### Activity #1: Polyphase AC generator system
- **Due by session #12**

### Activity #2: Design and build loaded voltage divider with modeling in C
- **Due by session #12**

### Activity #3: Design and build RC time-delay circuit with modeling in C
- **Due by session #12**

### Activity #4: Discrete-component power amplifier
- **Due by session #24**

### Activity #5: Design and build RC filter network with modeling in C
- **Due by session #24**

### Activity #6: Troubleshoot power amplifier
- **Due by session #24**

### Activity #7: Radio beacon using microcontroller programmed in C
- **Due by session #36**

### Activity #8: Produce a signal with specified harmonics
- **Due by session #36**

### Activity #9: Test cable impedance and length
- **Due by session #36**

### Activity #10: Analog signal conditioning system
- **Due by session #48**

### Activity #11: Design and build precise-gain amplifier with modeling in C
- **Due by session #48**

### Activity #12: Troubleshoot analog signal system
- **Due by session #48**

### Activity #13: High-current load control system
- **Due by the last day**

### Activity #14: Wire and configure a VFD for motor speed control
- **Due by the last day**

### Activity #15: Troubleshoot high-current load control system
- **Due by the last day**

### Activity #16: Clean and organize the entire lab room
- **Due by the last day**
Essential information about this course:

- This is a laboratory course, but the experiments are multi-concept systems rather than single-concept experiments.
- These experimental systems follow concepts taught in that semester’s theory course, which means the theory course outline and source texts are essential resources for you here.
- Half of your course grade comes from the number of attempts necessary to correctly complete each demonstration. Clarifying questions are welcome, but all results presented to the instructor will be assessed just like answers submitted on an exam.
- Half of your course grade comes from the number of attempts necessary to correctly complete each assessment activity (e.g. skills demonstrations and circuit troubleshooting). Just like the experiments, each assessment activity must be eventually completed correctly to pass the course.
- You should budget a minimum of 12 hours per week for this course. The lab is yours to use during all open-school hours. Do not let the lack of fixed hours for this course lead to procrastination – manage your time wisely!
- Successful students (1) review relevant theory before planning experimental systems, (2) read system requirements carefully, (3) set reasonable goals, and (4) prioritize hands-on lab time.

EET Program Learning Outcomes

(1) **COMMUNICATION and TEAMWORK** – Accurately communicate ideas across a variety of media (oral, written, graphical) to both technical and non-technical audiences; Function effectively as a member of a technical team.

(2) **SELF-MANAGEMENT** – Arrive on time and prepared; Work diligently until the job is done; Budget resources appropriately to achieve objectives.

(3) **SAFE WORK HABITS** – Comply with relevant national, state, local, and college safety regulations when designing, prototyping, building, and testing systems.

(4) **ANALYSIS and DIAGNOSIS** – Select and apply appropriate principles and techniques for both qualitative and quantitative circuit analysis; Devise and execute appropriate tests to evaluate electronic system performance; Identify root causes of electronic system malfunctions.

(5) **PROBLEM-SOLVING** – Devise and implement solutions for technical problems appropriate to the discipline.

(6) **DOCUMENTATION** – Interpret and create technical documents (e.g. electronic schematic diagrams, block diagrams, graphs, reports) relevant to the discipline.

(7) **INDEPENDENT LEARNING** – Select and research information sources to learn new principles, technologies, and/or techniques.
Values

This educational program exists for one purpose: to empower you with a comprehensive set of knowledge, skills, and habits to unlock opportunities in your chosen profession. The following values articulate personal attitudes guaranteed to fulfill this purpose, and the principles upon which this program is designed. They embody what I like to call a strong learning ethic, similar to a strong work ethic but applied to the learning process rather than a job.

Ownership – you are the sole proprietor of your education, of your career, and to a great extent your quality of life. No one can force you to learn, make you have a great career, or grant you a fulfilling life – these accomplishments are possible only when you accept responsibility for them.

Responsibility – ensuring the desired outcome, not just attempting to achieve the outcome. Responsibility is how we secure rights and privileges.

Initiative – independently recognizing needs and taking responsibility to meet them.

Integrity – living in a consistently principled manner, communicating clearly and honestly, applying your best effort, and never trying to advance at the expense of others. Integrity is the key to trust, and trust is the glue that binds all relationships personal, professional, and societal.

Perspective – prioritizing your attention and actions to the things we will all care about for years to come. Never letting short-term concerns eclipse the long-term.

Humility – no one is perfect, and there is always something new to learn. Making mistakes is a symptom of living, and for this reason we need to be gracious to ourselves and to others.

Safety – assessing hazards and avoiding unnecessary risk to yourself and to others.

Competence – your ability to consistently and independently apply knowledge and skill to the solution of practical problems. Competence includes the ability to verify the appropriateness of your solutions and the ability to communicate so that others understand how and why your solutions work.

Diligence – exercising self-discipline and persistence in learning, accepting the fact there is no easy way to absorb complex knowledge, master new skills, or overcome limiting habits. Diligence in work means the job is not done until it is done correctly: all objectives achieved, all documentation complete, and all root-causes of problems identified and corrected.

Community – your actions impact other peoples’ lives, for good or for ill. Conduct yourself not just for your own interests, but also for the best interests of those whose lives you affect.

Respect is the acknowledgment of others’ intrinsic capabilities, responsibilities, and worth. Everyone has something valuable to contribute, and everyone deserves to fully own their lives.
Course description

This course reinforces the content of IETTI-222 (Intermediate Electronics Theory) by way of experimental system design and construction, starting with only a block diagram and a general description of the system’s intended function. Students then engineer all details of the system, building and testing it in stages. Students also apply foundational circuit principles to the diagnosis of simulated and real faults in these same types of circuits. Mastery standards applied to all experimental and diagnostic activities guarantee attainment of learning outcomes.

Course learning outcomes

- Design, construct, document, and test complex electronic systems based on general specifications and high-level design ideas developed in partnership with the instructor, these systems incorporating polyphase AC networks, analog amplifiers, RF communication, microcontrollers, and high-current load control. (Addresses Program Learning Outcomes 1, 2, 3, 4, 5, 6, 7)

- Edit and write procedural code in the C programming language to simulate DC resistor circuits, resistor-capacitor delay networks, passive filters, and amplifier circuits. (Addresses Program Learning Outcomes 2, 4, 6, 7)

- Construct analog electronic and AC power circuits meeting specifications set by the instructor and demonstrate proper test equipment usage including multimeters, signal generators, and oscilloscopes. (Addresses Program Learning Outcomes 4, 5, 6)

- Troubleshoot faulted audio amplifier circuits, analog signal conditioning systems, and high-current load control systems from measurements taken at test points with circuit components and connections hidden from view. (Addresses Program Learning Outcomes 4, 6)

- Articulate diagnostic reasoning while troubleshooting these same circuits. (Addresses Program Learning Outcomes 1, 3)
Required Tools, Supplies, and Software

Listed by IETTI course number and course type (Thy = theory, Exp = Experiments, Prj = Projects).

Semester 1 = IETTI-101 (Theory), 103 (Experiments), and 102 (Projects)
Semester 2 = IETTI-104 (Theory), 112 (Experiments), and 105 (Projects)
Semester 3 = IETTI-222 (Theory), 221 (Experiments), and 220 (Projects)
Semester 4 = IETTI-223 (Theory), 225 (Experiments), and 106 (Projects)

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**Required Tools, Supplies, and Software**

**Scientific calculator** – at minimum your calculator must perform trigonometric functions (sine, cosine, tangent, etc.), offer multiple memory registers, and display values in both scientific and “engineering” notations. I recommend the Texas Instruments model TI-36X Pro because it easily performs complex-number arithmetic necessary for AC circuit analysis and is inexpensive.

**Personal computer** – all course materials are available in electronic format and are free (most are also open-source), making a portable computer extremely useful. The school provides personal computers for on-campus use, but having your own will enable you to work outside of school. Any operating system, any size hard drive, any amount of RAM memory, and any screen size is appropriate, but your computer needs to have a keyboard and mouse (i.e. no tablets). Useful features worth higher cost include an RJ-45 Ethernet port and an EIA/TIA-232 (9-pin) serial port.

**Multimeter** – this is your first and most important electronic test instrument. At minimum it must measure DC and AC voltage, DC and AC current (milliAmpere range), resistance, and “diode check” voltage drop. Useful features worth higher cost include microAmpere current measurement, true-RMS AC measurement (for second-semester courses and above), frequency measurement, capacitance measurement, and minimum/maximum value capture. Cost is a strong function of accuracy, frequency range, and safety (“Category” ratings for over-voltage exposure). The Fluke model 87-V is an excellent professional-grade choice for digital multimeters, and the Simpson 260 is an excellent professional-grade choice for analog multimeters. Note that Fluke offers a 25% educational discount for students.

**Oscilloscope** – once too expensive for student purchase, entry-level USB-based oscilloscopes now cost less than a textbook. Pico Technology is an excellent brand, and their model 2204A comes with high-quality probes as well. Plugged into your personal computer using a USB cable, the Picoscope turns your computer’s monitor into a high-resolution oscilloscope display. Features include two measurement channels, 10 MHz bandwidth, built-in arbitrary waveform generator (AWG), ± 100 Volt over-voltage protection, digital “cursors” for precise interpretation of amplitude and frequency, meter-style measurement capability, Fast Fourier Transform algorithm for frequency-domain measurement, export ability to several graphic image formats as well as comma-separated variable (.csv) files, and serial communications signal decoding. Together with your multimeter, solderless breadboard and Development Board (which you will construct in the IETTI-102 Project course and is yours to keep) this forms a complete electronics laboratory for doing experiments and projects outside of school.

**Soldering** – the equipment you purchase for soldering need not be expensive, if you purchase the right solder. For electronics work you must use rosin-core solder. Kester is an excellent brand, and you should avoid cheap imported solders. For lead-based solder, a 63% tin and 37% lead alloy (Sn63/Pb37) works very well. A one-pound roll is likely more solder than you will need in these courses, so I recommend buying just a small tube or small roll. I recommend a fine-tipped soldering iron (15 Watts continuous power, although some with adjustable temperature controls may have higher power ratings to get up to soldering temperature more quickly) and a solder diameter 0.031 inches or smaller for doing fine printed-circuit board work. Also, keep the tip of your soldering iron clean by wiping it against a damp sponge or paper towel when hot, and not leaving it hot any longer than necessary. Hakko, X-tronic, and Lonove are all recommended brands.

**Microcontroller** – these courses are not brand- or model-specific, but the Texas Instruments MSP430 series is highly recommended for their powerful features, modern design, and programmability in multiple languages (assembly, C, C++, and Sketch). I particularly recommend the model MSP-EXP430G2ET “LaunchPad” development board (MSP430G2553IN20 microcontroller chip) with Code Composer Studio for the IDE software. A hobbyist-grade microcontroller such as the popular Arduino and Parallax BASIC Stamp are permissible only in first-year courses, but not in second-year courses.
Required Tools, Supplies, and Software

All software required for these courses is free, and some of it is open-source.

**Schematic editor** – this is used to draft schematic diagrams for circuits. A good one is TinyCAD, but there are also web-based CAD tools such as circuitlab.com that are very effective and easy to use.

**Text editor** – this is used to create plain-text files, kind of like a word processor but lacking formatting features such as typeface, font size, etc. It is absolutely necessary for writing code of any kind. Notepad++ is a very good editor, but others work well too.

**NGSPICE** – this is a modern adaptation of the venerable SPICE circuit simulator which uses a text-coded “netlist” rather than a visual schematic diagram to describe circuits. Very powerful, and with decades of netlist examples from earlier versions of SPICE to use as references. The installer lacks sophistication, being nothing more than a compressed (zip) file that you unpack. Once installed, you should instruct your computer’s operating system to automatically associate any files ending in the extension .cir with the NGSPICE executable file ngspice.exe so that all of your netlist files will appear with the NGSPICE icon and will automatically load into NGSPICE when double-clicked.

**WSL** – Windows Subsystem for Linux is a “virtual machine” Linux operating system that runs within the Windows operating system, giving you a command-line user environment mimicking that of a Unix operating system. It is a free application from Microsoft, with instructions available from Microsoft on how to install. I recommend installing the “Debian” distribution of WSL. Once installed, you will issue these commands in the following order to install all the necessary programming tools:

- `sudo apt update`
- `sudo apt install build-essential`
- `sudo apt install indent`
- `sudo apt install python3`

**tshoot** – this is a specialized circuit-simulator program that inserts faults into circuits and tests your ability to locate them. The download consists of a single “tar” archive file which you must unpack and compile using the following two commands within a Unix-type operating system or within WSL. The fourth command listed below starts and runs the application:

- `mkdir tshoot ; mv -v *.tar tshoot ; cd tshoot`
- `tar xvf *.tar`
- `make`
- `./tshoot`

**IDE software** – an “Integrated Development Environment” is a software package used to write code, and for our purposes this would be code meant to run in a microcontroller. For the Texas Instruments MSP430 series, the main IDE is called Code Composer Studio, and it supports programming in assembly language, C, and C++. A third-party add-on to Code Composer Studio called Energia supports programming in the Sketch language, identical to that used by the popular Arduino microcontroller series.

**PCB layout editor** – this is specialized drafting software intended for creating graphic files to be sent to printed circuit board (PCB) manufacturers so you can order your own custom PCBs. PCB Artist is free and exceptionally easy to use, but only exports files to the manufacturer Advanced Circuits. Free PCB layout editors capable of exporting “Gerber” format files which are universally accepted by PCB manufacturers include EasyEDA, KiCad (very powerful but hard to learn), and pcb. Of these I recommend EasyEDA for beginners, or PCB Artist if you don’t mind being locked into one manufacturing option.

**Packet-sniffing software** – this is specialized software for monitoring network communications. An excellent (and free) option is Wireshark.
Grading standards for Experiment courses

Your grade for this course is based on percentage scores (in every calculation rounded down to whole-numbered values), with each category weighted as follows:

- Experiment scores = 50% (Note: all Experiments are mastery-based, which means they must be eventually completed at 100% competence in order to pass the course)
- Assessment scores = 50% (Note: all Assessments are mastery-based, which means they must be eventually completed at 100% competence in order to pass the course)

Please note the importance of completing all Experiments and all Assessments on or before their respective deadline dates. If any Experiment or Assessment is incomplete by the end of the school day of the deadline date, it will receive a 0% score. If any Experiment or Assessment is incomplete by the end of the last day of the course, you will earn a failing grade (F) for the course. All Experiments and Assessments must be complete by the end of the last day of the course to receive a passing grade for the course.

Carefully follow the instructions associated with each experiment! If there is a prescribed order, you must follow this order of steps or else you will receive a 0% score for that experiment. The same is true if you plagiarize any part of it (i.e. present someone else’s work as your own). For every experiment there will be multiple demonstrations, explanations, and/or challenges you must complete in the instructor’s presence, and these are all mastery-based which means they all must be completed with 100% competence. Multiple opportunities are given to master each, with a point deduction levied for every re-try. You are welcome and encouraged at any time to seek clarification from the instructor so that you understand what is being asked of you, but you are solely responsible for doing the work and solving the problems. This is similar to the policy during written exams in a Theory course: the instructor will happily clarify expectations, but will not solve the problems for you nor confirm if an answer is correct prior to scoring it.

Electronic submissions of Experiments and Assessments are acceptable for full credit. The standards are just as high for electronic submissions as for face-to-face demonstrations. For Experiments, video documentation of you completing all objectives in their proper order will count as full credit. For Assessments your work must either be videorecorded in one seamless take or performed on a live video stream so the instructor is able to ensure you are doing the work yourself with no aid.

This course is based on experiments and hands-on assessments, and does not have scheduled meeting times as is the case with instructor-facilitated theory sessions. However, your punctual and consistent attendance is important for your success, as these activities require significant time-on-task to complete.

If you must be late or absent, it is imperative that you contact your instructor as well as any classmates you may be coordinating with so plans may be adjusted. It is still your responsibility to meet all deadlines.

A failing (F) grade will be earned for the entire course if any experiment or assessment is not completed on or before the deadline date, or for any of the following behaviors: false testimony (lying), cheating on any assignment or assessment, plagiarism (presenting another’s work as your own), willful violation of a safety policy, theft, harassment, sabotage, destruction of property, or intoxication. These behaviors are grounds for immediate termination in this career, and as such will not be tolerated here.
Getting help in the lab

Success in this career is largely a function of your ability to independently solve complex problems. You will find that the design, construction, testing, and diagnosis of systems for experiments and projects are prime opportunities to hone this skill. Many times you will find yourself faced with a problem that you do not think you can solve. Your instructor’s job is to provide practical strategies and techniques you can use to solve the problem, without directly solving the problem for you. Although this may feel frustrating because the instructor is withholding a solution from you, know that if the instructor were to solve the problem for you it would actually hinder your own development.

Any time you call for help to diagnose a problem, your instructor will first check to see you have done the following:

- **Simplify** – make problems manageable by building and testing your system in stages, by dividing large systems into smaller sections to isolate problems, and by avoiding complexity that isn’t absolutely necessary to the function you are trying to obtain at that time. A common mistake is to build large systems without testing along the way in an attempt to save time, but this strategy almost never works!

- **Document** – draw a diagram before building any system, and use this to guide your analysis and design decisions. Also, have any other relevant documents available for reference, such as datasheets, tutorials, etc. A common mistake is to build systems without first building up this documentation, again in a futile effort to save time.

- **Measure and record** – take measurements using appropriate test equipment, because these measurements will reveal what your senses alone cannot perceive. Record those test results so you will not have to rely on memory to recall what you did.

- **Foundational Concepts** – always apply Foundational Concepts such as the guaranteed effects of opens and shorts, Ohm’s Law, Joule’s Law, Conservation of Energy and of Electric Charge, Kirchhoff’s Laws, properties of series and of parallel networks, etc. when solving problems. Reference a list of these if necessary, checking them one by one to stimulate and guide your reasoning.

A great way to remember these is to use the phrase, “Slow Down My Friend!” (Simplify, Document, Measure/record, and Foundational Concepts) which is also a reminder that problem-solving requires patience. A great many student problems are caused by impatience and an urge to take shortcuts!
Expectations for each experimental system

In the EET program the initial Experiments courses are based on small-scale experiments, each one designed to explore a single concept. Here in the later Experiments courses you build experimental systems involving multiple concepts, requiring research and design similar to that of real challenges on the job. The purpose of the introductory Experiments courses is to build competence in discrete skills; here the purpose is to develop a higher level of problem-solving and professionalism.

The systems you will build in this course borrow heavily from concepts and designs explored in previous courses, so you will find your previous coursework extremely useful as reference material.

Stand-alone demonstrations should be performed using minimal hardware – meaning the bare minimum of components connected together to perform each demonstration, ideally with that portion of the system functioning in complete isolation from all others. The purpose of this is to build the habit of building and testing large systems in stages which is a proven way to develop complex systems with as little troubleshooting as necessary. A deduction of $-5\%$ per re-try is levied on each unsuccessful stand-alone demonstration.

Complete system demonstrations must be performed after every stand-alone demonstration has been completed for that experimental system. All portions of the system must be in good working order, proven by having you demonstrate all bullet items listed for the complete system demonstration. If any portion of the complete system demonstration is faulty or otherwise incorrect, the instructor’s inspection will stop and a deduction of $-10\%$ will be levied. You will then revisit your system and make all necessary corrections and reviews, and are welcome to re-try as many times as necessary. The same $-10\%$ deduction applies to all failed re-tries.

The “schematic diagram challenge” deserves elaboration here. Sketching a complete and accurate schematic diagram is vitally important for every system you design and build, but it takes too long for the instructor to perform a wire-by-wire inspection of every student’s diagram on every system built. Instead, the instructor tests the accuracy of your schematic diagram by selecting random portions of your system and having you predict and measure signals there. These could be individual components or test points, they could be assuming normal operation or some special condition (e.g. a simulated fault), they could be selected from the physical system with you having to reference the schematic diagram, or vice-versa. In all cases, you must show an accurate correspondence between what you have built and what you have drawn, and demonstrate a thorough understanding of your system’s behavior. Preparation consists of thoroughly reviewing both your system and your diagram, predicting what kinds of signals you ought to measure at all points in your system and making absolutely sure your schematic diagram is complete and accurate.

Each experimental system you build will be a testament to your knowledge and skill as an electronics technician, and for this reason it is strongly recommended that you thoroughly document your work for inclusion in a portfolio you may show to employers.

As always, questions are welcome throughout the research, design, and construction process. You will never lose points for asking a question prior to an assessment, and your instructor will always clarify expectations so that you know what is being asked of you, but the moment you deem any part of your system ready the instructor’s job is to grade your work. This is the same as on a job: when you present a finished product to a supervisor or client, it must actually be ready. The time to ask for clarification is before the inspection, not during.
Design and build an experimental motor-generator system to generate three-phase AC electricity. The motor’s speed shall be adjustable by the user, and the three-phase generator’s output will be stepped up to higher voltage by a transformer bank wired from three individual transformers. Recommend basing your system on the “Experimental motor-generator set” described in the Case Tutorial chapter of the Polyphase AC module.

Block diagram:

- Instructor consultation – Discuss general plan, components available, safety considerations, etc. Document this in the “engineering notebook” document, and be sure to record all data here, even from mistakes!

Stand-alone demonstrations (may be completed in any order; –5% per re-try, each):

- Instructor certifies – Demonstrate the motor controller circuit’s start-stop capability, using two momentary pushbutton switches (one Start and one Stop).
- Instructor certifies – Demonstrate the motor controller’s variable-speed capability, using either a pushbutton or a potentiometer user interface to increase and decrease the speed.
- Instructor certifies – Demonstrate and record balanced phase/line voltages output by the generator, as well as measurement of generator phase sequence (also known as “phase rotation”, either ABC or CBA).
- Instructor certifies – Demonstrate how to infer the generator shaft speed by voltage measurement using an oscilloscope. Record a screenshot of the oscilloscope along with the inferred shaft speed.
- Instructor certifies – Demonstrate voltage transformation (step-up) by the three-phase transformer bank, with all phase/line voltages balanced.
- Instructor certifies – Demonstrate and record the mathematical relationship between line and phase quantities for Wye and Delta resistive loads energized by the transformer bank’s output.

Complete system demonstration (must be completed last, in a single session; –10% per re-try):

- Instructor certifies
  - Pushbutton start/stop control of motor
  - Variable speed control of motor
  - Balanced voltage step-up by transformer bank
  - Engineering notebook document containing recorded data and notes
  - Schematic diagram challenge

file we_3001

11
02 Assessment

NAME: ______________________  DUE DATE: ______

Design, build, and demonstrate a voltage divider network to energize a load with a specified output voltage from a voltage source of random value (e.g. a primary-cell battery), also writing a program (written in the C language) modeling this same circuit and predicting its performance. You will be allowed to measure the voltage of the random source before beginning your circuit design.

This exercise tests your ability to properly design and build a loaded voltage divider circuit, use a multimeter to measure both voltage and current, properly organize all electrical connections, and write an algorithm in C to predict series-parallel DC circuit behavior.

![Circuit Diagram]

The following components and materials will be available to you: lengths of hook-up wire; assortment of resistors; potentiometers; and a fixed voltage source provided by the instructor. You must provide your own tools, digital multimeter (DMM), a computer with C compiler software installed, and solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

**Source voltage** (measured after instructor chooses source): ______ Volts

**Load resistance** (instructor chooses): ______ Ohms

**Load voltage** (instructor chooses): ______ Volts

**Bleed current** (instructor chooses): ______ Amperes

The measured bleed current and load voltage should deviate from the instructor-specified value by no more than the greatest tolerance of any of the resistors. The same is true for the results of your modeling program.

**SEQUENCE:** (1) Instructor chooses criteria; (2) You write and compile the modeling program, testing it by yourself to ensure it works properly; (3) Instructor observes you running your program with the chosen criteria and documenting its results; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning everyone must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.
Design, build, and demonstrate a resistor-capacitor circuit that achieves a specified voltage between its output terminals within a specified range of time following the actuation of a switch, also writing a program (written in the C language) modeling this same circuit and predicting output voltage at multiple points in time.

This exercise tests your ability to apply inverse-exponential functions to RC networks, use an oscilloscope to measure voltage over time, properly organize all electrical connections, and write an algorithm in C to predict RC network behavior.

The following components and materials will be available to you: DC power supply with variable voltage output; an assortment of capacitors; an assortment of resistors; switches; potentiometers; oscilloscope; and lengths of hook-up wire. You must provide your own tools, a digital multimeter (DMM), a computer with C compiler software installed, and a solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

Source voltage (instructor chooses) = ________ V

Output voltage trajectory (instructor chooses) = ____ Rises or ____ Falls after actuation

Output voltage within time range (instructor chooses) = ________ V

Time range (instructor chooses) = between ________ seconds and ________ seconds

The performance of your circuit will be judged on whether or not the output voltage reaches the specified value within the specified time period, and whether this happens as it rises or falls. The performance of your modeling program will be judged by its output showing a series of printed voltage values calculated at different times covering at least the specified time period.

SEQUENCE: (1) Instructor chooses criteria; (2) You write and compile the modeling program, testing it by yourself to ensure it works properly; (3) Instructor observes you running your program with the chosen criteria and documenting its results; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.
Design and build an experimental power amplifier circuit using nothing but discrete components (i.e. no integrated circuits). The circuit must receive an input signal from some audio-frequency source (e.g. microphone, radio audio output, musical instrument pickup) and output to a loudspeaker.

Block diagram:

- Instructor consultation – Discuss general plan, components available, safety considerations, etc. Document this in the "engineering notebook" document, and be sure to record all data here, even from mistakes!

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

- Instructor certifies – Demonstrate and record that the DC power supply circuit outputs “clean” DC with negligible ripple voltage when unloaded.

- Instructor certifies – Demonstrate and record measurement of audio source for maximum voltage amplitude, to be used for amplifier gain calculation.

- Instructor certifies – Demonstrate and record measurement of audio source for signal bandwidth, determining the range of frequencies the amplifier must handle.

- Instructor certifies – Demonstrate the gain-stage’s voltage gain to be adjustable by potentiometer.

- Instructor certifies – Demonstrate and record gain-stage of amplifier operating with a maximum voltage gain suitable for amplifying the audio source at maximum volume (i.e. output waveform does not “clip” when given maximum audio source as the input signal at maximum voltage gain setting).

- Instructor certifies – Demonstrate and record power-stage of amplifier driving a resistor “dummy” load with minimal signal distortion as shown on in the time-domain (oscilloscope) and the frequency domain (spectrum analyzer).

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

- Instructor certifies
  - Amplifier system reproduces the audio source’s to the loudspeaker clearly with no audible distortion
  - Minimal “hum” present at the loudspeaker from power supply ripple voltage
  - Gain is adjustable from zero to maximum using a potentiometer in the gain-stage of the amplifier
  - Components do not overheat when operated near full power for extended periods of time (use a “dummy” load for this test!)
  - Engineering notebook document containing recorded data and notes
  - Schematic diagram challenge

file we_3003
Design, build, and demonstrate a filter network with a specified “pass” characteristic and cutoff frequency, also writing a program (written in the C language) modeling this same circuit and predicting its performance.

This exercise tests your ability to design a simple filter network per specification, combine resistors to form a desired equivalent resistance, operate an oscilloscope, operate a signal generator, test a filter network for proper function, and write an algorithm in C to predict filter network behavior.

The following components and materials will be available to you: a signal generator with variable voltage and frequency; an oscilloscope with probe; an assortment of non-polarized capacitors; an assortment of fixed resistors; and lengths of hook-up wire. You must provide your own tools, a computer with C compiler software installed, and a solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

**Filter characteristic** (instructor chooses) = ____ Low-pass    ____ High-pass

**Cutoff frequency** (instructor chooses) = ______ Hz

Both your modeling program and the live testing of your circuit must show the filter’s behavior below, at, and above the specified cutoff frequency. It is strongly recommended that you design your filter circuit such that all component impedance values lie between 1 kΩ and 100 kΩ at the cutoff frequency, to avoid measurement errors as well as excessive signal generator loading. If your design’s resistance value is not the same as any standard resistor size, your modeling program may represent that value as a single resistor but the circuit you build must use some combination of fixed resistors to achieve that necessary resistance (i.e. no potentiometers allowed in the real circuit).

**SEQUENCE:** (1) Instructor chooses criteria; (2) You write and compile the modeling program, testing it by yourself to ensure it works properly; (3) Instructor observes you running your program with the chosen criteria and documenting its results; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are **mastery-based**, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

**file we_1110**
NAME: ___________________________ DUE DATE: ________

Troubleshoot a fault within an audio power amplifier circuit. This circuit shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g. covering it up with a box or towel) but test points will be available for contact with instrument probes. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

The circuit shall be powered by the 120 Volt AC line, and will provide easy access to the gain control when the fault is hidden from view. Possible faults include:

- Any cable failed open
- Any cable failed shorted
- Any component failed open
- Any component failed shorted
- Any component value altered

First, you will demonstrate that the system functions properly. Then the instructor will either set up or supervise other students setting up a random fault in that system (hidden from view) while you are out of the room. You will then have a limited amount of time to independently perform measurements and other tests while under the continuous observation of the instructor. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. Your only access to the faulted circuit will be via the test points, and only one unpowered test will be permitted.

If you must work remotely rather than in-person, the faulted system must be at the instructor’s location while you request measurements and other diagnostic tests of the instructor via teleconferencing system (e.g. videoconference, telephone, text messaging).

Troubleshooting is mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%).
Design and build an experimental radio beacon sensing at least one channel of discrete (on/off) and broadcasting an audio-tone-modulated signal via radio to a pre-constructed receiver, with all electronics on the transmitting end powered by a single battery. A recommended design uses a packaged RF oscillator IC and a software-defined radio (SDR) unit for the receiver.

Block diagram:

- **Instructor consultation** – Discuss general plan, components available, safety considerations, FCC regulatory requirements, etc. Document this in the “engineering notebook” document, and be sure to record all data here, even from mistakes!

**Stand-alone demonstrations** (may be completed in any order; −5% per re-try, each):

- **Instructor certifies** – Identify and explain the meaning of those portions of Part 15 of Title 47 of the Code of Federal Regulations (CFR) applicable to this experimental system. Copy this text to your document.
- **Instructor certifies** – Demonstrate and record microcontroller (MCU) program written in the C language generating an audio-frequency signal suitable for modulating the RF oscillator. A pushbutton switch must control this audio signal via one of the microcontroller’s discrete inputs.
- **Instructor certifies** – Demonstrate and record the performance difference(s) between two different types of antenna that you build (e.g. dipole versus monopole).
- **Instructor certifies** – Demonstrate and record antenna polarization (i.e. signal strength improved with antennas oriented properly; signal strength degraded with antennas oriented improperly)
- **Instructor certifies** – Demonstrate and record battery-sourced power supply maintaining proper voltages while simultaneously powering “dummy” resistor loads simulating each block on the transmitter side (e.g. MCU, oscillator).

**Complete system demonstration** (must be completed last, in a single session; −10% per re-try):

- **Instructor certifies**
  - Discrete input signal to microcontroller controls the RF broadcast
  - Received signal is an audio tone suitable for a beacon, of any modulation type (e.g. AM, FM, LSB, USB) suitable for the receiver
  - Beacon works with transmitter outside lab room and receiver inside lab room
  - All power for the transmitting side supplied by a single battery
  - *Engineering notebook* document containing recorded data and notes
  - Schematic diagram challenge
  
  file we 3006
Connect a signal generator to a spectrum analyzer and configure that signal generator to output a signal containing certain harmonic frequencies. The instructor will arbitrarily select a fundamental frequency, and then specify sequential harmonics that are either all odd (e.g. 3rd, 5th, 7th), or both even and odd (e.g. 2nd, 3rd, 4th).

This exercise tests your ability to properly use a signal generator and spectrum analyzer, and also predict harmonic frequencies based on signal wave-shape and fundamental frequency.

The following components and materials will be available to you: signal generator; oscilloscope with spectrum analysis capability; and an assortment of cables for connecting these instruments. You must provide a copy of this page for your instructor to mark design criteria.

**Fundamental frequency** (instructor chooses) = ______ Hz

**Harmonic frequency** (instructor chooses) = ______ Hz

**Harmonic frequency** (instructor chooses) = ______ Hz

**Harmonic frequency** (instructor chooses) = ______ Hz

The harmonic frequencies specified by the instructor (above) should be the only significant harmonics within that frequency range (i.e. there should be no harmonics of significant magnitude with frequencies lying between any of those specified above).

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we_1106
Demonstrate the measurement of a cable’s characteristic impedance and physical length, the particular cable being chosen at random by the instructor. You are welcome to research properties of the cable (e.g. velocity factor) prior to connecting any test equipment to it.

This exercise tests your ability to properly configure and connect appropriate test equipment to a random cable for introducing test signals and measuring the cable’s response, and to properly interpret the results of the test to determine the cable’s actual parameters of characteristic impedance and length.

The following components and materials will be available to you: a signal generator with variable voltage and frequency; an oscilloscope with probe; an assortment of fixed resistors; potentiometers; and lengths of hook-up wire. You must provide your own tools and a solderless breadboard or terminal blocks as well as a copy of this page for your instructor to mark design criteria.

SEQUENCE: (1) Instructor identifies which system you will perform your challenge on; (2) You configure and connect the necessary test equipment to that system with no power applied; (3) Instructor energizes circuit for the very first time; (4) You perform your tests/measurements for the instructor to compare against the standard.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100%; 2 attempts = 80%; 3 attempts = 60%; 4 attempts = 40%; 5 attempts = 20%; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we_1120
10 Experiment – protective relay option

NAME: ___________________________   DUE DATE: ________

Design and build an experimental protective relay system using operational amplifiers to condition a signal representing the status of some electrical power network and comparators to automatically trigger a circuit breaker when certain conditions are met. For experimental-scale power systems, a latching electromechanical relay works well as a circuit breaker, with “trip” and “close” coils to actuate the latching power contact(s). Note: you will want to include in your design some provision for mitigating the inductive “kickback” transient voltage that will be generated by either circuit breaker coil when de-energizing!

**Block diagram:**

![Block diagram of protective relay system](image)

☐ **Instructor consultation** – Discuss general plan, components available, safety considerations, etc. Document this in the “engineering notebook” document, and be sure to record all data here, even from mistakes!

**Stand-alone demonstrations** (may be completed in any order; −5% per re-try, each):

☐ **Instructor certifies** – Demonstrate manual control of the circuit breaker using pushbuttons.

☐ **Instructor certifies** – Demonstrate and record the system’s “tripping” or “closing” time (i.e. the time delay between when the prescribed condition is met and the circuit breaker power contacts change state).

☐ **Instructor certifies** – Demonstrate and record clamping network limiting fault signal amplitude to a level safe for the scaling circuit.

☐ **Instructor certifies** – Demonstrate and record scaling circuit amplifying the signal to a level suitable for the comparator.

☐ **Instructor certifies** – Demonstrate the comparator successfully actuating the circuit breaker.

**Complete system demonstration** (must be completed last, in a single session; −10% per re-try):

☐ **Instructor certifies**

- Protective relay system is demonstrably *dependable*
- Protective relay system is demonstrably *secure*
- “Trip” and “Close” pushbuttons provide manual control of the circuit breaker
- Green LED illuminates when the circuit breaker receives a “trip” signal
- Red LED illuminates when the circuit breaker receives a “close” signal
- *Engineering notebook* document containing recorded data and notes
- Schematic diagram challenge
Design and build an experimental *weigh scale* using multiple load cells as the sensing elements and an operational amplifier network to sense and sum together the load cells’ signals to yield a total weight, and that triggers an “over-weight” indicator if the total weight sensed by all load cells exceeds a pre-determined threshold.

**Block diagram:**

- **Power source**
- **Voltage regulator**
- **Load cell**
- **Differential amplifier**
- **Summer**
- **Comparator**
- **Over-weight indicator**

☐ *Instructor consultation* – Discuss general plan, components available, safety considerations, etc. Document this in the “engineering notebook” document, and be sure to record all data here, even from mistakes!

**Stand-alone demonstrations** (may be completed in any order; −5% per re-try, each):

☐ *Instructor certifies* – Demonstrate and record signal range of a single load cell, establishing its mV/V per kilogram-force or pound calibration.

☐ *Instructor certifies* – Demonstrate the use of a differential amplifier to accurately sense and amplify the signal from a single load cell, outputting a constant V/lb or V/kgf ratio.

☐ *Instructor certifies* – Demonstrate a comparator triggering an LED based on the amplified signal from a single load cell.

☐ *Instructor certifies* – Demonstrate and record an opamp-based analog signal summer circuit accurately summing multiple signals together.

**Complete system demonstration** (must be completed last, in a single session; −10% per re-try):

☐ *Instructor certifies*

- Indicator reliably shows when a certain amount of weight is exceeded, regardless of how that weight is distributed over the multiple load cells
- Analog summer outputs a reliable V/lb or V/kgf ratio, regardless of how that weight is distributed over the multiple load cells
- The “over-weight” threshold is easily adjusted by the user
- *Engineering notebook* document containing recorded data and notes
- Schematic diagram challenge
Design, build, and demonstrate an operational amplifier circuit exhibiting a precise voltage gain, also writing a program (written in the C language) modeling this same circuit and predicting its performance.

This exercise tests your ability to properly design and build an amplifier circuit, select components necessary to achieve a specified voltage gain, use a multimeter to measure voltage and from those measurements infer voltage gain, properly organize all electrical connections, and write an algorithm in C to predict amplifier voltage gain given component values.

The following components and materials will be available to you: assortment of resistors; potentiometers; batteries to build a “split” power supply for the opamp if necessary; and operational amplifier ICs. You must provide your own tools, a digital multimeter (DMM), a computer with C compiler software installed, and your Development Board as well as a copy of this page for your instructor to mark design criteria.

**DC voltage gain** (instructor chooses) = _____ (unitless)

**Characteristic** (instructor chooses) = ___ Inverting or ___ Noninverting

When demonstrating voltage gain, you are free to choose whatever levels of test signal voltage you wish, provided that you conduct the test using multiple voltages to prove that your circuit’s voltage gain is reliable for all signals within its range. Your test voltage must be provided by a potentiometer powered by the opamp power supply. Your modeling software must accept user input at start-up so that the user may test different amplifier designs without having to re-compile the C code.

**SEQUENCE:** (1) Instructor chooses criteria; (2) You write and compile the modeling program, testing it by yourself to ensure it works properly; (3) Instructor observes you running your program with the chosen criteria and documenting its results; (4) You build and test your circuit (using a multimeter) without any power sources at all; (5) Instructor observes circuit energizing for the very first time; (6) You prove to the instructor that the circuit performs as predicted by your program, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are **mastery-based**, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we__1116
Troubleshoot a fault within the analog system you made. This circuitry shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g. covering it up with a box or towel) but test points will be available for contact with a multimeter’s probes. The external stimulus driving the system will also be adjustable during troubleshooting. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise.

Possible faults include:

- Any cable failed open
- Any cable failed shorted
- Any component failed open
- Any component failed shorted
- Any component value altered

First, you will demonstrate that the system functions properly. Then the instructor will either set up or supervise other students setting up a random fault in that system (hidden from view) while you are out of the room. You will then have a limited amount of time to independently perform measurements and other tests while under the continuous observation of the instructor. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. Your only access to the faulted circuit will be via the test points, and only one unpowered test will be permitted.

If you must work remotely rather than in-person, the faulted system must be at the instructor’s location while you request measurements and other diagnostic tests of the instructor via teleconferencing system (e.g. videoconference, telephone, text messaging).

Troubleshooting is *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%).

file 1020_1020
13 Experiment – PLC-based motor starter option

Design and build an experimental motor control circuit using a Programmable Logic Controller (PLC). The PLC program must make use of both counter and timer instructions, and “latch” the motor’s state so that the user pushbutton switches may be momentary contact. An “emergency stop” toggle or latching pushbutton switch must also be included that overrides the PLC.

☐ Instructor consultation – Discuss general plan, components available, safety considerations, etc. Document this in the “engineering notebook” document, and be sure to record all data here, even from mistakes!

Stand-alone demonstrations (may be completed in any order; –5% per re-try, each):

☐ Instructor certifies – Demonstrate the action of a latching on/off PLC control program, where momentary-contact “start” and “stop” switches toggle the motor’s state.

☐ Instructor certifies – Demonstrate the action of an up/down counter PLC instruction.

☐ Instructor certifies – Demonstrate the action of an on-delay timer PLC instruction.

☐ Instructor certifies – Demonstrate the action of an off-delay timer PLC instruction.

☐ Instructor certifies – Demonstrate proper lock-out/tag-out (LOTO) technique for safely performing work on the electric motor. Note: in the absence of a lockable disconnect, redundant taggable disconnects suffice to meet the NFPA 70E requirements.

☐ Instructor certifies – Demonstrate motor contactor safely controlling power to the motor at the command of a low-voltage (< 30 Volts), low-current control signal suitable for the PLC’s output channel, with any transient-snubbing components installed as necessary to protect semiconductor switching devices.

☐ Instructor certifies – Demonstrate accurate measurement of motor line current, both inrush and running, using a current transformer (CT).

Complete system demonstration (must be completed last, in a single session; –10% per re-try):

☐ Instructor certifies

• Motor start control is fail-safe (i.e. won’t start) in the event of a failed-open “start” switch circuit
• Motor start control is fail-safe (i.e. immediately stops) in the event of a failed-open “stop” switch circuit
• Motor power is overcurrent-protected
• Motor “running” and “stopped” indicators controlled by the PLC
• PLC prevents motor from re-starting more than 5 times in 1 minute to limit inrush heating
• Engineering notebook document containing recorded data and notes
• Schematic diagram challenge

file we_3012
Design and build an experimental circuit using a protective relay to provide overcurrent protection for some suitable high-current AC load (e.g. line-powered AC induction motor).

Instructor consultation – Discuss general plan, components available, safety considerations, etc. Document this in the “engineering notebook” document, and be sure to record all data here, even from mistakes!

Stand-alone demonstrations (may be completed in any order; −5% per re-try, each):

- Instructor certifies – Demonstrate remote tripping and closing of a circuit breaker rated for the load’s voltage and current.
- Instructor certifies – Demonstrate proper lock-out/tag-out (LOTO) technique for safely performing work on the load. Note: in the absence of a lockable disconnect, redundant taggable disconnects suffice to meet the NFPA 70E requirements.
- Instructor certifies – Demonstrate accurate measurement of load current using a current transformer (CT).
- Instructor certifies – Demonstrate proper operation of CT test switches in a live circuit.
- Instructor certifies – Demonstrate how to test a current transformer (CT), both turns ratio and winding polarity.
- Instructor certifies – Demonstrate how to set the protective relay’s ANSI “50” function parameters.
- Instructor certifies – Demonstrate how to set the protective relay’s ANSI “51” function parameters.

Complete system demonstration (must be completed last, in a single session; −10% per re-try):

- Instructor certifies
  - Protective relay’s “50” function works (set pick-up value low enough to trip on normal load current)
  - Protective relay’s “51” function works (set pick-up value low enough to trip on normal load current)
  - Motor power is overcurrent-protected by fuses in addition to the relay-controlled circuit breaker
  - Manual breaker “trip” and “close” pushbutton switches located remotely from the circuit breaker
  - Engineering notebook document containing recorded data and notes
  - Schematic diagram challenge

file we_3013
Connect a variable-frequency motor drive (VFD) to a source of single-phase 120 V AC power and a three-phase electric motor, then demonstrate variable-speed control over that motor. The motor will be switched between Stop and Run modes via the buttons (keypad) on the VFD, and the motor’s acceleration/deceleration rates will be configured for gentle starts and stops. All electrical connections must be made using a terminal strip for safety (no twisted wires, crimp splices, wire nuts, spring clips, or “alligator” clips permitted). The 120 VAC portion of the circuit must be fused for overcurrent protection.

This exercise tests your ability to correctly wire a VFD to a power source and to a three-phase induction motor, reset VFD parameters to their default values, program correct parameters in a VFD to control it per specified criteria, and to use a current transformer to measure motor line current.

The following components and materials will be available to you: variable-frequency motor drive; three-phase electric motor; lengths of hook-up wire; assorted potentiometers, and a current transformer. You must provide your own tools, Development Board, and digital multimeter (DMM) as well as a copy of this page for your instructor to mark design criteria.

Note that some VFDs require jumper wires installed in lieu of remote start/stop switches. The Allen-Bradley PowerFlex 4 VFD is an example of this, requiring a jumper wire between terminals 1 and 11 to take the place of an external “Stop” switch.
Instructor chooses motor control options, which cannot be set in the drive until it is powered up:

**Speed control options** (instructor chooses):
- 0-10 V analog signal
- Potentiometer (CW = faster)
- Potentiometer (CCW = faster)

**Acceleration/Deceleration rate** (instructor chooses):
- seconds (5 seconds minimum!)

**Maximum motor speed** (instructor chooses):
- _______ RPM

**How to reset the VFD to factory defaults** (you research and describe):

Instructor inspects wiring and powers up VFD, you reset VFD (completed)

**Base motor parameters** (from nameplate):
- \( V_{\text{line}} = \) _______ Volts
- \( I_{\text{line}} = \) _______ Amps @ full load
- Speed = _______ RPM @ 60 Hz

You show critical VFD parameters to instructor, then start motor and measure \( I_{\text{line}} \) (completed)

**SEQUENCE:** (1) Instructor chooses criteria; (2) You build and test your circuit (using a multimeter) without any power sources at all; (3) Instructor observes circuit energizing for the very first time; (4) You prove to the instructor that the circuit fulfills its intended function, using test equipment as necessary.

Quantitative results must fall within the tolerance of your circuit’s components to be considered correct. For students working remotely rather than in-person, the entire exercise will take place via videoconference to permit instructor observation from start to finish.

Circuit design assessments are *mastery-based*, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try requires new criteria (e.g. different circuit, different design parameters). Scoring is based on the number of attempts necessary to successfully design, build, and demonstrate a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%). Failing to follow instructions counts as an unsuccessful attempt and will require a re-try.

file we _1107
Troubleshoot a fault within a high-current load control system. This circuit shall be constructed in such a manner that all circuit components and simulated faults must be hidden from view (e.g. covering it up with a box or towel) but test points will be available for contact with a multimeter’s probes. A schematic diagram showing the circuit and its test points will be allowed for use during the troubleshooting exercise, as will computer software used to monitor and configure any electronic controllers in the system.

The circuit shall incorporate both a “Start” pushbutton and a “Stop” pushbutton for state control. Possible faults include:

- Electronic controller program/configuration error
- Power supply failure
- Any component failed open
- Any component failed shorted
- Any component value altered

First, you will demonstrate that the system functions properly. Then the instructor will either set up or supervise other students setting up a random fault in that system (hidden from view) while you are out of the room. You will then have a limited amount of time to independently perform measurements and other tests while under the continuous observation of the instructor. A successful troubleshooting exercise consists of both correctly identifying the location and nature of the fault, as well as logically defending the necessity of each diagnostic step. Incorrect fault identification, unnecessary steps, and/or incorrect defense of any step will result in a failed attempt. Your only access to the faulted circuit will be via the test points, and only one unpowered test will be permitted.

If you must work remotely rather than in-person, the faulted system must be at the instructor’s location while you request measurements and other diagnostic tests of the instructor via teleconferencing system (e.g. videoconference, telephone, text messaging).

Troubleshooting is mastery-based, meaning every one must be competently completed in order to pass the course, and you will be given multiple opportunities to re-try if you do not pass on the first attempt. Each re-try begins with another randomized fault on the same circuit. Scoring is based on the number of attempts necessary to successfully troubleshoot a circuit (e.g. 1 attempt = 100% ; 2 attempts = 80% ; 3 attempts = 60% ; 4 attempts = 40% ; 5 attempts = 20% ; 6 or more attempts = 0%).

file we_1027
16 Lab clean-up

NAME: ____________________________

This list represents all of the major work-items that must be done at every semester’s end to prepare the lab space for the upcoming semester. Each student will have at least one task assigned to them.

Non-technical tasks

○ Thoroughly clean whiteboard(s)
○ Vacuum-clean the floor of all debris
○ Clean all workbench surfaces
○ Organize all cables, cords, test leads neatly into their storage locations
○ Clean the interior of all electrical enclosures and cabinets with a vacuum cleaner and test equipment surfaces
○ Clean all electrical panel and test equipment outer surfaces
○ Note any depleted bins (electronic components, threaded fasteners, cables, etc.)

→ Report to instructor for re-ordering in preparation for next semester

Technical tasks

○ Check fastener storage bins to ensure no fasteners are misplaced
○ Check digital IC storage bins to ensure no ICs are misplaced
○ Check resistor storage bins to ensure no resistors are misplaced
○ Check inductor/transformer storage bins to ensure no inductors or transformers are misplaced
○ Check capacitor storage bins to ensure no capacitors are misplaced
○ Test oscilloscopes for basic functionality (e.g. all channels functional, all vertical sensitivity settings functional, all timebase settings functional, triggering functions properly)
○ Test signal generators for basic functionality (e.g. all waveshapes functional, magnitude adjustment functional, frequency adjustment(s) functional)
○ Test power supplies for basic functionality (e.g. voltage adjustments functional, current limits functional, voltage/current meters functional)
○ Test benchtop multimeters for basic functionality (e.g. all voltage ranges functional, all current ranges functional, overcurrent fuse good)
○ Test and clean all soldering stations (e.g. clean/replace sponge pads, check tips for wear, ensure correct temperature settings and that the tip solders well)
○ Test permanently-installed demonstration projects for basic functionality (read instructions on each!) and secure for break; ensure each project has a printed schematic diagram in place
○ Test renewable energy power grid (e.g. all circuit breakers trip and close, no fuses blown) and secure for break
When designing and constructing circuits for experimental and prototyping purposes, the following tips are recommended for success:

- **Sketch a schematic diagram before constructing anything.** You need to have a clear understanding of what it is you intend to build before you begin building, in order to avoid major errors and hazards, and planning your build in schematic form is an excellent way to do that. Having a clear diagram in hand also aids others who you might wish to help you if things don’t work as planned.

- **Build and test in stages.** If you try to build the entire system before testing it, you will very likely encounter multiple errors which will be more time-consuming to diagnose than if you took the time to build and test each portion of your circuit before building and testing the next portion.

- **Choose resistor values between 1,000 and 100,000 Ohms** unless there is some compelling design rationale for using a smaller or larger values. Reactance values within AC circuits should also fall within these same limits. Circuits built with low-value resistors tend to dissipate a lot of power when energized by constant-voltage sources, while circuits built with high-value resistors tend to exhibit “signal sag” when connected to loads and/or test equipment.

- **Use decoupling capacitors** connected in parallel with the DC power pins of every integrated circuit, to stabilize DC voltage for reliable operation. This is especially critical for high-speed digital circuits and sensitive analog circuits, where variations in DC supply voltage may compromise signal integrity. 1 μF ceramic capacitors work well for this purpose, and should be located as close to each IC’s power supply terminals as possible.

- **Diversify your learning experience** by using different types of test equipment (e.g. DMMs, VOMs, oscilloscopes), different types of construction techniques (e.g. solderless breadboards, soldered connections, terminal blocks), and different types of power sources. Remember, the reason you are in this course is to **learn**, not just to complete assignments!

When using sources of energy other than laboratory-quality power supplies, you may need to stabilize source voltage to ensure reliable circuit function. This is especially true when using chemical batteries, solar panels, and other electrical sources known for varying voltage output. A simple integrated circuit called a **three-terminal fixed voltage regulator** takes in power at some voltage larger than what your circuit needs, and dissipatively reduces the voltage level to a fixed value determined by the part number of the regulator IC. The popular LM78xx series of voltage regulators is recommended, where the last digits represent the fixed output voltage (e.g. 7805 = 5 Volts, 7812 = 12 Volts, etc.). An illustration showing how such a regulator might be installed in a solderless breadboard for general experiment/prototype use is shown here:

![Regulator Diagram](image)

Capacitors $C_1$ and $C_2$ help stabilize the regulated voltage if your circuit’s current happens to pulse rather than be steady over time. Consult the regulator IC’s datasheet for pin designations, recommended capacitor sizes, and also for general maximum voltage and current ratings.

file eet_tips
General Troubleshooting Advice

All electronic circuit faults fall into at least one of these categories:

- **Connection fault** – the components are not properly connected together.
- **Design flaw** – the circuit cannot work because something about it is incorrectly designed.
- **Lack of power/signal or poor quality** – the power and/or signal source is “dead” or “noisy”
- **Component fault** – one or more components is faulty.
- **Test equipment** – either the test equipment itself is faulty, or is not being used appropriately.

Of these categories, the one causing more problems for students initially learning about circuits than all the others is the first: connection fault. This is because the ability to translate an idea and/or a schematic diagram into a physical circuit is a skill requiring time to develop. Many such problems may be avoided by (1) drawing a complete schematic of what you intend to build before you build it, (2) marking that schematic to show which connections have been made and which are left to make as you are wiring it, and (3) using an ohmmeter (not your eyes!) to verify that every pair of points which should be connected are connected and that no points which should be electrically distinct from each other are in fact electrically common.

**Troubleshooting strategies**

- **Verify the symptom(s)** – Always check to see that the symptom(s) match what you’ve been told by others. Even if the symptoms were correctly reported, you may notice additional (unreported) symptoms helpful in identifying the fault.
- **Verify good power quality** – Is the source voltage within specifications, and relatively free of “ripple” and other noise?
- **Check signals at component terminals** – Use an oscilloscope or multimeter to check for proper signals at each of the component pins, to see if each one matches your expectations. An important check, especially for integrated circuits, is whether the measured output signal(s) are appropriate for the measured input signal(s).
- **Simply the system** – If possible, re-configure the circuit to be as simple as possible, because complexity makes faults harder to find.
- **Swap identical components** – If particular a component is suspected of being faulty, and you are able to swap another (identical) component for it, do so to see whether or not the problem moves with the old component. If so, that component is to blame; if not, the problem lies elsewhere.
- **Always look for Root Cause(s)** – don’t declare success simply by finding the proximate (i.e. the most direct) cause, but continue your search to find what design flaw, circumstance, or other distal cause led to it.