tradeoffs require care and effort. In this experiment, a direct approach to magnetic measurements, and the implications for design, are explored.

Basic Theory -- The important concepts of magnetic circuits, magnetic domains, the hysteresis loop, and saturation produce design considerations for devices. In the laboratory, we will attempt to cover the measurement and use of magnetic materials. In particular, some candidate designs for inductors and transformers will be tested.

Any real magnetic material exhibits a maximum value of B, called the saturation flux density B_{sat}, beyond which it displays permeability equal to that of vacuum. Since the flux φ in a material is found as $Ni/\mathcal{R}$, where $\mathcal{R}$ is reluctance, the current in all windings ultimately determines whether the saturation flux density has been reached. Alternatively, the flux φ is given by λ/N, or $\int v\,dt/N$. The integral of voltage ("volt·seconds") determines the flux, within some integration constant. A real core has two limitations due to flux: the maximum value, determined by the integral of voltage, and the integration constant, which can be shown to equal $Ni_{ave}/\mathcal{R}$. Maximum volt·seconds and a maximum dc current result from the saturation limit. Hysteresis and eddy current loss can also be viewed as flux limitations. The applied voltages and currents must not cause excessive power loss in the material.

In a transformer, saturation should be avoided to keep leakage flux low. For ac applications, this means that only the volt·second integral is relevant. If a dc current is imposed on a transformer winding, a second flux contribution appears, and can even drive the core into saturation. In most power-frequency transformers, the number of turns is high, and tolerance for dc current is low. Dc current must be avoided. In an inductor, dc current is intended as the basis for energy storage. Inductors must be designed to tolerate high dc currents, while

providing consistent, linear, inductance. These two requirements are in conflict with the need for inductors of substantial value.

Another important issue in magnetics design is the current capacity of the wire used to wind the magnetic device. For instance, a design might call for a great many turns and a small core. While this is possible when small wire is used, the wire might melt if the intended currents are applied. This limitation is a very real one. It is not uncommon to require hundreds or even thousands of windings in power frequency devices, and the temptation to use ever-smaller wire is great. To realize a design, it is helpful to realize that only a fraction of any core opening can actually be filled with wire (some must be allowed for insulation and for air spaces around loose windings). It is also helpful to have some guidance about current capabilities of copper. While no absolute rules can exist, it is often preferred not to exceed 200 to 500 A/cm² in copper wires wound on cores. This range gives some rough assistance in picking the wire sizes needed.

A transformer design procedure might be as follows:

- Identify the frequency, voltage, current, and power requirements.
- Choose a wire size adequate for the current.
- Find the volt·second level needed to meet ratings.
- Identify a magnetic core with low losses over the intended frequency range, and proper l, A, and winding opening size to support the necessary volt·second integral.
- Compute winding and core losses to see if they are at acceptable levels.
- Build and test the device.

An inductor design would seek to:

- Identify the frequency, voltage, and dc current requirements.
- Identify the energy storage or *L* requirement.
- Choose a wire size as needed.
- Find the volt·second level needed.
- Compute a gap length, if necessary to meet energy and i_{dc} requirements.
- Build and test the device.

Procedure --

Part 1: Core hysteresis loops

1. You will be assigned a few test cores of various types. Use a ruler to obtain geometric data for each one, or use manufacturer's data about shape and size.
2. Wrap approximately 25 turns of wire around each test core.
3. Measure the inductance of each device at 1000 Hz with the lab RLC meter.
4. Place each core, in turn, in the circuit shown in the pre-lab above, with proper choices of the "integrating divider" *R* and *C*. You should substitute a current probe for the 0.1 Ω resistor. Be sure to include the 50 Ω resistor to protect the input source.
5. Use the oscilloscope in X-Y mode to observe the hysteresis loop at some frequency. Sketch the loop in your notebook, and also get a print of it. Measure the slope of either side of the loop near the origin (B=0 and H=0). Don't forget to make note of the slope units.
6. Decrease the applied frequency until a saturation effect is obvious. Again, sketch the waveforms. Measure the slope of the loop as far into saturation as possible. Also record the v_c value at saturation.
7. Apply a small dc offset from the input supply, and observe the change in the loop. Record your observations. Keep in mind that v_c measures the integral of voltage, and not λ directly.

Part II -- Transformer design and testing

1. Create a transformer by adding a second 25 turn winding on one of your test cores specified by your instructor.
2. Observe transformer performance by using the circuit shown in Figure 2, with R_{load} = 1 kΩ. Vary the source voltage frequency and amplitude so that saturation effects can be noted. You should sketch waveforms which demonstrate both saturated action and correct transformer action.
4. If there is time, use a 1N4004 diode in series with 50 Ω as a load, and repeat your observations.
5. If there is time, use a 1N4004 diode bridge and 50 Ω load. How does this alter the results?
6. If there is time, substitute a faster diode such as an MUR160 and repeat steps 4 and 5.

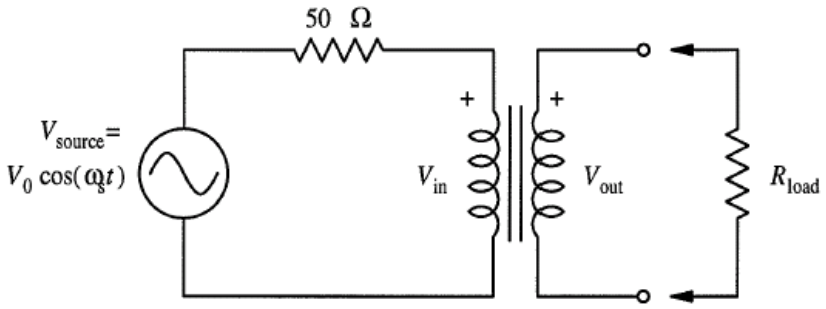


Figure 2. Core test circuit -- transformer.

Study Questions --

1. Calculate the permeability of each core at 1000 Hz from the lab RLC meter data. Calculate unsaturated permeability from the slopes of the hysteresis loops. Do your numbers agree?
2. Calculate B_{sat} from your hysteresis curves. What volt·second rating do you expect for your 25 turn inductors? How do the converter and transformer results compare to your expectations?
3. How does a dc current load affect the output of a transformer?
4. How many turns would be required to create a 10 mH inductor with each of your cores? What would the dc current rating be, based on saturation limits?

ECE 469 -- POWER ELECTRONICS LABORATORY

Design Project -- Part I

Objective -- The intent of the last set of experiments is to help guide the laboratory teams through a converter design problem. Each group will design, build, and test a different dc-dc or dc-ac converter. In Part I, effects of capacitor ESR and switch forward voltage drop will be a special focal point.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. It is imperative that you come prepared this week, since your ability to obtain the necessary lab data in a timely fashion depends entirely on your preparation. The following paper design should be submitted as you enter the lab. **Copy your result into your lab notebook *before* arriving in class**.

1. You will be provided with specifications for a dc-dc or dc-ac converter. Assume that a supply of capacitors similar in properties to those tested during Experiment #8 is available. Also assume that inductors with values around 250 μH and dc current ratings of 7 A are available.

   a) Draw a converter circuit capable of performing the intended function.

   b) Given your assigned specifications, find the minimum switching frequency for which $L > L_{crit}$.

   c) Compute the range of load resistances that correspond to the stated output power levels.

   d) Find the value of capacitor necessary to meet the intended ripple requirements.

2. If the switching frequency were changed to 100 kHz in the above converter, what would the value of L_{crit} become?

3. A *complete* SPICE, PSIM, PowerEsim, or Simulink simulation of your proposed circuit, *with explanation*, can be submitted for extra credit equal to one pre-lab assignment.

Discussion --

Introduction -- Several example problems have been worked in your courses concerning inductance and capacitance selection in converters. We have obtained data on capacitors and inductors. In the final series of experiments, our previous work will culminate in the design of an actual converter. This first experiment will test the basic design values, with the objective of developing a tentative circuit. Effects of capacitor ESR and switch voltage drops will be examined. The second experiment will concern implementation with discrete devices, along with gate drives and the realization of switching functions. The last experiment of the series will examine power loss and heat transfer considerations, and will include tests of the finished converter.

It is important to keep an especially careful record of work during the design project, since each experiment will build on earlier ones.

Basic Theory -- The concepts we have seen can now be integrated in a tentative converter design. Critical inductance, switching frequency, ripple levels, and variation of the duty cycle have all been studied. Of special note at this time are the effects of voltage drops in real switches and the effects of ESR in capacitors.

Voltage drops can be integrated into converter design in a straightforward manner. Consider the circuit shown below, in which an ideal diode and a voltage source have been used to model a real diode. The output voltage V_{out} can be written in terms of switching functions as:

$$V_{out} = q_1 V_{in} - q_2 V_{forward\,(diode)}$$

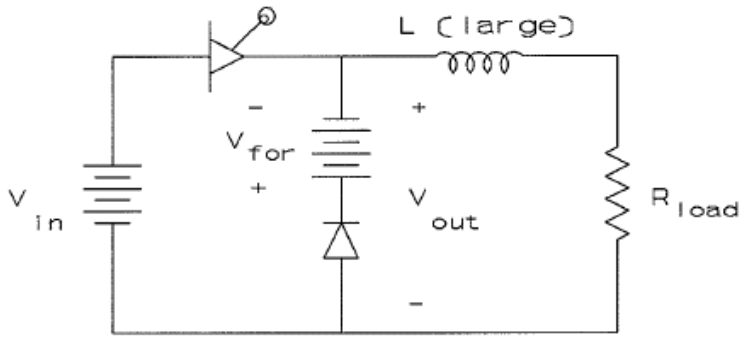


Figure 1. Buck converter with simple model for real diode

If V_{for} is assumed to be roughly 1 V, the average value of V_{out} can be found as

$$V_{out(ave)} = D_1 V_{in} + D_1 - 1$$

The input current is still $I_{in} = q_1 I_{out}$, so $P_{in(ave)} = D_1 V_{in} I_{out}$. But now,

$$P_{out(ave)} = D_1 V_{in} I_{out} - D_2 V_{for} I_{out},$$

which gives an efficiency of

$$\eta = 1 - \frac{D_2 V_{for}}{D_1 V_{in}}$$

This is certainly less than 100 %, and represents the loss in the real diode while it is on. A series resistor could also have been included as part of the diode or transistor models. This would have created a somewhat more complicated output expression, but the principles are the same. The necessary algebra is left to the student.

Capacitor ESR results in output "jumps" and extra ripple. For example, an electrolytic capacitor with tan δ = 0.10 and C = 200 μF ideally has ESR of 4 mΩ at 20 kHz. (The actual ESR is higher since the wires and plates add their own series resistance to the effective value associated with leakage.) Consider the effect in the boost converter shown in Figure 2. When switch #1 is on, the output current charges the capacitor, but there is a voltage drop across the ESR which appears at the output. As switch #1 turns off, the internal capacitor voltage V_c follows a triangular ripple behavior, and does not change at the moment of switching. The capacitor current changes abruptly, which in turn reverses the voltage drop across the ESR, and causes an abrupt shift in V_{out}. The total output voltage for this converter can be calculated without too much trouble, if the capacitor voltage is assumed to change in a triangular manner. The V_{out} waveform is shown in Figure 3.

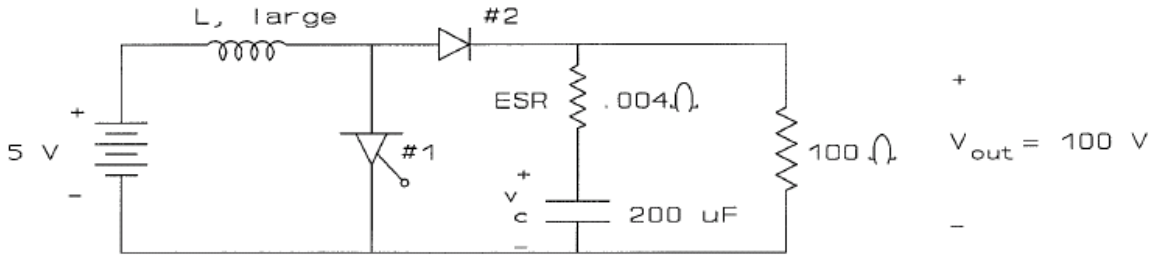


Figure 2. Boost converter with capacitor ESR included

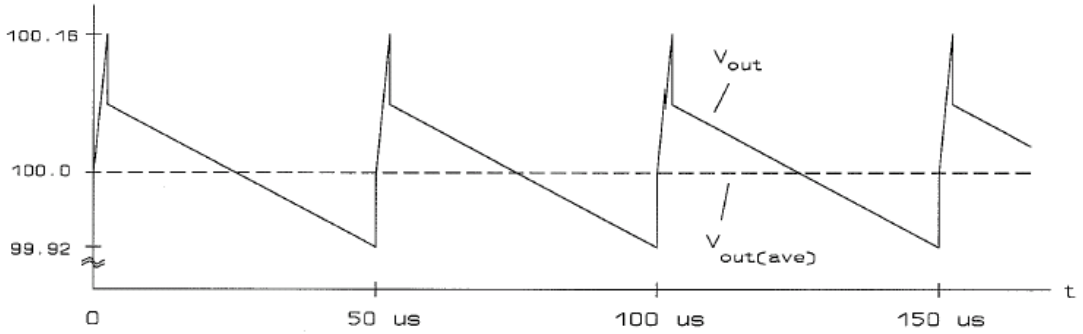


Figure 3. Output voltage waveform for boost converter of Figure 2

As indicated in Figure 3, the ESR voltage drop can be a significant fraction of the output voltage ripple. If a maximum output ripple is specified, the value of ESR at the switching frequency will have to be taken into account when designing the converter. For example, the above converter displays output ripple of about 240 mV, although a ripple of less than 160 mV would have been expected if the capacitor were a perfect 200 μF device. In this experiment, data on ESR effects and on switch voltage drops will be taken to support more accurate converter design.

Procedure --

1. Measure a pot-core or powered iron inductor at 1000 Hz with the lab RLC meter. Use this core, along with an FET control box, to build a converter as designed in your pre-lab. Be sure to place a capacitor across V_{in}, so that it will appear as a voltage source.

2. Observe V_{out} under a range of conditions. Be sure to test for a variety of values within your required converter operating range. Sketch V_{out} under what you find to be roughly worst-case V_{out} ripple. Be sure to record duty cycle data, along with sufficient data to calculate efficiency.

3. Observe voltage drops across the FET and the diode under your range of operating conditions. The intent is to gather data for circuit models of your actual diode and FET.

4. If the converter you have built does not meet the specifications for output ripple, try other capacitors in an effort to solve the problem. **Experience with your converter circuit is more important than meeting all specifications in detail.** The HP 6060B is an especially useful tool for loading.

5. In the next part of the design project, you will be using actual FET and diode parts, in place of the control box. Be sure you have collected all data needed for models of your devices and for the capacitors. Also, observe inductor current to confirm the minimum switching frequency for which $L > L_{crit}$.

Study Questions --

1. Be sure to include the "baseline" design related to this week's pre-lab in your design project report.

2. Model the *on* condition of the FET as a 0.1 Ω resistor, and the *on* condition of the diode as a 1 V drop. What value of V_{out} vs. duty ratio would be expected for your converter? Does this agree with measured data?

3. Will you need an FET with lower resistance to meet the requirements?

4. Compute the ESR of your capacitors from the waveform data.

5. Find the peak currents and voltages in your inductor and capacitor.

6. Based on the results, refine your design to bring it as close as possible to meeting the specifications.

7. Two common problems in dc-dc converters are: (a) the user accidently connects the input voltage in the reverse direction, and (b) a short circuit is accidently connected at the output. Would the converter you are designing be able to handle these faults?

CONVERTER SPECIFICATION SETS

Your instructor will assign one of the specification sets below to your group. Your group can also propose a specification set, or your instructor may provide an alternative list.

A. **Input Voltage Range: 5 V to 10 V**
Output Voltage: 12 V ± 1 %
Output Load Range: 5 W to 20 W

B. **Input Voltage Range: 10 V to 28 V**
Output Voltage: -12 V ± 2 %
Output Load Range: 5 W to 20 W

C. **Input Voltage Range: -5 V to -16 V**
Output Voltage: 5 V ± 1 %
Output Load Range: 10 W to 25 W

D. **Input Voltage Range: 10 V to 35 V**
Output Voltage: +5 to +12 (adjustable) V ± 40 mV
Output Load Range: 0 W to 20 W

E. **Input Voltage Range: 20 V to 40 V**
Output Voltage: either +80 or -80 V ± 3 % Output polarity is team choice.
Output Load Range: 10 W to 20 W

F. **Input Voltage Range: 10 V to 18 V**
Output Voltage: ±15 V ± 2 % Dual outputs.
Output Load Range: 2 W to 20 W

G. **Input Voltage Range: 3.6 V to 7.2 V Battery power.**
Output Voltage: 3.3 V ± 1 %
Output Load Range: 0 W to 30 W

H. **Input Voltage Range: 10 V to 18 V**
Output Voltage: 13.8 V ± 1 % **Must be isolated.**
Output Load Range: 0 W to 50 W

I. **Input Voltage Range: 9 V to 15 V**
Output Voltage: 24 V ± 3 %
Output Load Range: 12 W to 35 W

J. **Input Voltage Range: 3 V to 8 V** **Battery power.**
Output Voltage: 5 V ± 1 %
Output Load Range: 0 W to 25 W

K. **Input Voltage Range: 34 V to 45 V**
Output Voltage: 48 V ± ½ %
Output Load Range: 0 W to 150 W

L. **Input Voltage Range: 10 V to 15 V**
Output Voltage: 2.0 V ± 1 % isolated
Output Load Range: 0 W to 20 W

M. **Input Voltage Range: 25 V to 40 V**
Output Voltage: 12 V ± 1 %
Output Load Range: 10 W to 100 W

N.

Input Voltage Range: 30 V to 60 V
Output Voltage: 48 V ± 2 % Must be isolated.
Output Load Range: 50 W to 100 W

O.

Input Voltage Range: 25 V_{RMS}, 50-60 Hz
Output Voltage: 13 V **adjustable ± 1 V, with current limited to 5 A**
Output Load Range: 0 W to 70 W

P. **Input Voltage Range: 20 V to 30 V RMS, 60 Hz**

Output Voltage: 12 V dc ± 1 %

Output Load Range: 50 W to 100 W

Q. **Input Voltage Range: 22 V to 26 V**

Output Voltage: $12\sqrt{2}\cos(120\pi t)$ V ± 0.2 V

Output Load: 50 W

R.

Input Voltage Range: 5 V to 12 V

Output Voltage: 1 to 2 V ± 0.02 V (adjustable)

Output Load: 20 to 40 A

S.

Input Voltage Range: 48 V to 60 V

Output Voltage: 42 V ± 1 %

Output Load: 20 to 150 W

T.

Input Voltage Range: 10 V to 18 V

Output Voltage: 10 to 14.8 V, ripple not to exceed 50 mV_{RMS} ***Output current-limited to 2.5 A.***

Output Load: 0 to 2.5 A, battery load

U.

Input Voltage: $|25\sqrt{2}\cos(120\pi t)|$ V, input power factor to exceed 0.9

Output Voltage: 16 V ± 2% (suitable for isolated laptop supply)

Output load: 0 to 4 A

V.

Input Voltage: 10 V to 18 V (automotive)

Output voltage: 16 V ± 2% (suitable for isolated laptop charger)

Output load: 0 to 4 A

W.

Input Voltage: 10 V to 14 V

Output Voltage: 2.7 V ±0.5%

Output load: 0 to 10 A

ECE 469 -- POWER ELECTRONICS LABORATORY

Design Project -- Part II

Objective -- The second experiment in the design sequence will implement converters with discrete devices. In this context, gate drive considerations for semiconductor switches will be examined.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Be especially careful to study the circuit diagrams in this write-up. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different problem.

1. In the circuit below, the FET has on-state resistance of 0.05 Ω and the diode has forward drop of 1 V. We are also interested in timing effects of the gate drive. The ideal switch #1 in the figure is controlled to have a duty ratio of exactly 50% and a switching frequency of 250 kHz. A simplified gate-control model of the power MOSFET, which demonstrates a few of the properties of a real device, is as follows:

- The gate-source region can be modelled as a capacitor. A typical value for devices such as those in your converter boxes is around 1000 pF.
- The drain-source channel can be modelled as a low resistance whenever the gate-source voltage V_{gs} exceeds a threshold value, V_{th}. A typical value of V_{th} is about 4.0 V. The channel is a very high resistance when $V_{gs} < V_{th}$.
- The combination of 10 Ω resistor, 1 kΩ resistor, and gate-source capacitor gives rise to RC time delays that will change the operating duty ratio away from the 50% control signal.

a) Find V_{load} for these conditions. What is the inductor current?

b) What are the average power losses in the FET and diode? How much power is consumed in delivering the signal to the gate?

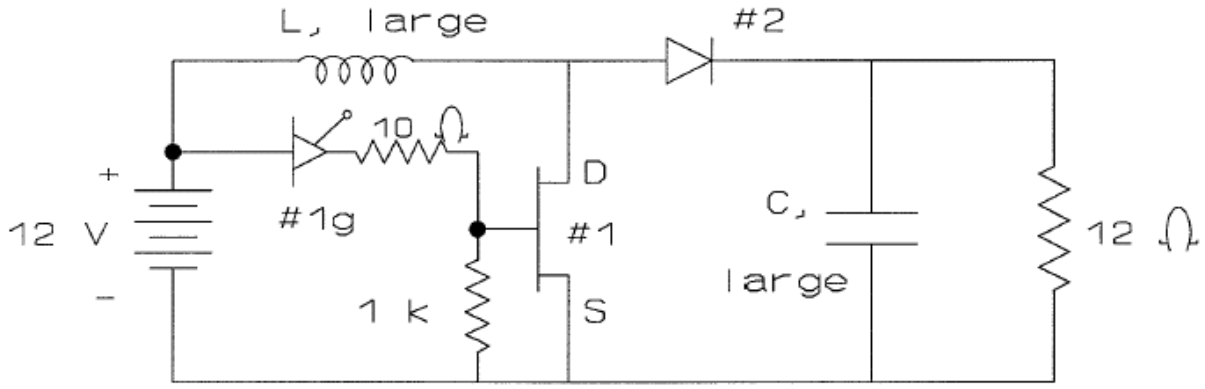


Figure 1. Boost converter with FET for pre-lab assignment

Discussion --

Introduction -- An ideal switch, with the exception of a diode, requires a third *gate* terminal to determine its state. In the ideal case, a switching function is applied directly to this gate (without regard to electrical ground or isolation). The switch is instantaneously on whenever the gate is high and instantaneously off whenever the gate is low. While the concept of a gate terminal carries over to real switches, there are a host of new considerations introduced by a *real* gate. The signal applied to the gate must be supplied by some electronic circuit. The potential at the gate normally has restrictions relative to the potentials on the switch terminals. Operation of a real gate requires energy (and hence power and time); it must be supplied from some drive circuit. There could be issues of reference nodes. As you might guess, there is a time difference between the application of a gate signal and the actual switching action. In addition to gate characteristics, semiconductor switches have internal properties, such as resistance and capacitance, which limit time rates of change of voltage or current even with a perfect delay-free gate signal.

In this experiment, some characteristics and considerations associated with gate drives will be examined as the design project circuit is implemented in a complete discrete circuit. A gate drive typically tries to minimize commutation time while not adding significantly to power requirements. It also can involve a "level-shift" or "high-side" process to control switch action to off-ground terminals. Gate drives are low-power electronic circuits, and are designed much differently from the converters in which they operate. They are commonly switching circuits, however, so many concepts of switch networks still apply.

Basic Theory -- Gate drives: Modern power semiconductors fall into two major classes based on gate issues: thyristors and field-gated devices. In the past, BJTs were also used. A BJT can be modeled as a current-controlled current source, and requires current into the base when it is to be on. This current is supplied at low voltage (so that power is low), but can be as high as a tenth or more of the switch on-state current. Base drives for power BJTs can be a challenge, since they usually must supply several amps in a precisely-controlled square wave. In the case of the FET and other field-controlled devices, the steady-state gate current is essentially zero, and the gate voltage determines switch operation. However, there is still a need for short-term high currents to charge gate regions rapidly and force the fastest possible switching. These voltage-controlled gates are much easier to address than BJT base drives, which helps to explain the declining use of power BJTs in switching converters. The SCR, as a typical thyristor, is a “latching” device, and requires only a pulse at the gate in order to turn on. The newer gate turn-off thyristors (GTOs) are also latching devices, but in this case can be forced to turn off. The drawback of a GTO is that the turn-off drive pulse is similar to a base drive -- many amperes must be drawn out of the gate to force turn-off.

The basic requirements are simple enough, but details add great complexity. Let us first examine the FET, which is considered by many to have the simplest gate characteristics. The MOSFET consists of a channel of doped semiconductor (most often p-type) spread between drain and source terminals. A small region of heavily doped material of opposite type is implanted at the two terminals. A layer of insulation is mounted next to the channel. When voltage is applied to the gate electrode, charge carriers are attracted into the region near the gate. More carriers come in as the gate voltage rises, until the channel is "inverted," and matches the polarity at the source and drain. Current can flow between the source and drain if adequate numbers of charge carriers are present.

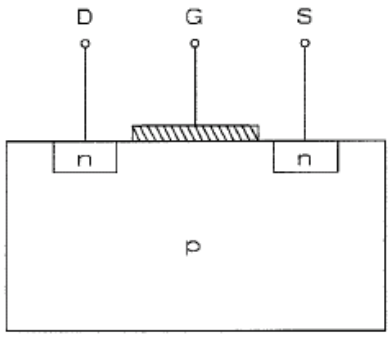


Figure 2. Simplified MOSFET in cross section

To turn the FET on, the gate region must be charged. The region certainly represents a capacitance, and the gate drive must be designed so as to charge this capacitance sufficiently. The channel will invert when the gate voltage exceeds a threshold level, V_{th}. In fact, the gate voltage must be maintained at a level considerably greater than V_{th} (usually above $2V_{th}$), so that enough charge will be present in the channel for low effective channel resistance. The gate drive must therefore apply an "overdrive" gate voltage on the order of more than 100%.

To turn the FET off, the gate region must be discharged, and the gate voltage must be drawn and maintained below V_{th}. Real devices have wide error tolerances on V_{th}. For example, the IRFP360 FET used in the lab converter boxes can have any V_{th} between 2.0 and 4.0, depending on the device and the operating temperature. For good performance, a gate drive would apply about 10 V between gate and source for such a device.

Some gate drive design considerations are apparent:

- For turn-on, the drive must rapidly charge the gate to a voltage much higher than V_{gs}, while not exceeding the dielectric breakdown limit of the gate insulator. Typical gate-source capacitance values range from several hundred to several thousand picofarads.
- For turn-off, the drive must rapidly discharge the gate to a voltage lower than V_{th}, again without exceeding dielectric limits.

Several device specifications are important in the FET gate drive design. Referring to summary IRF521 specification sheets, notice the following relevant information:

- V_{th} between 2.0 and 4.0 V.
- Limits on gate-source voltage (gate dielectric breakdown limit):

  -20 V < V_{gs} < +20 V.
- Maximum gate current level: 1.5 A (absolute value).
- Gate-source input capacitance: 600 pF.

With these data, it is possible to design many different gate drive circuits. Consider the performance of a gate drive consisting of a nearly ideal switch operated from a 12 V source with 50 Ω output impedance, similar to the pre-lab. At turn-on, the gate capacitance is uncharged, and the maximum gate current is V_{in}/R_s, or 0.24 A in this example. With an RC time constant of 600 pF × 50 Ω = 30 ns, this gate drive will charge the gate to more than 10 V in about 60 ns. The actual device turn-on time of 110 ns (from the data sheets) is reasonably consistent with this number. Slightly faster turn-on could be achieved by using a smaller R_s. A value as low as 8 Ω could be used without excessive gate current, although in practice values below about 10 Ω require special design methods. At turn-off, the gate must discharge through the second resistor. This resistor has the undesirable effect of drawing power whenever the FET is on, so it is kept relatively high. It also acts as a voltage divider for V_{gs}. For the circuit of Figure 3, turn-off is relatively slow.

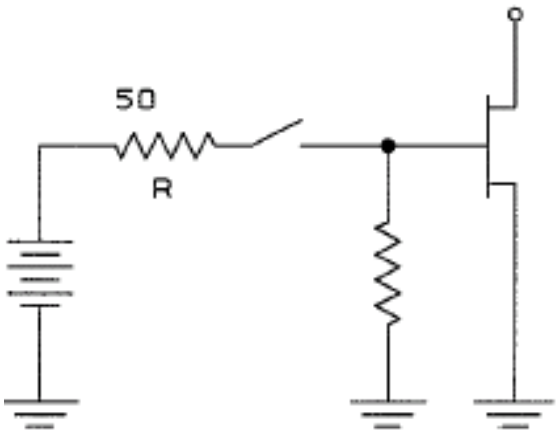


Figure 3. Sample FET gate drive circuit

More specific requirements on field-type gate drives are becoming apparent:

- The gate drive must provide a voltage between the gate and source of about 10 to 18 V, with low voltage source impedance, for fast turn-on.

- The gate drive should provide a low impedance discharge path during turn-off. This path can apply zero volts across the gate and source, or could use $V_{gs} < 0$ if a negative voltage source is available.
- The gate drive can be designed so that current is drawn only in a brief pulse. In principle, most of the $\frac{1}{2}CV^2$ energy in the gate can be recovered, so that power requirements can be made very low.

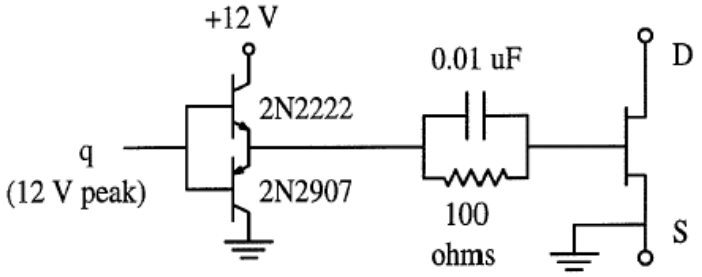


Figure 4. High-performance gate drive circuit for FET.

A typical high-performance gate drive circuit appears in Figure 4. Although the circuit contains many semiconductors, it can be implemented for the most part in an integrated circuit.

The main drawback of FET gate drives is the need to apply a substantial voltage between the gate and source as long as the device is to be on. In many converters, this is not a trivial manner. The familiar buck dc-dc converter is shown in Figure 5. For the unit of Figure 5a to work, a voltage equal to V_{in} + 10 V must be applied to the FET gate whenever switch #1 is to be on. This second voltage source, higher than the available source, can be a major stumbling block in building a converter. If the switch is relocated as in Figure 5b, the problem of higher voltage level is alleviated, but the output is no longer relative to ground potential. While not an issue in isolated converters, the voltage requirements of FETs make them difficult to use in many situations.

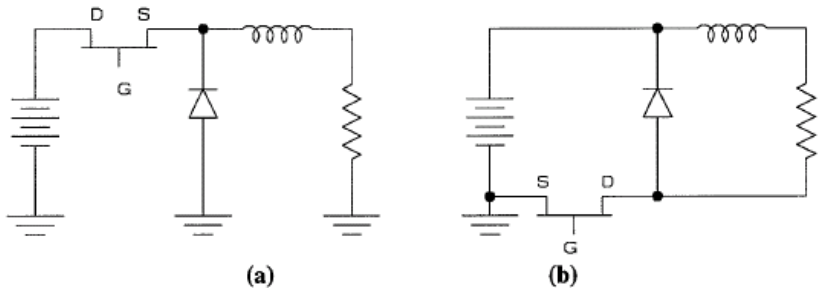


Figure 5. The buck converter with FET switch

Thyristors, as latching devices, need a gate signal only until sufficient anode current flows. Then the gate signal can be removed and the device stays on. For example, the 2N6508 requires a gate signal of 75 mA or more at a voltage of up to 1.5 V. The gate signal will not be needed once the anode current reaches 40 mA. This can occur as little as 2 μs after the start of the gate pulse. A pulse transformer can serve as a suitable driver for such requirements. This has the important advantage of isolation of the gate.

Most SCR applications are tied to an ac power line frequency, so that turn-on speed is often not a major consideration. With this in mind, it is relatively easy to build an SCR gate drive. Again, certain details make the issue harder. A controlled rectifier circuit is shown below. The load inductance guarantees a complete set of switching functions -- or does it? Take the case of circuit start-up. Inductor current is initially zero, and three-phase voltages are applied to the SCRs. While a gate signal is applied to SCR A, the inductor current changes as v_L/L. A large inductor will mean a slow change, and a long time may pass before the SCR anode current exceeds the "holding" value. To alleviate this, a small resistor can be added as a ballast load, to ensure SCR turn-on latching. Otherwise, the circuit will not operate. This effect was important in the early SCR experiment. If you look back, you will see the ballast resistor in that circuit.

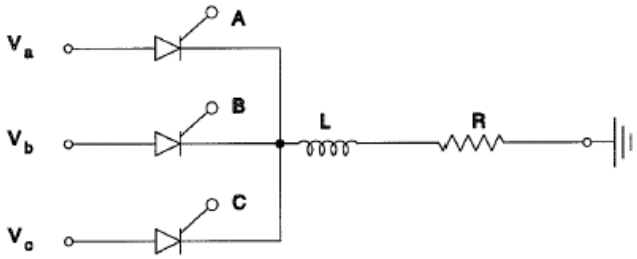


Figure 6. SCR controlled rectifier for three-phase input.

Basic Theory -- Introduction to snubbers: During the first design project experiment, many circuits exhibited high momentary voltages across the switches. Power FETs fail quickly when a V_{ds} value beyond their limit is imposed. The voltage spikes occur for two reasons. The first is that each circuit connection, wire, or component, has inductance, and thus behaves as a current source over short time intervals. When one attempts to reduce any current by switching action, a negative voltage $v_L = L(di/dt)$ will be produced. The faster the switch, or the larger the inductor, the more extreme this negative voltage. In an FET switching 10 A in 100 ns, even with a circuit inductance as low as 1.0 μH, a voltage of 100 V will be generated, independent of the converter voltage levels. This voltage will appear across the switch as it turns off, causing commutation loss and possibly approaching the switch voltage limits. The second reason for momentary high voltages is the presence of capacitance which interacts with inductance in a resonant fashion. A series resonant LC circuit can produce very high momentary voltages across each of its passive components. This behavior is oscillatory, and is often called "ringing."

Voltage peaking leads to extra losses and even switch failure. To avoid them, it is necessary to minimize the circuit inductance and to keep di/dt sufficiently small. The first of these methods involves careful design and circuit construction. Leads should be short and of proper size. Loops or other features which enhance magnetic field coupling must be avoided. The second of these seems to imply a slower switch -- which works, at the cost of high commutation losses and poorer circuit operation. Instead, it is desirable to act upon the switching trajectory

itself. After all, the problem is a switching trajectory which reaches high voltages and high currents simultaneously.

Circuits which act directly on the switching trajectory are called "snubbers." The function of a snubber is to shape (and especially reduce peaks in) the switching trajectory and hence protect the switching device. Snubbers are wired as close as possible to a switch, and in effect are part of the switch itself for purposes of converter design. For example, a capacitor can be placed across the semiconductor, so that some of the energy needed by the load during commutation is provided by the capacitor. Consider the case of transistor turn-off in a buck converter. If the diode is very fast, and the transistor is assumed to have a linear change of current over time during commutation, the results are well-determined. The inductor voltage is $L(di_L/dt)$, and is therefore negative whenever the inductor current falls. The capacitor current $i_C = C(dv_C/dt)$ will be non-zero as soon as inductor voltage attempts to change. The voltage across the transistor will change "slowly," in a resonant fashion, so as to satisfy KVL and KCL. If the inductor is very large, di_L/dt in it is small, and the voltage across the transistor changes strictly as $dv/dt = (i_L - i_{trans})/C$. This linear function leads to a parabolic change in voltage. In any case, the voltage is much lower during commutation than without the capacitor. In practice, a linear voltage change is more desirable. This can be achieved by using a series RC pair. An RC snubber causes the switch voltage to change relatively slowly during turn-off. Unfortunately, the opposite occurs during turn-on. In this case, the transistor voltage changes slowly, beginning at V_{in}, during switching. The switching power loss will actually increase. It is apparent that a turn-off snubber and a turn-on snubber have different requirements. To avoid this difficulty, it is necessary to add a diode so that the RC snubber discussed above will operate only during transistor turn-off. This circuit is shown in Figure 7. The diode and other parts carry current only for a short time, their peak ratings are used for design. In Figure 7, during turn-off, the RC combination causes voltage to change relatively slowly. The time constant can be selected so that the commutation interval is extended only slightly. While the transistor is off, the snubber capacitor charges up to V_{off}. But at transistor turn-on, the snubber circuit diode prevents current flow from the snubber capacitor. The second resistor, R_2, discharges C during the transistor's on-time so that the snubber will again be ready for turn-off.

This RCD snubber, along with several variations, is very popular, and has been used successfully in a wide range of circuits. This snubber is known as a **lossy snubber**, since energy is dissipated in its resistances. The intent is to decrease the total switching losses by adding a lossy snubber. See your ECE 464 text for more information. Lossless snubbers, which use only switches and energy storage elements, are feasible, and have been discussed in the literature.

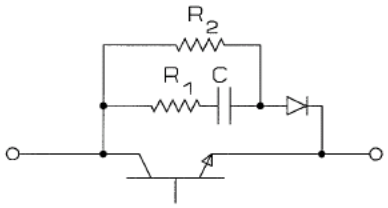


Figure 7. An RCD snubber for the transistor in a dc-dc converter.

Procedure --

1. We will study an FET gate drive in the context of your converter. Obtain an FET and diode with ratings appropriate to your converter. Measure the characteristics of these devices on the power curve tracer.

2. Assemble the drive circuit shown in Figure 8. The UC3843 integrated circuit is a controllable pulse generator for use in dc-dc converters. Notice that the circuit includes a snubber.

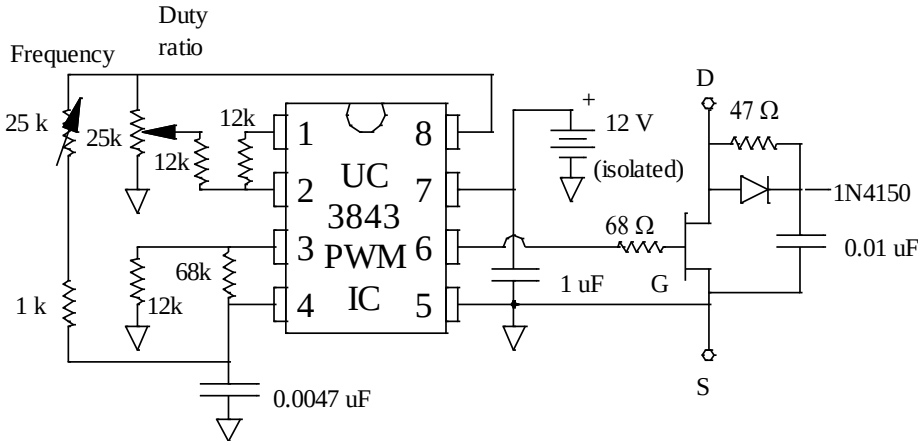


Figure 8. UC3843 based gate drive system.

3. Insert the FET and diode into your converter circuit. Pay attention to grounds and to isolation requirements for voltage sources.

4. Observe the FET voltage and current, and the gate voltage. Choose a reasonable value of frequency and duty ratio, based on your converter requirements. Sketch the waveforms. What are the turn-on and turn-off times of your switches?

5. Vary the duty ratio and frequency. Again observe the FET signals. Take data necessary to find effects of D and f on rise and fall times. Be sure to observe the effect of very high switching frequency.

6. Use the X-Y mode of your oscilloscope to observe and sketch the switching trajectories. Think about how the snubber affects them.

7. Check your converter to see if it meets the specifications. Try making adjustments where necessary. What are the input voltage and power limitations of your converter?

Study Questions --

1. Compute (approximately) the power used in your gate drive circuit. How is converter efficiency affected?
2. Include the curves gathered in the lab on the curve tracer for your devices. What is V_{th} for your FET? What voltage drops and resistances model your semiconductors?
3. Calculate a value of gate capacitance from your measured fall time. Is the value consistent with the data sheets?
4. Use your data to predict the performance of your converter. Can you meet specifications with these parts?

[1] Data sheets from various On Semiconductor Data Books (IRF 5xx, MTH15N35, 2N3055, 2N6508, MUR3040PT).

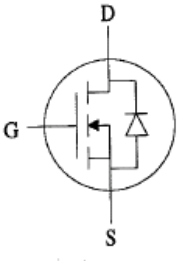
[2] SG3526 data sheets from Signetics Corp., UC3843 data from Motorola Corp.

[3] IRFP360 data from *HEXFET Designer's Manual, Vol. III*, International Rectifier Corp., El Segundo, Calif., 1993, pp. 1001-1006.

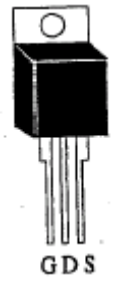
[4] UC3843 block diagram is from *Linear/Interface ICs Device Data, Vol. I*, Motorola Corp., Phoenix, AZ, 1993, p. 3-509.

[5] UC3526 diagrams are from *Power Supply Control Products Data Book*, Texas Instruments, Dallas, TX, 2000, p. 3-68.

Summary Specification Sheets for Parts



IRF 520 and IRF 521 (MOSFET):

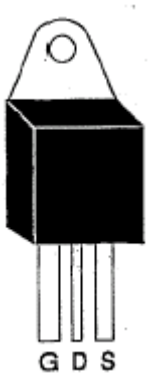


Rating	**Symbol**	**Maximum limit**
Drain-source voltage	V_{DSS}	100 V (520), 60 V (521)
Gate-source voltage	V_{GS}	±20 V
Drain current	I_D	8 A continuous, 32 A momentary peak
Junction temperature	T_J	150°C

Characteristic	**Symbol**	**Typical value**
Thermal resistance, junction-case	Θ_{JC}	3.12 K/W
junction-ambient	Θ_{JA}	62.5 K/W (no sink)
Residual current, V_{GS}=0, V_{DS}=max	I_{DSS}	0.2 mA
Gate threshold voltage	$V_{GS(th)}$	2 to 4 V
On-state resistance, V_{GS}=10	$R_{DS(on)}$	0.3 Ω

Input capacitance	C_{iss}	600 pF
Turn-on delay time	$t_{d(on)}$	40 ns
Rise time	t_r	70 ns
Turn-off delay time	$t_{d(off)}$	100 ns
Fall time	t_f	70 ns

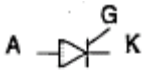
IRFP360 (MOSFET) and MTW15N35:

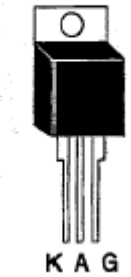


Rating	**Symbol**	**Maximum limit**
Drain-source voltage	V_{DSS}	400 V (360), 350 V (15N35)
Gate-source voltage	V_{GS}	±20 V
Drain current	I_D	23 A continuous, 90 A momentary peak
Junction temperature	T_J	150°C

Characteristic	**Symbol**	**Typical value**
Thermal resistance, junction-case	Θ_{JC}	0.45 K/W
junction-ambient	Θ_{JA}	40 K/W (no sink)
Residual current, V_{GS}=0, V_{DS}=max	I_{DSS}	0.25 mA
Gate threshold voltage	$V_{GS(th)}$	2 to 4 V
On-state resistance, V_{GS}=10	$R_{DS(on)}$	0.2 Ω
Input capacitance	C_{iss}	4500 pF
Turn-on delay time	$t_{d(on)}$	18 ns (360), 60 ns (15N35)
Rise time	t_r	79 ns (360), 180 ns (15N35)
Turn-off delay time	$t_{d(off)}$	100 ns (360), 450 ns (15N35)
Fall time	t_f	67 ns (360), 180 ns (15N35)

2N6508 (SCR):





Rating	**Symbol**	**Maximum limit**
Blocking voltage (forward or backward)	$V_{AK(off)}$	600 V
Peak gate current	I_{GM}	2 A
Forward current	I_T	25 A RMS, 16 A ave, 300 A ½ cycle surge
Junction temperature	T_J	125°C

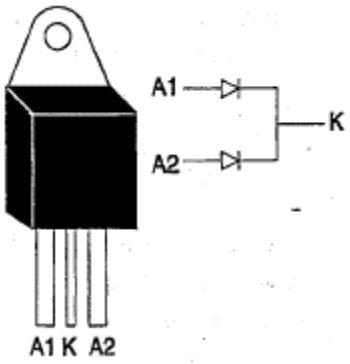
Characteristic	**Symbol**	**Typical value**
Thermal resistance, junction-case	Θ_{JC}	1.5 K/W
Residual current, I_G=0, V_{AK}=max	$I_{T(off)}$	2 mA
Gate trigger current	I_{GT}	25 mA (75 mA worst case)
Gate trigger voltage	V_{GT}	1 V
Holding current	I_H	35 mA
On-state residual voltage	$V_{AK(on)}$	1 V (I_T=3 A), 1.8 V (I_T=50 A)

Turn-on time	t_{gt}	1.5 μs
Turn-off time	t_q	35 μs
Critical rate of rise of off-state voltage	dv/dt_C	50 V/μs

MUR3040PT (ultra-fast power rectifier):

Rating	**Symbol**	**Maximum limit**
Peak reverse voltage	V_R	400 V
Forward current, per leg	$I_{F(ave)}$	15 A, 150 A ½ cycle surge
Junction temperature	T_J	175°C

Characteristic	**Symbol**	**Typical value**
Thermal resistance, junction-case	Θ_{JC}	1.5 K/W
junction-ambient	Θ_{JA}	40 K/W
Reverse current, V_R=max	I_R	500 μA
Forward voltage, I_F = 15 A	V_F	1.2 V
Reverse recovery time	t_{rr}	60 ns (max)



UC3843 (PWM control integrated circuit):

Rating	**Symbol**	**Maximum limit**
Supply voltage	V_S	30 V (max), 8.5 V (min)
Analog input voltage (pins 1-3)	V_{in}	-0.3 V to V_S
Junction temperature	T_J	150°C
Operating temperature	T_A	0° to 70°C

Characteristic	**Symbol**	**Typical value**
Thermal resistance, junction-ambient	Θ_{JA}	125 K/W
Frequency range	f	10 Hz to 500 kHz
Output rise and fall times	t_r, t_f	50 ns
Duty ratio range	D	0-97%

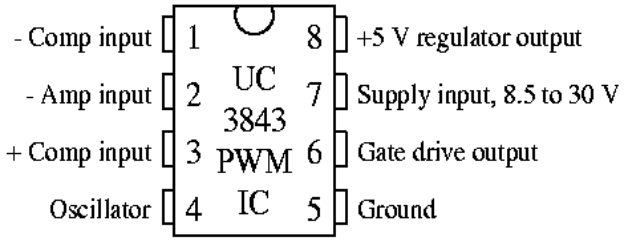


Figure 9. Pin diagram for UC3843.

SG3526 (double-ended PWM control integrated circuit):

Rating	**Symbol**	**Maximum limit**
Supply voltage	V_S	40 V (max), 7 V (min)
Logic input voltage (pins 5, 8, 12)	V_{in}	-0.3 to +5.5 V
Analog input voltage (pins 1, 2, 6, 7)	V_{in}	-0.3 V to V_S
Junction temperature	T_J	150°C

Characteristic	**Symbol**	**Typical value**
Thermal resistance, junction-ambient	Θ_{JA}	66 K/W
Frequency range	f	1 Hz to 500 kHz
Reverse current, V_R=max	I_R	500 μA
Forward voltage, I_F = 15 A	V_F	1.2 V
Reverse recovery time	t_{rr}	60 ns (max)

UC3843 Operation:

The UC3843 contains several modules, as shown in the block diagram of Figure 10.

- A +5V series regulator for logic power and to provide a reference signal. The regulator works over an input range of +8.5V to +30V.
- An undervoltage lockout circuit to shut the IC down and reset it if the +5V level falls too much.
- An oscillator to provide a triangle waveform and a clock pulse train over the range 10 Hz to 500 kHz. The period is approximately ½(RC), where R and C are the timing components connected at pins 9 and 10, respectively.
- An amplifier (a bit like an op-amp) with gain-bandwidth product of 1 MHz. This amplifier is actually a transconductance device, and we elect not to use it because the non-inverting terminal is tied internally to the oscillator.
- A comparator for pulse-width modulation. The oscillator triangle is compared to the amplifier output to generate the main PWM square wave.
- A single totem-pole output. This output can drive up to 200 mA loads at up to 30 V. It is designed primarily for MOSFET gate drives.
- Double-pulse lockout logic. If the comparator inputs cross each other more than once per clock period, multiple PWM pulses would be produced. The double-pulse logic ensures that only the first pulse is accepted. No others will have any effect until the logic resets with the next clock pulse.
- The chip can drive a MOSFET over nearly the full 0 to 100% duty ratio range.

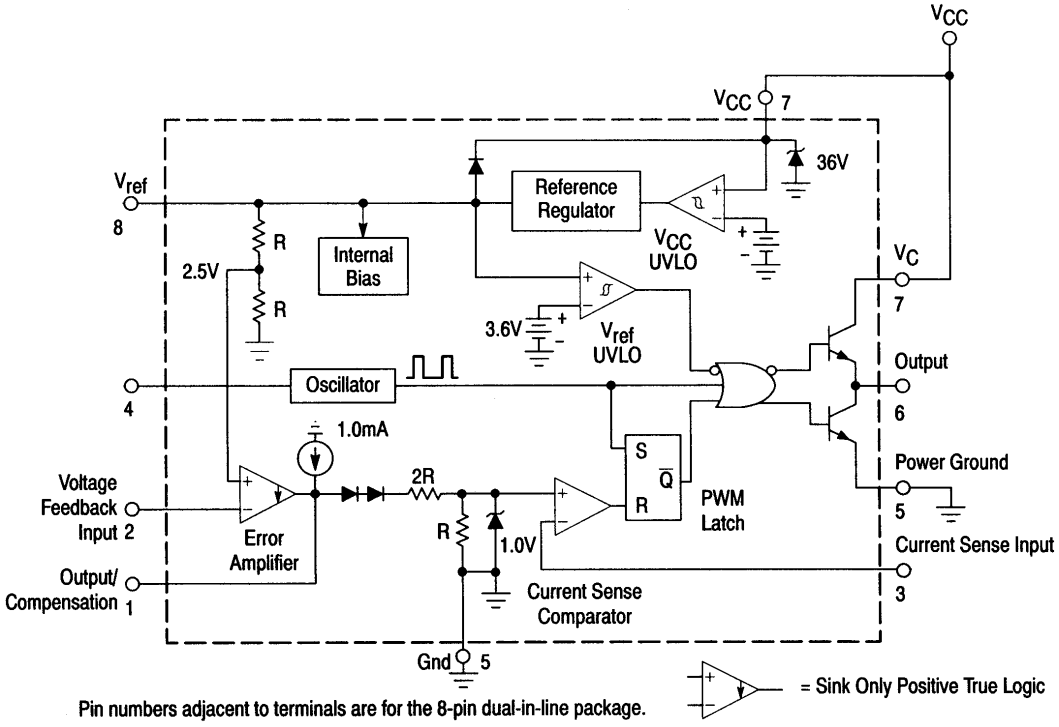


Figure 10. Block diagram of UC3843 from [4].

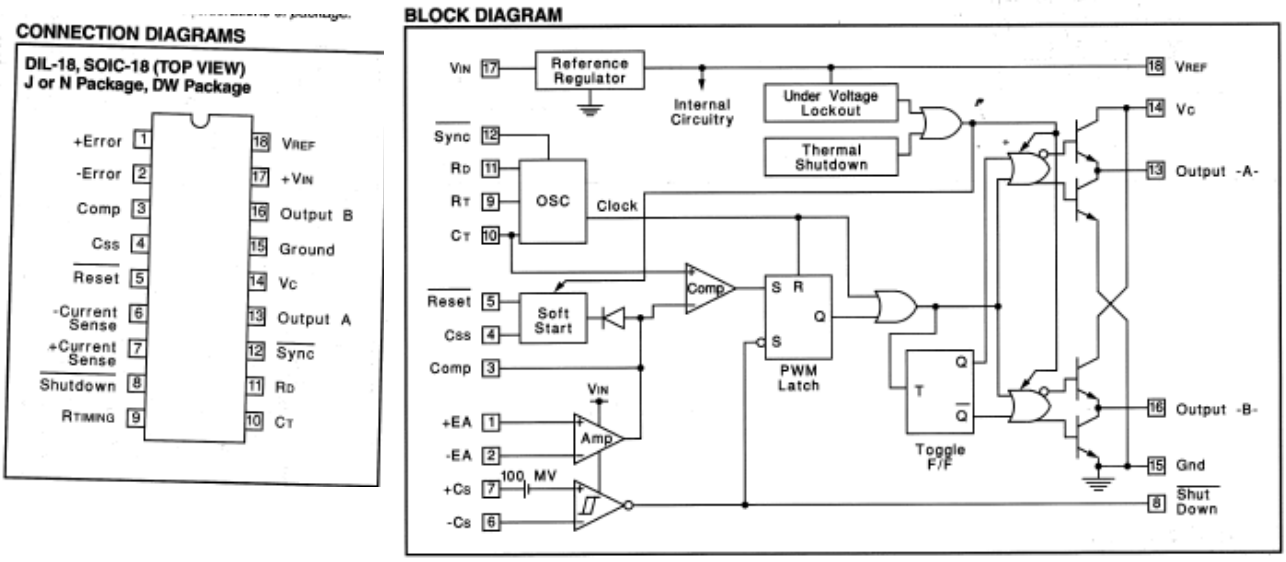


Fig. 11. Pin and block diagram for UC3526 (same as SG3526) from [5].

ECE 469 -- POWER ELECTRONICS LABORATORY

Design Project -- Part III

Objective -- The last experiment of this course will involve completion and operating tests of the team designs. The first design project experiment involved selection of real capacitor and inductor components to meet converter requirements. The second focused on gate drives for the FET and overall discrete implementation of the circuit. This last experiment will cover semiconductor heat transfer and converter system implementation, and some aspects of control. Please take advantage of data sheets provided with Part II to supplement this material.

Pre-Lab Assignment -- Read this experiment. Study the procedure, and bring any questions to class. Solve the following on a separate sheet, for submission as you enter the lab. Your instructor may elect to assign a different problem.

1. A boost converter is shown below. The active switch has $R_{DS(on)}$ = 0.05 Ω, and the diode has a forward drop of 1 V. The inductor has series resistance of 0.05 Ω. Output voltage feedback has been provided, as shown in the figure. The duty ratio is limited, and will not go beyond the range of 0 to 75%. Notice that the amplifier and comparator in combination yield a duty ratio of (50 - V_{out})/5.

   a) In steady-state conditions, what are the values of V_{out} and V_{err}?

   b) The switch is initially off and the circuit is in steady state, then the PWM IC turns on. What are V_{out} and V_{err} just before turn-on? What about just after turn-on?

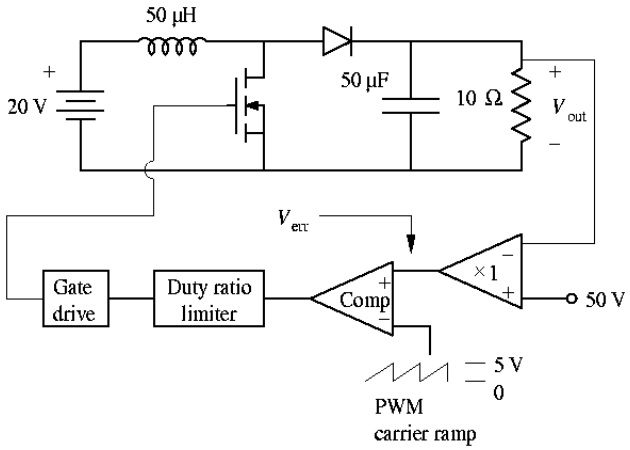


Figure 1. Boost converter with proportional feedback.

Discussion --

Introduction -- Converter Control: The designer of a converter has relatively little control over how the unit is used. Among the unknowns are the input power source and the output load, but additional conditions such as ambient temperature, residual voltages, time-rate-of-change of the load, response to a short-circuit or to an

open-circuit applied at the load terminals, device protection, reliability, cost, and electromagnetic performance often depend on customer requirements rather than on the designer's intent. The pre-lab assignment explores an output-feedback control that can avoid some of these limitations. The basic idea, as taught in a control systems course, is to subtract some fraction of the circuit output from an intended "reference" value, and use the result as a new input signal. When this is done, the output can be made almost arbitrarily close to the desired value even in the presence of load changes, supply changes, residual drops across switches, and other disturbances.

A second, but related, concept is that of compensation. An example of this is a dc-dc converter in which the controlled switch duty ratio is computed from the intended value of output and the measured value of input. For example, a buck converter can be built to have $D = V_{out(ref)}/V_{in}$. If the input supply level changes, D will change to compensate. V_{out} will be equal to $V_{out(ref)}$ even with load and supply changes. In a realistic converter, voltage drops across the switches are unknown, and the output will not be perfectly controlled with compensation alone.

Basic Theory -- Converter Control: Of the many ways to implement feedback control in a dc-dc converter, perhaps the simplest is called **output voltage control**. Here, the output voltage is sensed and subtracted from a given reference value. The result is amplified, and applied to the duty ratio input of a pulse width controller. Figure 1 shows a block diagram that would allow a single op-amp to be used with a PWM IC to implement this concept. In a buck converter which output voltage control, the input-output relationship can be written:

$$V_{out} = kV_{in}\left(V_{ref} - V_{out}\right)$$

Simplifying this,

$$V_{out}\left(1 + kV_{in}\right) = kV_{ref}V_{in}$$

If k is large so that $kV_{in} >> 1$, then both sides can be divided by kV_{in} to give

$$V_{out} \approx V_{ref}$$

This result applies even when residual switch voltages are included: a large gain will produce output equal to the reference value, in spite of changes in supply, load, or other uncontrolled parameters, as long as the converter duty ratio is within the allowed limits.

While this style of "proportional gain" feedback is appealing and useful, it has two important drawbacks. The first is that the output is not exactly equal to the input, even in steady state, because k cannot be infinite. This

is clear when you consider that the converter duty ratio D is given by $D = k(V_{ref} - V_{out})$. Since we expect D to have some value greater than zero, the value $V_{ref} - V_{out}$ must also be greater than zero. A second drawback is that not only can k not be infinite, but in a converter the gain k cannot be made very large. If k is too large, then any slight disturbance will drive D to the limits 0 or 1, and the converter output will jump around almost at random. Figure 1 shows a gain of just 1, for example.

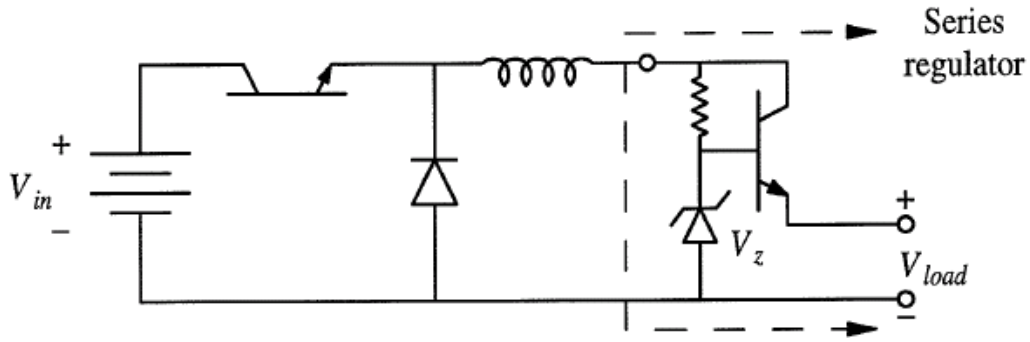


Figure 2. Buck converter with series regulator at the output.

Converter control can also be implemented in the context of series regulators for output filtering. Consider the regulator circuit in Figure 2. The zener diode has been used to provide a reference signal for the series regulator. Recall that the transistor exhibits a small voltage drop (typically around 0.7 V) between the base and the emitter. If the base is set to 5.7 V, for example, we might expect 5 V at the emitter. But the emitter supplies current for the output load. Consider the effect of an external load change which attempts to decrease emitter voltage V_e. Then more current will flow into the base, and collector current I_c will increase since it is given by βI_b. The emitter current will rise, which would be expected to result in an increase in V_e. Similarly, an attempt to increase V_e will produce lower emitter current.

This circuit will work as long as the "pass" transistor is in its active state. The transistor must not act as a switch. The active state can assured by avoiding saturation and cutoff conditions. This, in turn, requires that there be sufficient voltage at the collector so that saturation is always avoided, and that there be sufficient base current to avoid cutoff. A simple way to assure both of these is to keep $V_c > V_{out} + 2$ V, and to use a high-gain transistor with a high bias current through the zener diode. For a pass transistor with $\beta = 25$, and $I_{out} < 2$ A, the required bias current is 80 mA. The zener diode thus requires power of 0.08×6, or about ½ W. A final circuit, designed for $V_{out} + 2 < V_c < V_{out} + 5$, is shown in Figure 3.

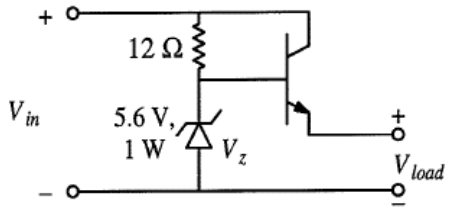


Figure 3. Series regulator designed for V_{in} of 7 to 10 V and $V_{load} \approx 5$ V.

Basic Theory -- Thermal Effects: Power lost in a semiconductor (or anything else) is converted to heat. Naturally, this will cause a temperature rise in the semiconductor. Semiconductor devices have a maximum temperature at which they can function -- typically between 125°C and 175°C. We must ensure that the semiconductor temperature will remain below the limit under operating conditions. To do this, it is important to understand some basic concepts of heat flow.

Temperature can be defined as a potential associated with heat flow, just as voltage can be defined as a potential associated with current flow. In solid substances, the flow of heat follows Fourier's Law of Heat Conduction, which states that the heat flux per unit area q (the units are W/m²) is proportional to the temperature gradient in the material. The constant of proportionality is defined as thermal conductivity, and is given the symbol k, so that

$$q = k\nabla T$$

Fourier's Law represents the effect of heat conduction (heat flow between solid objects in physical contact).

When fluids are involved, the heat flow is referred to as "convection," in which motion of the fluid carries away much of the heat. Again, the heat flux depends on a temperature difference, and a *heat transfer coefficient*, h can be defined so that

$$q = h\nabla T$$

The heat transfer coefficient is much more complicated than thermal conductivity, since it includes flow rates, directions, the surface area of the heat generator, and a variety of other parameters.

The third type of heat transfer, radiation, is more complicated still. In this case, heat flux has been found to be proportional to the fourth power of the temperature difference. The result is

$$q = e\sigma(\Delta T)^4,$$

where σ is the Stefan-Boltzman constant, $\sigma = 5.670 \cdot 10^{-8}$ W/(m^{2}K^4), and e is the "emissivity" of the object, $e = q_{actual}/q_{ideal}$. Typical values of e are:

Material	emissivity
polished metal	0.05
oxidized aluminum	0.10
flat black paint	0.90

A flat black heat sink with temperature of 50°C and e = 0.9 will transfer 0.04 W/m² to its surroundings at 20°C. In many situations, radiation heat transfer can be neglected.

In the case of both conduction and convection, heat flux depends on a temperature difference. The thermal conductivity can be used to define a "thermal resistance," analogous to electrical resistance. The total heat flow in watts can be multiplied by the thermal resistance to give the temperature difference, so that the temperature of a semiconductor T_j is equal to $P_{loss}(\theta_{ja}) + T_a$, where θ_{ja} is the thermal resistance in K/W between the semiconductor and the surrounding ambient, and T_a is the ambient temperature. (Please realize that only temperature *difference* is involved, so that units of K become equivalent to units of °C. Most manufacturers give θ in °C/W.)

Measurement of temperature is an important topic in many electrical design problems. Some of the properties used for this purpose include:

- Thermal expansion coefficients of liquids or metals.
- Resistors which change with temperature, such as thermistors.
- The thermocouple effect, by which unlike metals produce a temperature-dependent voltage at their junction.
- Infrared radiation.

We will use thermocouple and infrared probes in the lab for measurements.

Procedure --

Part 1: Converter checkout (open loop)

1. Operate your converter over its specification range. Measure its efficiency under several operating conditions.
2. Check the operation of your converter over its full range. Make note of any combinations of V_{in} and P_{out} for which you could not meet the specifications.
3. Measure and record the temperatures of the switching devices under conditions of maximum load and minimum V_{in}. Let the circuit stabilize for about ten minutes, but shut it down if your measured values go beyond 120°C. If the temperature reaches steady state, record it and record information to allow you to calculate power loss in the FET and the diode.
3. Take temperature measurements at two other combinations of P_{out} and V_{in}.

Part 2: Feedback control

1.During the temperature stabilization time, build the circuit of Figure 4 for use in a feedback loop. Notice that the circuit output is $5(V_{ref} - V_{out})$.

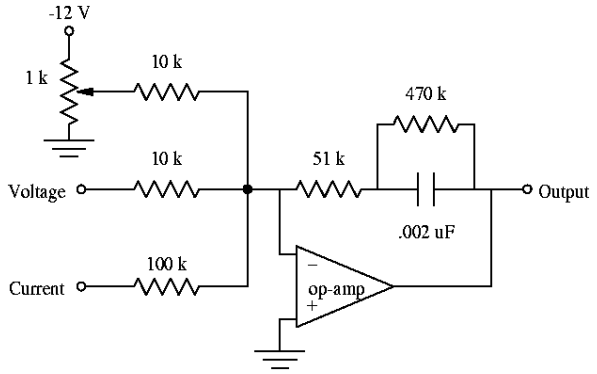


Figure 4. Op-amp feedback circuit for proportional-integral control.

2. Insert the feedback control unit into the converter, as follows:

   a) The circuit output attaches to pin 2 of the PWM integrated circuit.

   b) The "voltage" input attaches to the converter output.

   c) The ground node attaches to the converter output ground.

   d) For a buck converter, connect the "current" input to ground.

   e) For a buck-boost converter, place a 0.1 Ω resistor in series with the inductor, on the ground side. The voltage on this resistor goes to the "current" input.

   f) For a boost converter, place a 0.1 Ω resistor in series with the converter input source, on the ground side. Connect the voltage on this resistor to the "current" input.

3. Set up the converter with minimum load. Turn it on, and determine whether the control circuit is functioning.

4. Vary V_{in}, and observe the control action on V_{out}. What is the circuit line regulation?

Study Questions --

1. Estimate the thermal resistances θ_{jc} and θ_{ja} from your temperature data and from measurements of power loss in your switches.

2. **Discuss your converter design project results in some depth.**

APPENDICIES

Standard Resistor Values

5% tolerance, multipliers

(values from 1.0 Ω to 4.7 MΩ)

1.0	1.1	1.2	1.3	1.5	1.6	1.8		
2.0	2.2	2.4	2.7	3.0	3.3	3.6	3.9	
4.3	4.7	5.1	5.6	6.2	6.8	7.5	8.2	9.1

1% tolerance, multipliers

(values from 10.0 Ω to 1.00 MΩ)

1.00	1.02	1.05	1.07	1.10	1.13	1.15	1.18	1.21	1.24	1.27	1.30
1.33	1.37	1.40	1.43	1.47	1.50	1.54	1.58	1.62	1.65	1.69	1.74
1.78	1.82	1.87	1.91	1.96							
2.00	2.05	2.10	2.15	2.21	2.26	2.32	2.37	2.43	2.49	2.55	2.61
2.67	2.74	2.80	2.87	2.94							
3.01	3.09	3.16	3.24	3.32	3.40	3.48	3.57	3.65	3.74	3.83	3.92
4.02	4.12	4.22	4.32	4.42	4.53	4.64	4.75	4.87	4.99		
5.11	5.23	5.36	5.49	5.62	5.76	5.90					
6.04	6.19	6.34	6.49	6.65	6.81	6.98					
7.15	7.32	7.50	7.68	7.87							
8.06	8.25	8.45	8.66	8.87							
9.09	9.31	9.53	9.76								

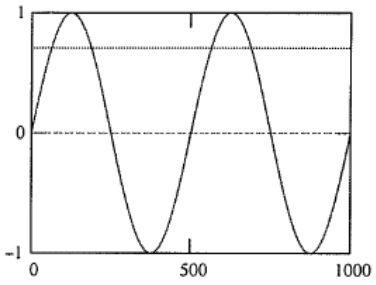
Color codes:

Black – 0 Brown – 1 Red – 2 Orange – 3 Yellow – 4 Green – 5 Blue – 6 Violet – 7 Gray – 8 White – 9 As multipliers, all these are 10^n. Gold indicates 10^{-1} and silver 10^{-2}.

APPENDIX

Common Waveforms

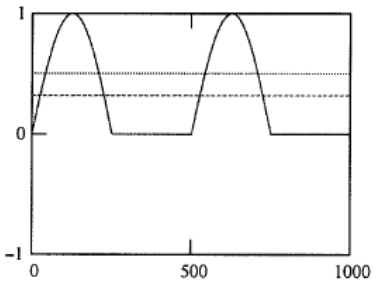
Sine Wave



AVE: $\frac{1}{T}\int_0^T \text{vsin}(i)\,di = 0$

RMS: $\sqrt{\frac{1}{T}\int_0^T \text{vsin}(i)^2\,di} = \frac{1}{\sqrt{2}} = 0.707$

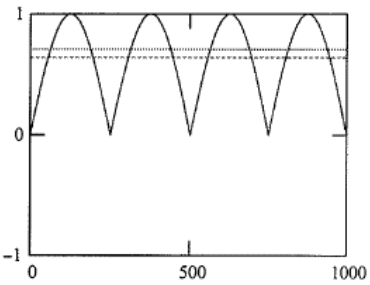
Half Wave Rectified Sine



$\frac{1}{T}\int_0^T \text{HWR}(i)\,di = 0.318$

$\sqrt{\frac{1}{T}\int_0^T \text{HWR}(i)^2\,di} = 0.5$

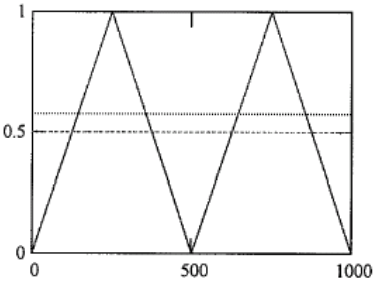
Full Wave Rectified Sine



$\frac{1}{T}\int_0^T \text{FWR}(i)\,di = 0.637$

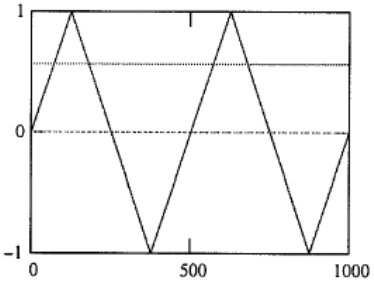
$\sqrt{\frac{1}{T}\int_0^T \text{FWR}(i)^2\,di} = \frac{1}{\sqrt{2}} = 0.707$

Triangle wave



AVE: $\frac{1}{T}\int_0^T \text{tri1}(i)\,di = 0.5$

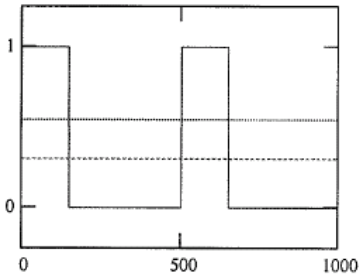
RMS: $\sqrt{\frac{1}{T}\int_0^T \text{tri1}(i)^2\,di} = \frac{1}{\sqrt{3}} = 0.577$



$\frac{1}{T}\int_0^T \text{tri2}(i)\,di = 0$

$\sqrt{\frac{1}{T}\int_0^T \text{tri2}(i)^2\,di} = \frac{1}{\sqrt{3}} = 0.577$

Switching function



$\frac{1}{T}\int_0^T q(i)\,di = D$

$\sqrt{\frac{1}{T}\int_0^T q(i)^2\,di} = \sqrt{D}$

(example: $D = \frac{1}{3}$)

APPENDIX

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