

## INST 233 (Protective Relays), section 1

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### Lab

Protective Relay system: *Question 91*, **completed objectives due by the end of day 3, section 3**

Miniature AC power grid documentation: *Question 92*, generator schematic diagrams

Miniature AC power grid documentation: *Question 93*, substation schematic diagrams

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### Exam

*Day 3 of next section* – **Complete mastery of these objectives due by the last day of the quarter**

*Specific objectives for the “mastery” exam:*

- Electricity Review: Calculate phasor voltages and currents in an AC reactive circuit given a schematic diagram
  - Match ANSI device number designations (40, 50, 51, 52, 79, 81, 86, 87) with descriptions of protective relay functions
  - Sketch proper wire connections to create a three-phase transformer bank from three independent power transformers
  - Calculate proper wire size for current transformer (CT) field wiring given burden ratings, CT classification, and other relevant system parameters
  - Calculate phasor magnitudes and angles in three-phase electrical circuits, given schematic or pictorial diagrams of the components
  - Determine the possibility of suggested faults in a simple protective relay circuit given a wiring diagram, meter measurements, and/or reported symptoms
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### **Recommended daily schedule**

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#### Day 1

**Theory session topic:** Electrical concept review

Questions 1 through 20; answer questions 1-8 in preparation for discussion (remainder for practice)

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#### Day 2

**Theory session topic:** Power grids, switchgear and relays

Questions 21 through 40; answer questions 21-28 in preparation for discussion (remainder for practice)

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#### Day 3

**Theory session topic:** Phasors and AC circuit analysis

Questions 41 through 60; answer questions 41-47 in preparation for discussion (remainder for practice)

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#### Day 4

**Theory session topic:** Polyphase circuits and AC calculations

Questions 61 through 80; answer questions 61-70 in preparation for discussion (remainder for practice)

Feedback questions (*81 through 90*) are optional and may be submitted for review at the end of the day

## How To . . .

**Access the worksheets and textbook:** go to the *Socratic Instrumentation* website located at <http://www.ibiblio.org/kuphaldt/socratic/sinst> to find worksheets for every 2nd-year course section organized by quarter, as well as both the latest “stable” and “development” versions of the *Lessons In Industrial Instrumentation* textbook. Download and save these documents to your computer.

**Maximize your learning:** complete all homework *before* class starts, ready to be assessed as described in the “Inverted Session Formats” pages. Use every minute of class and lab time productively. Follow all the tips outlined in “Question 0” as well as your instructor’s advice. Do not take constructive criticism personally. Make every reasonable effort to solve problems on your own before seeking help.

**Identify upcoming assignments and deadlines:** read the first page of each course worksheet.

**Relate course days to calendar dates:** reference the calendar spreadsheet file (`calendar.xlsx`), found on the BTC campus Y: network drive. A printed copy is posted in the Instrumentation classroom.

**Locate industry documents assigned for reading:** use the Instrumentation Reference provided by your instructor (on CD-ROM and on the BTC campus Y: network drive). There you will find a file named `00_index_OPEN_THIS_FILE.html` readable with any internet browser. Click on the “Quick-Start Links” to access assigned reading documents, organized per course, in the order they are assigned.

**Study for the exams:** Mastery exams assess specific skills critically important to your success, listed near the top of the front page of each course worksheet for your review. Familiarize yourself with this list and pay close attention when those topics appear in homework and practice problems. Proportional exams feature problems you haven’t seen before that are solvable using general principles learned throughout the current and previous courses, for which the only adequate preparation is independent problem-solving practice every day. Answer the “feedback questions” (practice exams) in each course section to hone your problem-solving skills, as these are similar in scope and complexity to proportional exams. Answer these feedback independently (i.e. no help from classmates) in order to most accurately assess your readiness.

**Calculate course grades:** download the “Course Grading Spreadsheet” (`grades_template.xlsx`) from the Socratic Instrumentation website, or from the BTC campus Y: network drive. Enter your quiz scores, test scores, lab scores, and attendance data into this Excel spreadsheet and it will calculate your course grade. You may compare your calculated grades against your instructors’ records at any time.

**Identify courses to register for:** read the “Sequence” page found in each worksheet.

**Receive extra instructor help:** ask during lab time, or during class time, or by appointment. Tony may be reached by email at [tony.kuphaldt@btc.edu](mailto:tony.kuphaldt@btc.edu) or by telephone at 360-752-8477.

**Identify job openings:** regularly monitor job-search websites. Set up informational interviews at workplaces you are interested in. Participate in jobshadows and internships. Apply to jobs long before graduation, as some employers take *months* to respond! Check your BTC email account daily for alerts.

**Impress employers:** sign the FERPA release form granting your instructors permission to share academic records, then make sure your performance is worth sharing. Document your project and problem-solving experiences for reference during interviews. Honor all your commitments.

**Begin your career:** participate in jobshadows and internships while in school to gain experience and references. Take the first Instrumentation job that pays the bills, and give that employer at least two years of good work to pay them back for the investment they have made in you. Employers look at delayed employment, as well as short employment spans, very negatively. Failure to pass a drug test is an immediate disqualifier, as is falsifying any information. Criminal records may also be a problem.

[file howto](#)

## General Values, Expectations, and Standards

Success in this career requires professional integrity, resourcefulness, persistence, close attention to detail, and intellectual curiosity. If you are ever in doubt as to the values you should embody, just ask yourself what kind of a person you would prefer to hire for your own enterprise. Those same values will be upheld within this program.

**Learning** is the purpose of any educational program, and a worthy priority in life. Every circumstance, every incident, every day here will be treated as a learning opportunity, every mistake as a “teachable moment”. Every form of positive growth, not just academic ability, will be regarded as real learning.

**Responsibility** means *ensuring* the desired outcome, not just *trying* to achieve the outcome. To be a responsible person means you *own* the outcome of your decisions and actions.

**Integrity** means being honest and forthright in all your words and actions, doing your very best every time and never taking credit for the achievement of another.

**Safety** means doing every job correctly and ensuring others are not endangered. Lab safety standards include wearing closed-toed shoes and safety glasses in the lab room during lab hours, wearing ear protection around loud sounds, using ladders to reach high places, using proper lock-out/tag-out procedures, no energized electrical work above 30 volts without an instructor present in the lab room, and no power tool use without an instructor present in the lab room.

**Diligence** in study means exercising self-discipline and persistence, realizing that hard work is a necessary condition for success. This means, among other things, investing the necessary time and effort in studying, reading instructions, paying attention to details, utilizing the skills and tools you already possess, and avoiding shortcuts. Diligence in work means the job is not done until it is done *correctly*: all objectives achieved, all problems solved, all documentation complete, and no errors remaining.

**Self-management** means allocating your resources (time, equipment, labor) wisely, and not just focusing on the closest deadline.

**Communication** means clearly conveying your thoughts and paying attention to what others convey, across all forms of communication (e.g. oral, written, nonverbal).

**Teamwork** means working constructively with your classmates to complete the job at hand. Remember that here the first job is *learning*, and so teamwork means working to maximize everyone’s learning (not just your own). The goal of learning is more important than the completion of any project or assignment.

**Initiative** means recognizing needs and taking action to meet those needs without encouragement or direction from others.

**Representation** means your actions reflect this program and not just yourself. Doors of opportunity for all BTC graduates may be opened or closed by your own conduct. Unprofessional behavior during tours, jobshadows, internships, and/or jobs reflects poorly on the program and will negatively bias employers.

**Trustworthiness** is the result of consistently exercising these values: people will recognize you as someone they can rely on to get the job done, and therefore someone they would want to employ.

**Respect** means acknowledging the intrinsic value, capabilities, and responsibilities of those around you. Respect is gained by consistent demonstration of valued behaviors, and it is lost through betrayal of trust.

## General Values, Expectations, and Standards (continued)

**Punctuality and Attendance:** late arrivals are penalized at a rate of 1% grade deduction per incident. Absence is penalized at a rate of 1% per hour (rounded to the nearest hour) except when employment-related, school-related, weather-related, or required by law (e.g. court summons). Absences may be made up by directing the instructor to apply “sick hours” (12 hours of sick time available per quarter). Classmates may donate their unused sick hours. Sick hours may not be applied to unannounced absences, so be sure to alert your instructor and teammates as soon as you know you will be absent or late. Absence on an exam day will result in a zero score for that exam, unless due to a documented emergency.

**Mastery:** any assignment or objective labeled as “mastery” must be completed with 100% competence (with multiple opportunities to re-try). Failure to complete by the deadline date caps your grade at a C-. Failure to complete by the end of the *next* school day results in a failing (F) grade for that course.

**Time Management:** Use all available time wisely and productively. Work on other useful tasks (e.g. homework, feedback questions, job searching) while waiting for other activities or assessments to begin. Trips to the cafeteria for food or coffee, smoke breaks, etc. must not interfere with team participation.

**Orderliness:** Keep your work area clean and orderly, discarding trash, returning tools at the end of every lab session, and participating in all scheduled lab clean-up sessions. Project wiring, especially in shared areas such as junction boxes, must not be left in disarray at the end of a lab shift. Label any failed equipment with a detailed description of its symptoms.

**Independent Study:** the “inverted” instructional model used in this program requires independent reading and problem-solving, where every student must demonstrate their learning at the start of the class session. Question 0 of every worksheet lists practical study tips. The “Inverted Session Formats” pages found in every worksheet outline the format and grading standards for inverted class sessions.

**Independent Problem-Solving:** make an honest effort to solve every problem before seeking help. When working in the lab, help will not be given unless and until you run your own diagnostic tests.

**Teamwork:** inform your teammates if you need to leave the work area for any reason. Any student regularly compromising team performance through absence, tardiness, disrespect, or other disruptive behavior(s) will be removed from the team and required to complete all labwork individually. The same is true for students found inappropriately relying on teammates.

**Communication:** check your email daily for important messages. Ask the instructor to clarify any assignment or exam question you find confusing, and express your work clearly.

**Academic Progress:** your instructor will record your academic achievement, as well as comments on any negative behavior, and will share all these records with employers if you sign the FERPA release form. You may see these records at any time, and you should track your own academic progress using the grade spreadsheet template. Extra-credit projects will be tailored to your learning needs.

**Office Hours:** your instructor’s office hours are by appointment, except in cases of emergency. Email is the preferred method for setting up an appointment with your instructor to discuss something in private.

**Grounds for Failure:** a failing (F) grade will be earned in any course if any mastery objectives are past deadline by more than one school day, 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.

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## Program Outcomes for Instrumentation and Control Technology (BTC)

### #1 Communication

Communicate and express concepts and ideas across a variety of media (verbal, written, graphical) using industry-standard terms.

### #2 Time management

Arrives on time and prepared to work; Budgets time and meets deadlines when performing tasks and projects.

### #3 Safety

Complies with national, state, local, and college safety regulations when designing and performing work on systems.

### #4 Analysis and Diagnosis

Analyze, evaluate, and diagnose systems related to instrumentation and control including electrical and electronic circuits, fluid power and signaling systems, computer networks, and mechanisms; Select and apply correct mathematical techniques to these analytical and diagnostic problems; Select and correctly use appropriate test equipment to collect data.

### #5 Design and Commissioning

Select, design, construct, configure, and install components necessary for the proper function of systems related to instrumentation and control, applying industry standards and verifying correct system operation when complete.

### #6 System optimization

Improve technical system functions by collecting data and evaluating performance; Implement strategies to optimize the function of these systems.

### #7 Calibration

Assess instrument accuracy and correct inaccuracies using appropriate calibration procedures and test equipment; Select and apply correct mathematical techniques to these calibration tasks.

### #8 Documentation

Interpret and create technical documents (e.g. electronic schematics, loop diagrams, functional diagrams, P&IDs, graphs, narratives) according to industry standards.

### #9 Independent learning

Select and research information sources to learn new principles, technologies, and techniques.

### #10 Job searching

Develop a professional resume and research job openings in the field of industrial instrumentation.

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## INST 233 Course Outcomes

*Each and every outcome in this course is assessed at a mastery level (i.e. 100% competence)*

- Calculate phasor magnitudes and angles in three-phase electrical circuits, given schematic or pictorial diagrams of the components. [Ref: Program Learning Outcome #4]
- Calculate phasor voltages and currents in an AC reactive circuit given a schematic diagram. [Ref: Program Learning Outcome #4]
- Calculate proper wire size for current transformer (CT) field wiring given burden ratings, CT classification, and other relevant system parameters. [Ref: Program Learning Outcome #5]
- Sketch proper wire connections to create a three-phase transformer bank from three independent power transformers. [Ref: Program Learning Outcome #5]
- Determine the possibility of suggested faults in a simple protective relay circuit given a wiring diagram, meter measurements, and/or reported symptoms. [Ref: Program Learning Outcome #4]
- Correlate ANSI device number designations with descriptions of protective relay functions. [Ref: Program Learning Outcome #4]
- Demonstrate proper use of equipment to commission CT circuits. [Ref: Program Learning Outcome #4]
- Demonstrate proper safety protocols for working with live CT circuits. [Ref: Program Learning Outcome #3]
- Communicate effectively with teammates to plan work, arrange for absences, and share responsibilities in completing all labwork. [Ref: Program Learning Outcomes #1 and #2]
- Test an electromechanical instantaneous overcurrent (50) relay. [Ref: Program Learning Outcome #7]
- Test an electromechanical time-overcurrent (51) relay. [Ref: Program Learning Outcome #7]
- Determine phase rotation in a three-phase power system. [Ref: Program Learning Outcome #7]
- Program an electronic protective relay as per specified system protection and instrument transformer parameters, testing this relay's operation to verify the correctness of those settings. [Ref: Program Learning Outcome #5]
- Interpret the event report generated by an electronic protective relay following a trip event. [Ref: Program Learning Outcome #4]

## Course Syllabus

### INSTRUCTOR CONTACT INFORMATION:

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**DEPT/COURSE #:** INST 233

**CREDITS:** 3      **Lecture Hours:** 11      **Lab Hours:** 44      **Work-based Hours:** 0

**COURSE TITLE:** Protective Relays

**COURSE DESCRIPTION:** In this course you will learn how to commission, test, and analyze basic protective relays and instrument transformers used to protect equipment in electrical power systems. This course also reviews phasor mathematics for three-phase electrical circuits. Pre/Corequisite course: INST232 (PLC Systems) **Prerequisite course:** MATH&141 (Precalculus 1) with a minimum grade of “C”

**COURSE OUTCOMES:** Configure, test, and analyze overcurrent protective relays and instrument transformers.

**COURSE OUTCOME ASSESSMENT:** Protective relay configuration, testing, and analysis outcomes are ensured by measuring student performance against mastery standards, as documented in the Student Performance Objectives. Failure to meet all mastery standards by the deadline will result in a failing grade for the course.

## STUDENT PERFORMANCE OBJECTIVES:

- Without references or notes, within a limited time (3 hours total for each exam session), independently perform the following tasks. Multiple re-tries are allowed on mastery (100% accuracy) objectives, each with a different set of problems:
  - Calculate voltages, currents, and phase shifts in an AC reactive circuit, with 100% accuracy (mastery)
  - Match ANSI device number designations (40, 50, 51, 52, 79, 81, 86, 87) with descriptions of protective relay functions, with 100% accuracy (mastery)
  - Sketch proper wire connections to create a three-phase transformer bank from three independent power transformers, with 100% accuracy (mastery)
  - Calculate proper wire size for current transformer (CT) field wiring given burden ratings, CT classification, and other relevant system parameters, with 100% accuracy (mastery)
  - Calculate phasor magnitudes and angles in three-phase electrical circuits, given schematic or pictorial diagrams of the components, with 100% accuracy (mastery)
  - Determine the possibility of suggested faults in a simple protective relay circuit given a wiring diagram, meter measurements, and/or reported symptoms, with 100% accuracy (mastery)
- In a team environment and with full access to references, notes, and instructor assistance, perform the following tasks:
  - Demonstrate proper use of equipment to commission CT circuits
  - Demonstrate proper safety protocols for working with live CT circuits
  - Test an electromechanical instantaneous overcurrent (50) relay
  - Test an electromechanical time-overcurrent (51) relay
  - Determine phase rotation in a three-phase power system
- Independently perform the following tasks on a functioning bus-connected three-phase generating station with 100% accuracy (mastery). Multiple re-tries are allowed with different specifications/conditions each time):
  - Program an electronic overcurrent (50/51) relay as per specified system protection and instrument transformer parameters, testing this relay's operation to verify the correctness of those settings.

**COURSE OUTLINE:** A course calendar in electronic format (Excel spreadsheet) resides on the Y: network drive, and also in printed paper format in classroom DMC130, for convenient student access. This calendar is updated to reflect schedule changes resulting from employer recruiting visits, interviews, and other impromptu events. Course worksheets provide comprehensive lists of all course assignments and activities, with the first page outlining the schedule and sequencing of topics and assignment due dates. These worksheets are available in PDF format at <http://www.ibiblio.org/kuphaldt/socratic/sinst>

- INST233 Section 1: 4 days theory and labwork
- INST233 Section 2: 2 days theory and labwork + 1 day for review and mastery exam + 1 day for proportional exam



**METHODS OF INSTRUCTION:** Course structure and methods are intentionally designed to develop critical-thinking and life-long learning abilities, continually placing the student in an active rather than a passive role.

- **Independent study:** daily worksheet questions specify *reading assignments*, *problems* to solve, and *experiments* to perform in preparation (before) classroom theory sessions. Open-note quizzes ensure accountability for this essential preparatory work. The purpose of this is to convey information and basic concepts, so valuable class time isn't wasted transmitting bare facts, and also to foster the independent research ability necessary for self-directed learning in your career.
- **Classroom sessions:** a combination of *Socratic discussion*, short *lectures*, *small-group* problem-solving, and hands-on *demonstrations/experiments* review and illuminate concepts covered in the preparatory questions. The purpose of this is to develop problem-solving skills, strengthen conceptual understanding, and practice both quantitative and qualitative analysis techniques.
- **Lab activities:** an emphasis on constructing and documenting *working projects* (real instrumentation and control systems) to illuminate theoretical knowledge with practical contexts. Special projects off-campus or in different areas of campus (e.g. BTC's Fish Hatchery) are encouraged. Hands-on *troubleshooting exercises* build diagnostic skills.
- **Tours and guest speakers:** quarterly *tours* of local industry and *guest speakers* on technical topics add breadth and additional context to the learning experience.

**STUDENT ASSIGNMENTS/REQUIREMENTS:** All assignments for this course are thoroughly documented in the following course worksheets located at:

<http://www.ibiblio.org/kuphaldt/socratic/sinst/index.html>

- INST233\_sec1.pdf
- INST233\_sec2.pdf

**EVALUATION AND GRADING STANDARDS:** (out of 100% for the course grade)

- Completion of all mastery objectives = 50%
- Mastery exam score = 10%
- Proportional exam score = 30%
- Lab score = 10%
- Preparation/Participation penalty = -1% per failed
- Tardiness penalty = -1% per incident (1 “free” tardy per course)
- Attendance penalty = -1% per hour (12 hours “sick time” per quarter)

All grades are criterion-referenced (i.e. no grading on a “curve”)

100% ≥ <b>A</b> ≥ 95%	95% > <b>A-</b> ≥ 90%		
90% > <b>B+</b> ≥ 86%	86% > <b>B</b> ≥ 83%	83% > <b>B-</b> ≥ 80%	
80% > <b>C+</b> ≥ 76%	76% > <b>C</b> ≥ 73%	73% > <b>C-</b> ≥ 70%	(minimum passing course grade)
70% > <b>D+</b> ≥ 66%	66% > <b>D</b> ≥ 63%	63% > <b>D-</b> ≥ 60%	60% > <b>F</b>

Absence on a scheduled exam day will result in a 0% score for the proportional exam unless you provide documented evidence of an unavoidable emergency.

If you fail a mastery exam, you must re-take a different version of that mastery exam on a different day. Multiple re-tries are allowed, on a different version of the exam each re-try. There is no penalty levied on your course grade for re-taking mastery exams, but failure to successfully pass a mastery exam by the due date will result in a failing grade (F) for the course.

If any other “mastery” objectives are not completed by their specified deadlines, your overall grade for the course will be capped at 70% (C- grade), and you will have one more school day to complete the unfinished objectives. Failure to complete those mastery objectives by the end of that extra day (except in the case of documented, unavoidable emergencies) will result in a failing grade (F) for the course.

The lab score is based on the number of times taken to master each objective. Successfully passing all objectives on the first attempt results in a 100% score.

Individual preparation for Socratic dialogue sessions is measured by a “prep quiz” and/or individual questioning and/or personal inspection of your work by the instructor. A second (“summary”) score for every Socratic session marks your participatory dialogue and ability to give reasoned answers to challenge questions on that session’s topic(s). In the event of absence, these scores may be credited by having your preparatory work and demonstration of understanding reviewed at any time before the end of the quarter in a one-on-one dialogue with the instructor.

**REQUIRED STUDENT SUPPLIES AND MATERIALS:**

- Course worksheets available for download in PDF format
- *Lessons in Industrial Instrumentation* textbook, available for download in PDF format  
→ Access worksheets and book at: <http://www.ibiblio.org/kuphaldt/socratic/sinst>
- Ampacity ratings of wire from the *National Electrical Code* (NFPA 70) reference, available for free online viewing at <http://www.nfpa.org>
- NFPA 70E “Standard for Electrical Safety in the Workplace”
- Spiral-bound notebook for reading annotation, homework documentation, and note-taking.
- Instrumentation reference CD-ROM (free, from instructor). This disk contains many tutorials and datasheets in PDF format to supplement your textbook(s).
- Tool kit (see detailed list)
- Scientific calculator capable of performing complex-number arithmetic in both rectangular and polar forms. TI-36X Pro, TI-83, or TI-84 recommended.
- Portable personal computer with Ethernet port and wireless. Windows OS strongly preferred, tablets discouraged.

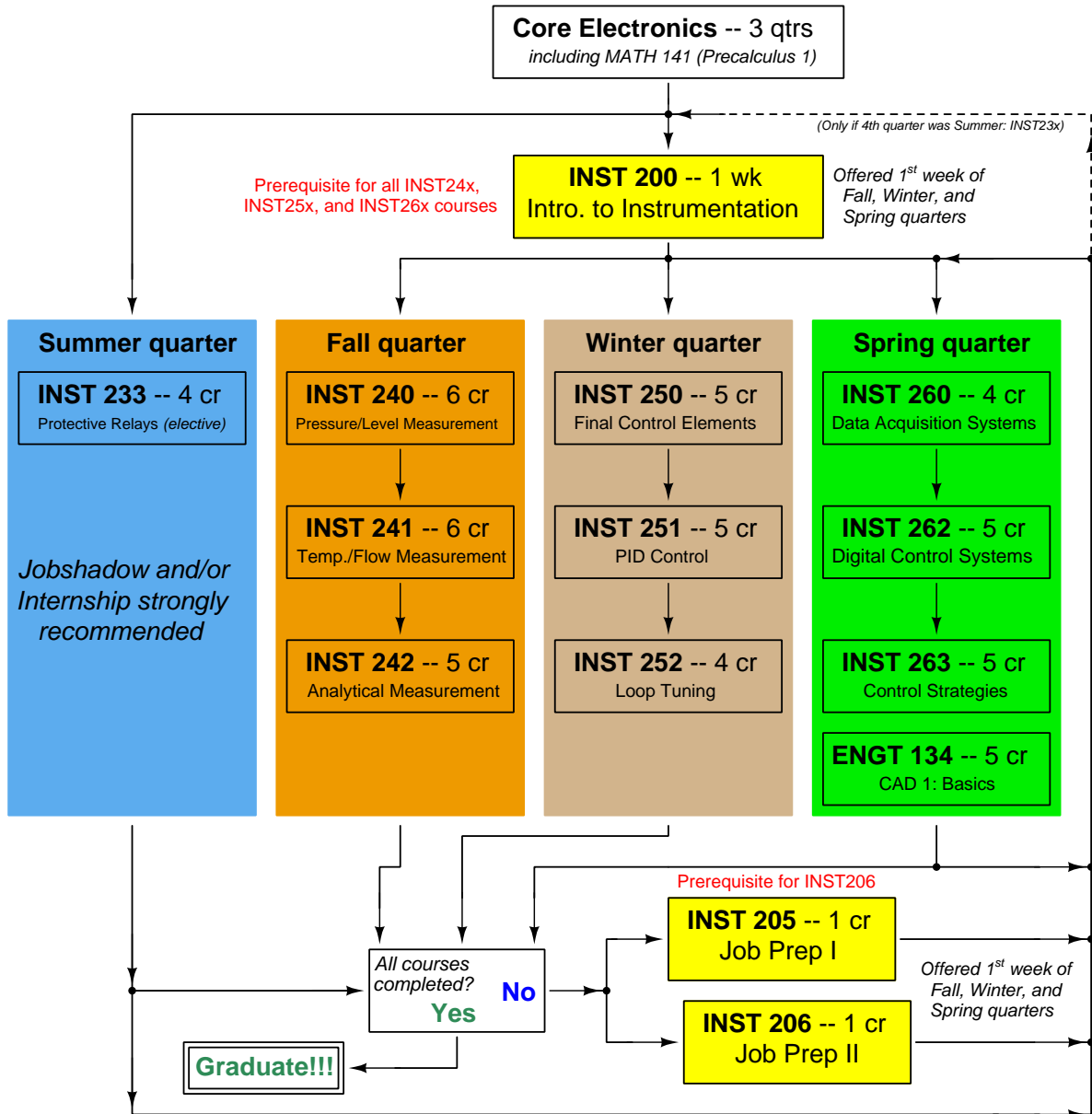
**ADDITIONAL INSTRUCTIONAL RESOURCES:**

- The BTC Library hosts a substantial collection of textbooks and references on the subject of Instrumentation, as well as links in its online catalog to free Instrumentation e-book resources available on the Internet.
- “BTCInstrumentation” channel on YouTube (<http://www.youtube.com/BTCInstrumentation>), hosts a variety of short video tutorials and demonstrations on instrumentation.
- Instrumentation student club meets regularly to set up industry tours, raise funds for scholarships, and serve as a general resource for Instrumentation students.

**CAMPUS EMERGENCIES:** If an emergency arises, your instructor may inform you of actions to follow. You are responsible for knowing emergency evacuation routes from your classroom. If police or university officials order you to evacuate, do so calmly and assist those needing help. You may receive emergency information alerts via the building enunciation system, text message, email, or BTC’s webpage (<http://www.btc.edu>), Facebook or Twitter. Refer to the emergency flipchart in the lab room (located on the main control panel) for more information on specific types of emergencies.

**ACCOMMODATIONS:** If you think you could benefit from classroom accommodations for a disability (physical, mental, emotional, or learning), please contact our Accessibility Resources office. Call (360)-752-8345, email [ar@btc.edu](mailto:ar@btc.edu), or stop by the AR Office in the Admissions and Student Resource Center (ASRC), Room 106, College Services Building

# Sequence of second-year Instrumentation courses



The particular sequence of courses you take during the second year depends on when you complete all first-year courses and enter the second year. Since students enter the second year of Instrumentation at four different times (beginnings of Summer, Fall, Winter, and Spring quarters), the particular course sequence for any student will likely be different from the course sequence of classmates.

Some second-year courses are only offered in particular quarters with those quarters not having to be in sequence, while others are offered three out of the four quarters and must be taken in sequence. The following layout shows four typical course sequences for second-year Instrumentation students, depending on when they first enter the second year of the program:

### Possible course schedules depending on date of entry into 2nd year



file sequence

## General tool and supply list

### Wrenches

- Combination (box- and open-end) wrench set, 1/4" to 3/4" – *the most important wrench sizes are 7/16", 1/2", 9/16", and 5/8"; get these immediately!*
- Adjustable wrench, 6" handle (sometimes called "Crescent" wrench)
- Hex wrench ("Allen" wrench) set, fractional – 1/16" to 3/8"
- *Optional:* Hex wrench ("Allen" wrench) set, metric – 1.5 mm to 10 mm
- *Optional:* Miniature combination wrench set, 3/32" to 1/4" (sometimes called an "ignition wrench" set)

Note: *always maximize surface engagement on a fastener's head to reduce stress on that fastener. (e.g. Using box-end wrenches instead of adjustable wrenches; using the proper size and type of screwdriver; never using any tool that mars the fastener such as pliers or vise-grips unless absolutely necessary.)*

### Pliers

- Needle-nose pliers
- Diagonal wire cutters (sometimes called "dikes")

### Screwdrivers

- Slotted, 1/8" and 1/4" shaft
- Phillips, #1 and #2
- Jeweler's screwdriver set
- *Optional:* Magnetic multi-bit screwdriver (e.g. Klein Tools model 70035)

### Electrical

- Multimeter, Fluke model 87-IV or better
- Assortment of alligator-clip style jumper wires
- Soldering iron (10 to 40 watt) and rosin-core solder
- Resistor, potentiometer, diode assortments (from first-year lab kits)
- Package of insulated compression-style fork terminals (14 to 18 AWG wire size, #10 stud size)
- Wire strippers/terminal crimpers for 10 AWG to 18 AWG wire and insulated terminals
- *Optional:* ratcheting terminal crimp tool (e.g. Paladin 1305, Ferrules Direct FDT10011, or equivalent)

### Safety

- Safety glasses or goggles (available at BTC bookstore)
- Earplugs (available at BTC bookstore)

### Miscellaneous

- Simple scientific calculator (non-programmable, non-graphing, no conversions), TI-30Xa or TI-30XIIS recommended. Required for some exams!
- Portable personal computer capable of wired Ethernet connectivity, Wi-Fi connectivity, displaying PDF documents, creating text documents, creating and viewing spreadsheets, running PLC programming software (MS Windows only), and executing command-line utilities such as `ping`.
- Masking tape (for making temporary labels)
- Permanent marker pen
- Teflon pipe tape
- Utility knife
- Tape measure, 12 feet minimum
- Flashlight

file tools

## Methods of instruction

This course develops self-instructional and diagnostic skills by placing students in situations where they are required to research and think independently. In all portions of the curriculum, the goal is to avoid a passive learning environment, favoring instead *active engagement* of the learner through reading, reflection, problem-solving, and experimental activities. The curriculum may be roughly divided into two portions: *theory* and *practical*. All “theory” sessions follow the *inverted* format and contain virtually no lecture.

### Inverted theory sessions

The basic concept of an “inverted” learning environment is that the traditional allocations of student time are reversed: instead of students attending an instructor-led session to receive new information and then practicing the application of that information outside of the classroom in the form of homework, students in an inverted class encounter new information outside of the classroom via homework and apply that information in the classroom session under the instructor’s tutelage.

A natural question for instructors, then, is what their precise role is in an inverted classroom and how to organize that time well. Here I will list alternate formats suitable for an inverted classroom session, each of them tested and proven to work.

#### Small sessions

Students meet with instructors in small groups for short time periods. Groups of 4 students meeting for 30 minutes works very well, but groups as large as 8 students apiece may be used if time is limited. Each of these sessions begins with a 5 to 10 minute graded inspection of homework with individual questioning, to keep students accountable for doing the homework. The remainder of the session is a dialogue focusing on the topics of the day, the instructor challenging each student on the subject matter in Socratic fashion, and also answering students’ questions. A second grade measures each student’s comprehension of the subject matter by the end of the session.

This format also works via teleconferencing, for students unable to attend a face-to-face session on campus.

#### Large sessions

Students meet with instructors in a standard classroom (normal class size and period length). Each of these sessions begins with a 10 minute graded quiz (closed-book) on the homework topic(s), to keep students accountable for doing the homework. Students may leave the session as soon as they “check off” with the instructor in a Socratic dialogue as described above (instructor challenging each student to assess their comprehension, answering questions, and grading the responses). Students sign up for check-off on the whiteboard when they are ready, typically in groups of no more than 4. Alternatively, the bulk of the class session may be spent answering student questions in small groups, followed by another graded quiz at the end.

#### Correspondence

This format works for students unable to attend a “face-to-face” session, and who must correspond with the instructor via email or other asynchronous medium. Each student submits a thorough presentation of their completed homework, which the instructor grades for completeness and accuracy. The instructor then replies back to the student with challenge questions, and also answers questions the student may have. As with the previous formats, the student receives another grade assessing their comprehension of the subject matter by the close of the correspondence dialogue.

## Methods of instruction (continued)

In all formats, students are held accountable for completion of their homework, “completion” being defined as successfully interpreting the given information from source material (e.g. accurate outlines of reading or video assignments) and constructive effort to solve given problems. It must be understood in an inverted learning environment that students *will* have legitimate questions following a homework assignment, and that it is therefore unreasonable to expect mastery of the assigned subject matter. What is reasonable to expect from each and every student is a basic outline of the source material (reading or video assignments) complete with major terms defined and major concepts identified, plus a good-faith effort to solve every problem. Question 0 (contained in every worksheet) lists multiple strategies for effective study and problem-solving.

### Sample rubric for pre-assessments

- **No credit** = Any homework question unattempted (i.e. no effort shown on one or more questions); incomprehensible writing; failure to follow clear instruction(s)
- **Half credit** = Misconception(s) on any major topic explained in the assigned reading; answers shown with no supporting work; verbatim copying of text rather than written in student’s own words; outline missing important topic(s); unable to explain the outline or solution methods represented in written work
- **Full credit** = Every homework question answered, with any points of confusion clearly articulated; all important concepts from reading assignments accurately expressed in the outline and clearly articulated when called upon by the instructor to explain

*The minimum expectation at the start of every student-instructor session is that all students have made a good-faith effort to complete 100% of their assigned homework. This does not necessarily mean all answers will be correct, or that all concepts are fully understood, because one of the purposes of the meeting between students and instructor is to correct remaining misconceptions and answer students’ questions. However, experience has shown that without accountability for the homework, a substantial number of students will not put forth their best effort and that this compromises the whole learning process. Full credit is reserved for good-faith effort, where each student thoughtfully applies the study and problem-solving recommendations given to them (see Question 0).*

### Sample rubric for post-assessments

- **No credit** = Failure to comprehend one or more key concepts; failure to apply logical reasoning to the solution of problem(s); no contribution to the dialogue
- **Half credit** = Some misconceptions persist by the close of the session; problem-solving is inconsistent; limited contribution to the dialogue
- **Full credit** = Socratic queries answered thoughtfully; effective reasoning applied to problems; ideas communicated clearly and accurately; responds intelligently to questions and statements made by others in the session; adds new ideas and perspectives

*The minimum expectation is that each and every student engages with the instructor and with fellow students during the Socratic session: posing intelligent questions of their own, explaining their reasoning when challenged, and otherwise positively contributing to the discussion. Passive observation and listening is not an option here – every student must be an active participant, contributing something original to every dialogue. If a student is confused about any concept or solution, it is their responsibility to ask questions and seek resolution.*



## Methods of instruction (continued)

If a student happens to be absent for a scheduled class session and is therefore unable to be assessed on that day's study, they may schedule a time with the instructor to demonstrate their comprehension at some later date (before the end of the quarter when grades must be submitted). These same standards of performance apply equally make-up assessments: either inspection of homework or a closed-book quiz for the pre-assessment, and either a Socratic dialogue with the instructor or another closed-book quiz for the post-assessment.

## Methods of instruction (continued)

### Lab sessions

In the lab portion of each course, students work in teams to install, configure, document, calibrate, and troubleshoot working instrument loop systems. Each lab exercise focuses on a different type of instrument, with a limited time period typically for completion. An ordinary lab session might look like this:

- (1) Start of practical (lab) session: announcements and planning
  - (a) The instructor makes general announcements to all students
  - (b) The instructor works with team to plan that day's goals, making sure each team member has a clear idea of what they should accomplish
- (2) Teams work on lab unit completion according to recommended schedule:
  - (First day) Select and bench-test instrument(s), complete prototype sketch of project
  - (One day) Connect instrument(s) into a complete loop
  - (One day) Each team member drafts their own loop documentation, inspection done as a team (with instructor)
  - (One or two days) Each team member calibrates/configures the instrument(s)
  - (Remaining days, up to last) Each team member troubleshoots the instrument loop
- (3) End of practical (lab) session: debriefing where each team reports on their work to the whole class

### Troubleshooting assessments must meet the following guidelines:

- Troubleshooting must be performed *on a system the student did not build themselves*. This forces students to rely on another team's documentation rather than their own memory of how the system was built.
- Each student must individually demonstrate proper troubleshooting technique.
- Simply finding the fault is not good enough. Each student must consistently demonstrate sound reasoning while troubleshooting.
- If a student fails to properly diagnose the system fault, they must attempt (as many times as necessary) with different scenarios until they do, reviewing any mistakes with the instructor after each failed attempt.

file instructional

## Distance delivery methods

Sometimes the demands of life prevent students from attending college 6 hours per day. In such cases, there exist alternatives to the normal 8:00 AM to 3:00 PM class/lab schedule, allowing students to complete coursework in non-traditional ways, at a “distance” from the college campus proper.

For such “distance” students, the same worksheets, lab activities, exams, and academic standards still apply. Instead of working in small groups and in teams to complete theory and lab sections, though, students participating in an alternative fashion must do all the work themselves. Participation via teleconferencing, video- or audio-recorded small-group sessions, and such is encouraged and supported.

There is no recording of hours attended or tardiness for students participating in this manner. The pace of the course is likewise determined by the “distance” student. Experience has shown that it is a benefit for “distance” students to maintain the same pace as their on-campus classmates whenever possible.

In lieu of small-group activities and class discussions, comprehension of the theory portion of each course will be ensured by completing and submitting detailed answers for *all* worksheet questions, not just passing daily quizzes as is the standard for conventional students. The instructor will discuss any incomplete and/or incorrect worksheet answers with the student, and ask that those questions be re-answered by the student to correct any misunderstandings before moving on.

Labwork is perhaps the most difficult portion of the curriculum for a “distance” student to complete, since the equipment used in Instrumentation is typically too large and expensive to leave the school lab facility. “Distance” students must find a way to complete the required lab activities, either by arranging time in the school lab facility and/or completing activities on equivalent equipment outside of school (e.g. at their place of employment, if applicable). Labwork completed outside of school must be validated by a supervisor and/or documented via photograph or videorecording.

Conventional students may opt to switch to “distance” mode at any time. This has proven to be a benefit to students whose lives are disrupted by catastrophic events. Likewise, “distance” students may switch back to conventional mode if and when their schedules permit. Although the existence of alternative modes of student participation is a great benefit for students with challenging schedules, it requires a greater investment of time and a greater level of self-discipline than the traditional mode where the student attends school for 6 hours every day. No student should consider the “distance” mode of learning a way to have more free time to themselves, because they will actually spend more time engaged in the coursework than if they attend school on a regular schedule. It exists merely for the sake of those who cannot attend during regular school hours, as an alternative to course withdrawal.

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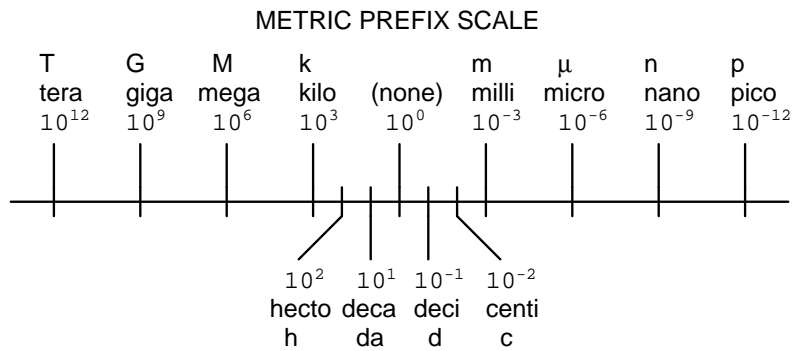
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## Metric prefixes and conversion constants

- **Metric prefixes**

- Yotta =  $10^{24}$  Symbol: Y
- Zeta =  $10^{21}$  Symbol: Z
- Exa =  $10^{18}$  Symbol: E
- Peta =  $10^{15}$  Symbol: P
- Tera =  $10^{12}$  Symbol: T
- Giga =  $10^9$  Symbol: G
- Mega =  $10^6$  Symbol: M
- Kilo =  $10^3$  Symbol: k
- Hecto =  $10^2$  Symbol: h
- Deca =  $10^1$  Symbol: da
- Deci =  $10^{-1}$  Symbol: d
- Centi =  $10^{-2}$  Symbol: c
- Milli =  $10^{-3}$  Symbol: m
- Micro =  $10^{-6}$  Symbol:  $\mu$
- Nano =  $10^{-9}$  Symbol: n
- Pico =  $10^{-12}$  Symbol: p
- Femto =  $10^{-15}$  Symbol: f
- Atto =  $10^{-18}$  Symbol: a
- Zepto =  $10^{-21}$  Symbol: z
- Yocto =  $10^{-24}$  Symbol: y



- **Conversion formulae for temperature**

- $^{\circ}\text{F} = (^{\circ}\text{C})(9/5) + 32$
- $^{\circ}\text{C} = (^{\circ}\text{F} - 32)(5/9)$
- $^{\circ}\text{R} = ^{\circ}\text{F} + 459.67$
- $\text{K} = ^{\circ}\text{C} + 273.15$

### Conversion equivalencies for distance

- 1 inch (in) = 2.540000 centimeter (cm)
- 1 foot (ft) = 12 inches (in)
- 1 yard (yd) = 3 feet (ft)
- 1 mile (mi) = 5280 feet (ft)

**Conversion equivalencies for volume**

1 gallon (gal) = 231.0 cubic inches (in<sup>3</sup>) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm<sup>3</sup>)

**Conversion equivalencies for velocity**

1 mile per hour (mi/h) = 88 feet per minute (ft/m) = 1.46667 feet per second (ft/s) = 1.60934 kilometer per hour (km/h) = 0.44704 meter per second (m/s) = 0.868976 knot (knot – international)

**Conversion equivalencies for mass**

1 pound (lbm) = 0.45359 kilogram (kg) = 0.031081 slugs

**Conversion equivalencies for force**

1 pound-force (lbf) = 4.44822 newton (N)

**Conversion equivalencies for area**

1 acre = 43560 square feet (ft<sup>2</sup>) = 4840 square yards (yd<sup>2</sup>) = 4046.86 square meters (m<sup>2</sup>)

**Conversion equivalencies for common pressure units (either all gauge or all absolute)**

1 pound per square inch (PSI) = 2.03602 inches of mercury (in. Hg) = 27.6799 inches of water (in. W.C.) = 6.894757 kilo-pascals (kPa) = 0.06894757 bar

1 bar = 100 kilo-pascals (kPa) = 14.504 pounds per square inch (PSI)

**Conversion equivalencies for absolute pressure units (only)**

1 atmosphere (Atm) = 14.7 pounds per square inch absolute (PSIA) = 101.325 kilo-pascals absolute (kPaA) = 1.01325 bar (bar) = 760 millimeters of mercury absolute (mmHgA) = 760 torr (torr)

**Conversion equivalencies for energy or work**

1 british thermal unit (Btu – “International Table”) = 251.996 calories (cal – “International Table”) = 1055.06 joules (J) = 1055.06 watt-seconds (W-s) = 0.293071 watt-hour (W-hr) = 1.05506 x 10<sup>10</sup> ergs (erg) = 778.169 foot-pound-force (ft-lbf)

**Conversion equivalencies for power**

1 horsepower (hp – 550 ft-lbf/s) = 745.7 watts (W) = 2544.43 british thermal units per hour (Btu/hr) = 0.0760181 boiler horsepower (hp – boiler)

**Acceleration of gravity (free fall), Earth standard**

9.806650 meters per second per second (m/s<sup>2</sup>) = 32.1740 feet per second per second (ft/s<sup>2</sup>)

### Physical constants

Speed of light in a vacuum ( $c$ ) =  $2.9979 \times 10^8$  meters per second (m/s) = 186,281 miles per second (mi/s)

Avogadro's number ( $N_A$ ) =  $6.022 \times 10^{23}$  per mole ( $\text{mol}^{-1}$ )

Electronic charge ( $e$ ) =  $1.602 \times 10^{-19}$  Coulomb (C)

Boltzmann's constant ( $k$ ) =  $1.38 \times 10^{-23}$  Joules per Kelvin (J/K)

Stefan-Boltzmann constant ( $\sigma$ ) =  $5.67 \times 10^{-8}$  Watts per square meter-Kelvin<sup>4</sup> ( $\text{W}/\text{m}^2 \cdot \text{K}^4$ )

Molar gas constant ( $R$ ) = 8.314 Joules per mole-Kelvin (J/mol-K)

### Properties of Water

Freezing point at sea level =  $32^\circ\text{F} = 0^\circ\text{C}$

Boiling point at sea level =  $212^\circ\text{F} = 100^\circ\text{C}$

Density of water at  $4^\circ\text{C} = 1000 \text{ kg}/\text{m}^3 = 1 \text{ g}/\text{cm}^3 = 1 \text{ kg}/\text{liter} = 62.428 \text{ lb}/\text{ft}^3 = 1.94 \text{ slugs}/\text{ft}^3$

Specific heat of water at  $14^\circ\text{C} = 1.00002 \text{ calories}/\text{g} \cdot ^\circ\text{C} = 1 \text{ BTU}/\text{lb} \cdot ^\circ\text{F} = 4.1869 \text{ Joules}/\text{g} \cdot ^\circ\text{C}$

Specific heat of ice  $\approx 0.5 \text{ calories}/\text{g} \cdot ^\circ\text{C}$

Specific heat of steam  $\approx 0.48 \text{ calories}/\text{g} \cdot ^\circ\text{C}$

Absolute viscosity of water at  $20^\circ\text{C} = 1.0019 \text{ centipoise (cp)} = 0.0010019 \text{ Pascal-seconds (Pa}\cdot\text{s)}$

Surface tension of water (in contact with air) at  $18^\circ\text{C} = 73.05 \text{ dynes}/\text{cm}$

pH of pure water at  $25^\circ\text{C} = 7.0$  (*pH scale = 0 to 14*)

### Properties of Dry Air at sea level

Density of dry air at  $20^\circ\text{C}$  and 760 torr =  $1.204 \text{ mg}/\text{cm}^3 = 1.204 \text{ kg}/\text{m}^3 = 0.075 \text{ lb}/\text{ft}^3 = 0.00235 \text{ slugs}/\text{ft}^3$

Absolute viscosity of dry air at  $20^\circ\text{C}$  and 760 torr =  $0.018 \text{ centipoise (cp)} = 1.8 \times 10^{-5} \text{ Pascal-seconds (Pa}\cdot\text{s)}$

file conversion\_constants

**How to get the most out of academic reading:**

- Outline, don't highlight! Identify every major idea presented in the text, and express these ideas in your own words. A suggested ratio is one sentence of your own thoughts per paragraph of text read.
- Articulate your thoughts as you read (i.e. "have a conversation" with the author). This will develop *metacognition*: active supervision of your own thoughts. Note points of agreement, disagreement, confusion, epiphanies, and connections between different concepts or applications.
- Work through all mathematical exercises shown within the text, to ensure you understand all the steps.
- Imagine explaining concepts you've just learned to someone else. Teaching forces you to distill concepts to their essence, thereby clarifying those concepts, revealing assumptions, and exposing misconceptions. Your goal is to create the simplest explanation that is still technically accurate.
- Create your own questions based on what you read, as a teacher would to challenge students.

**How to effectively problem-solve and troubleshoot:**

- Rely on principles, not procedures. Don't be satisfied with memorizing steps – learn *why* those steps work. Each step should make logical sense and have real-world meaning to you.
- Sketch a diagram to help visualize the problem. Sketch a graph showing how variables relate. When building a real system, always prototype it on paper and analyze its function *before* constructing it.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting, perform *diagnostic tests* rather than just visually inspect for faults.
- Simplify the problem and solve that simplified problem to identify strategies applicable to the original problem (e.g. change quantitative to qualitative, or visa-versa; substitute easier numerical values; eliminate confusing details; add details to eliminate unknowns; consider simple limiting cases; apply an analogy). Remove components from a malfunctioning system to simplify it and better identify the nature and location of the problem.
- Check for exceptions – does your solution work for *all* conditions and criteria?
- Work "backward" from a hypothetical solution to a new set of given conditions.

**How to manage your time:**

- Avoid procrastination. Work now and play later, every single day.
- Consider the place you're in when deciding what to do. If there is project work to do and you have access to the lab, do that work and not something that could be done elsewhere (e.g. homework).
- Eliminate distractions. Kill your television and video games. Turn off your mobile phone, or just leave it at home. Study in places where you can concentrate, like the Library.
- Use your "in between" time productively. Don't leave campus for lunch. Arrive to school early. If you finish your assigned work early, begin working on the next assignment.

**Above all, cultivate persistence,** as this is necessary to master anything non-trivial. The keys to persistence are (1) having the desire to achieve that mastery, and (2) realizing challenges are normal and not an indication of something gone wrong. A common error is to equate *easy* with *effective*: students often believe learning should be easy if everything is done right. The truth is that mastery never comes easy!

file question0

## Checklist when reading an instructional text

*“Reading maketh a full man; conference a ready man; and writing an exact man”* – Francis Bacon

Francis Bacon’s advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner’s thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, write their own outline and reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

Briefly **OUTLINE THE TEXT**, as though you were writing a detailed Table of Contents. Feel free to rearrange the order if it makes more sense that way. Prepare to articulate these points in detail and to answer questions from your classmates and instructor. Outlining is a good self-test of thorough reading because you cannot outline what you have not read or do not comprehend.

Demonstrate **ACTIVE READING STRATEGIES**, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

Identify **IMPORTANT THEMES**, especially **GENERAL LAWS** and **PRINCIPLES**, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

Form **YOUR OWN QUESTIONS** based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

Devise **EXPERIMENTS** to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

Specifically identify any points you found **CONFUSING**. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.



## General challenges following a tutorial reading assignment

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

## General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

## Questions

### Question 1

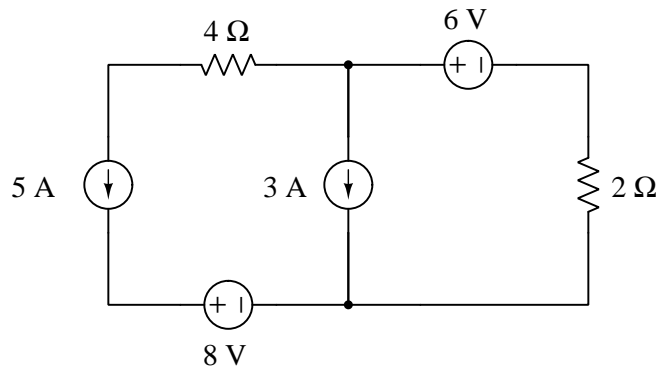
Electrical circuits are ubiquitous in industrial instrumentation, and so it is imperative that you master their analysis. Here we will practice the application of some fundamental laws of electric circuits, in order to strengthen these analytical abilities.

For each example circuit, solve for all voltage values, all current values, all voltage polarities and current directions (where applicable). Also, identify the function of each component as either a *source* or a *load*. Assume all components are ideal. In each step of your analysis, identify which of the following principles applies:

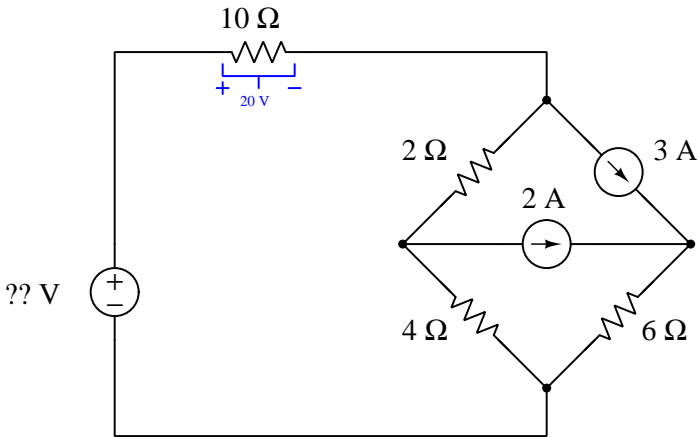
- Conservation of Energy
- Conservation of Electric Charge
- Properties of a series network
- Properties of a parallel network
- Kirchhoff's Voltage Law (KVL)
- Kirchhoff's Current Law (KCL)
- Ohm's Law
- Capacitance and Inductance

Survey all the examples shown below, and present your analysis for at least one of them.

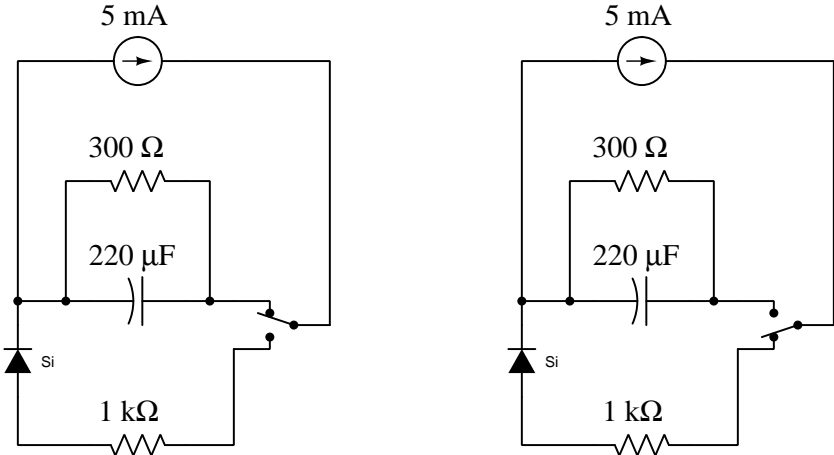
#### Circuit example #1:



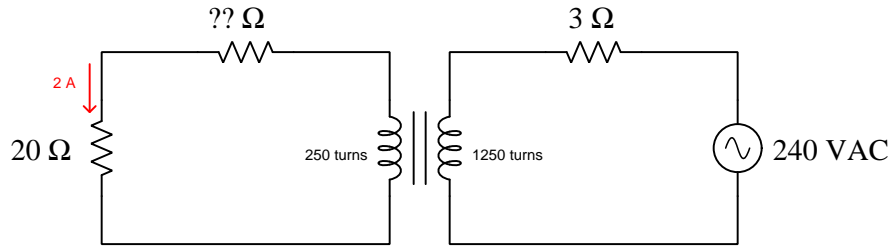
Circuit example #2:



Circuit example #3:



Circuit example #4:



**Suggestions for Socratic discussion**

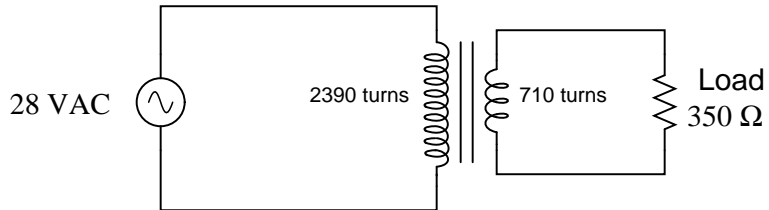
- Alter one or more of the given values in a circuit, then re-analyze that circuit. Do any of the components switch from source to load or vice-versa?
- Consider a case where one of the components shown in the schematic diagram happen to fail, either *open* or *shorted*, then identify how this failure will affect your re-analysis of the circuit.

[file i02832](#)

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Question 2

Calculate the load current and load voltage in this transformer circuit:



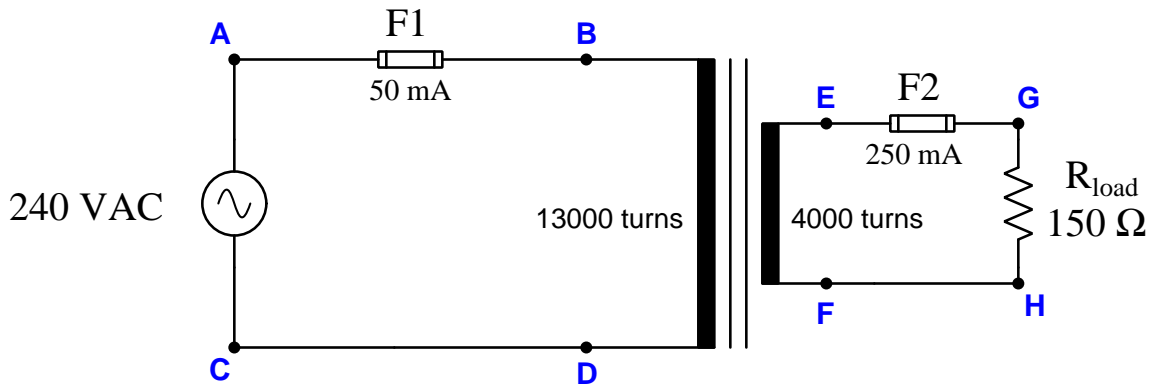
$I_{load} =$

$V_{load} =$

[file i03243](#)

Question 3

Suppose a voltmeter registers 0 volts between test points **E** and **F** in this step-down transformer circuit, as well as 238 volts between test points **B** and **D**:



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
Fuse F1 blown		
Fuse F2 blown		
Primary windings failed open		
Secondary winding failed open		
$R_{load}$ failed shorted		
$R_{load}$ failed open		
Wire between F and H failed open		

Finally, identify the *next* diagnostic test or measurement you would make on this system. Explain how the result(s) of this next test or measurement help further identify the location and/or nature of the fault.  
[file i02719](#)

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#### Question 4

Read and outline the [Simplified Tutorial](#) of the *Phasor Mathematics* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
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- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02836](#)

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#### Question 5

Read and outline the [Simplified Tutorial](#) of the *Resistance, Reactance, and Impedance* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

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- (3) General principles, especially physical laws, referenced in the text.
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- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02837](#)

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## Question 6

Complex number arithmetic makes possible the analysis of AC circuits using (almost) the exact same Laws that were learned for DC circuit analysis. The only bad part about this is that doing complex-number arithmetic by hand can be very tedious. Some calculators, though, are able to add, subtract, multiply, divide, and invert complex quantities as easy as they do scalar quantities, making this method of AC circuit analysis relatively easy.

This question is really a series of practice problems in complex number arithmetic, the purpose being to give you lots of practice using the complex number facilities of your calculator (or to give you a *lot* of practice doing trigonometry calculations, if your calculator does not have the ability to manipulate complex numbers!).

### Addition and subtraction:

$$\begin{aligned}(5 + j6) + (2 - j1) &= & (10 - j8) + (4 - j3) &= & (-3 + j0) + (9 - j12) &= \\(3 + j5) - (0 - j9) &= & (25 - j84) - (4 - j3) &= & (-1500 + j40) + (299 - j128) &= \\(25\angle 15^\circ) + (10\angle 74^\circ) &= & (1000\angle 43^\circ) + (1200\angle -20^\circ) &= & (522\angle 71^\circ) - (85\angle 30^\circ) &= \end{aligned}$$

### Multiplication and division:

$$\begin{aligned}(25\angle 15^\circ) \times (12\angle 10^\circ) &= & (1\angle 25^\circ) \times (500\angle -30^\circ) &= & (522\angle 71^\circ) \times (33\angle 9^\circ) &= \\ \frac{10\angle -80^\circ}{1\angle 0^\circ} &= & \frac{25\angle 120^\circ}{3.5\angle -55^\circ} &= & \frac{-66\angle 67^\circ}{8\angle -42^\circ} &= \\(3 + j5) \times (2 - j1) &= & (10 - j8) \times (4 - j3) &= & \frac{(3+j4)}{(12-j2)} &= \end{aligned}$$

### Reciprocation:

$$\begin{aligned}\frac{1}{(15\angle 60^\circ)} &= & \frac{1}{(750\angle -38^\circ)} &= & \frac{1}{(10+j3)} &= \\ \frac{1}{\frac{1}{15\angle 45^\circ} + \frac{1}{92\angle -25^\circ}} &= & \frac{1}{\frac{1}{1200\angle 73^\circ} + \frac{1}{574\angle 21^\circ}} &= & \frac{1}{\frac{1}{23k\angle -67^\circ} + \frac{1}{10k\angle -81^\circ}} &= \\ \frac{1}{\frac{1}{110\angle -34^\circ} + \frac{1}{80\angle 19^\circ} + \frac{1}{70\angle 10}} &= & \frac{1}{\frac{1}{89k\angle -5^\circ} + \frac{1}{15k\angle 33^\circ} + \frac{1}{9.35k\angle 45}} &= & \frac{1}{\frac{1}{512\angle 34^\circ} + \frac{1}{1k\angle -25^\circ} + \frac{1}{942\angle -20} + \frac{1}{2.2k\angle 44^\circ}} &= \end{aligned}$$

Full answers are given in the Answers section later in this document, as well as a discussion of how to perform these calculations easily using a Texas Instruments TI-84 calculator.

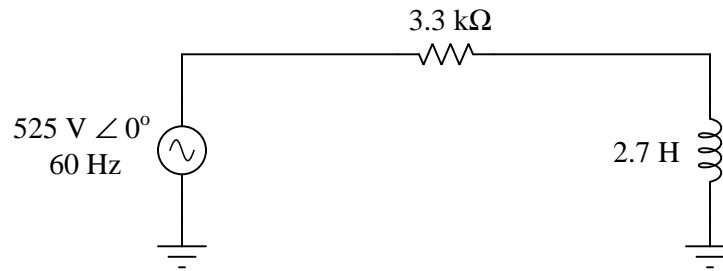
### Suggestions for Socratic discussion

- Your calculator's manual will be an excellent reference for learning how to enter and interpret complex numbers. Show where in the manual you were able to find instructions on entering complex numbers, displaying them in different forms (e.g. polar vs. rectangular), and performing basic arithmetic operations on complex numbers.

[file i00846](#)

Question 7

Complete the following table of values for this circuit, expressing each quantity in both rectangular and polar forms:



---	$R$	$L$	Total
$V$ (polar)			525 V ∠ 0°
$V$ (rect.)			525 + j0 V
$I$ (polar)			
$I$ (rect.)			
$Z$ (polar)			
$Z$ (rect.)			

**Suggestions for Socratic discussion**

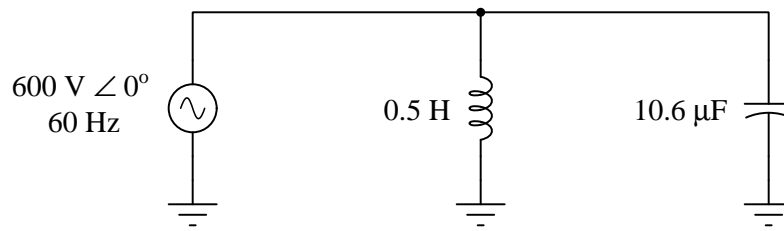
- Predict the effects on all voltages and currents in this circuit if the inductor fails open.
- Predict the effects on all voltages and currents in this circuit if the inductor fails shorted.
- Predict the effects on all voltages and currents in this circuit if the resistor fails open.
- Predict the effects on all voltages and currents in this circuit if the resistor fails shorted.
- Predict the effects on all voltages and currents in this circuit if the resistor gets replaced by a capacitor with the same impedance magnitude.
- Predict the effects on all voltages and currents in this circuit if the inductor gets replaced by a capacitor with the same impedance magnitude.

[file i03048](#)



Question 8

Complete the following table of values for this circuit, expressing each quantity in both rectangular and polar forms:



--	<i>L</i>	<i>C</i>	Total
<i>V</i> (polar)			600 V $\angle 0^\circ$
<i>V</i> (rect.)			600 + j0 V
<i>I</i> (polar)			
<i>I</i> (rect.)			
<i>Z</i> (polar)			
<i>Z</i> (rect.)			

**Suggestions for Socratic discussion**

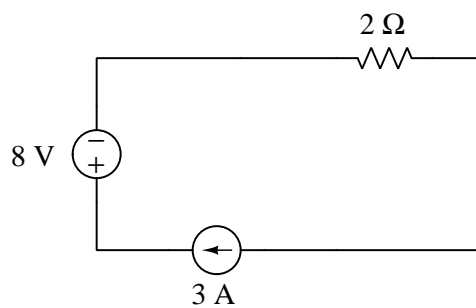
- Predict the effects on all voltages and currents in this circuit if the inductor fails open.
- Predict the effects on all voltages and currents in this circuit if the inductor fails shorted.
- Predict the effects on all voltages and currents in this circuit if the capacitor fails open.
- Predict the effects on all voltages and currents in this circuit if the capacitor fails shorted.
- Predict the effects on all voltages and currents in this circuit if the capacitor gets replaced by a resistor with the same impedance magnitude.
- Predict the effects on all voltages and currents in this circuit if the inductor gets replaced by a resistor with the same impedance magnitude.

[file i03044](#)

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Question 9

Calculate all voltages and currents in this series-parallel DC circuit, annotating all voltages with + and – symbols and all currents with arrows pointing in the direction of conventional flow. Also, determine whether each component is functioning as an electrical *source* or an electrical *load*:



In each step of your analysis, identify which of the following principles applies:

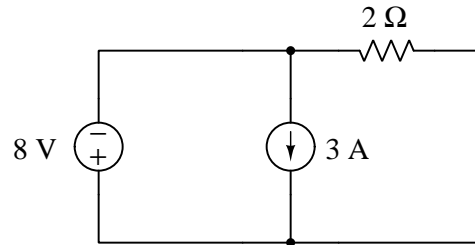
- Conservation of Energy
- Conservation of Electric Charge
- Properties of a series network
- Properties of a parallel network
- Kirchhoff's Voltage Law (KVL)
- Kirchhoff's Current Law (KCL)
- Ohm's Law

[file i02851](#)

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Question 10

Calculate all voltages and currents in this series-parallel DC circuit, annotating all voltages with + and – symbols and all currents with arrows pointing in the direction of conventional flow. Also, determine whether each component is functioning as an electrical *source* or an electrical *load*:



In each step of your analysis, identify which of the following principles applies:

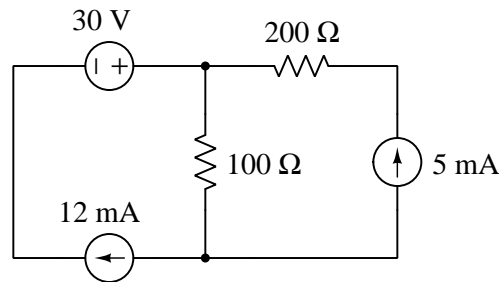
- Conservation of Energy
- Conservation of Electric Charge
- Properties of a series network
- Properties of a parallel network
- Kirchhoff's Voltage Law (KVL)
- Kirchhoff's Current Law (KCL)
- Ohm's Law

[file i02868](#)

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Question 11

Calculate all voltages and currents in this series-parallel DC circuit, annotating all voltages with + and – symbols and all currents with arrows pointing in the direction of conventional flow. Also, determine whether each component is functioning as an electrical *source* or an electrical *load*:



In each step of your analysis, identify which of the following principles applies:

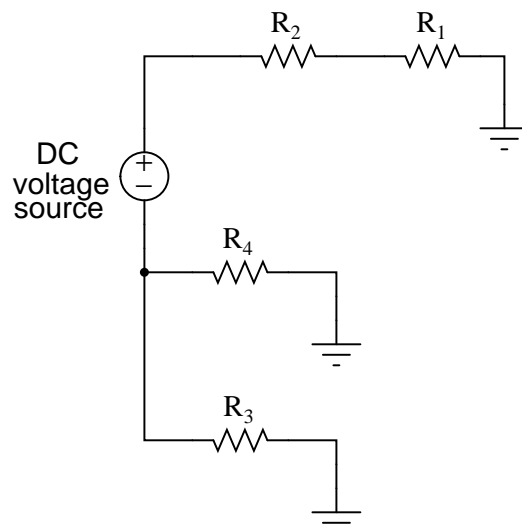
- Conservation of Energy
- Conservation of Electric Charge
- Properties of a series network
- Properties of a parallel network
- Kirchhoff's Voltage Law (KVL)
- Kirchhoff's Current Law (KCL)
- Ohm's Law

[file i02867](#)

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Question 12

Determine what will happen to all voltage drops in this circuit if the resistance of resistor  $R_4$  happens to decrease:



- $V_{R1}$  = (increase, decrease, or stay the same)
- $V_{R2}$  = (increase, decrease, or stay the same)
- $V_{R3}$  = (increase, decrease, or stay the same)
- $V_{R4}$  = (increase, decrease, or stay the same)

**Suggestions for Socratic discussion**

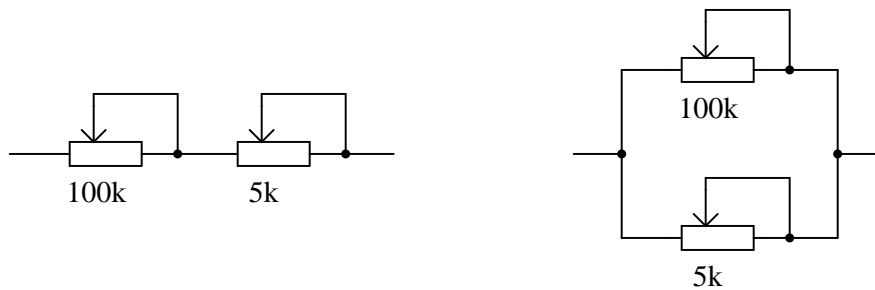
- Explain how the problem-solving strategy of *limiting cases* applies to this particular problem.

[file i02911](#)

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Question 13

Examine these two variable-resistance (*rheostat*) networks, each one with a large-range potentiometer and a small-range potentiometer:



For each network, determine which pot is the *coarse* adjustment and which pot is the *fine* adjustment for total network resistance, and explain your reasoning.

**Suggestions for Socratic discussion**

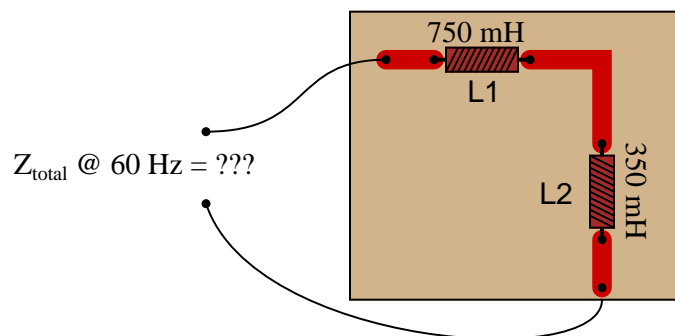
- A good problem-solving technique is to perform a “thought experiment” on the given system. Here, determine the effect on total network resistance while each potentiometer (one at a time) is adjusted through its entire range while the other potentiometer is left in its mid-position.

[file i03144](#)

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Question 14

Calculate the total impedance offered by these two inductors to a sinusoidal signal with a frequency of 60 Hz:



Show your work using two different problem-solving strategies:

- Calculating total inductance ( $L_{total}$ ) first, then total impedance ( $Z_{total}$ ).
- Calculating individual impedances first ( $Z_{L1}$  and  $Z_{L2}$ ), then total impedance ( $Z_{total}$ ).

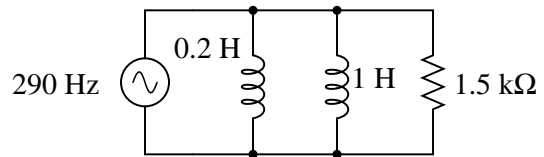
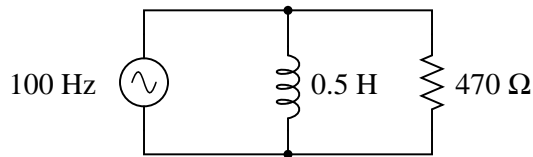
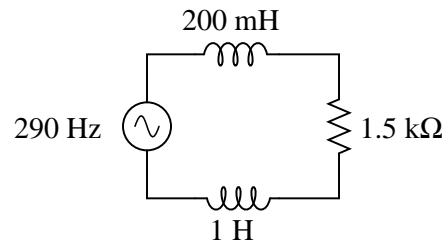
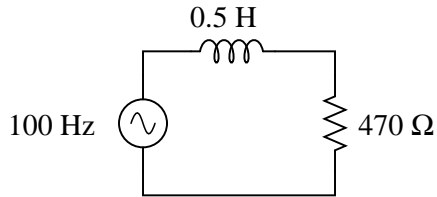
Do these two strategies yield the same total impedance value? Why or why not?

[file i01031](#)

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Question 15

Calculate the total impedances (complete with phase angles) for each of the following inductor-resistor circuits:

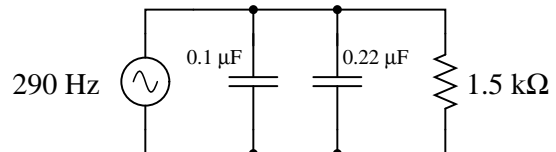
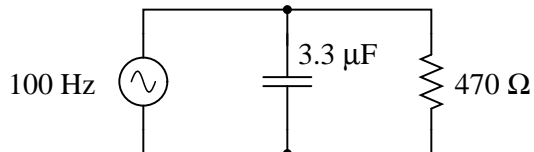
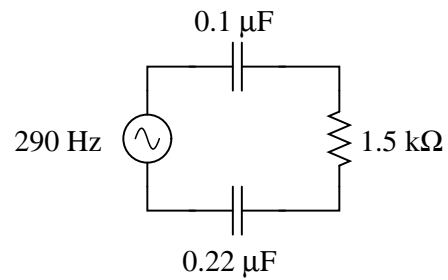
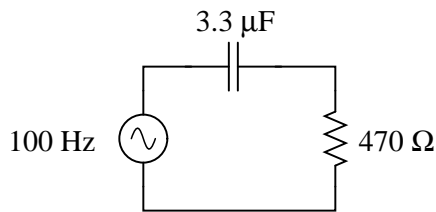


[file i01060](#)

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Question 16

Calculate the total impedances (complete with phase angles) for each of the following capacitor-resistor circuits:

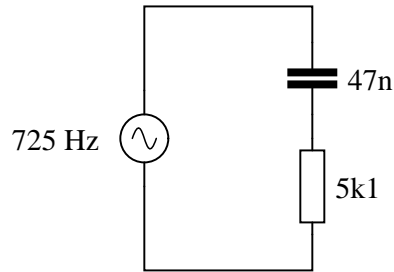


[file i01072](#)

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Question 17

Which component, the resistor or the capacitor, will drop more voltage in this circuit?



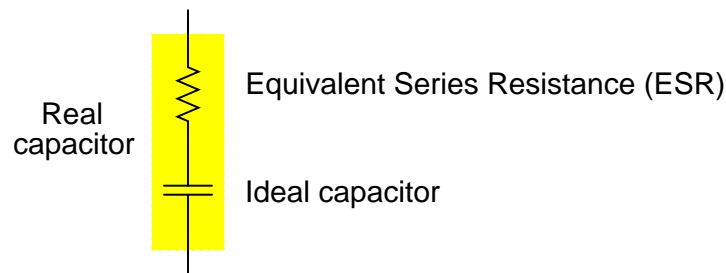
Also, calculate the total impedance ( $Z_{total}$ ) of this circuit, expressing it in both rectangular and polar forms.

[file i01039](#)

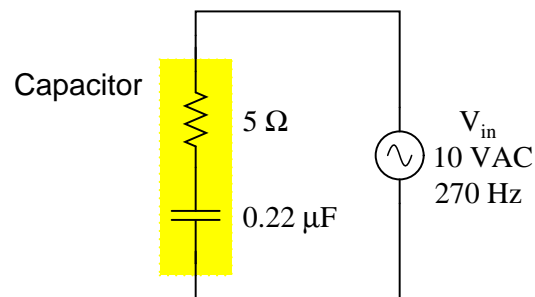
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Question 18

Due to the effects of a changing electric field on the dielectric of a capacitor, some energy is dissipated in capacitors subjected to AC. Generally, this is not very much, but it is there. This dissipative behavior is typically modeled as a series-connected resistance:



Calculate the magnitude and phase shift of the current through this capacitor, taking into consideration its equivalent series resistance (ESR):



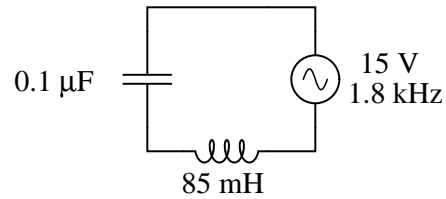
Compare this against the magnitude and phase shift of the current for an ideal 0.22 μF capacitor.

[file i01050](#)

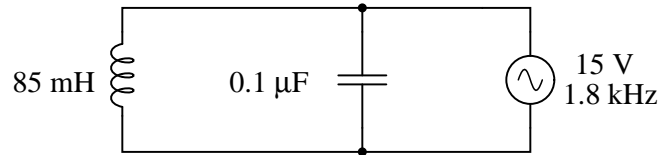
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Question 19

Is this circuit's overall behavior capacitive or inductive? In other words, from the perspective of the AC voltage source, does it "appear" as though a capacitor is being powered, or an inductor?



Now, suppose we take these same components and re-connect them in parallel rather than series. Does this change the circuit's overall "appearance" to the source? Does the source now "see" an equivalent capacitor or an equivalent inductor? Explain your answer.



**Suggestions for Socratic discussion**

- Which component "dominates" the behavior of a series LC circuit, the one with the least reactance or the one with the greatest reactance?
- Which component "dominates" the behavior of a parallel LC circuit, the one with the least reactance or the one with the greatest reactance?

[file i01076](#)

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Question 20



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### Question 21

Read and outline the [Simplified Tutorial](#) of the *Electrical Power Grids* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

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- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02833](#)

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### Question 22

Read and outline the [Simplified Tutorial](#) of the *Circuit Breakers and Disconnects* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

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- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02834](#)

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### Question 23

Read and outline the [Simplified Tutorial](#) of the *Principles of Protective Relaying* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the MODEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

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- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02835](#)

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### Question 24

Read selected portions of the sales brochure for the Siemens model 3AP1 DTC high-voltage circuit breaker and answer the following questions:

This particular model of circuit breaker is a “dead tank” design. Explain what this phrase means.

This particular model of circuit breaker not only has current-interrupting contacts, but also disconnect and “earthing” switch contacts as well. Identify where each of these contacts is located in the assembly and explain their functions.

[file i03036](#)

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Question 25

Read selected portions of the sales brochure for the Siemens model 3AP1/2 live-tank high-voltage circuit breakers and answer the following questions:

Explain what the phrase “live tank” means with regard to a circuit breaker, referencing illustrations or photographs in the document to aid in your explanation.

Identify at least two different styles of high-voltage circuit breakers described in this document, showing where power goes in and out of the breaker units.

Explain how the spring mechanism works to store mechanical energy to trip and close the circuit breaker contacts. Note that the diagram shows different colored arrows to designate the “opening” and “closing” directions.

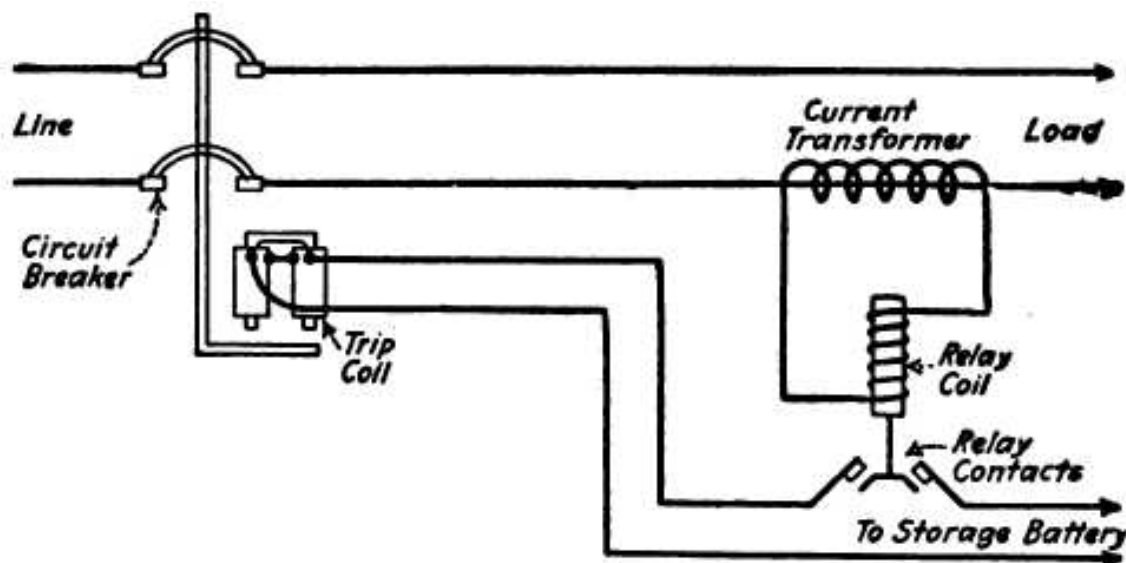
Compare the following current ratings of a 550 kV model 3AP2 circuit breaker, and explain why each one is different:

- Rated normal current = \_\_\_\_\_
- Rated peak withstand current = \_\_\_\_\_
- Rated short-circuit breaking current = \_\_\_\_\_
- Rated short-circuit making current = \_\_\_\_\_

file i03038

## Question 26

Examine this schematic diagram sampled from Victor H. Todd's 1922 book *Protective Relays* showing a very simple protection circuit comprised of a two-pole power circuit breaker with an externally energized "trip coil", a current transformer, a DC storage battery, and a "plunger-style" protective relay:



First, identify the purpose of this protective system. What abnormal condition is it designed to sense, and how does it protect the system against damage from this abnormal condition?

Suppose this relay has been calibrated to "pick up" at a current transformer output of 3.2 amps AC. If the current transformer's ratio is 800:5, how many amps of line current does this represent?

Finally, identify how the "pickup" value (i.e. the trip threshold) for this protective relay might be adjusted by a technician.

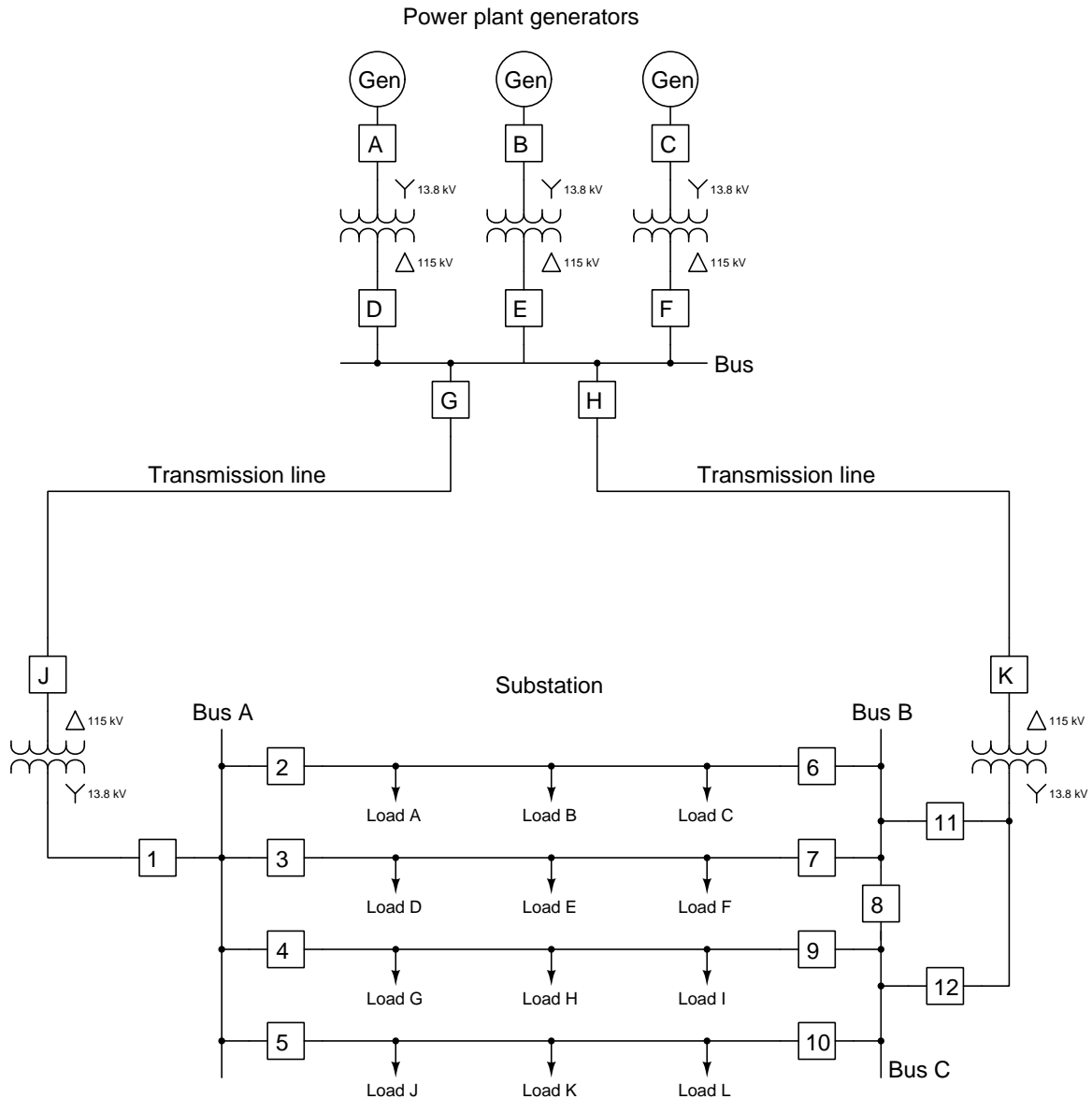
### Suggestions for Socratic discussion

- Which ANSI number code best corresponds to this particular protective relay function? How can you tell?
- Suppose the storage battery became discharged so that it measured only about 90 volts rather than 120 volts. How would this affect the operation of this protective system, if at all?
- Suppose the current transformer failed with an internally shorted winding, so that its effective turns ratio became closer to being 1:1 than it is now. How would this affect the operation of this protective system, if at all?
- Two important concepts are used in the electric power industry to express the reliability of the system: *dependability* and *security*. Dependability is the likelihood that a protective device or system will shut off power as designed in the event of a fault. Security is the likelihood that a protective device will allow power to remain on when there is no fault (i.e. the likelihood it will not needlessly trip). Identify a specific fault in this protective system that could compromise its dependability, and another specific fault that could compromise its security.

[file i02862](#)

Question 27

Examine this single-line diagram of a power system and answer the following questions:



Suppose Load F fails in such a way that it draws far more current than it should. Identify which circuit breaker(s) must trip in order to interrupt the fault current while maintaining power to as many other loads as possible.

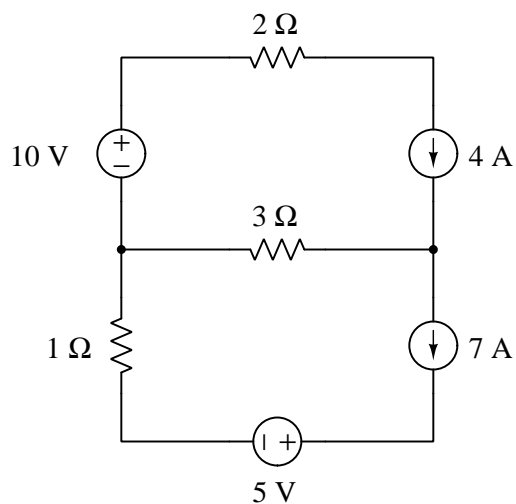
Suppose circuit breaker #5 fails to trip when commanded. Identify which other circuit breaker(s) must trip in order to de-energize breaker #5 while maintaining power to as many loads as possible.

Suppose one of the high-voltage insulators on Bus C fails, causing a high amount of current to flow into that bus. Identify which circuit breakers must trip in order to de-energize that bus while maintaining power to as many loads as possible.

[file i02864](#)

Question 28

Calculate all voltages and currents in this series-parallel DC circuit, annotating all voltages with + and - symbols and all currents with arrows pointing in the direction of conventional flow. Also, determine whether each component is functioning as an electrical *source* or an electrical *load*:



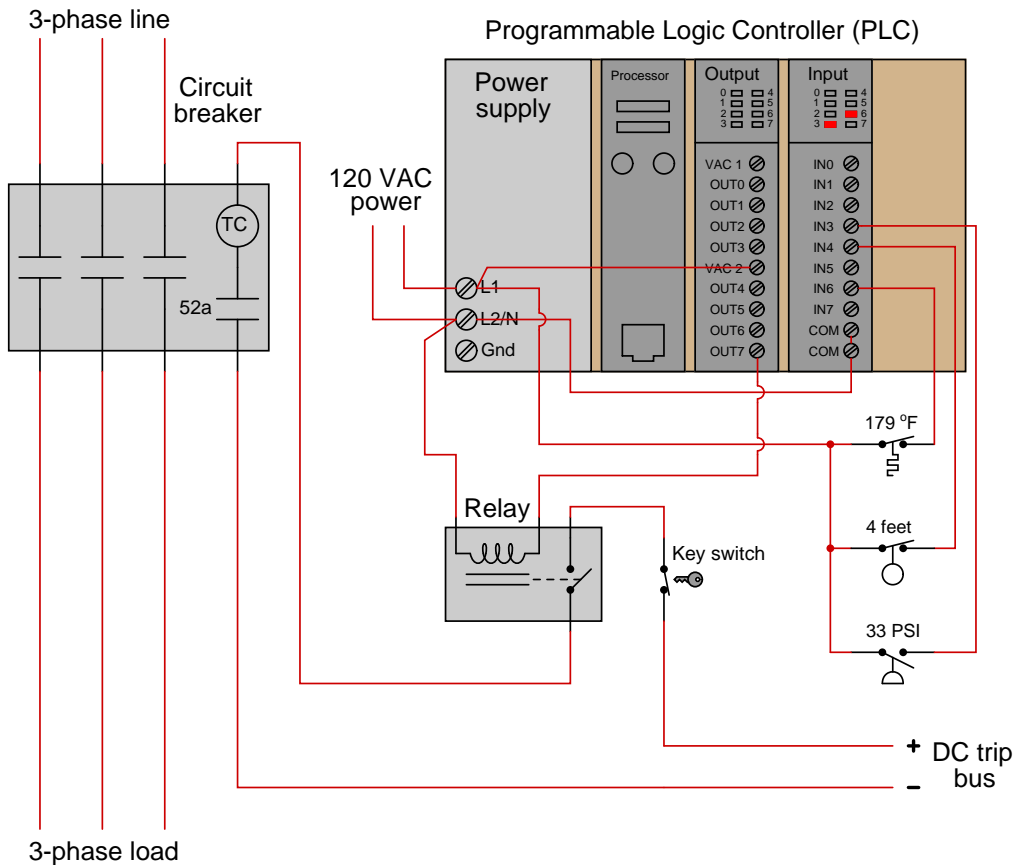
In each step of your analysis, identify which of the following principles applies:

- Conservation of Energy
- Conservation of Electric Charge
- Properties of a series network
- Properties of a parallel network
- Kirchhoff's Voltage Law (KVL)
- Kirchhoff's Current Law (KCL)
- Ohm's Law

[file i02869](#)

## Question 29

A *programmable logic controller* (PLC) may be used to command a high-voltage circuit breaker to trip in the event of dangerous process conditions, such as the system shown here:



Assume this process system is operating as it should (i.e. no abnormal conditions). Based on the status LED indicators you see on the input card of the PLC, determine whether each of the process switches is designed to trip on a *low* condition or a *high* condition. Then, determine what you would have to do to the circuit to simulate a shutdown condition for each of the process switches (i.e. make the PLC “think” it sees an abnormal condition, so that it will act to trip the breaker):

- Temperature switch: trips on *low* temperature or *high* temperature? How to simulate trip condition?
- Level switch: trips on *low* liquid level or *high* liquid level? How to simulate trip condition?
- Pressure switch: trips on *low* fluid pressure or *high* fluid pressure? How to simulate trip condition?

### Suggestions for Socratic discussion

- Explain why the LED status indicators are so helpful for system troubleshooting in a PLC-controlled system.
- Identify the purpose of the key switch in this circuit.
- Suppose you were asked to install a manual pushbutton “Emergency Trip” switch to trip the circuit breaker. Where would you connect such a switch in this circuit?

[file i02113](#)

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Question 30

Examine the single-line electrical diagram example contained in “Informative Annex D – Incident Energy and Arc Flash Boundary Calculation Methods” of the NFPA 70E document “Standard for Electrical Safety in the Workplace” and answer the following questions:

Identify how each of the following devices are represented in this diagram:

- Transformers
- Disconnects
- Circuit breakers
- Fuses

Several “tie breakers” are shown in this diagram, connecting bus segments together to form a larger bus. Identify where these tie breakers are in the diagram, and explain their purpose in the power distribution system.

Each transformer shown in this diagram bears a percentage rating. What, exactly, does this percentage rating refer to?

Suppose the 5 MVA transformer feeding bus 2B suffers a catastrophic internal short-circuit. Identify the points at which power will be automatically disconnected from this failed transformer, either by fuses or by circuit breakers tripped by protective relays. Is it possible to restore power to bus 2B while this transformer is still out of service? If so, explain how this could be accomplished.

Suppose the 2.5 MVA transformer feeding bus 7A suffers a catastrophic internal short-circuit. Identify the points at which power will be automatically disconnected from this failed transformer, either by fuses or by circuit breakers tripped by protective relays. Is it possible to restore power to bus 7A while this transformer is still out of service? If so, explain how this could be accomplished.

**Suggestions for Socratic discussion**

- Should tie breakers and tie switches typically be left in their open or closed states? Explain your reasoning.
- Calculate the maximum bolted-fault current for a three-phase transformer rated at 480 volt output and 1.5 MVA, with 6% impedance.
- Note the tie breaker arrangement between busses 1A and 1B: there is a direct tie breaker in parallel with an inductor having its own pair of breakers. When initially connecting these two busses together, the protocol is to close the direct tie breaker *last*, relying on the other two breakers and the associated inductor to make the first connection between the busses. Explain why this is so.

[file i03034](#)

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Question 31

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Question 32

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Question 33

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Question 34

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Question 35



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Question 36

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Question 37

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Question 38

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Question 39

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Question 40

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Question 41

Explain what *AC reactance* is, and how it differs from *resistance* despite being measured in the same units (ohms). Then, calculate reactance values for the following components:

- 45 millihenry inductor at 400 Hz = \_\_\_\_\_  $\Omega$
- 12 microfarad capacitor at 50 Hz = \_\_\_\_\_  $\Omega$
- Brown-Red-Orange resistor at 1000 Hz = \_\_\_\_\_  $\Omega$
- 1.5 henry inductor at 440 Hz = \_\_\_\_\_  $\Omega$

After you have done this, express each components impedance ( $Z$ ) in *phasor* (complex number) form.

**Suggestions for Socratic discussion**

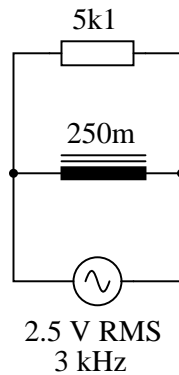
- One way to think of electrical resistance and electrical impedance in analogous terms is to liken them to mechanical *friction* and mechanical *inertia*, respectively. Explain this association in terms of energy transfer.
- Explain why the impedance of a real component differs from the impedance of an *ideal* component, especially inductors.
- Will a series-connected inductor serve as a *low-pass* filter or a *high-pass* filter? Explain your answer.
- Explain how to build a *low-pass* filter circuit using a capacitor and a resistor.

[file i03066](#)

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Question 42

Calculate the individual currents through the inductor and through the resistor, the total current, and the total circuit impedance:



[file i01054](#)

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Question 43

Read and outline the [Simplified Tutorial](#) of the *Phasors and AC Circuit Measurements* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02838](#)

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### Question 44

Read and outline the [Simplified Tutorial](#) of the *Phasor Diagrams* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

After closely reading and outlining a text, you should be ready to share the following with your classmates and instructor:

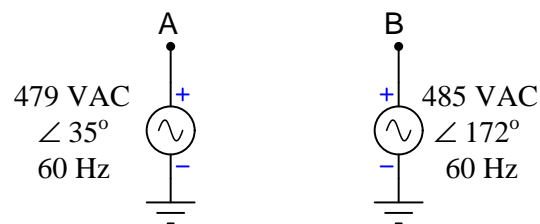
- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying long sentences, working through mathematical examples, cross-referencing text with illustrations or other text, identifying the author’s problem-solving strategies, etc.).
- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02839](#)

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### Question 45

Calculate the amount of voltage between points A and B ( $V_{AB}$ ) given the generator values shown:



State your answer both in symbolic form (e.g. ??? volts  $\angle$  ?? degrees) as well as in a phasor diagram showing the given generator voltages along with  $V_{AB}$ .

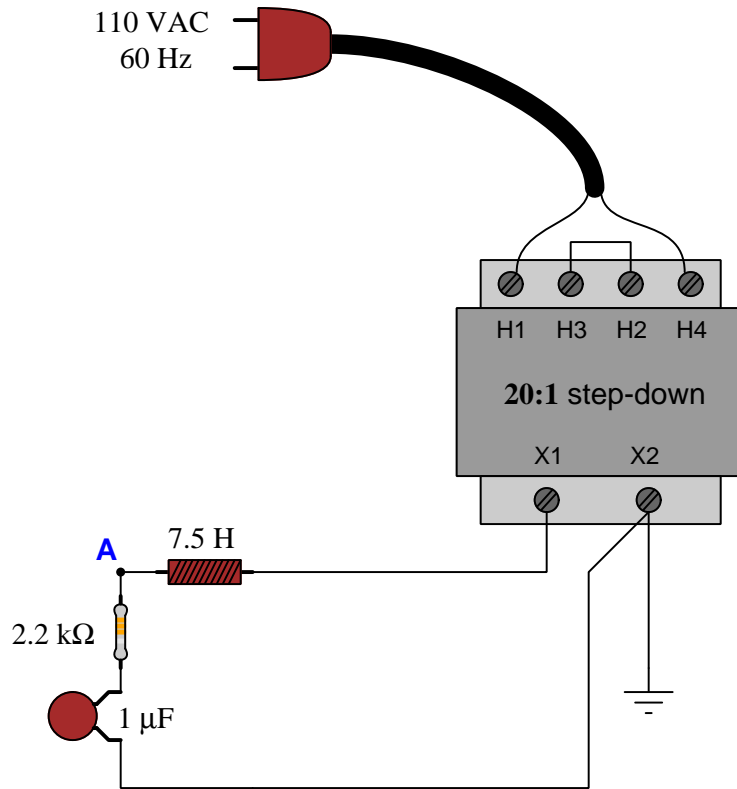
#### Suggestions for Socratic discussion

- A very effective problem-solving strategy when you are unsure of where to begin is to *simplify the problem at hand* and solve that simplified version of the problem. For example, calculate  $V_{AB}$  if the two generators’ voltages were absolutely identical, in both magnitude and phase.
- A very effective problem-solving strategy when you are unsure of where to begin is to *simplify the problem at hand* and solve that simplified version of the problem. For example, calculate  $V_{AB}$  if generator B were turned off (i.e. outputting zero volts).
- A very effective problem-solving strategy when you are unsure of where to begin is to *simplify the problem at hand* and solve that simplified version of the problem. For example, calculate  $V_{AB}$  if generator A were turned off (i.e. outputting zero volts).
- Would it be safe to connect points A and B together with the generator voltages as shown? Explain why or why not.
- Is the calculated voltage for  $V_{AB}$  equivalent to the voltage for  $V_{BA}$ ? Why or why not?

[file i03040](#)

Question 46

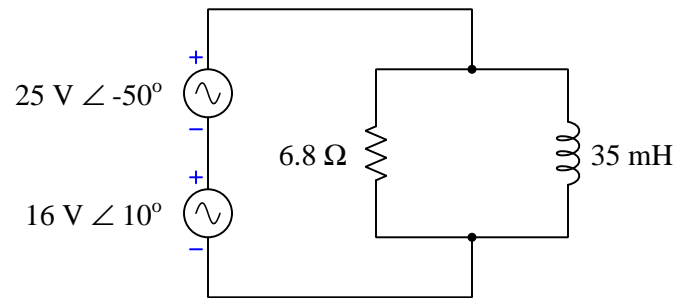
Calculate the amount of voltage between point A and ground ( $V_A$ ) given the component values shown:



State your answer both in symbolic form (e.g. ??? volts  $\angle$  ?? degrees) as well as in a phasor diagram showing the source voltage (its phase angle assumed to be zero degrees) and  $V_A$ .  
[file i03049](#)

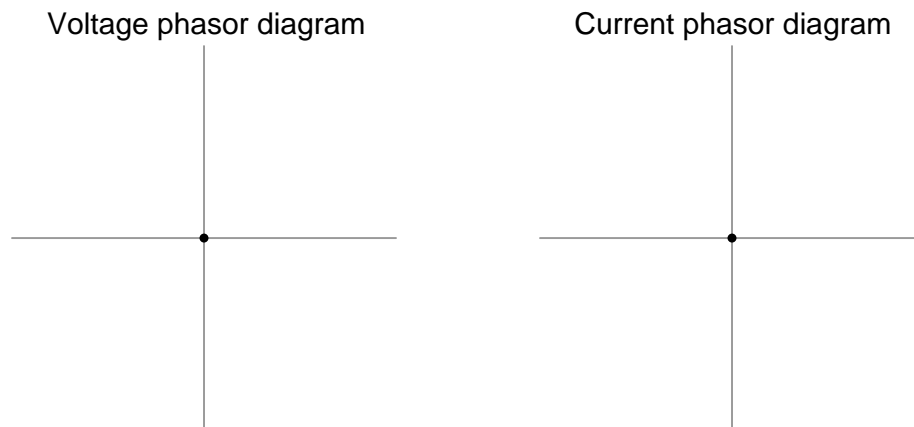
Question 47

Calculate all voltages and currents in this series-parallel AC circuit, representing each of these quantities in phasor (complex-number) form, assuming both sources have a frequency of 60 Hz:



Annotate all voltage polarities and current directions in the schematic diagram. *Hint: approach this task as if the circuit were DC rather than AC.*

Also, sketch a phasor diagram showing all voltages summing to zero around the circuit (Kirchhoff's Voltage Law) and a phasor diagram showing all currents summing to zero at a node (Kirchhoff's Current Law).

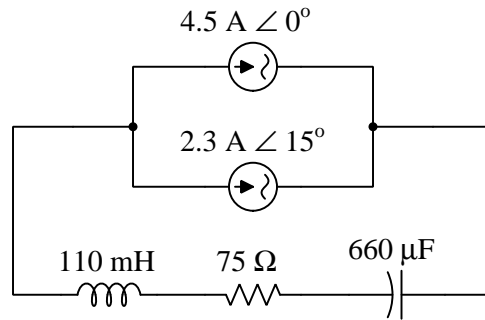


[file i03367](#)

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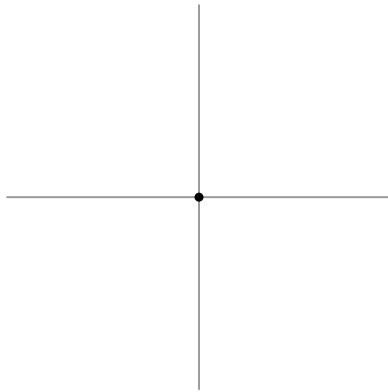
Question 48

Compute all voltages and currents in this circuit, assuming sources operating at a frequency of 60 Hz:

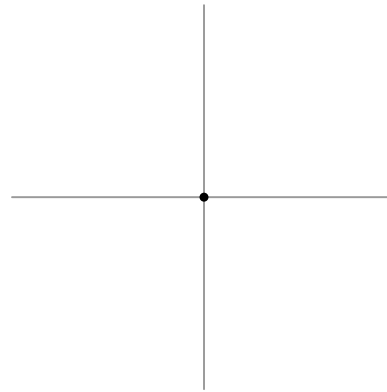


Also, sketch a phasor diagram showing all voltages summing to zero around the circuit (Kirchhoff's Voltage Law) and a phasor diagram showing all currents summing to zero at a node (Kirchhoff's Current Law).

Voltage phasor diagram



Current phasor diagram

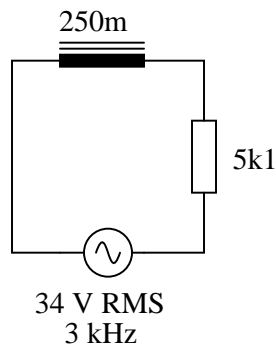


[file i04302](#)

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Question 49

Calculate all voltages and currents in this circuit, as well as the total impedance:

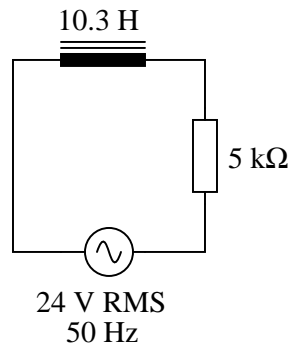


[file i01033](#)

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Question 50

Solve for all voltages and currents in this series LR circuit, and also calculate the phase angle of the total impedance:

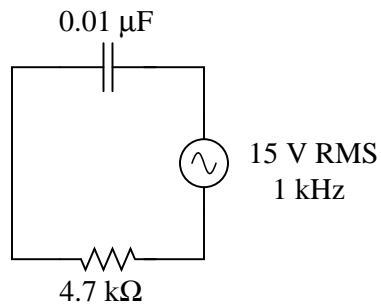


[file i01051](#)

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Question 51

Solve for all voltages and currents in this series RC circuit:

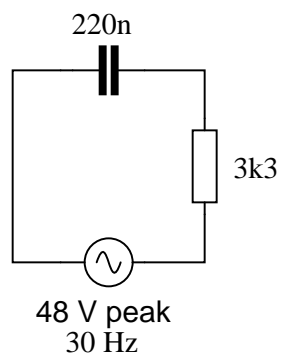


[file i01052](#)

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Question 52

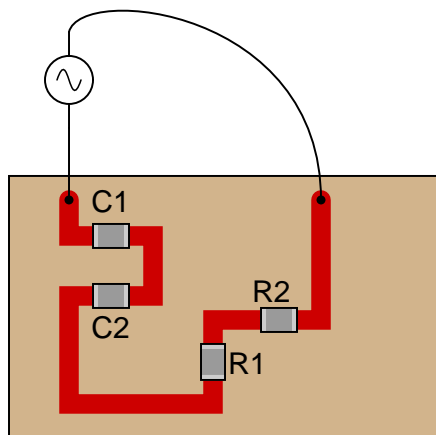
Solve for all voltages and currents in this series RC circuit, and also calculate the phase angle of the total impedance:



[file i01053](#)

Question 53

Determine the total current and all voltage drops in this circuit, stating your answers the way a multimeter would register them:



- $C_1 = 125 \text{ pF}$
- $C_2 = 71 \text{ pF}$
- $R_1 = 6.8 \text{ k}\Omega$
- $R_2 = 1.2 \text{ k}\Omega$
- $V_{supply} = 20 \text{ V RMS}$
- $f_{supply} = 950 \text{ kHz}$

Also, calculate the phase angle ( $\theta$ ) between voltage and current in this circuit, and explain where and how you would connect an oscilloscope to measure that phase shift.

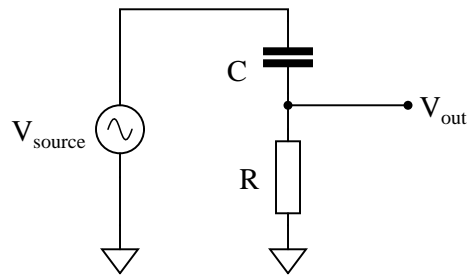
[file i01070](#)



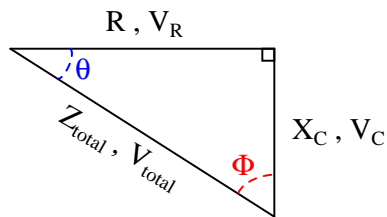
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Question 54

A student is asked to calculate the phase shift for the following circuit's output voltage, relative to the phase of the source voltage:



He recognizes this as a series circuit, and therefore realizes that a right triangle would be appropriate for representing component impedances and component voltage drops (because both impedance and voltage are quantities that add in series, and the triangle represents phasor addition):



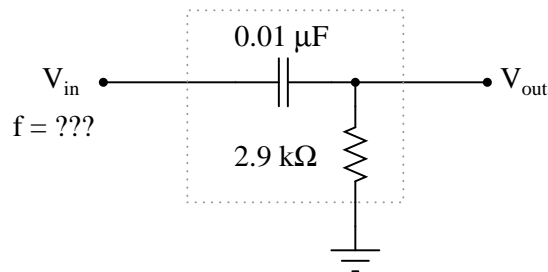
The problem now is, which angle does the student solve for in order to find the phase shift of  $V_{out}$ ? The triangle contains two angles besides the  $90^\circ$  angle,  $\theta$  and  $\Phi$ . Which one represents the output phase shift, and more importantly, *why*?

[file i01061](#)

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Question 55

Determine the input frequency necessary to give the output voltage a phase shift of  $40^\circ$ :



[file i01063](#)

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Question 56

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Question 57

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Question 58

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Question 59

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Question 60

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Question 61

Read and outline the [Tutorial](#) of the *Polyphase AC* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the ModEL Project home page at the following URL:

<http://www.ibiblio.org/kuphaldt/socratic/model>

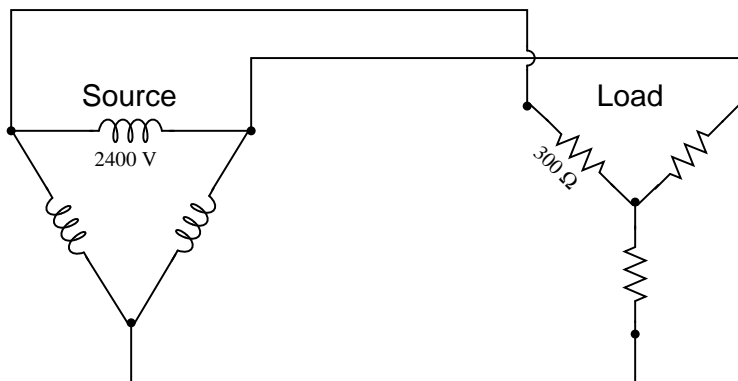
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- (3) General principles, especially physical laws, referenced in the text.
- (4) Questions of your own you would pose to another reader, to challenge their understanding.
- (5) Ideas for experiments that could be used to either demonstrate some concept applied in the text, or disprove a related misconception.
- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02834](#)

Question 62

Calculate all voltages, currents, and total power in this balanced Delta-Y system:



- $V_{line} =$
- $I_{line} =$
- $V_{phase(source)} =$
- $I_{phase(source)} =$
- $V_{phase(load)} =$
- $I_{phase(load)} =$
- $P_{total} =$

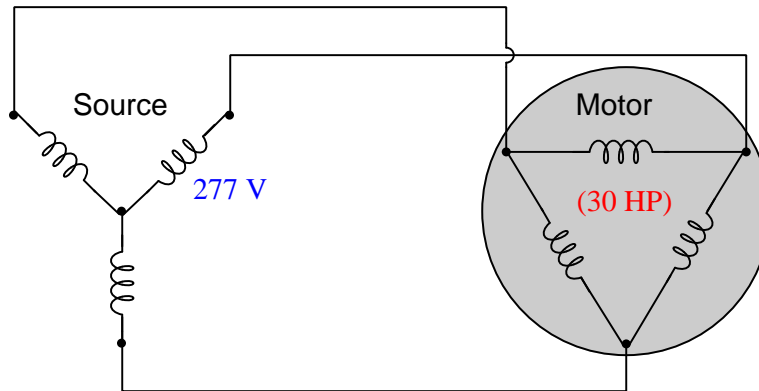
**Suggestions for Socratic discussion**

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) “why” for every step of your analysis, rather than merely describing those steps.
- Identify two currents in this circuit that are guaranteed to be equal in value, even if the source and load happened to be imbalanced.
- Identify two currents in this circuit that are unequal in value, and explain why one of them is larger than the other.
- Identify two voltages in this circuit that are guaranteed to be equal in value, even if the source and load happened to be imbalanced.
- Identify two voltages in this circuit that are unequal in value, and explain why one of them is larger than the other.
- Suppose the center of the wye-connected load were connected to earth ground. Determine the amount of voltage between each vertex of the delta-connected source and earth ground.
- Suppose one of the vertices of the delta-connected source were connected to earth ground. Determine the amount of voltage between each terminal of the wye-connected load and earth ground.
- Suppose one of the vertices of the delta-connected source were connected to earth ground. Determine the amount of voltage between the center point of the wye-connected load and earth ground.

[file i02270](#)

### Question 63

Calculate all voltages, currents, and total power in this balanced three-phase system where a Wye-connected source provides electrical power to a 30 horsepower Delta-connected motor. Assume the motor operates at full load (100% power) with perfect power factor and perfect efficiency:



- $V_{line} =$
- $I_{line} =$
- $V_{phase(source)} =$
- $I_{phase(source)} =$
- $V_{phase(load)} =$
- $I_{phase(load)} =$
- $P_{total} =$

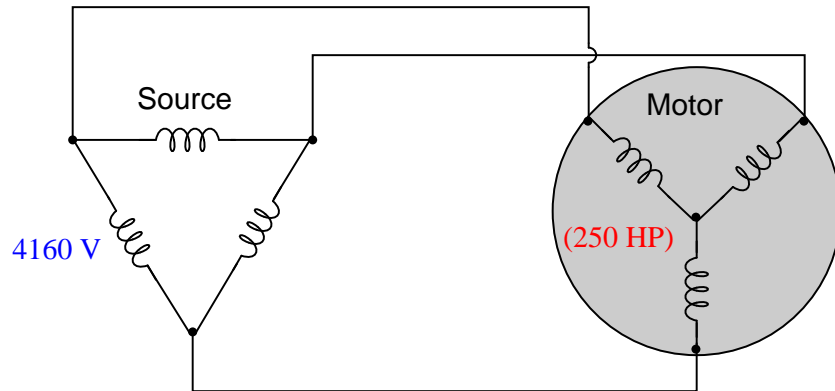
#### Suggestions for Socratic discussion

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) “why” for every step of your analysis, rather than merely describing those steps.
- Identify two currents in this circuit that are guaranteed to be equal in value, even if the source and load happened to be imbalanced.
- Identify two currents in this circuit that are unequal in value, and explain why one of them is larger than the other.
- Identify two voltages in this circuit that are guaranteed to be equal in value, even if the source and load happened to be imbalanced.
- Identify two voltages in this circuit that are unequal in value, and explain why one of them is larger than the other.
- How might the results differ if the motor were not 100% efficient?
- How might the results differ if the power factor were less than 1?

[file i02440](#)

### Question 64

Calculate all voltages, currents, and total power in this balanced three-phase system where a Delta-connected source provides electrical power to a 250 horsepower Y-connected motor. Assume the motor operates at full load (100% power) with perfect power factor and perfect efficiency:



- $V_{line} =$
- $I_{line} =$
- $V_{phase(source)} =$
- $I_{phase(source)} =$
- $V_{phase(load)} =$
- $I_{phase(load)} =$
- $P_{total} =$

#### Suggestions for Socratic discussion

- Identify which fundamental principles of electric circuits apply to each step of your analysis of this circuit. In other words, be prepared to explain the reason(s) “why” for every step of your analysis, rather than merely describing those steps.
- Identify two currents in this circuit that are guaranteed to be equal in value, even if the source and load happened to be imbalanced.
- Identify two currents in this circuit that are unequal in value, and explain why one of them is larger than the other.
- Identify two voltages in this circuit that are guaranteed to be equal in value, even if the source and load happened to be imbalanced.
- Identify two voltages in this circuit that are unequal in value, and explain why one of them is larger than the other.
- How might the results differ if the motor output the same amount of mechanical power, but at a lesser efficiency level (i.e.  $< 100\%$ )?
- How might the results differ if the power factor were less than 1?

[file i02448](#)

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Question 65

Read selected portions of the Delco-Remy “DELCOTRON GENERATORS (10-SI, 15-SI, AND 27-SI SERIES, 100 TYPE)” Service Bulletin (document 1G-266, December 1978) and answer the following questions:

Are these generator units three-phase or single-phase, internally? If three-phase, are their stator windings connected in a wye or a delta configuration?

Identify an image showing the *rotor* assembly of this machine, especially one showing the individual North and South magnetic poles on the rotor’s face.

The rotor in this machine contains an electromagnet coil, which the manual refers to as the *field coil* because energizing this coil creates a magnetic field on the rotor. Identify an image showing a cross-section of this coil within the rotor, and also identify how an electric current is conducted to this rotating coil from a stationary source.

Identify an image showing the *stator* assembly of this machine, especially one showing the individual winding poles on the stator’s inner circumference.

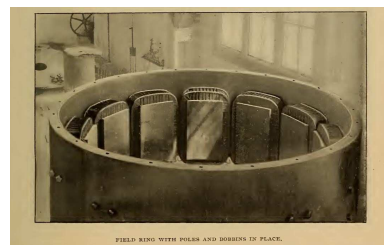
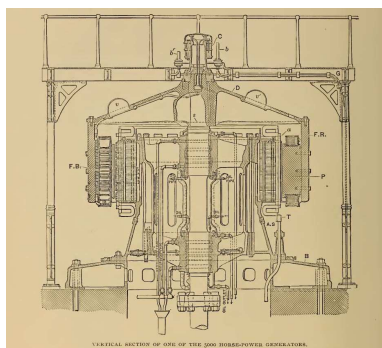
Figure 5 on page 2 of this manual shows an internal schematic diagram of the generator and its built-in voltage regulator circuitry. Examine this schematic, and then answer the following questions:

- How is AC power generated at the stator converted into DC power to charge the vehicle’s battery?
- What purpose is served by the *diode trio*?
- Which transistor directly controls current through the rotor’s field coil?
- Why does the indicator lamp de-energize once the generator comes up to speed and begins to output power?

[file i00453](#)

Question 66

The following photographs show a 5000 horsepower AC generator constructed for a hydroelectric power plant located at Niagara Falls in 1895. These came from an article in *Cassier's Magazine*, Volume 8, entitled "Electric Power Generation at Niagara" (written by Lewis, Buckley, and Stillwell) on the design and construction of what was then an engineering marvel:



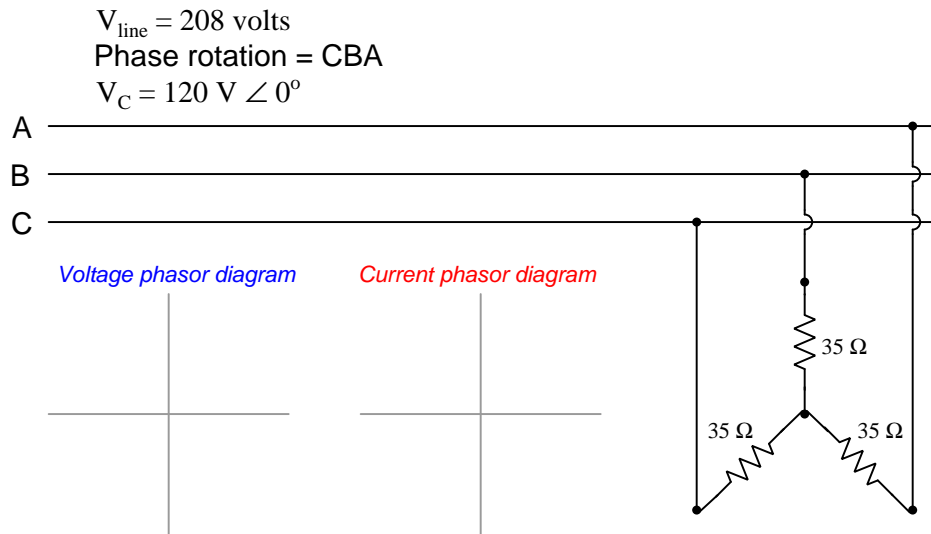
From these images, identify the generator's *rotor*, *stator*, and *slip ring* assemblies.

How is the output voltage of this generator unit controlled? How is the output frequency controlled?

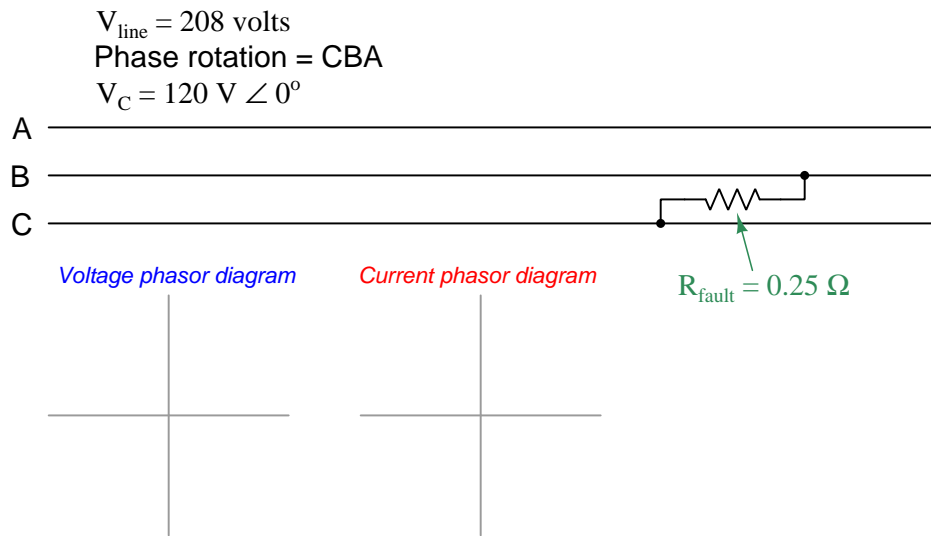
[file i01982](#)

Question 67

Sketch phasor diagrams for both phase voltage and phase current in this balanced 3-phase power system:



Now suppose the load is removed from this system and a low-resistance fault appears between phases B and C. Sketch phasor diagrams for both phase voltage and phase current, assuming the source generator is “stiff” (i.e. its voltage does not sag appreciably even under heavy loads):

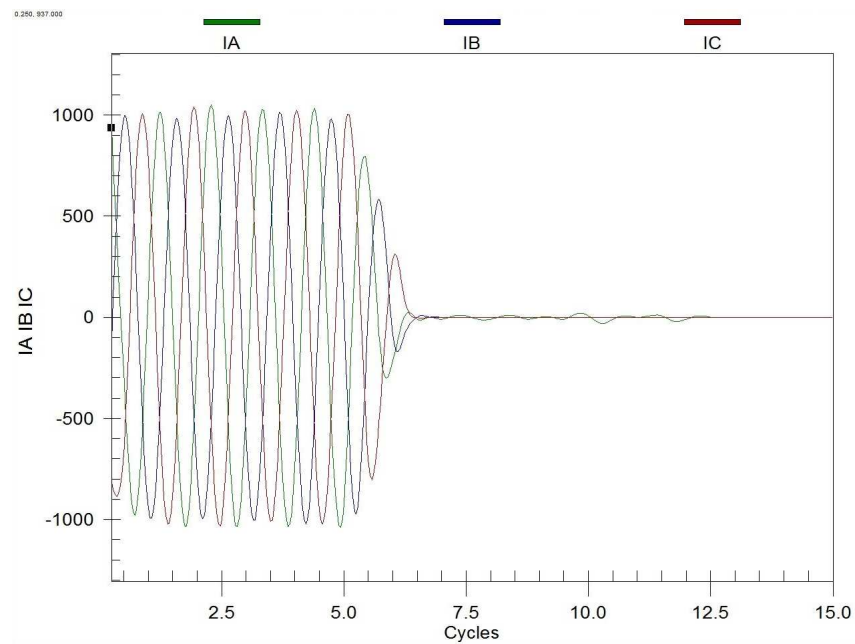
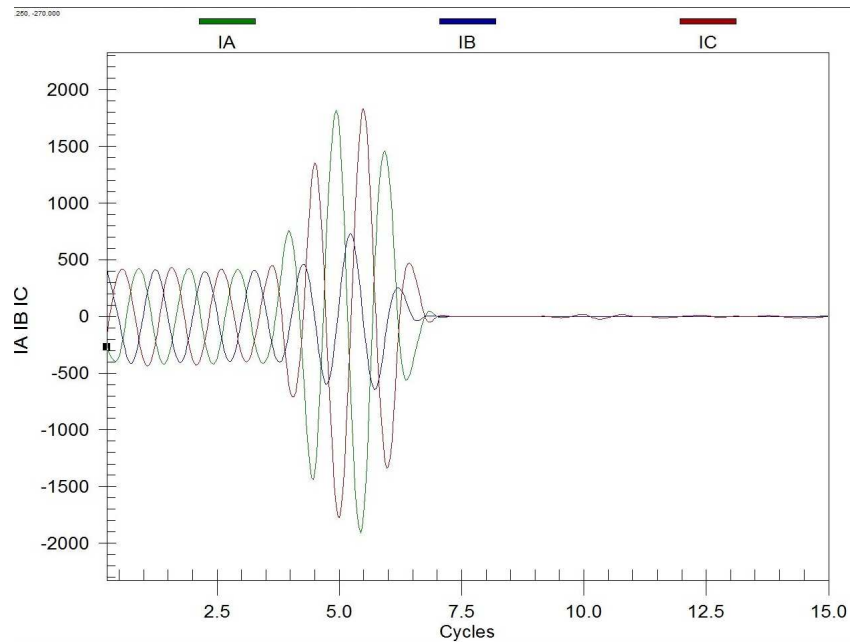


file i00833



### Question 68

An *oscillograph* is a time-domain recording of voltages or currents, typically archived after a fault event in an electrical power system. Two examples of oscillographs are shown here, each one representing line currents in a three-phase power line connected to a power station generator:



First, identify the phase rotation of this power system based on the color-coding of the oscillograph traces. Is it ABC or is it CBA? How are you able to determine this fact?

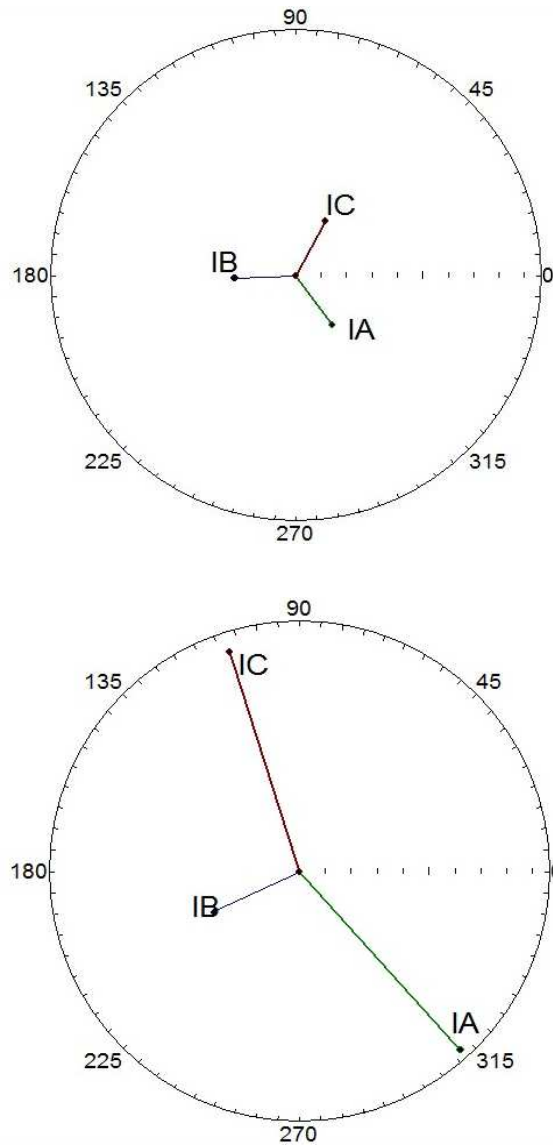
Identify which of these two oscillographs represents a *sustained overload* condition that finally trips a time-delayed protective relay.

Identify which of these two oscillographs represents a *sudden short-circuit fault* between two of the three lines in this power system, that trips an “instantaneous” protective relay. Also, identify which two lines (A, B, C) were shorted together in this fault.

file i02019

Question 69

Modern electric power instrumentation is able to display three-phase circuit quantities as *phasor diagrams*. The following examples show screenshots from a protective relay as it senses line currents from a three-phase generator, the first screenshot representing normal operation and the second screenshot representing a fault:



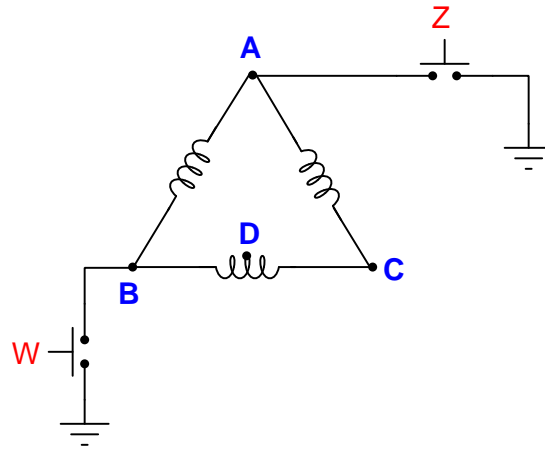
First, identify the phase rotation of this power system based on the color-coding of the phasors. Is it ABC or is it CBA? How are you able to determine this fact?

Next, identify the nature of the fault in this power system, being as specific as you can.

[file i02020](#)

Question 70

Predict the amount of AC voltage between the following test points and earth ground in this delta-connected AC generator given the specified switch states. Assume that this generator is designed to have a (balanced) phase voltage of 120 volts AC:



(Switch W pressed ; switch Z unpressed)

- $V_A =$  \_\_\_\_\_ volts AC
- $V_B =$  \_\_\_\_\_ volts AC
- $V_C =$  \_\_\_\_\_ volts AC
- $V_D =$  \_\_\_\_\_ volts AC

(Switch W unpressed ; switch Z pressed)

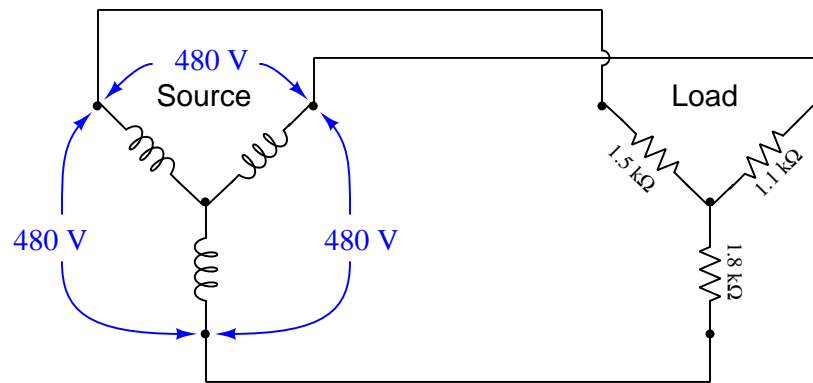
- $V_A =$  \_\_\_\_\_ volts AC
- $V_B =$  \_\_\_\_\_ volts AC
- $V_C =$  \_\_\_\_\_ volts AC
- $V_D =$  \_\_\_\_\_ volts AC

Lastly, explain what would happen if both pushbutton switches were pressed simultaneously.

[file i03534](#)

Question 71

In this Y-Y system, the source outputs balanced voltages (i.e. all line voltages are 480 VAC, shifted  $120^\circ$  from each other) but the load is imbalanced:



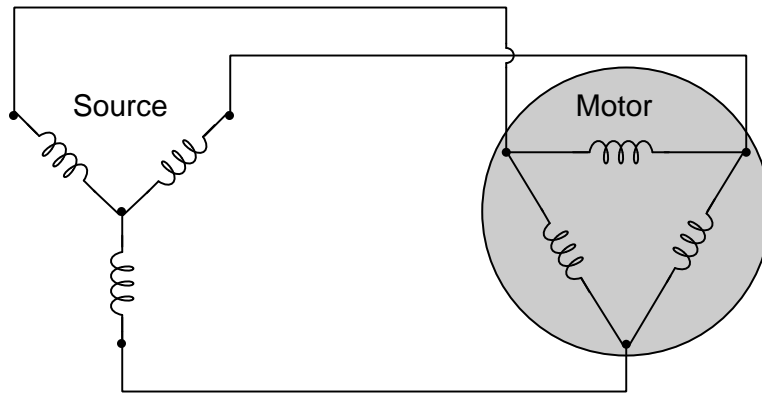
Identify points within this circuit absolutely guaranteed to share the same current, despite the imbalanced load.

Identify pairs of points within this circuit absolutely guaranteed to share the same voltage, despite the imbalanced load.

Now suppose the centers of the wye source and wye load were connected together to form a *4-wire* three-phase circuit. Determine the amount of voltage between each terminal of the wye-connected source and earth ground.

file i04726

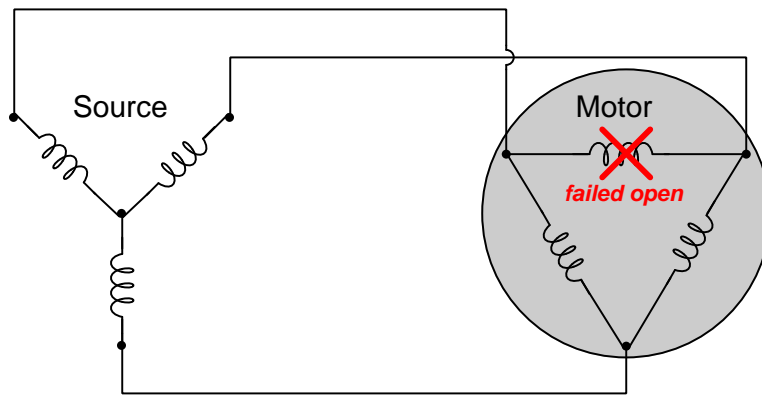
Question 72



Identify points within this circuit absolutely guaranteed to share the same current, whether or not the source or load happen to be balanced.

Identify point-pairs within this circuit absolutely guaranteed to share the same voltage between them, whether or not the source or load happen to be balanced.

Now suppose one of the windings inside the motor fails open. Answer both of the above questions for this new (faulted) scenario:

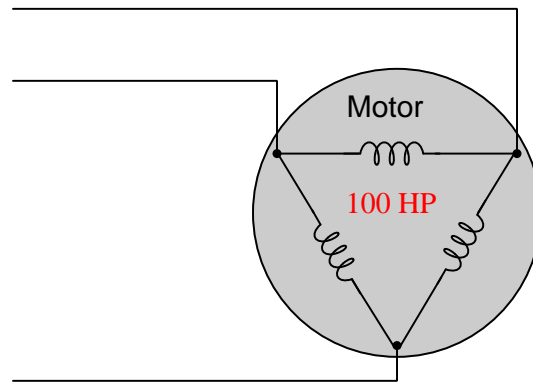


file i04458

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Question 73

Calculate the amount of current passing through each of the phase windings of this 100 horsepower electric motor while operating at full load, assuming a line voltage of 460 volts, 100% motor efficiency, and a power factor of 1:

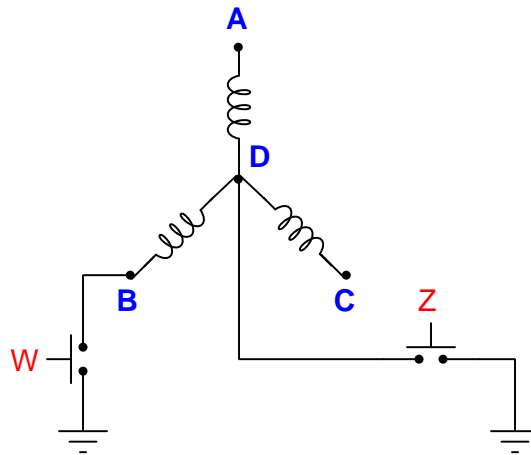


$$I_{phase} = \underline{\hspace{2cm}}$$

[file i01297](#)

Question 74

Predict the amount of AC voltage between the following test points and earth ground in this wye-connected AC generator given the specified switch states. Assume that this generator is designed to have a (balanced) phase voltage of 120 volts AC:



(Switch W pressed ; switch Z unpressed)

- $V_A =$  \_\_\_\_\_ volts AC
- $V_B =$  \_\_\_\_\_ volts AC
- $V_C =$  \_\_\_\_\_ volts AC
- $V_D =$  \_\_\_\_\_ volts AC

(Switch W unpressed ; switch Z pressed)

- $V_A =$  \_\_\_\_\_ volts AC
- $V_B =$  \_\_\_\_\_ volts AC
- $V_C =$  \_\_\_\_\_ volts AC
- $V_D =$  \_\_\_\_\_ volts AC

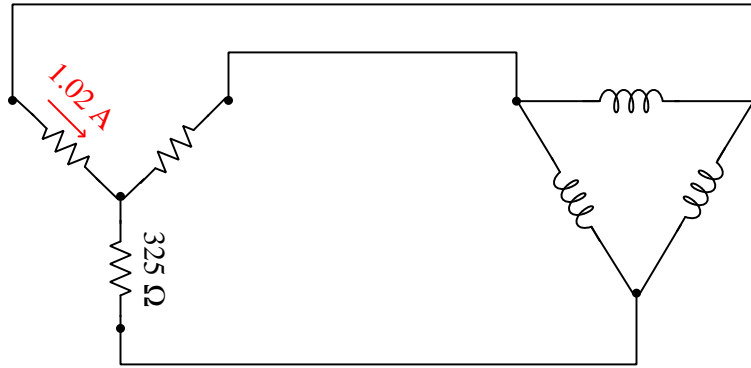
Lastly, explain what would happen if both pushbutton switches were pressed simultaneously.

[file i03799](#)



Question 75

Calculate the following circuit values, assuming a balanced three-phase system:



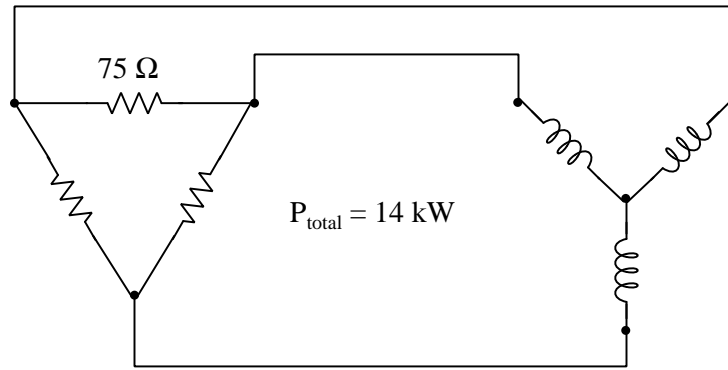
- $V_{phase}$  (source) = \_\_\_\_\_
- $I_{phase}$  (source) = \_\_\_\_\_
- $V_{phase}$  (load) = \_\_\_\_\_
- $I_{phase}$  (load) = \_\_\_\_\_
- $V_{line}$  = \_\_\_\_\_
- $I_{line}$  = \_\_\_\_\_
- $P_{total}$  = \_\_\_\_\_

file i01193

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Question 76

Calculate the following circuit values, assuming a balanced three-phase system:



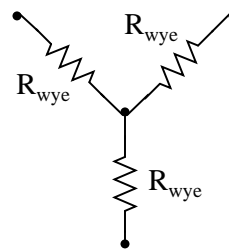
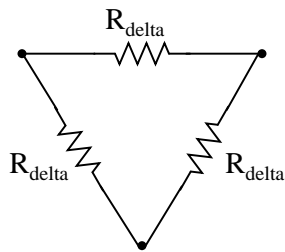
- $V_{\text{phase}}$  (source) = \_\_\_\_\_
- $I_{\text{phase}}$  (source) = \_\_\_\_\_
- $V_{\text{phase}}$  (load) = \_\_\_\_\_
- $I_{\text{phase}}$  (load) = \_\_\_\_\_
- $V_{\text{line}}$  = \_\_\_\_\_
- $I_{\text{line}}$  = \_\_\_\_\_

[file i01623](#)

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Question 77

Suppose you need to design a three-phase electric heater to dissipate 15 kW of heat when powered by 480 VAC. Your options are to build a delta-connected heater array or a wye-connected heater array:



Calculate the proper resistance value for each array, to achieve the desired heat output:

$$R_{\text{delta}} = \text{_____ } \Omega$$

$$R_{\text{wye}} = \text{_____ } \Omega$$

[file i01040](#)

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Question 78

A three-phase electric motor operating at a line voltage of 4160 volts AC (RMS) draws 27.5 amps of current (RMS) through each of its lines. Calculate the amount of electrical power consumed by this motor.

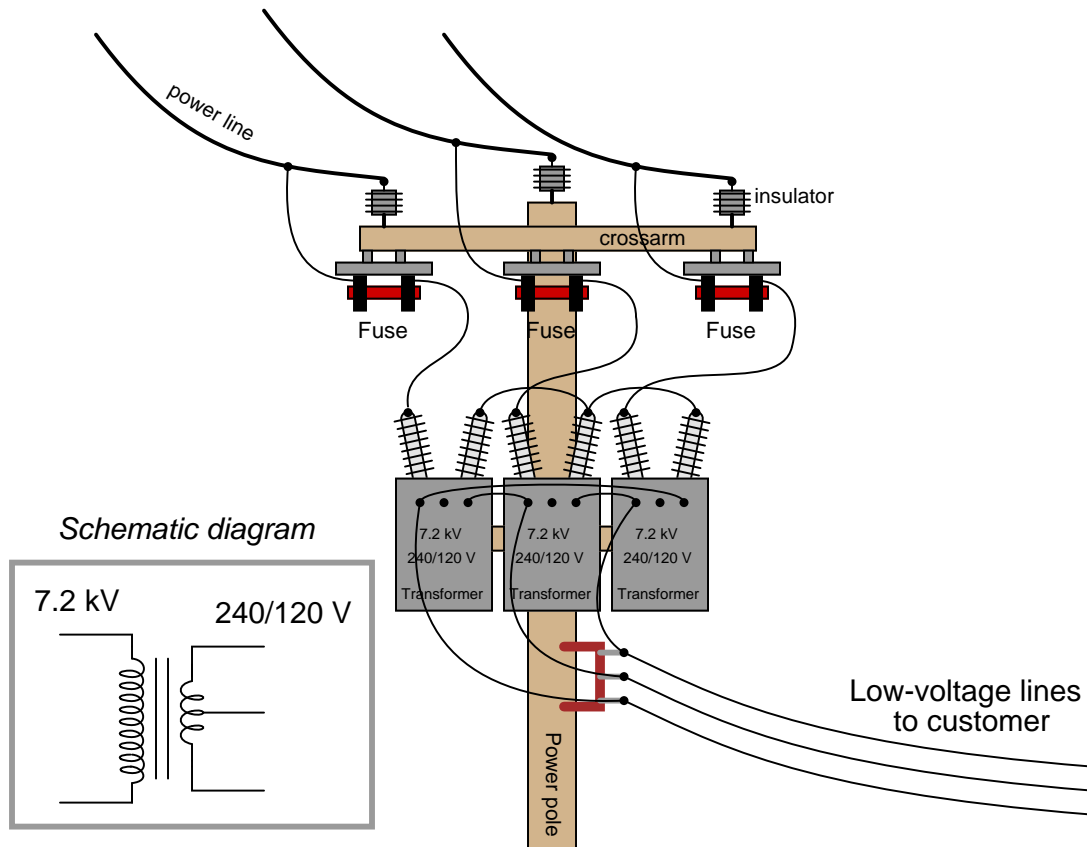
Assuming the motor is 92% efficient and operating at a power factor of 1, calculate its mechanical output power in the unit of horsepower.

[file i01206](#)

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Question 79

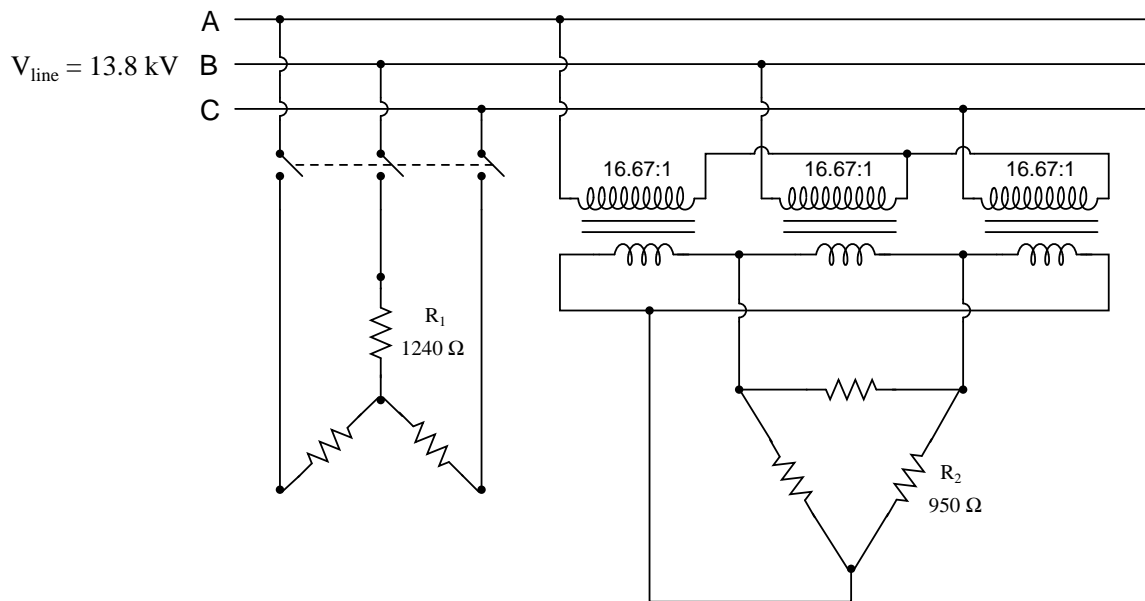
Examine the primary and secondary connections on this three-phase transformer bank, and then determine the line voltage to the customer, assuming 12.5 kV line voltage on the distribution power lines. The schematic diagram shown in the grey box is typical for each of the three transformers:



[file i01041](#)

Question 80

Calculate the operating current through each of the load resistances shown in this circuit (assuming each three-phase load is balanced):

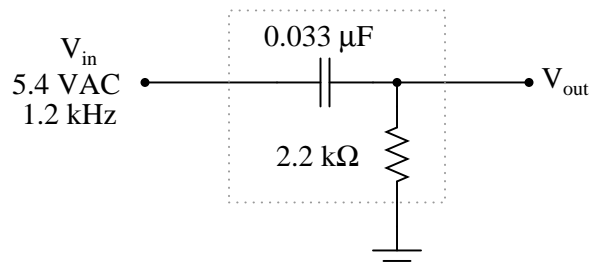


Also, calculate the power dissipated by each load.

[file i02119](#)

Question 81

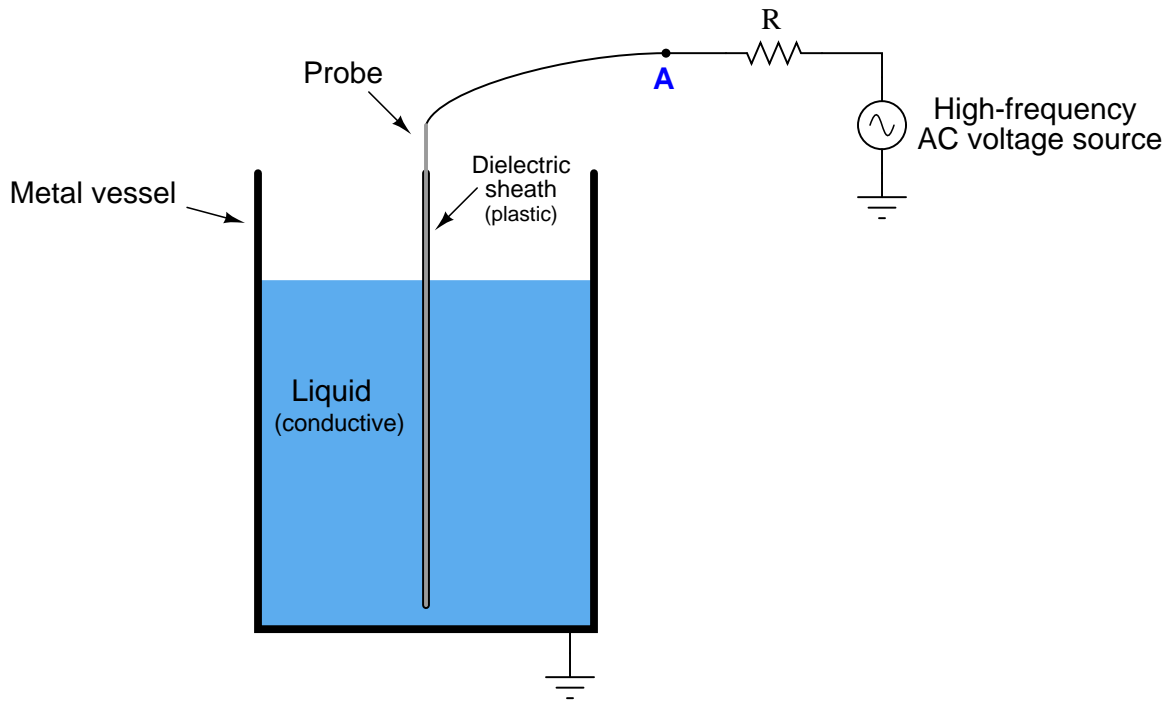
Calculate the output voltage of this phase-shifting circuit, expressing it in polar form (magnitude and phase angle relative to the source voltage):



[file i01062](#)

Question 82

This liquid level sensor circuit uses a plastic-coated metal rod as one “plate” of a capacitor, and the metal vessel as the other “plate” of the capacitor:



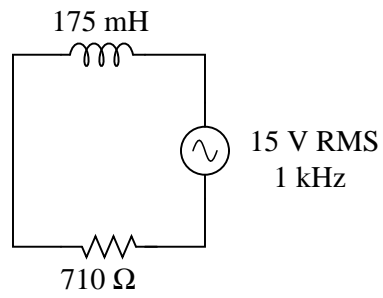
Sketch an equivalent circuit showing the level sensing probe as an ideal circuit element, and then determine the following if the liquid level in the vessel happens to increase:

- Probe capacitance: (*increase, decrease, or remain the same*)
- Capacitive reactance: (*increase, decrease, or remain the same*)
- AC voltage between point **A** and ground: (*increase, decrease, or remain the same*)

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Question 83

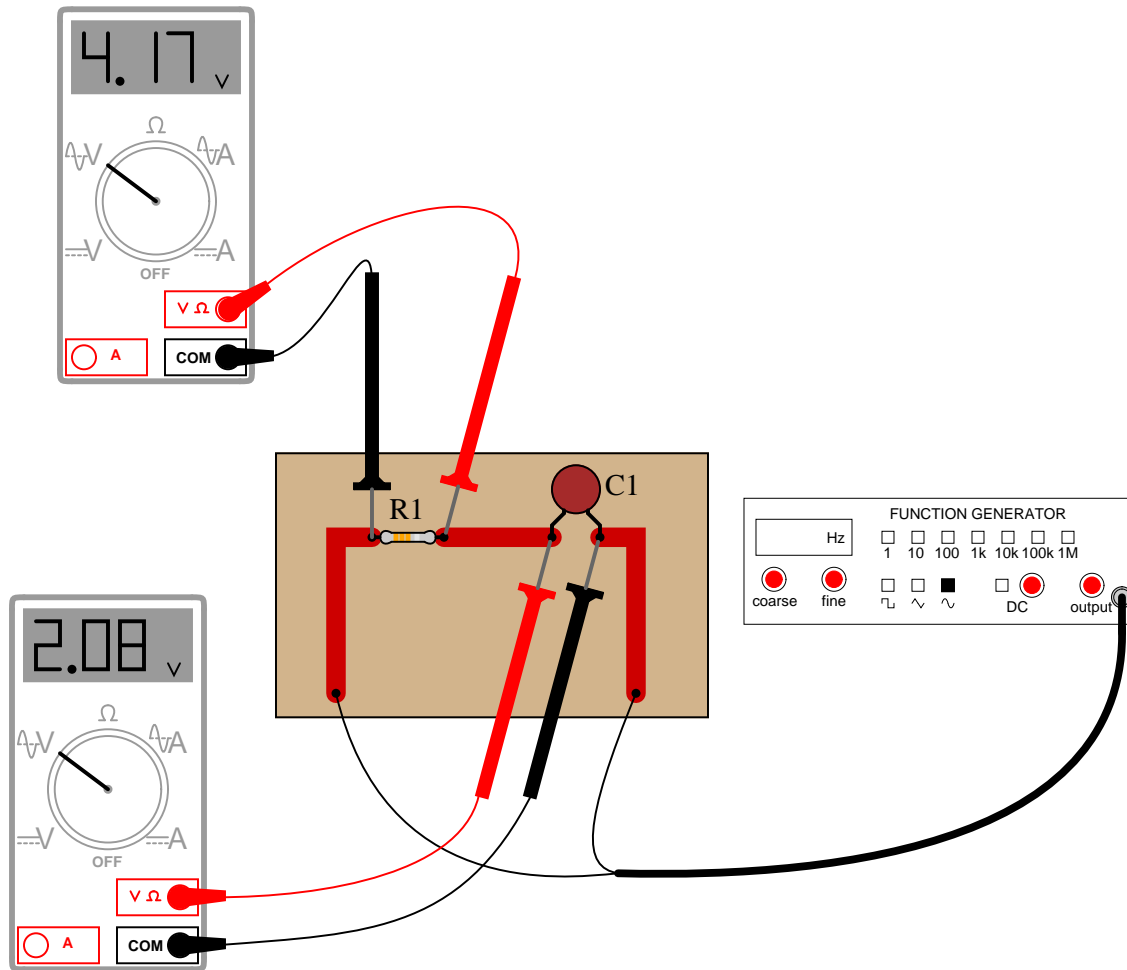
Solve for all voltages and currents in this series LR circuit:



Also, calculate the phase shift between  $V_R$  and  $V_{supply}$ , as well as the phase shift between  $V_L$  and  $V_{supply}$ .

Question 84

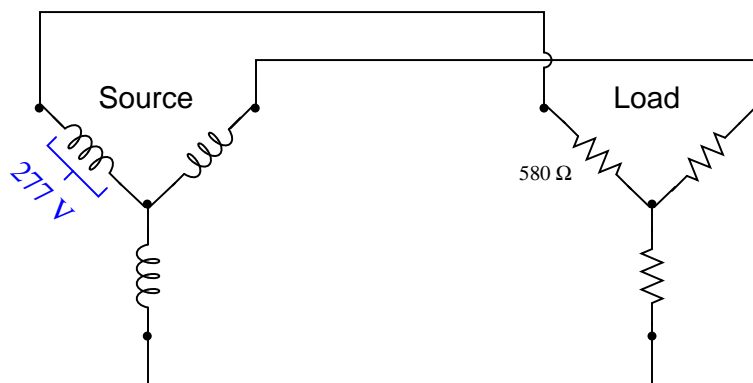
Determine the phase angle ( $\theta$ ) of the current in this circuit, with respect to the supply voltage:



file i01071

Question 85

Calculate all voltages, currents, and total power in this balanced Y-Y system:

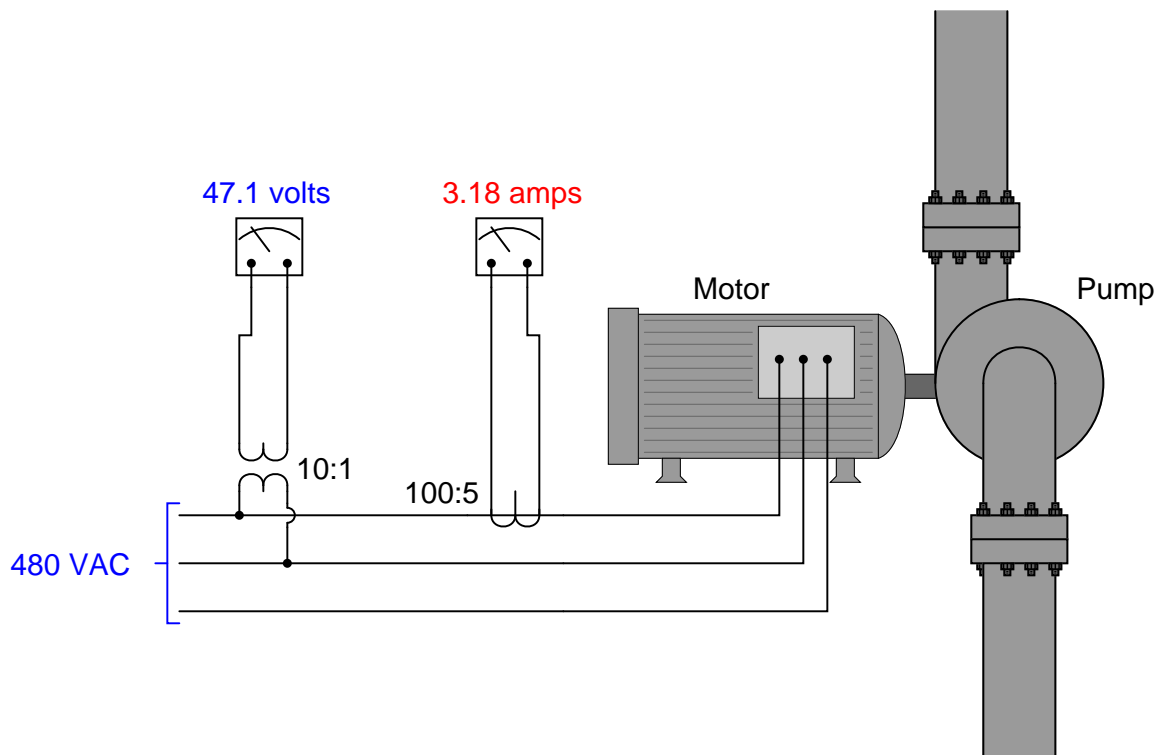


- $E_{line} =$
- $I_{line} =$
- $E_{phase(source)} =$
- $I_{phase(source)} =$
- $E_{phase(load)} =$
- $I_{phase(load)} =$
- $P_{total} =$



Question 86

Suppose a three-phase 480 VAC electric motor is used to turn a pump:

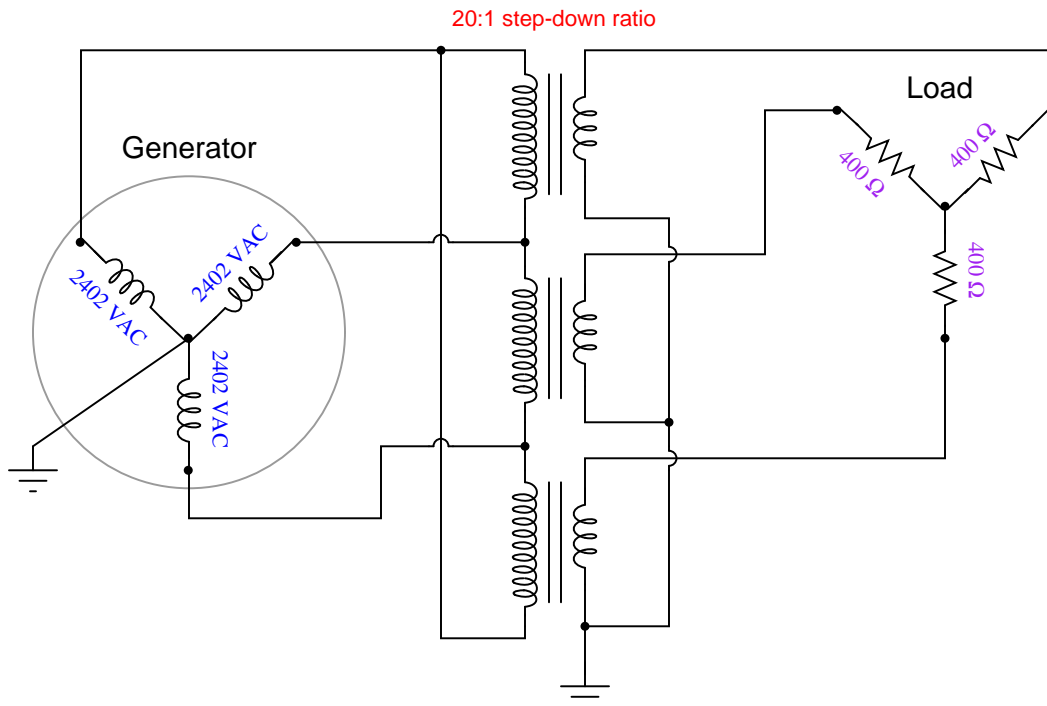


A *current transformer* (CT) with a ratio of 100:5 is used to measure line current. A *potential transformer* (PT) with a ratio of 10:1 is used to measure line voltage. Based on this measurement (assuming the motor presents a balanced load), calculate the following:

- The electrical power delivered to the motor (in horsepower)
- Assuming 93% efficiency, the mechanical power output by the motor (in horsepower)
- Assuming 93% efficiency, the heat dissipation of the motor (in kilowatts)

Question 87

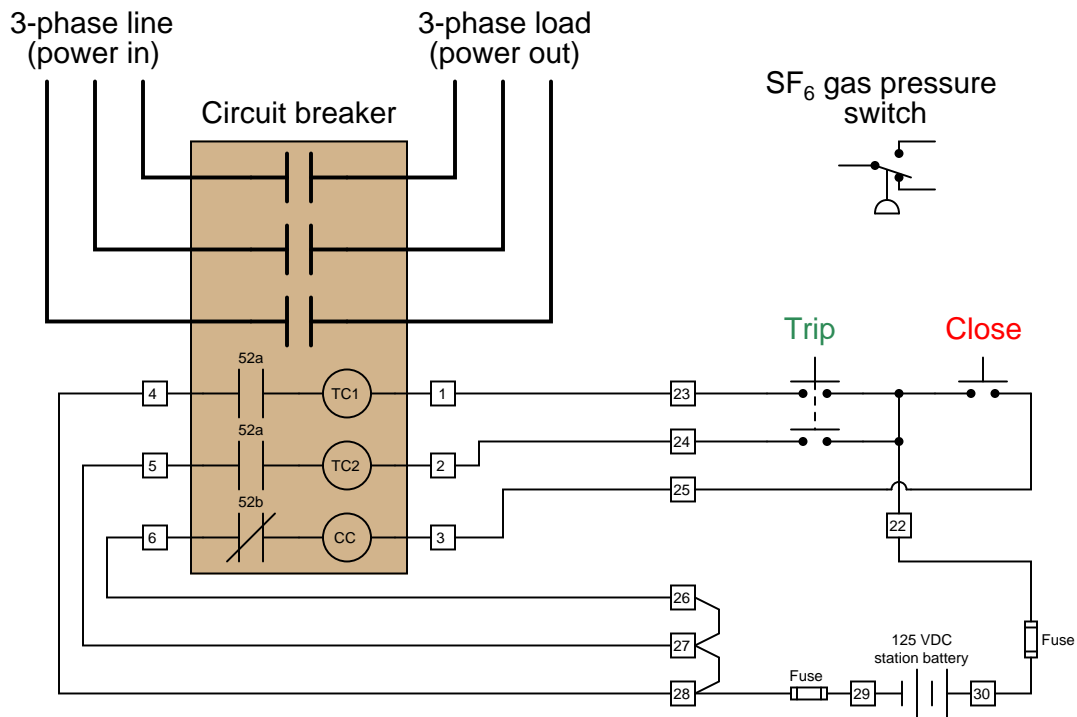
Calculate the following parameters in this three-phase (balanced) AC power system:



- $V_{line}$  (generator) =
- $I_{line}$  (generator) =
- $V_{line}$  (load) =
- $I_{line}$  (load) =
- $P_{total}$  =

Question 88

A high-voltage circuit breaker is manually operated from a remote location using a pair of pushbutton switches, connected to “trip” and “close” solenoid coils within the breaker:



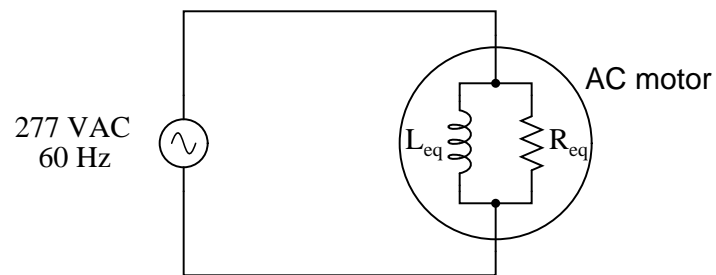
This particular circuit breaker is gas-quenched by sulfur hexafluoride gas ( $\text{SF}_6$ ), which is normally pressurized inside the circuit breaker to approximately 45 PSI for optimum electrical performance.

A low-pressure lockout switch is being installed on the circuit breaker to detect if the  $\text{SF}_6$  gas pressure ever drops below 35 PSI. The purpose of this switch is to disable the breaker from either closing or tripping if the gas pressure is abnormally low.

Your task is to modify the circuit shown above to include this pressure switch. The single-pole, double-throw pressure switch is shown in the upper-right corner of the diagram, not yet connected to the 125 VDC trip/close circuit.

Question 89

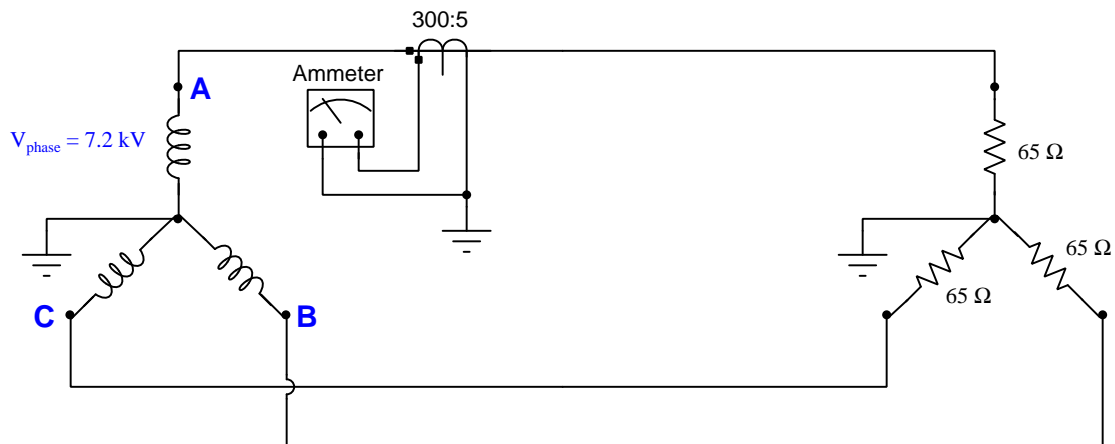
An AC electric motor under load can be considered as a parallel combination of resistance and inductance:



Calculate the equivalent inductance ( $L_{eq}$ ) if the measured source current is 27.5 amps and the motor's equivalent resistance ( $R_{eq}$ ) is 11.2  $\Omega$ .

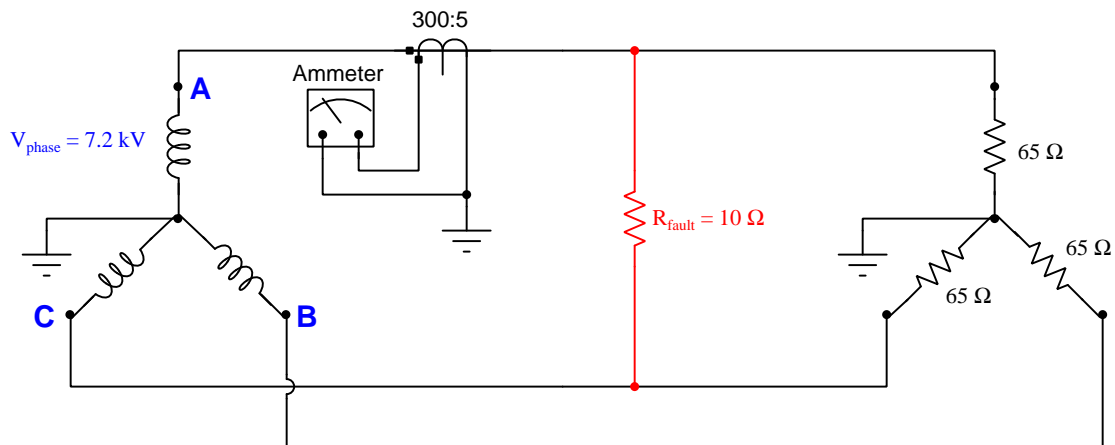
Question 90

Calculate the amount of current output to the ammeter by the current transformer (CT) under normal load conditions, assuming a balanced three-phase source and a balanced three-phase load:



$I_{\text{ammeter}} = \underline{\hspace{2cm}} \text{ A}$

Now, re-calculate the ammeter's current supposing a tree branch falls across lines A and C, causing a low-resistance fault:



$I_{\text{ammeter}} = \underline{\hspace{2cm}} \text{ A}$

Hint: you will need to consider phase angles for the fault current calculation! Feel free to assume an ABC phase rotation, where  $V_A = 7200 \text{ V } \angle 0^\circ$  and  $V_B = 7200 \text{ V } \angle -120^\circ$  and  $V_C = 7200 \text{ V } \angle 120^\circ$ .

[file i02881](#)

**Lab Exercise – introduction**

Your team’s task is to perform commissioning tests on one or more circuit breakers as well as commission and test a protective relay for one protection zone within the lab’s miniature three-phase power grid. Your instructor will assign the circuit breaker and protection zone for your team.

The following table of objectives show what you and your team must complete within the scheduled time for this lab exercise. Note how some of these objectives are individual, while others are for the team as a whole:

Objective completion table:

<b>Performance objective</b>	<b>Grading</b>	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>Team</b>
Team meeting	mastery	–	–	–	–	
Manually synchronize a generator with the grid	mastery					– – – – –
Alternator disassembly, testing, and reassembly	mastery	–	–	–	–	
Verify phase rotation of a three-phase source	mastery	–	–	–	–	
Commissioning tests and system inspection	mastery	–	–	–	–	
Test e/m 50 (inst. overcurrent) relay	mastery	–	–	–	–	
Test e/m 51 (time overcurrent) relay	mastery	–	–	–	–	
“Stab” into a live CT circuit to measure current	mastery					– – – – –
Configure digital relay per specification	mastery					– – – – –
Simulated fault and relay trip verification	mastery	–	–	–	–	
Relay event report interpretation	mastery	–	–	–	–	
<i>Safety and professionalism</i>	deduction					
<i>Lab percentage score</i>	proportional					– – – – –
Decommission and lab clean-up	(ungraded)	–	–	–	–	

The “proportional” score for this activity is based on the number of attempts require to master each objective. Every failed attempt is marked by a 0, and every pass by a 1. The total number of 1 marks divided by the total number of marks (both 1’s and 0’s) yields a percentage value. Team objectives count as part of every team member’s individual score. The *Safety and professionalism* deduction is a flat –10% per instance, levied on occasions of unprofessional or unsafe conduct.

**It is essential that your team plans ahead what to accomplish each day. A short (10 minute) team meeting at the beginning of each lab session is a good way to do this, reviewing what’s already been done, what’s left to do, and what assessments you should be ready for. There is a lot of work involved with building, documenting, and troubleshooting these working instrument systems!**

As you and your team work on this system, you will invariably encounter problems. You should always attempt to solve these problems as a team before requesting instructor assistance. If you still require instructor assistance, write your team’s color on the lab whiteboard with a brief description of what you need help on. The instructor will meet with each team in order they appear on the whiteboard to address these problems.

## Lab Exercise – objectives and expectations

Each objective is assessed at the *mastery* level, which means it is not complete until it meets *all* expectations. Re-tries are allowed, but failed attempts will be recorded and factored into your score for this lab exercise.

### Team meeting

### Manual generator synchronization

Manually synchronize one three-phase generator with others on the lab's miniature AC power grid using synchronization lamps as indicators.

### Alternator disassembly, testing, and reassembly

Disassemble, test, reassemble, and answer technical questions about a three-phase alternator unit.

### Phase rotation testing

Empirically determine the phase rotation of a three-phase generator using either an oscilloscope or an RC network.

### Commissioning tests

Complete a battery of tests on one of the circuit breakers installed in the lab's miniature AC power grid system, complete with a visual inspection of any work performed.

### Test electromechanical “50” relay

Test and adjust if necessary an electromechanical-style instantaneous overcurrent (ANSI 50) protective relay, as per parameters randomly chosen by the instructor.

### Test electromechanical “51” relay

Test and adjust if necessary an electromechanical-style time overcurrent (ANSI 51) protective relay, as per parameters randomly chosen by the instructor.

### Live CT “stab” test

Demonstrate how to use a special “stab” tool to measure current from an energized current transformer (CT), through the contacts of a CT test switch.

### Configure digital relay

Configure the settings of a digital-style protective relay as per parameters randomly chosen by the instructor.

### Simulated fault and relay trip verification

Safely implement a fault chosen by your instructor in the lab's miniature AC power grid, verifying that the protective relay does indeed trip as it should.

### Relay event report interpretation

Collect electronic data from a protective relay following a trip event, and correctly interpret all aspects of the relay's event recording including text-based event report, oscillography, and/or phasor diagram displays.

## Lab Exercise – objectives and expectations (continued)

### Lab percentage score

Successful completion of the lab exercise requires demonstrated mastery of all objectives. A percentage value is based on the number of attempts required to achieve mastery on these objectives: the number of objectives divided by the number of total attempts equals the percentage. Thus, a perfect lab percentage score is possible only by completing all objectives on the first attempt. Marks given for team objectives factor into each individual's score. If one or more members of a team repeatedly compromise team performance, they may be removed from the team and required to complete remaining lab exercises alone.

Deductions from this percentage value will be levied for instances of unsafe or unprofessional conduct (see below), the final result being the lab percentage score.

### Safety and professionalism (deduction)

In addition to completing the specified learning objectives in each lab exercise, each student is responsible for abiding by all lab safety standards and generally conducting themselves as working professionals (see the *General Values, Expectations, and Standards* page near the beginning of every worksheet for more detail). Expectations include maintaining an orderly work environment and returning all tools and test equipment by the end of every school day (team), as well as following clear instructions (e.g. instructions given in equipment manuals, lab documentation, verbally by the instructor), communicating with teammates, formulating a plan to complete the lab project in the allotted time, and productively managing time. As with the other objectives, chronic patterns of poor performance in this domain may result in the offending student being removed from the team. Deductions to the lab percentage score will *not* be made for performance already graded such as tardiness and attendance.

## General format and philosophy

This lab exercise is *project-based*: the instructor serves as the project engineer, while each student's role is to implement the standards set for the project while budgeting time and resources to complete it by the deadline date. Students perform real work as part of the lab exercise, managing their work day and functioning much the same as they will on the job. The tools and equipment and materials used are all industry-standard, and the problems encountered are realistic. This instructional design is intentional, as it is proven effective in teaching project management skills and independent working habits.

When you require the instructor's assistance to answer a question or to check off an objective, write your name (or your team's name) on the lab room whiteboard. Questions take priority over checkoffs, so please distinguish questions from other requests (e.g. writing a question-mark symbol “?” after your name makes this clear). **There will be times when you must wait for extended periods** while the instructor is busy elsewhere – instant service is an impossibility. Adequate time *does* exist to complete the lab exercise if you follow all instructions, communicate well, and work productively. Use all “down time” wisely: filling it with tasks not requiring the instructor's assistance such as other lab objectives, homework, feedback questions, and job searches.

Remember that the lab facility is available to you at all hours of the school day. Students may perform non-hazardous work (e.g. circuit work at less than 30 volts, documentation, low air pressures, general construction not requiring power tools) at *any time during the school day* without the instructor's presence so long as that work does not disturb the learning environment for other students.

**DO NOT TAKE SHORTCUTS** when completing tasks! Learning requires focused attention and time on task, which means that most “shortcuts” actually circumvent the learning process. Read the lab exercise instructions, follow all instructions documented in equipment manuals, and follow all advice given to you by your instructor. Make a good-faith effort to solve all problems on your own *before* seeking the help of others. Always remember that this lab exercise is just a means to an end: no one *needs* you to build this project; it is an activity designed to develop marketable knowledge, skills, and self-discipline. In the end it is your *professional development* that matters most, not the finished project!



### **Lab Exercise – team meeting**

An important first step in completing this lab exercise is to **meet with your instructor** as a team to locate the circuit breaker to be commissioned, as well as discuss safety concerns, team performance, and specific roles for team members. If you would like to emphasize exposure to certain equipment (e.g. use a particular type of control system, certain power tools), techniques (e.g. fabrication), or tasks to improve your skill set, this is the time to make requests of your team so that your learning during this project will be maximized.

## Lab Exercise – manually synchronize a generator with the grid

The lab's miniature AC power grid is equipped with multiple generating stations, each of which must be synchronized with the grid before closing its circuit breaker and placing it "on line". Manual synchronization entails bringing the generator up to speed and monitoring some form of differential voltage monitor indicating the phase relationship between the generator's output voltage and the power grid's voltage. The circuit breaker should only be closed when the generator's speed is slightly greater than the power line's frequency and the phase shift is at a minimum.

The simplest form of differential voltage monitor is a set of "sync lamps" connected across the poles of the open circuit breaker (or connected to PTs which have primary windings connected across the poles of the breaker). The lamps will glow brightest when the generator and grid are  $180^\circ$  out of phase, and glow dimmest (or go out completely) when the two are in-phase.

A more sophisticated differential voltage monitor suitable for manual synchronization is the *synchroscope*, a special panel meter with a needle that can rotate without ever hitting a stop. Zero phase shift is indicated by the needle pointing straight up, while  $180^\circ$  phase shift is indicated by the needle pointing straight down.

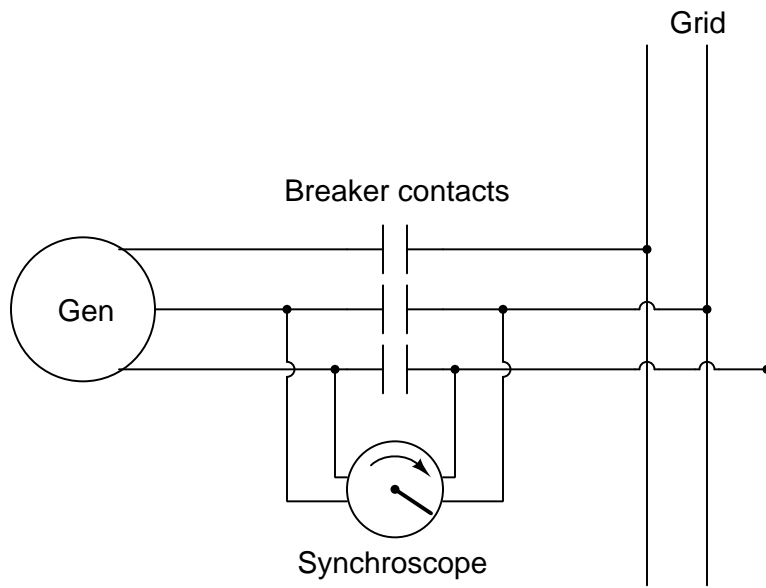
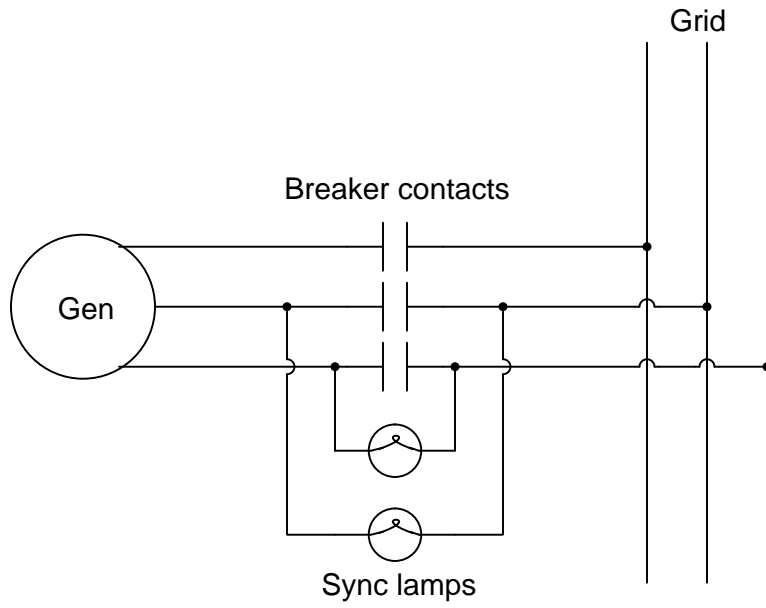
If the generator and power grid are at different frequencies, the sync lamps will oscillate in brightness at a frequency equal to the difference in generator and line frequencies. A synchroscope's needle will rotate at a speed equal to this difference frequency.

If the generator and power grid are at different voltage levels, the sync lamps will never fully go out, but will merely become brighter and dimmer at the difference frequency. A synchroscope has no way of showing differences in voltage level.

Once your generator is successfully synchronized with the grid and its circuit breaker closed, it becomes electrically "locked" in phase with the rest of the grid. Attempting to speed it up or slow it down while on-line merely places more or less load on the generator – it cannot actually speed up or slow down without pulling the entire grid (and all the generators on it) to that new speed. Likewise, attempting to change the output voltage by exciting the field winding more or less only changes the amount of reactive power the generator produces – it cannot actually raise or lower grid voltage without pulling the entire grid (and all the generators on it) to that new voltage level.

If something dramatic happens to pull your generator out of sync with the grid while its circuit breaker is closed, very large currents will begin to flow in and out of your generator as it falls in and out of phase with the grid. The generator will also experience very high mechanical torque at its shaft. The phenomenon of falling out of phase with the grid is called "slipping a pole" and it can be catastrophic for large generators, both electrically and mechanically. The protective relay(s) at each generating station should be set to trip the generator off-line if this ever happens.

The act of manually synchronizing an AC generator to the grid helps one visualize the phase relationships between a multiple rotating machines. Even if the section of the power grid your team has been assigned to protect does not contain a generator, there is merit in learning how to synchronize AC generators.



## Lab Exercise – alternator disassembly, testing, and reassembly

Each team will be given a Delco-Remy brand automotive alternator, which they must disassemble, test, and reassemble. Disassembly must be done as far as possible using standard hand tools (e.g. wrenches, screwdrivers, pliers, etc.). These alternator units, while smaller in size than alternators used in full-scale power generating stations, nevertheless operate on the same principles and are constructed similarly to their full-scale cousins.

Delco-Remy alternators are three-phase machines, with stator windings either connected in a Wye or Delta configuration to produce low-voltage AC (approximately 15 VAC) power. A bank of rectifying diodes converts this AC into DC suitable for charging the vehicle's battery and operating DC vehicle accessories (e.g. radio, windshield wiper motor, etc). Please note that the stator windings will have to be disconnected from the rectifying diodes prior to any resistance tests! The field winding is located on the rotor, powered by an external DC source (12 VDC maximum) through *slip rings* and carbon brushes.

Testing consists of the following:

- Phase-to-phase resistance measurements using an ohmmeter on a low-resistance measurement range.
- Rotor field winding resistance measurement using an ohmmeter on a low-resistance measurement range.
- Phase-to-ground insulation resistance measurements using an insulation tester (i.e. high-voltage ohmmeter) set to an appropriate voltage level
- Rotor field winding to ground resistance measurement using an insulation tester (i.e. high-voltage ohmmeter) set to an appropriate voltage level
- Count the number of magnetic poles on the rotor. *This number will be used to calculate the frequency of the generated voltage at a given shaft speed.*

While your alternator is disassembled, your instructor will query each team member regarding the function and location of the alternator's *stator windings*, *rotor*, *field winding*, *slip rings*, and *brushes*. Your instructor will also ask you to calculate output frequency (in Hz) given shaft speed (in RPM), or vice-versa. All team members must correctly answer these questions in order for the team to complete this objective.

A Delco-Remy service bulletin document has been included in your Instrumentation Reference, describing this machine's construction, operation, and testing in some detail.

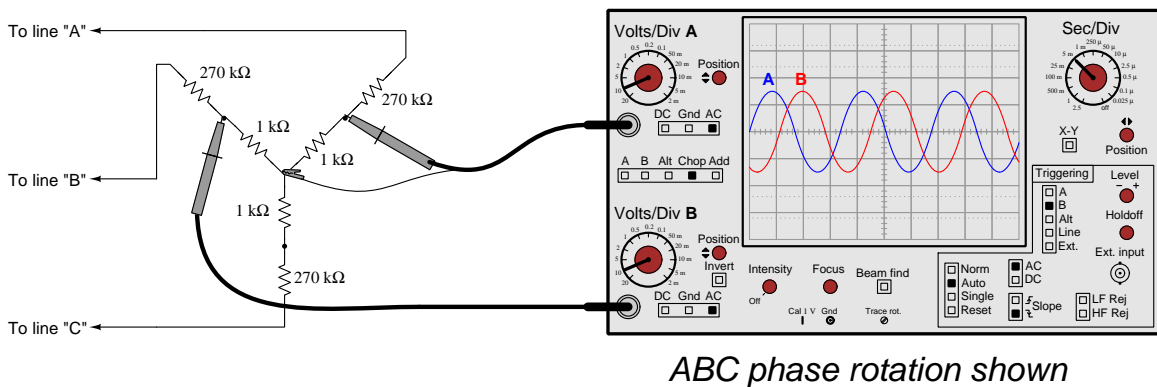
### Common mistakes:

- Failing to disconnect the stator winding leads from the rectifier assemblies prior to performing resistance measurements.
- Failing to insert a "keeper" pin into the brush holders during reassembly.

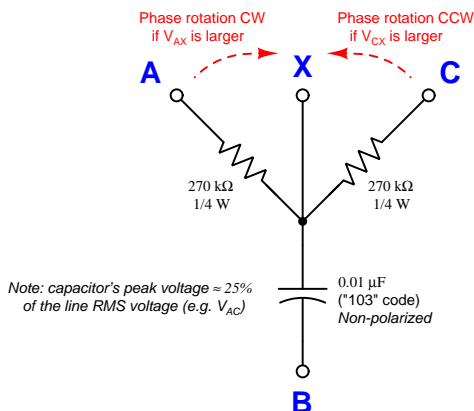
## Lab Exercise – phase rotation (sequence) testing

Once live three-phase power is available in the lab power grid, you will be required to verify its *phase rotation* by connecting a suitable test instrument to it, either directly to the power lines (where applicable) or through potential transformers pre-connected to the grid. If your station happens to be a generator, you will need to verify its phase rotation *before* attempting to place it on-line (i.e. close the breaker to connect it to the grid).

Suitable test equipment exists in the lab for you to measure phase rotation. A multi-channel oscilloscope is one form of suitable test equipment, but others exist as well. Be sure to consult the manual before using this equipment on the power system, as system voltages and currents are capable of damaging equipment if incorrectly connected. A sample schematic shown here illustrates how you may build a three-phase voltage divider for safely testing phase rotation in cases where the line voltage could damage the test instrument's inputs. This Wye-connected resistor network also provides a "ground" reference if the power system lacks one:



You may construct your own phase rotation tester by building this simple circuit and using a voltmeter to compare the voltage dropped by the two resistors:



Directions for use:

- (1) Connect **A**, **B**, and **C** to 3-phase lines
- (2) Leave **X** floating (not connected to power system)
- (3) Measure  $V_{AX}$  and  $V_{CX}$  with an AC voltmeter
- (4) If  $V_{CX} > V_{AX}$  then phase sequence is ABC
- (5) If  $V_{AX} > V_{CX}$  then phase sequence is ACB

All three-phase power conductors in our lab's power system are color-coded *Black* (L1 or A), *Red* (L2 or B), and *Blue* (L3 or C), following common industrial practice in the United States.

## Lab Exercise – commissioning tests

Commissioning a circuit breaker and associated instrumentation involves the following tests, shown here in table format to facilitate documentation of your measurements. You should print this table and write all your test results in it, then leave this in the enclosure with the protective relay as a permanent record. Note that a “quantitative” test is one where a numerical value must be recorded and assessed, whereas a “qualitative” test is one that is simply pass/fail:

Test description	Results
CT circuit wire connections secure (all phases) <i>(qualitative)</i> Perform this as the <i>first</i> CT test!	Phase A = Phase B = Phase C =
CT ratio check (all phases) <i>(quantitative)</i>	Phase A = Phase B = Phase C =
CT polarity check (all phases) <i>(qualitative)</i>	Phase A = Phase B = Phase C =
CT secondary circuit total resistance <i>(quantitative) – ohmmeter</i>	Phase A = $\Omega$ Phase B = $\Omega$ Phase C = $\Omega$
CT secondary circuit insulation resistance <i>(quantitative) – insulation tester</i>	Phase A = $\Omega$ Phase B = $\Omega$ Phase C = $\Omega$
Protective relay input burden (all phases) <i>(quantitative) – ohmmeter</i>	Phase A = $\Omega$ Phase B = $\Omega$ Phase C = $\Omega$
CT circuit ground resistance (all phases) <i>(quantitative) – ohmmeter</i>	Phase A = $\Omega$ Phase B = $\Omega$ Phase C = $\Omega$
CT test switch shorting function (all phases) <i>(qualitative)</i>	Phase A = Phase B = Phase C =
Breaker trip circuit connections secure <i>(qualitative)</i> Perform this as the <i>first</i> 52/TC circuit test!	
Breaker close circuit connections secure <i>(qualitative)</i> Perform this as the <i>first</i> 52/CC circuit test!	
DC station supply voltage (unloaded) DC station supply voltage (while tripping breaker) <i>(quantitative) – voltmeter</i>	VDC =     V VDC =     V
Breaker trip coil circuit loop resistance <i>(quantitative) – ohmmeter</i>	52/TC = $\Omega$
Breaker close coil circuit loop resistance <i>(quantitative) – ohmmeter</i>	52/CC = $\Omega$

Note that some circuit breakers are equipped with multiple *sets* of current transformers, not just one CT for each of the three phases. In such cases you must document the test results of each and every CT.

In order to accurately measure electrical resistance for certain commissioning tests (e.g. CT circuit total resistance) where the expected value is quite low, you will need to compensate for the electrical resistance of your meter's test leads. Good-quality digital multimeters such as the Fluke 87 series provide a "Relative" function whereby you can set the meter to measure resistance, connect the test leads together, and press a button to make this the "zero" reference point for measurement. Be sure to do this for the appropriate tests, re-checking the "zero" point before each new test.

Given the low-current nature of the lab's miniature three-phase power grid, it is relatively easy to perform *primary injection* testing of current transformers. This is where a relatively large amount of alternating current is sent through the primary CT conductors, in order to test how accurately this current is registered at the protective relay (i.e. realistically testing the CT ratio).

You may generate this injection current using a step-down transformer and a Variac for control, or you may use the relay test set which contains both of these devices. Connect the AC source such that its current flows through the regular power conductors and through the center of the CTs. Monitor current using a suitable ammeter on the primary wiring and the current displayed by the digital relay in order to confirm accurate measurement (within  $\pm 5\%$  of full-load current). Using the digital protective relay as an ammeter during this test is recommended because this places the exact same amount of burden on the CT as it will experience when the system is in operation. Connecting a second ammeter in series with the CT secondary circuit places additional burden in that circuit which may very well affect the CT ratio!

#### **Common mistakes:**

- Incorrectly setting up or interpreting transformer polarity tests.
- Failing to compensate for ohmmeter test lead resistance when performing low-resistance tests.

### Lab Exercise – electromechanical relay testing

Even though your protective relay scheme uses a digital relay, part of this lab project is testing a legacy electromechanical relay such as the General Electric IAC series or Westinghouse CO series overcurrent (50/51) relays.

Consult the manufacturer's manuals on these relays for instructions on testing. You may wire your own high-current AC source using step-down transformers and a Variac for control, or use a relay test set. Your instructor will provide you with criteria for testing the relay. Assume the use of the same CTs (i.e. use those same ratios) you are using in your digital relay protection scheme:

#### Instantaneous overcurrent (50) function:

Quantity	Value	Who determines
Pick-up current, primary amps		Instructor
CT ratio		You research
Pick-up current, secondary amps		You calculate

#### Time overcurrent (51) function:

Quantity	Value	Who determines
Pick-up current, secondary amps		Instructor
Time dial setting		Instructor

The instructor will verify your successful testing of both relay functions. The instantaneous (50) function simply has one point to test, but the time (51) function requires multiple tests to verify against the given trip-time curve.

#### Common mistakes:

- Maintaining high amounts of test current through the relay for too long, causing its operating coils to heat up. This skews the calibration of the relay!



## Lab Exercise – live CT secondary current measurement

A practical but also potentially hazardous job function for relay technicians is to take live current measurements on CT secondary circuits. Practical reasons include data logging and verification of relay measurement accuracy without removing the relay from service. The hazards are simple to understand: current transformers are capable of generating very high voltages if ever their secondary windings are open-circuited while the primary conductor is carrying current.

Special “test probes” are built to connect into “test jacks” on CT test switch assemblies for this purpose. The test jack provides a means for a regular ammeter to be inserted into the CT secondary circuit without ever breaking that circuit. The *Instrument Transformers* learning module (part of the Modular Electronics Learning Project) describes test probes and their safe usage.

Some legacy electromechanical protective relays such as the General Electric series used “paddle” plugs to connect and disconnect the relays from outside devices such as CTs. These “paddles” could be removed and replaced with special “test plugs” providing connection points for ammeters and other devices so that these devices could connect in-line with the live relay.

In order to ensure your personal safety when using any of these devices to “stab into” a live CT circuit, you must absolutely ensure you will not inadvertently open-circuit the secondary winding of a CT. This means you must thoroughly test your plug/probe, leads, and ammeter before insertion into the test jacks. A continuity test is all that is required, performed at the contacting terminals of the plug/probe to ensure a complete circuit from one terminal through the ammeter and back out the other terminal.

One of the commissioning tests you must complete as part of this lab activity is the empirical determination of CT ratio. If the CTs you are testing are equipped with test switches allowing insertion of test jacks, you may use this live CT current measurement as part of that ratio check: comparing current measured through the CT’s primary winding against CT secondary current measured at the test jack.

Your instructor will observe your preparation and testing of a live CT circuit. Do not attempt to do this without instructor supervision!

### Common mistakes:

- Not correctly understanding the physical structure of the test switch prior to inserting the test probe. *Inspect the test switch jack very closely until you understand exactly how CT current flows through it, and how the probe interrupts this normal pathway!*

## Lab Exercise – digital relay settings

You will typically find a generic settings sheet for your digital relay in the manufacturer’s manual, or else as a separate download from the relay manufacturer’s website. This settings sheet will have several cells or blanks where you may hand-write the basic settings to be programmed into the protective relay. It is up to you and your team to determine how to implement those general settings given the specific features provided by your relay and the assigned protection zone within the power system. Your instructor will provide specific settings or parameters as needed in order to make this objective unique to each student completing it.

Digital protective relays may often be configured via multiple means. For example, protective relays manufactured by Schweitzer Engineering Laboratories (SEL) may be programmed through panel pushbuttons, through ASCII serial data communication using a terminal emulator program such as `Hyperterminal` on a personal computer, or through `AcSELeRator QuickSet SEL-5030` software on a personal computer providing a point-and-click user interface. It matters little how you set the relay parameters so long as they are all set correctly.

For the Schweitzer relays most of the important parameters may be set by any of the above means. Some of the parameters, however (particularly the “Logic” parameters) may only be set via serial link, and are not accessible through the front pushbutton panel.

## Lab Exercise – simulated system fault and relay event report

After your system's protective relay has been properly configured, it is ready to be tested on a simulated fault. The simulation of a fault may be done with a relay test set (injecting secondary CT current signals into the relay inputs), with a high-current AC source (injecting primary CT current signals into the installed CTs), by placing a heavy load on the system (a suitable test for a generating station is to have it trip on the inrush current of an induction motor during start-up), or by placing an actual fault into the power system itself. Your team will work together with your instructor to devise a suitable test for the protection scheme of your relay. If the test itself harbors any danger – as is in the cases of the primary injection or actual fault tests – your instructor must be present to supervise the execution of that test.

It is also a fair test to place a fault on the power system that should *not* cause your team's protective function to trip, but which will cause some other protective function to activate. This tests the *selectivity* of your protective function to ensure it only trips for faults within its protection zone while ignoring faults lying outside of its protection zone.

For each fault, the team must show the *event report* generated by the digital relay and interpret the data contained in that report. This event report will show the onset of the fault, the point in time at which the protective relay “picks up” the fault, the point in time at which the relay asserts a trip command to the circuit breaker(s), and the time at which the fault becomes cleared by the open breaker(s). Event reports are accessed by connecting a personal computer to the digital relay through a communications port. Protective relays manufactured by Schweitzer Engineering Laboratories (SEL) show event reports via ASCII serial data communication using a terminal emulator program such as **Hyperterminal** on a personal computer, or through **AcSELeRator QuickSet SEL-5030** software on a personal computer.

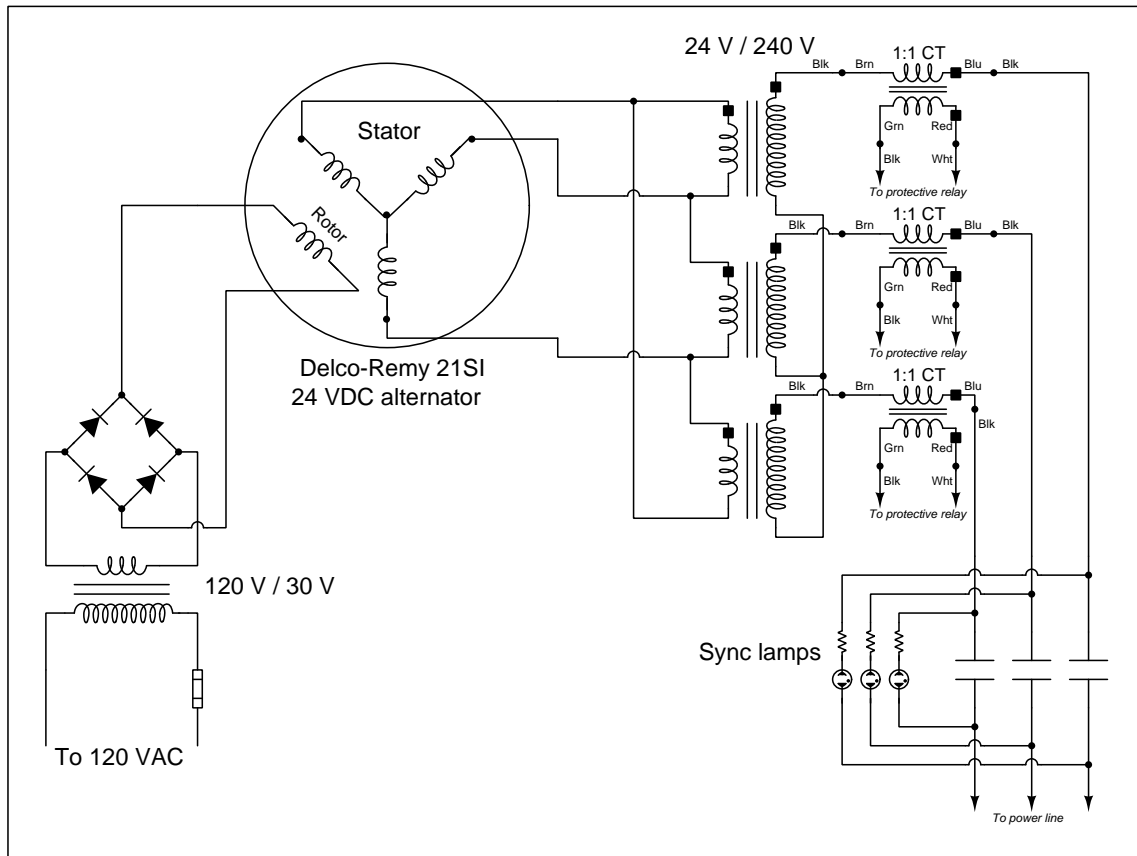
If your team's protective relay provides oscillography and/or phasor diagram displays in addition to text-based fault reports (as do SEL relays), you must show these as well. **AcSELeRator QuickSet SEL-5030** software is necessary to generate and display oscillographs and phasor diagram animations for SEL relays.

[file i03020](#)

Question 92

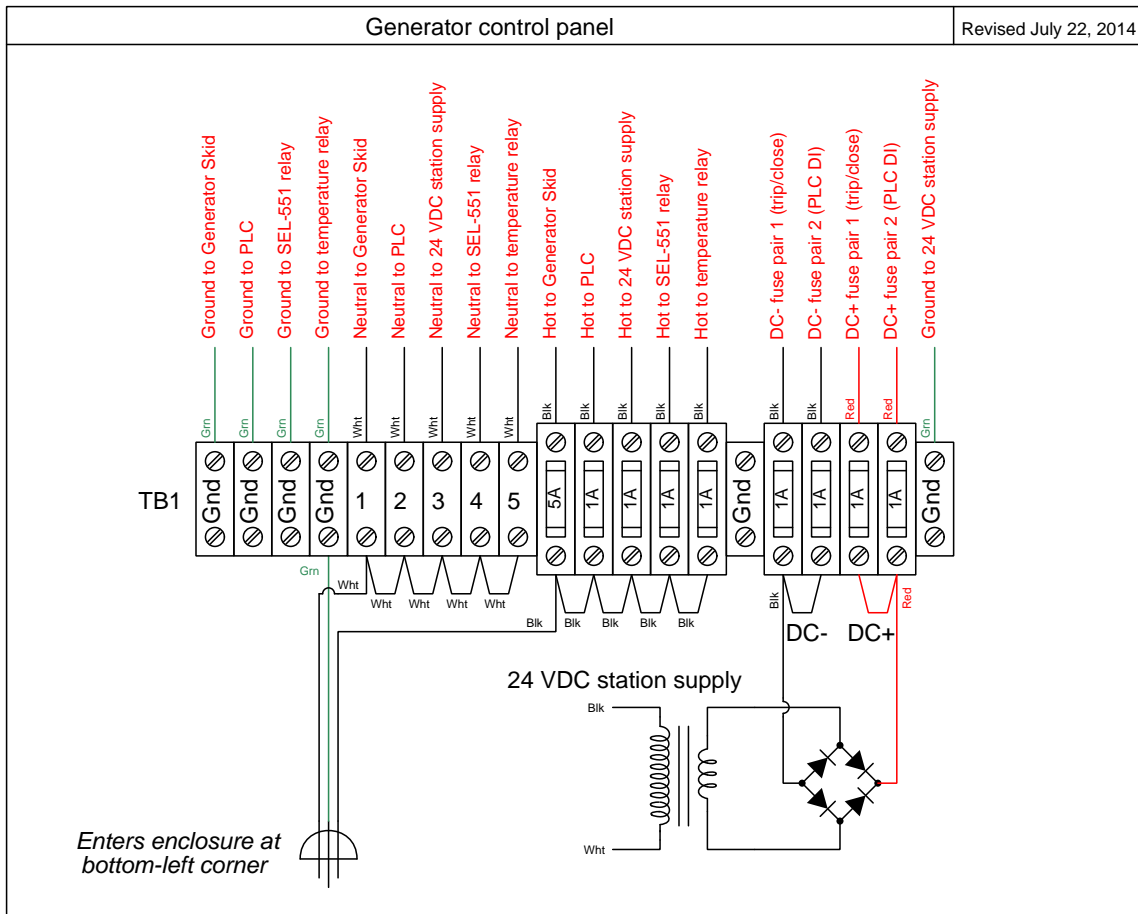
In the Instrumentation lab at Bellingham Technical College there exists a miniature three-phase AC power grid consisting of multiple generators and multiple substations. This question serves as a reference for a number of the schematic diagrams documenting each generating station in this system.

**Generator field and power wiring**



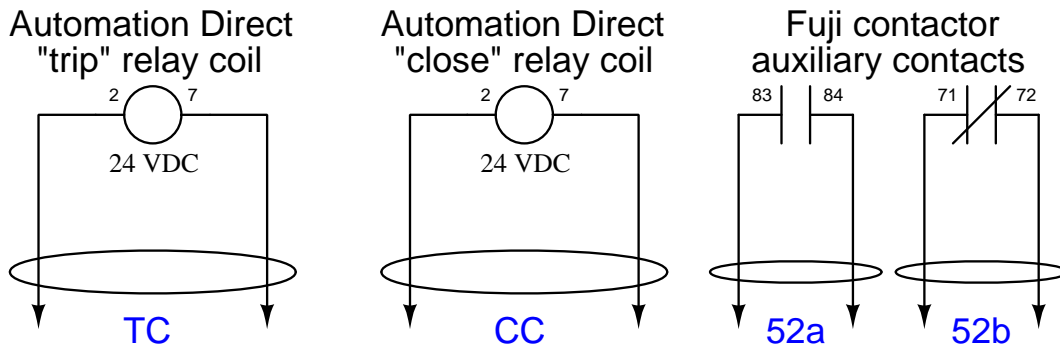
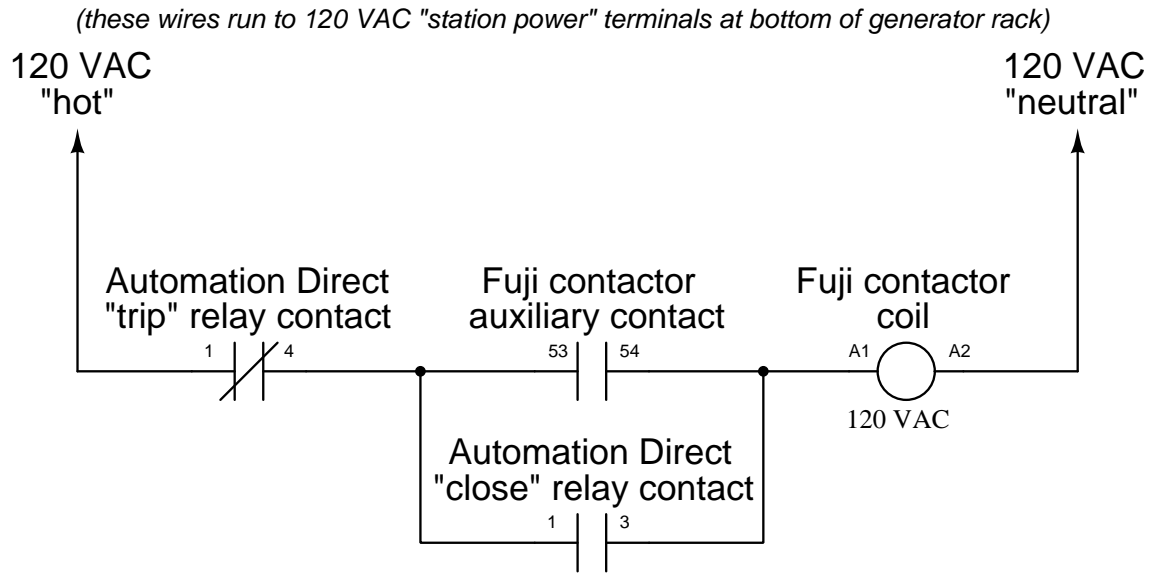
This is typical of each generator skid. At full speed (600 RPM, 60 Hz output frequency) each generator only outputs about 8 Volts AC because this is a much slower speed than it was designed to run when spun by a truck or boat engine. We run it this slow in order to achieve the standard grid frequency of 60 Hz.

# 120 VAC and DC station control power distribution



Located in the generator control panel.

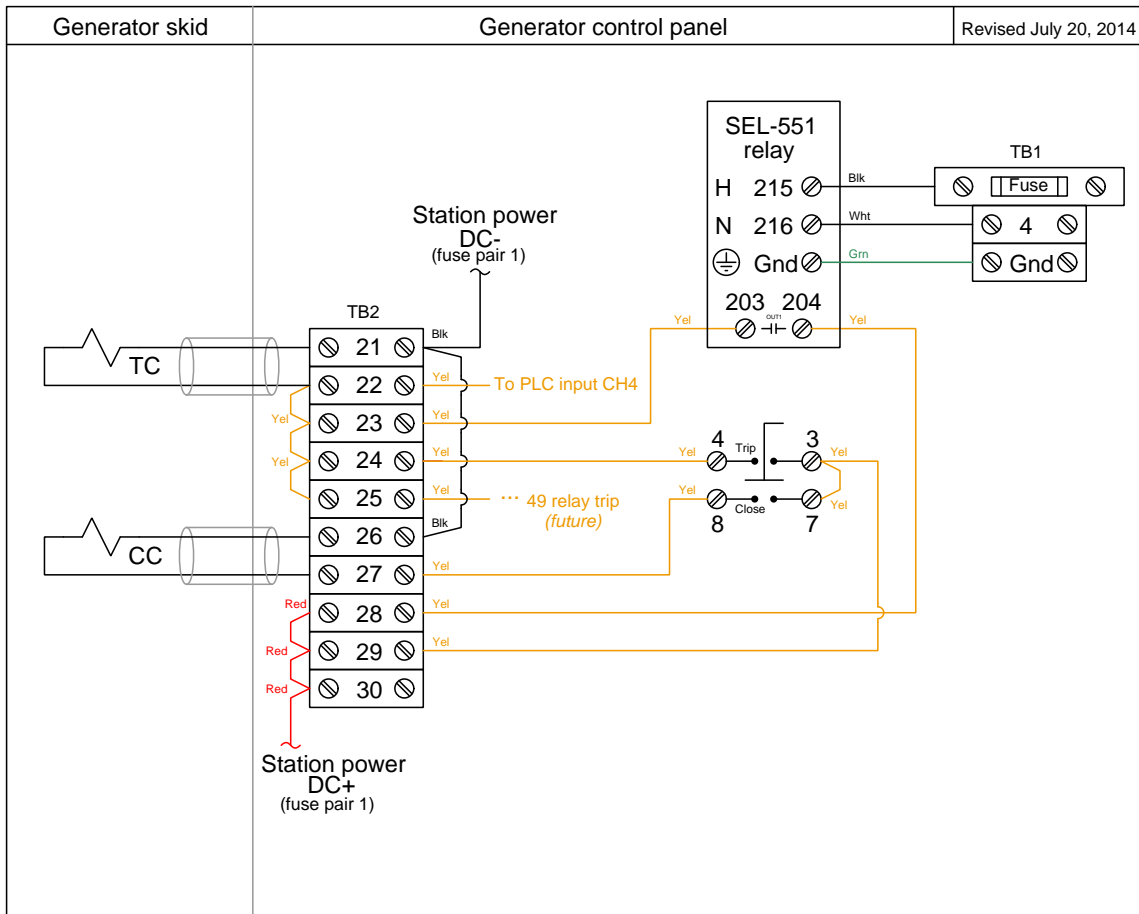
## Generator circuit breaker details



*(these two-conductor cables run to terminal blocks at bottom of generator rack)*

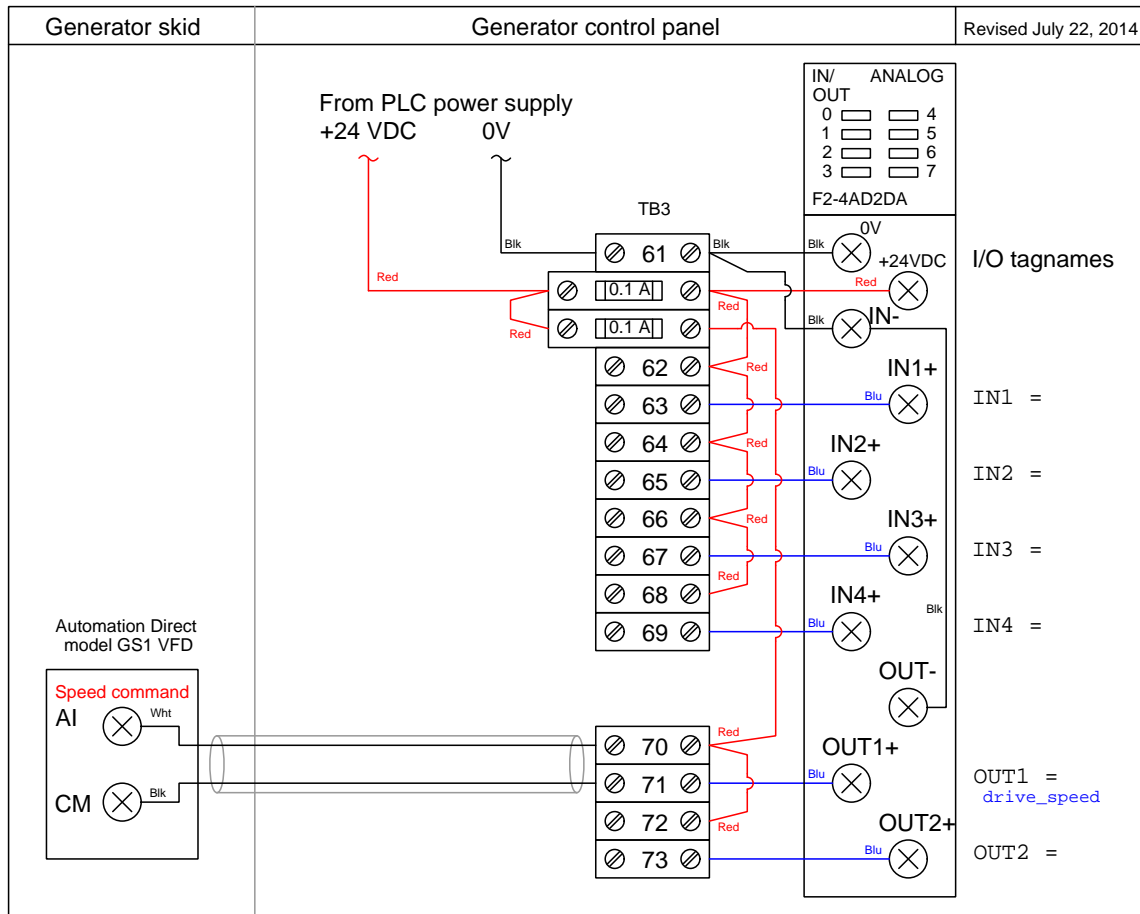
Located on the generator skid, near the very top where the three-phase AC power exits. We are using a standard Fuji 3-phase motor contactor as the circuit breaker element, and a pair of ice-cube style relays wired to latch the contactor on and off, so that the contactor mimics the behavior of a spring-actuated power circuit breaker (IEEE/ANSI number code 52).

# Trip/close wiring



Located in the generator control panel.

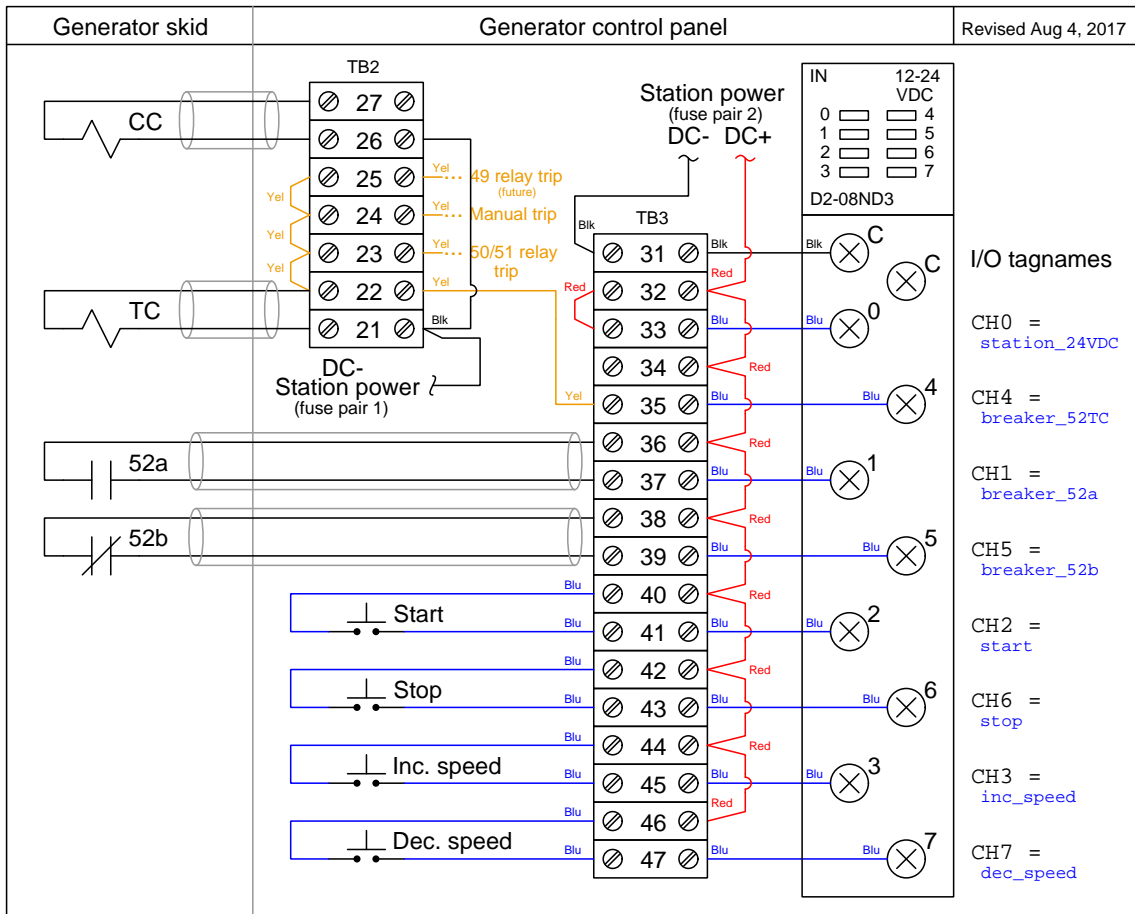
## PLC analog inputs/outputs



Located in the generator control panel. The one analog output sends a 4-20 mA speed control signal to the VFD, which then drives a three-phase motor to spin the generator. This VFD-controlled motor mimics a prime mover such as a hydro turbine or steam engine which would ordinarily be the mechanical driver for a real power station generator. The motor couples to the generator by a V-belt and sheave system with a speed reduction ratio of approximately 3:1, so the motor must spin 1800 RPM to make the generator spin 600 RPM to output 60 Hz.

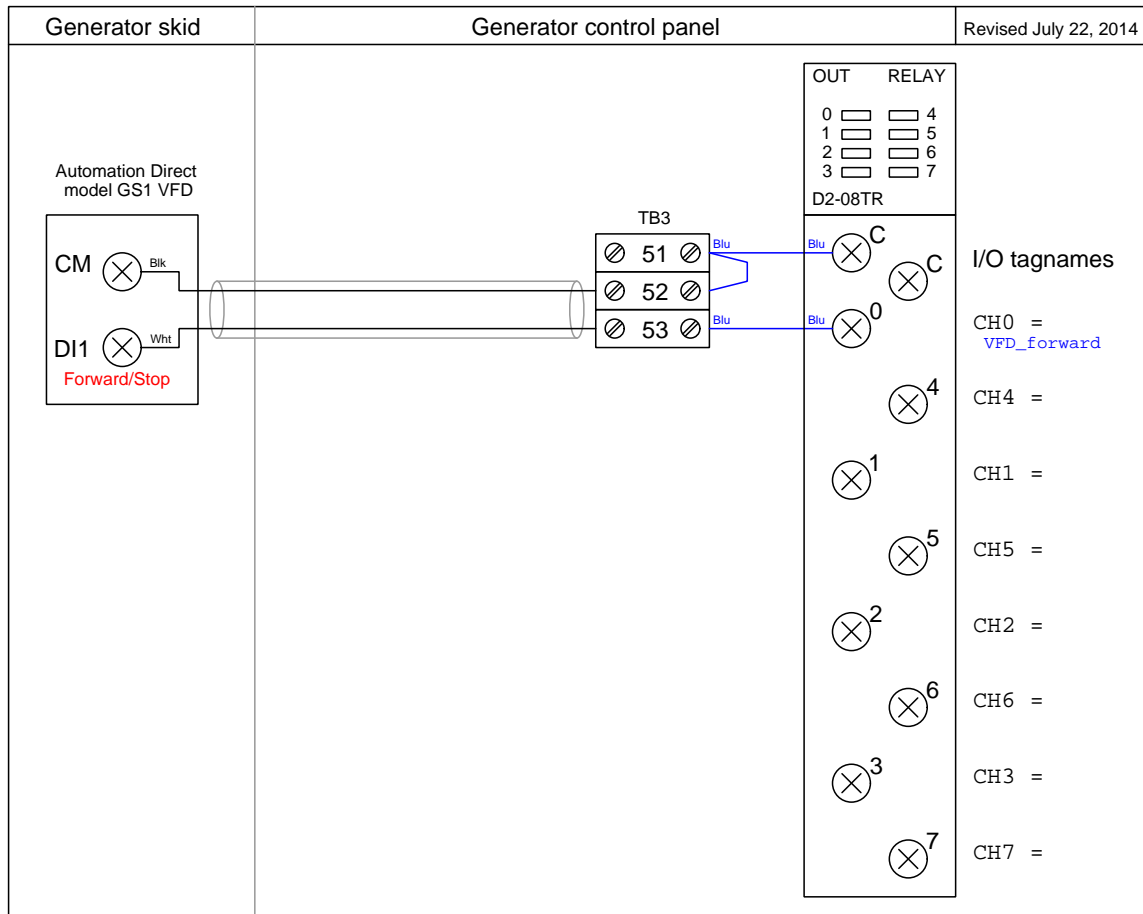


## PLC discrete inputs



Located in the generator control panel.

## PLC discrete outputs



Located in the generator control panel.  
[file i01472](#)

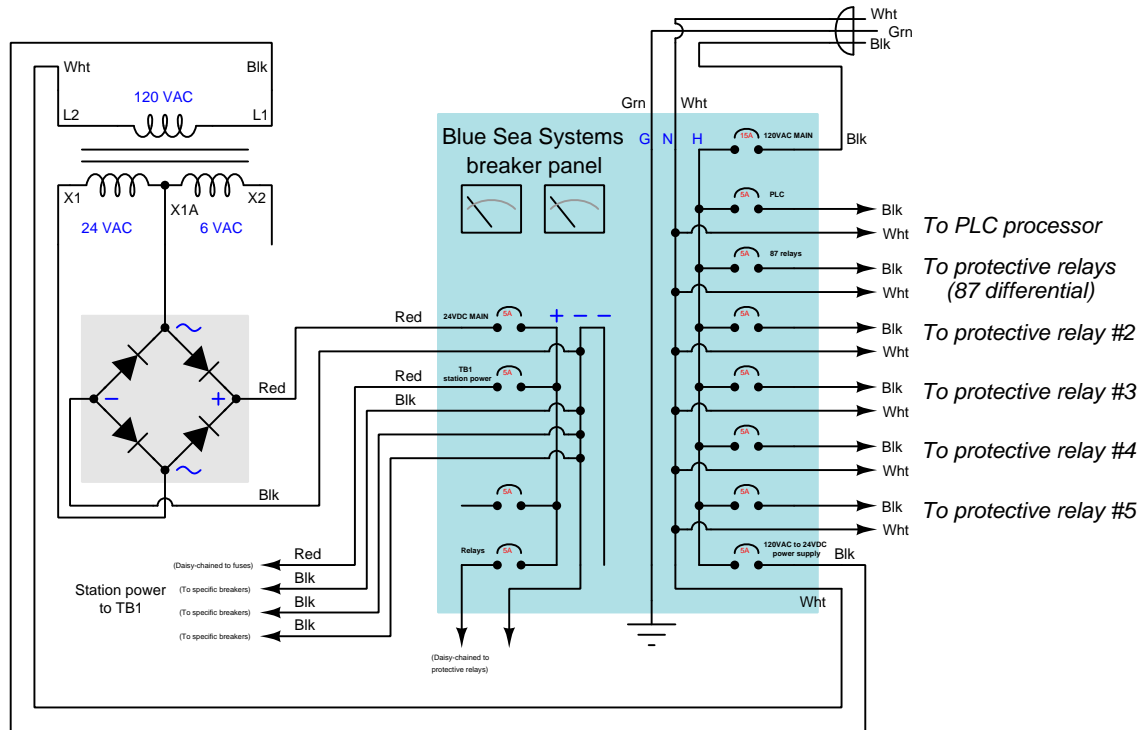
Question 93

In the Instrumentation lab at Bellingham Technical College there exists a miniature three-phase AC power grid consisting of multiple generators and multiple substations. This question serves as a reference for a number of the schematic diagrams documenting each substation in this system.

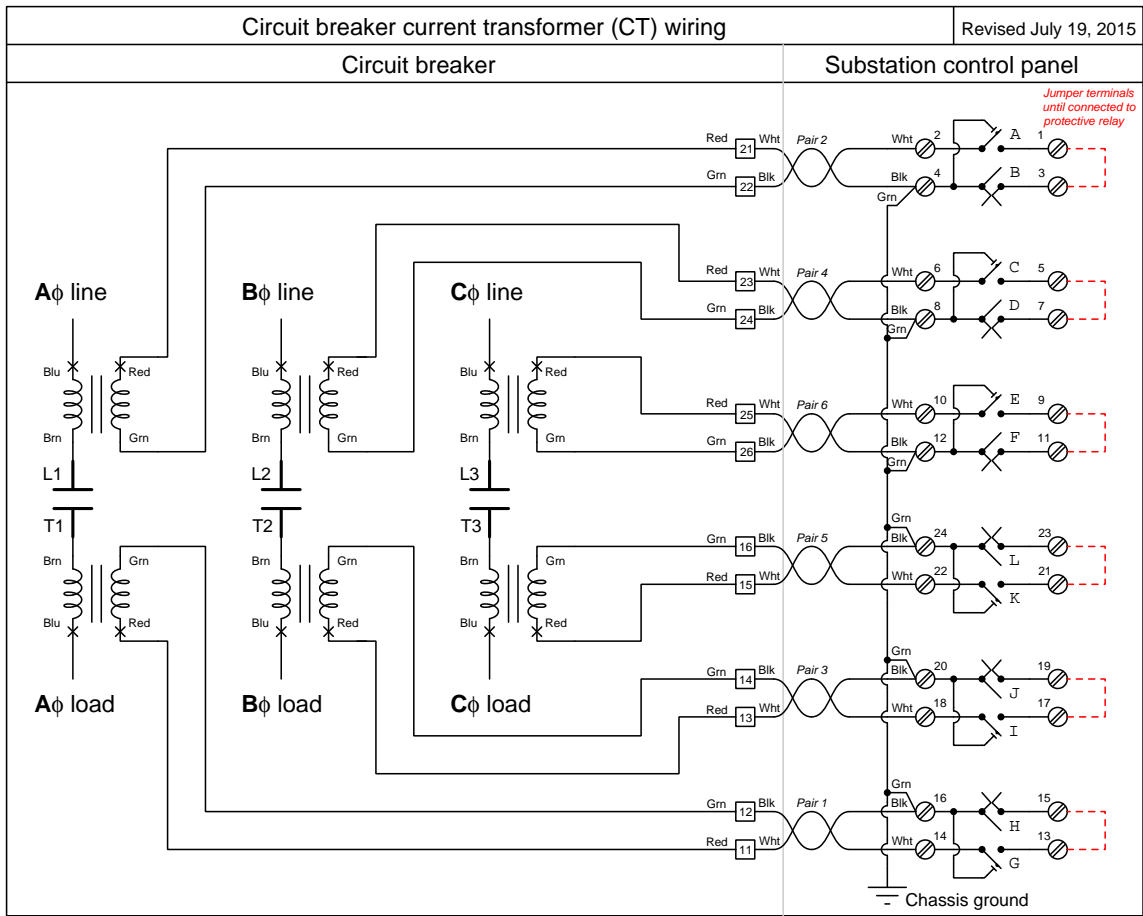
Station power diagram

Station power wiring diagram

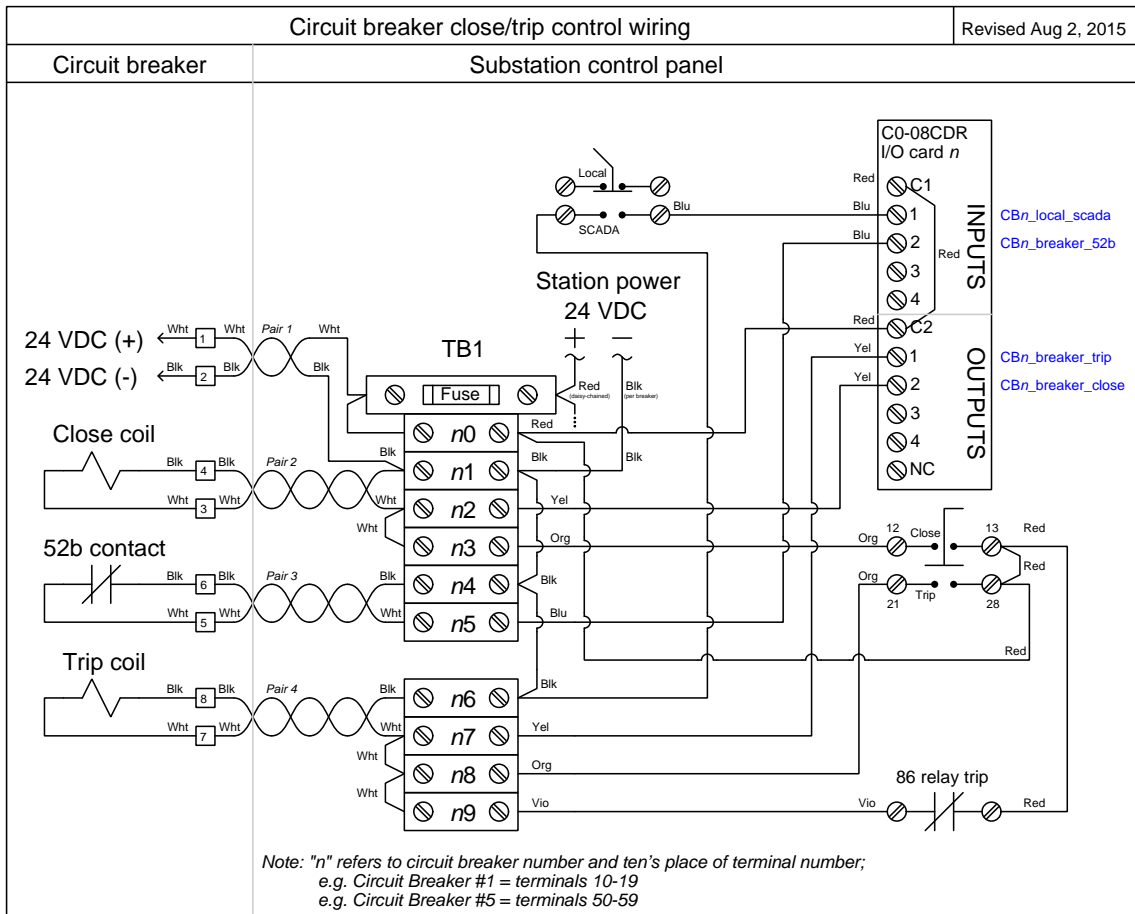
Revised August 19, 2015



# Circuit breaker current transformer (CT) wiring



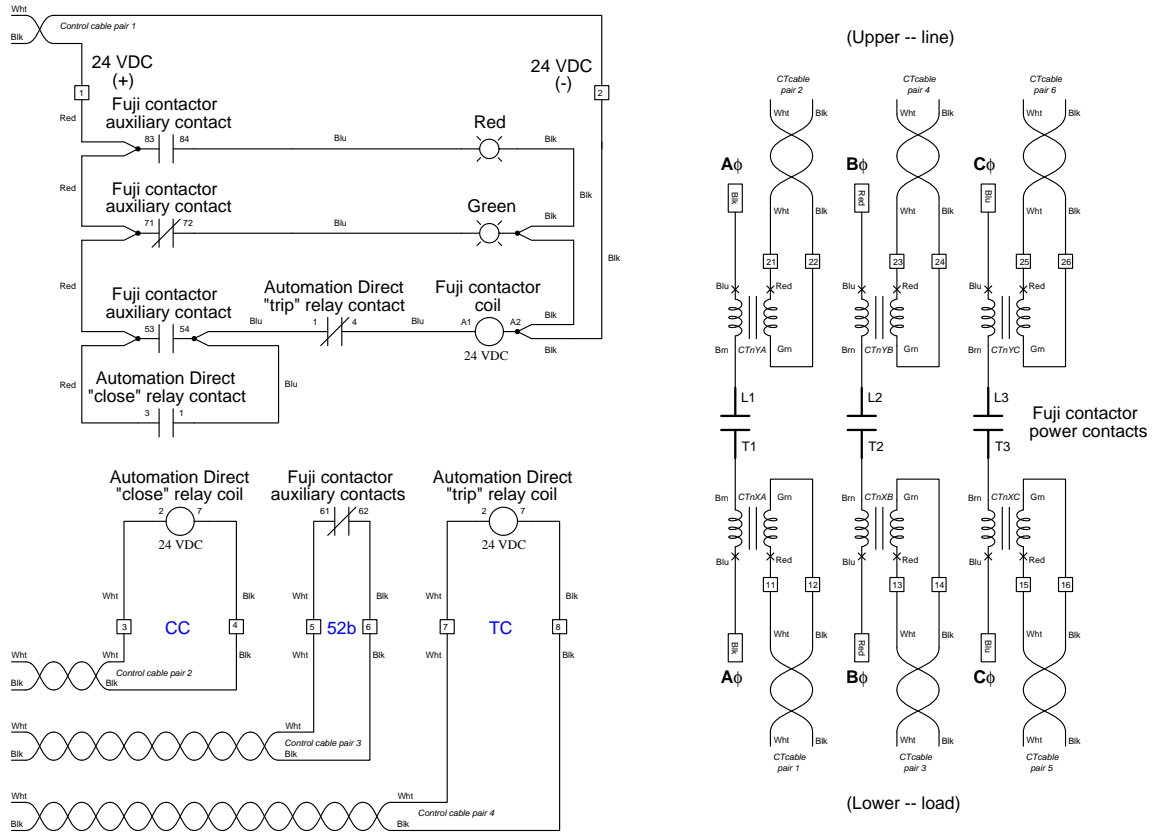
# Circuit breaker trip/close wiring



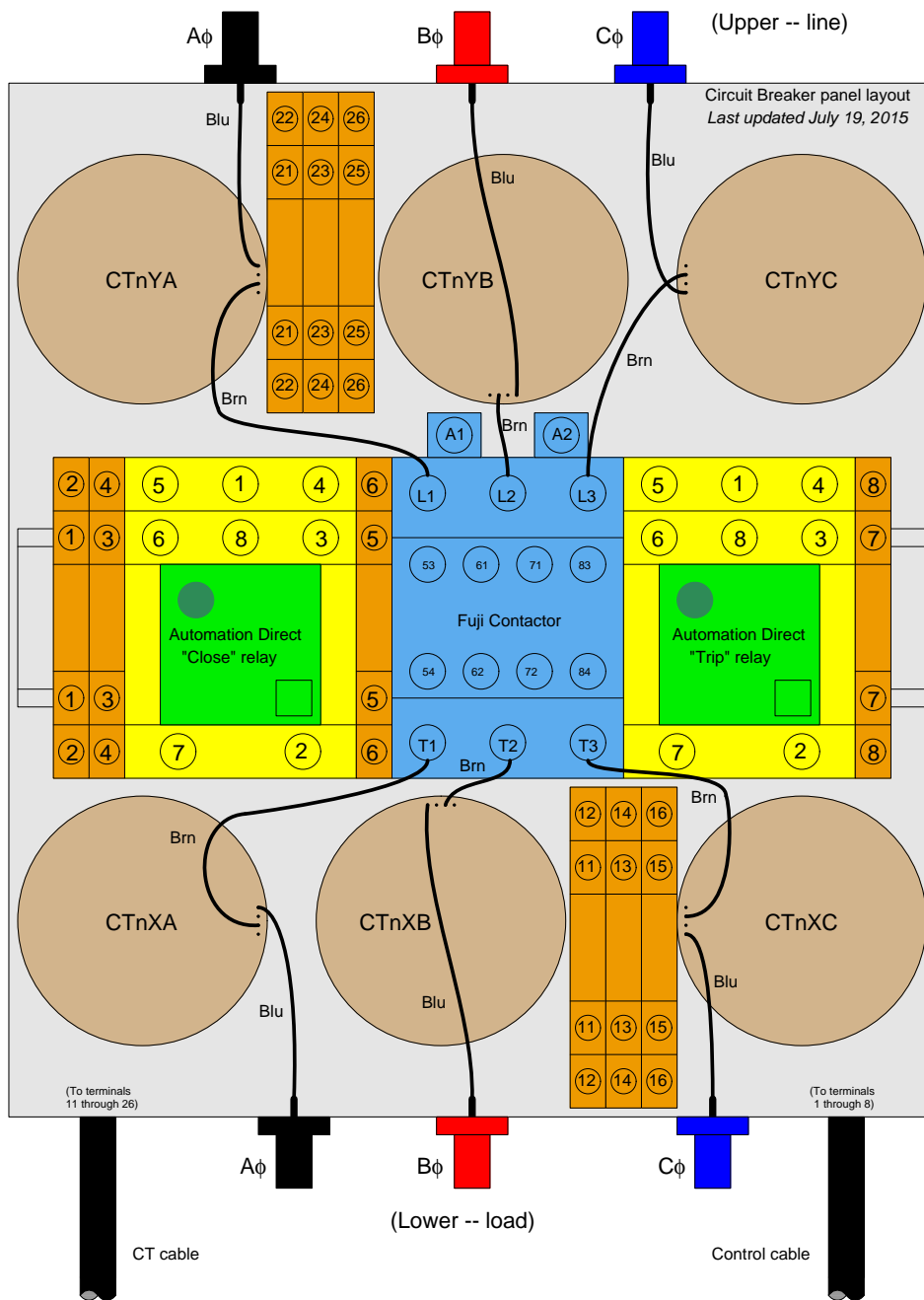
# Circuit breaker internal wiring diagram

## Circuit Breaker internal wiring diagram

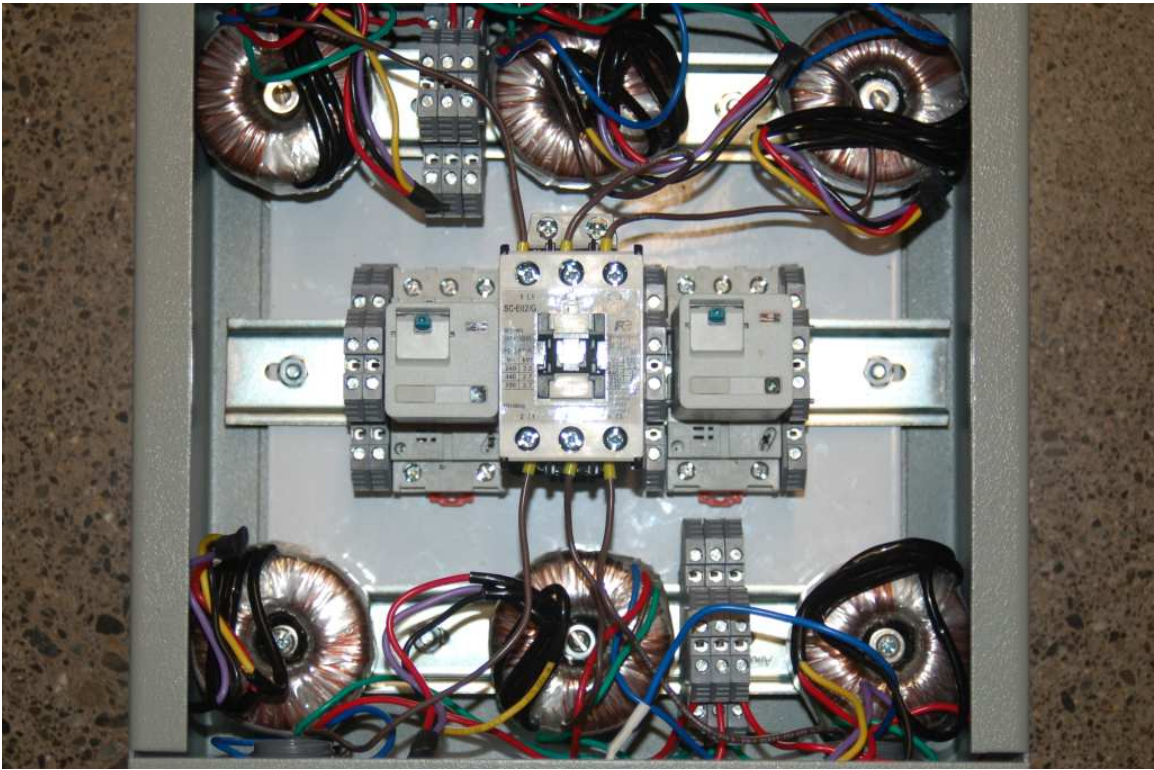
Last updated July 19, 2015



# Circuit breaker internal layout



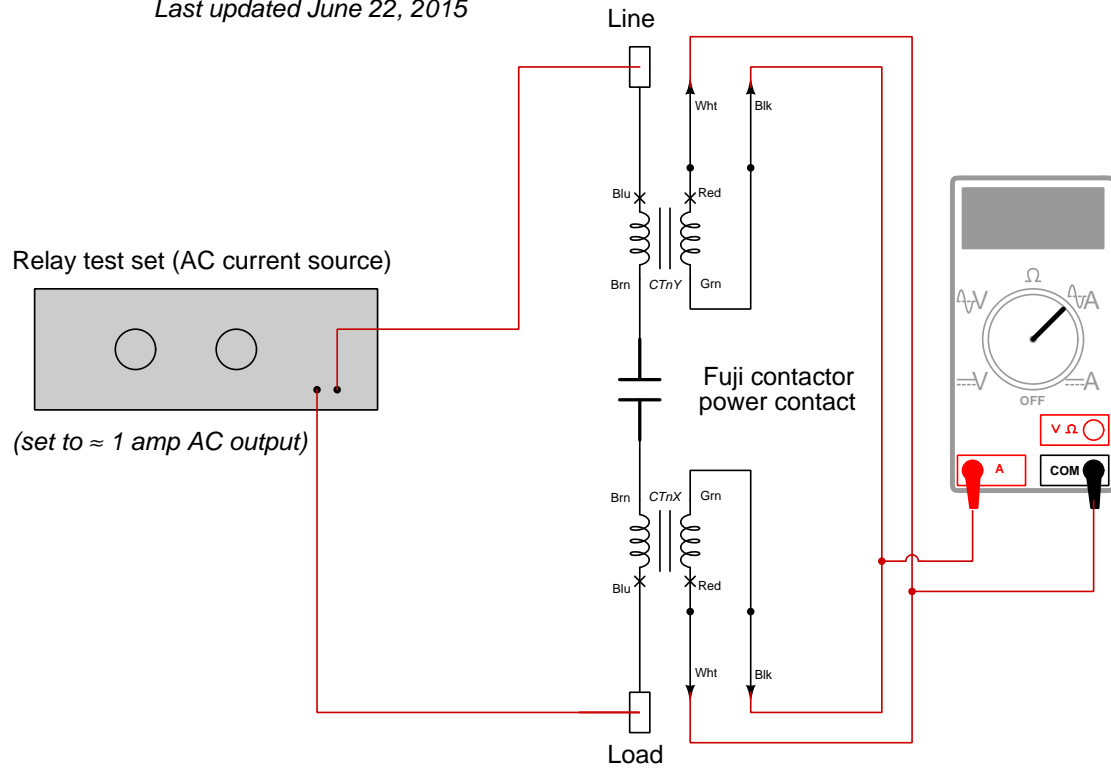
Photograph of typical circuit breaker





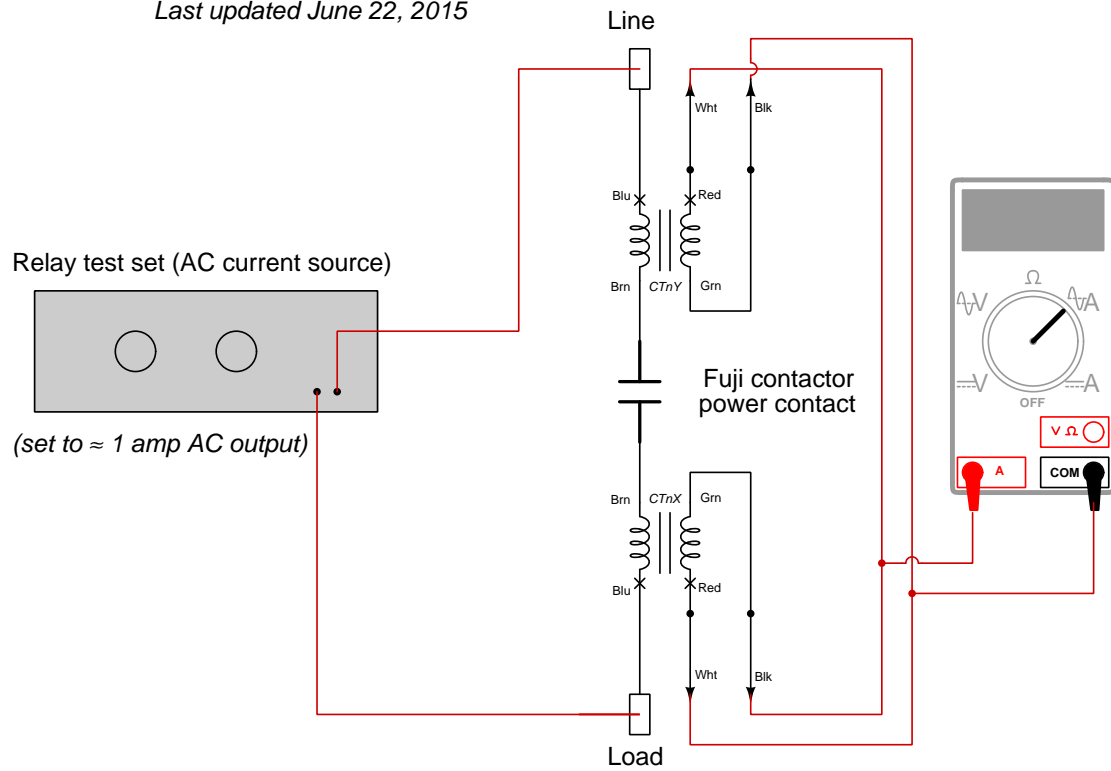
# Current transformer polarity test setup current transformer secondary windings aiding

Last updated June 22, 2015

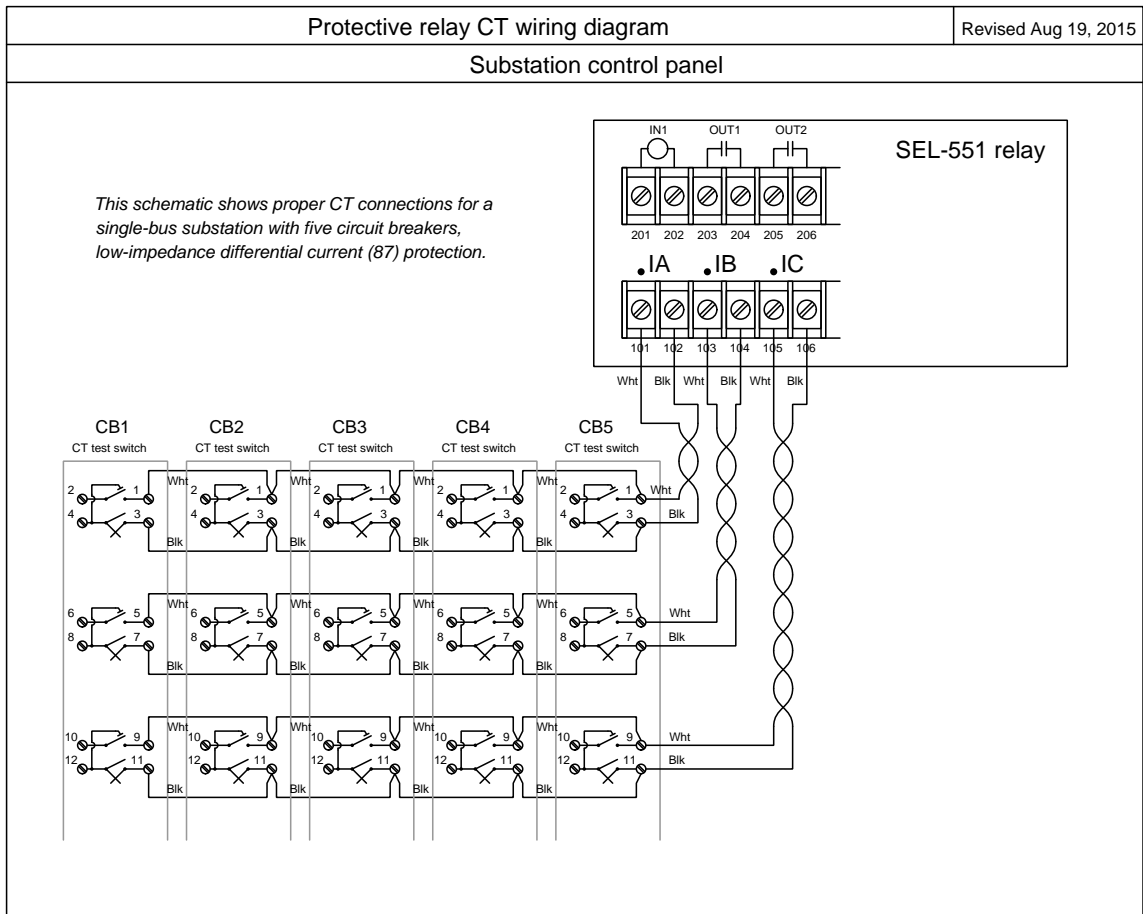


# Current transformer polarity test setup current transformer secondary windings opposing

Last updated June 22, 2015

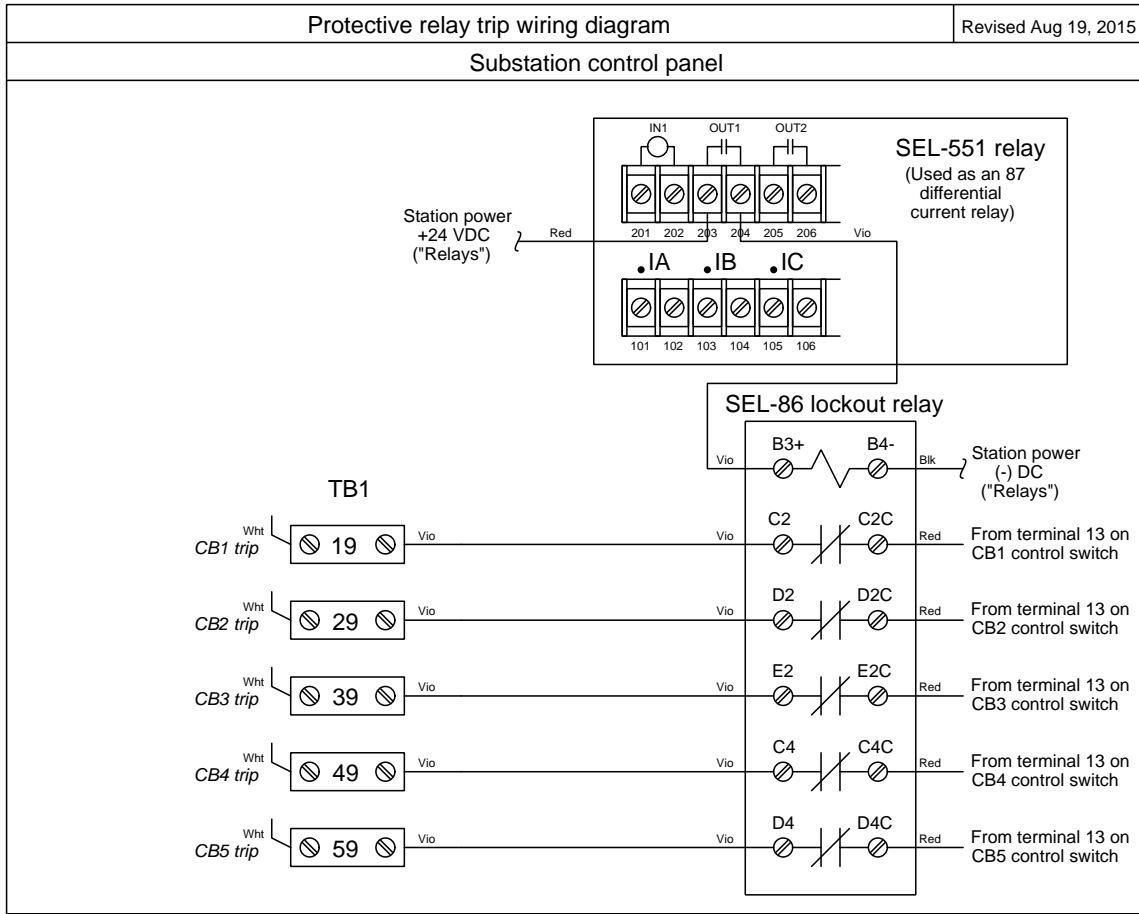


# Protective relay CT wiring



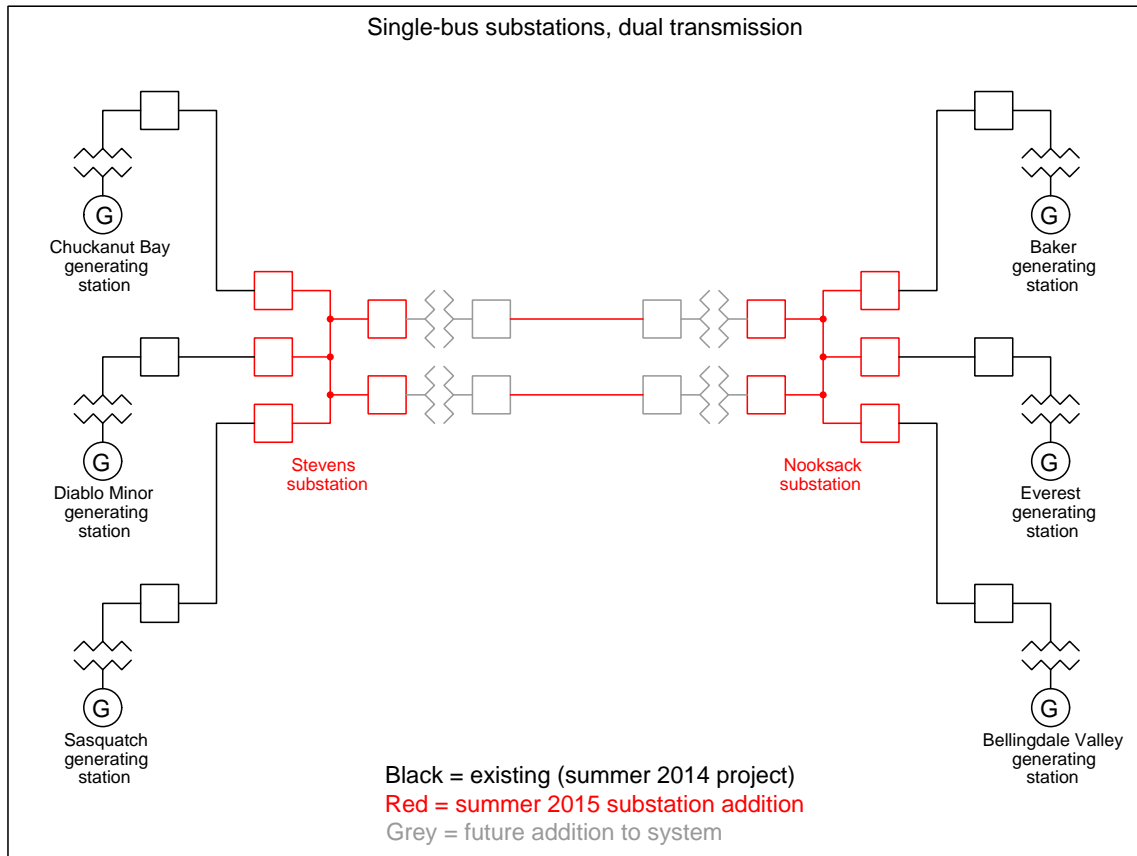
This scheme parallels all the CT secondary windings, to form a crude low-impedance version of differential current (IEEE/ANSI number code 87) protection.

# Protective relay trip wiring

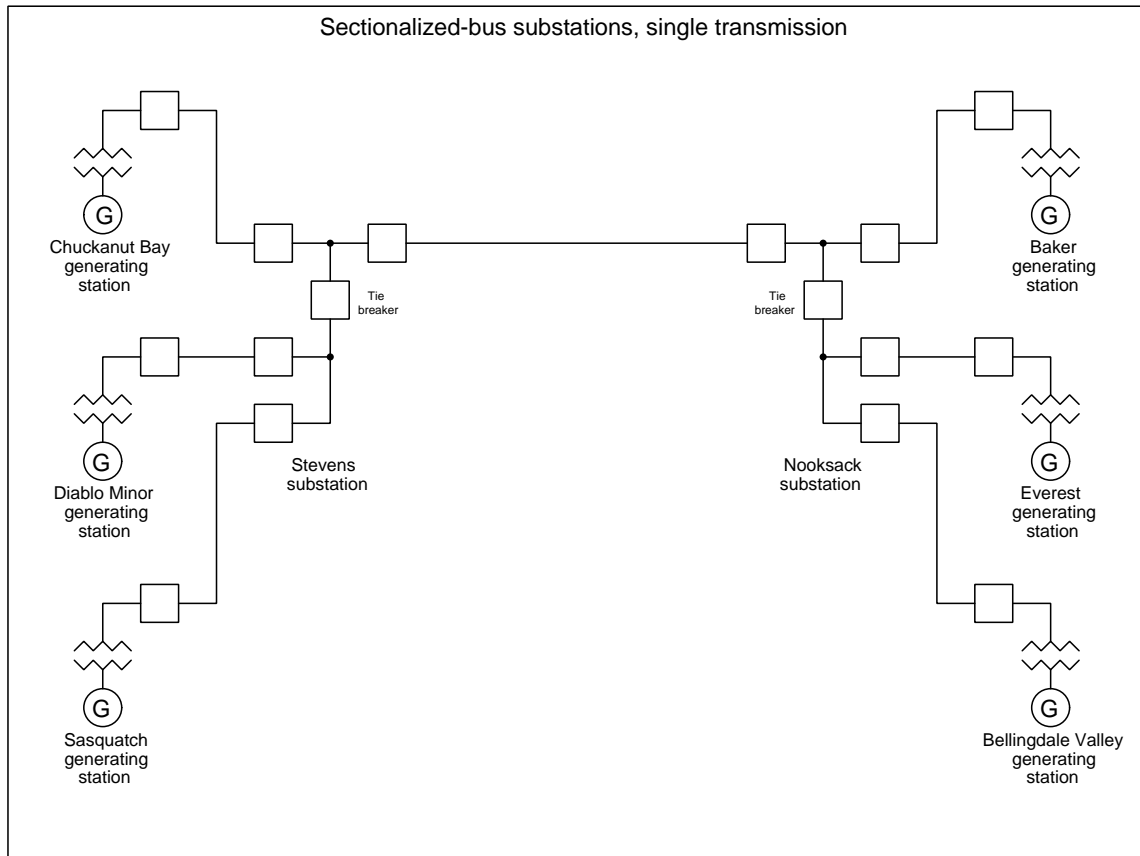


This scheme parallels all the CT secondary windings, to form a crude low-impedance version of differential current (IEEE/ANSI number code 87) protection.

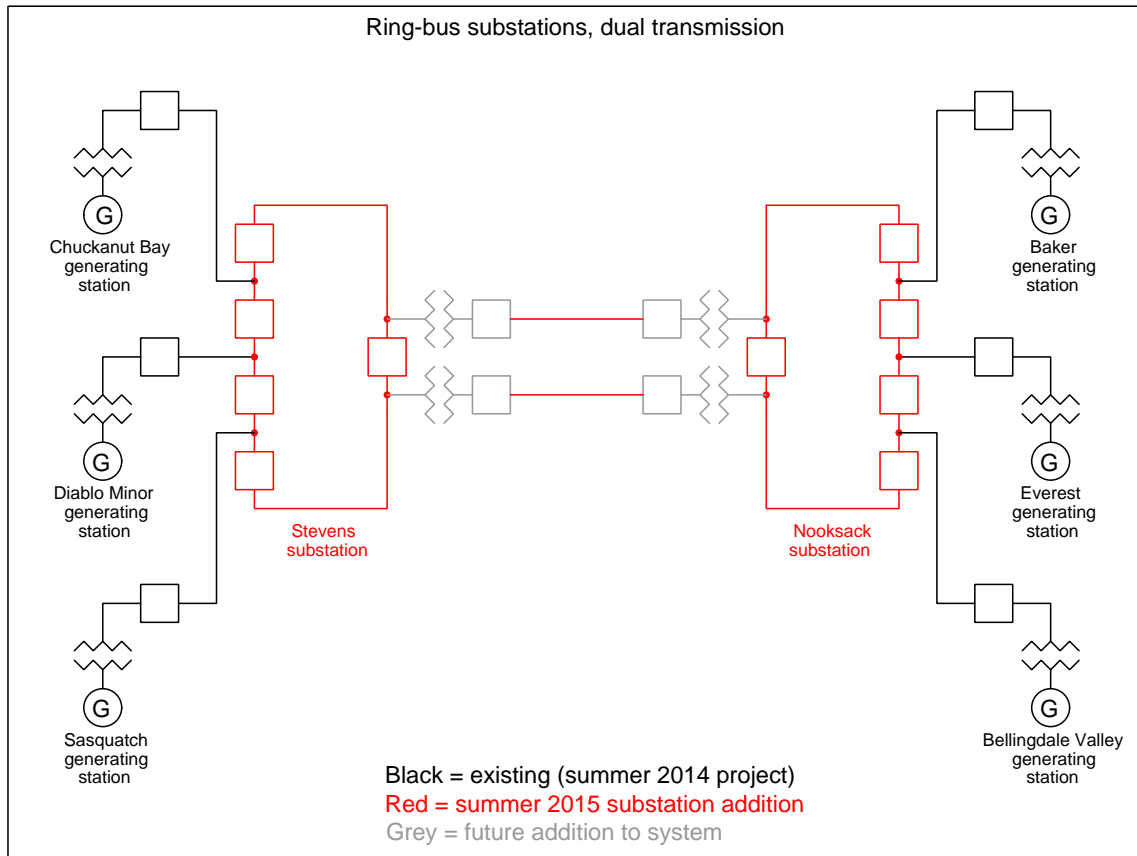
# Substation configuration option: single bus



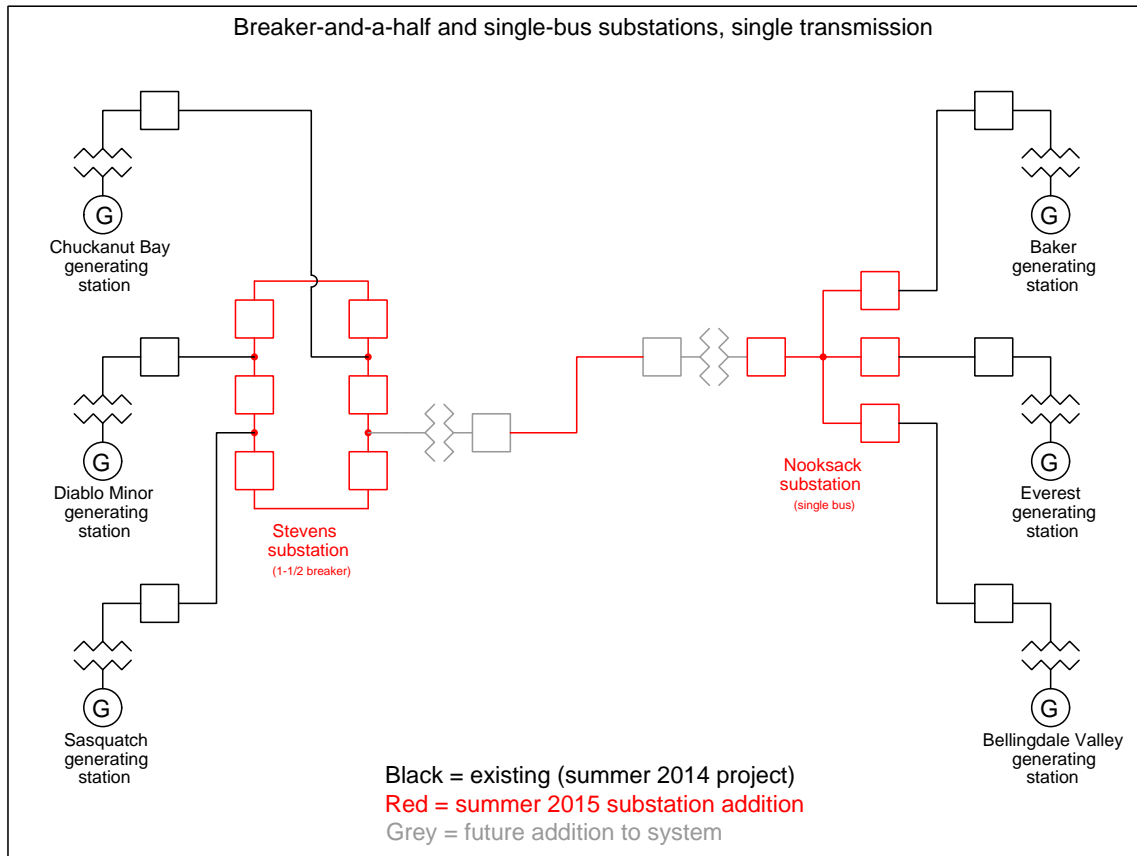
# Substation configuration option: sectionalized bus



# Substation configuration option: ring bus

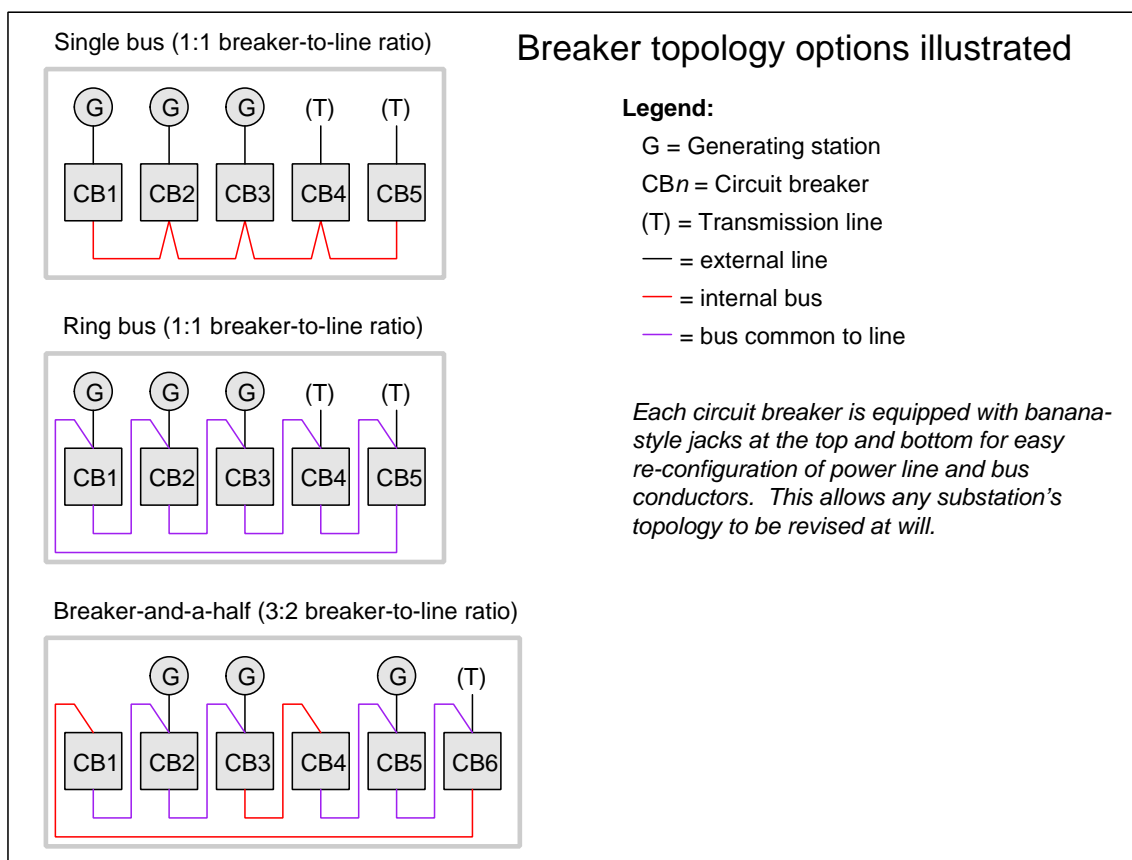


# Substation configuration option: breaker-and-a-half





## Substation breaker options illustrated



Choosing between different breaker and bus topologies is a matter of moving jumper wires on the three-phase line and load terminals on each breaker.

[file i01983](#)

Answer 1

**Summary of principles:**

- Conservation of Energy
  - Energy cannot be created or destroyed
- Conservation of Electric Charge
  - Electric charges cannot be created or destroyed
- Properties of a series network
  - Definition: *only one path for electric current*
  - Current the same through each component (Conservation of Electric Charge)
  - Voltages add to equal the total (Conservation of Energy)
  - Resistances add to equal to total
- Properties of a parallel network
  - Definition: *each component connected across the same two sets of electrically common points*
  - Voltage the same across each component (Conservation of Energy)
  - Currents add to equal the total (Conservation of Electric Charge)
  - Resistances diminish to equal to total
- Kirchhoff's Voltage Law (KVL)
  - A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)
- Kirchhoff's Current Law (KCL)
  - Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)
- Ohm's Law
  - The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it:  $V = IR$
- Capacitance and Inductance
  - The ability to store energy in and retrieve energy from electric fields and magnetic fields, respectively
  - Current through capacitance is equal to the product of its capacitance and the rate-of-change of voltage across it:  $I = C \frac{dV}{dt}$
  - Voltage across inductance is equal to the product of its inductance and the rate-of-change of current through it:  $V = L \frac{dI}{dt}$

---

Answer 2

---

Answer 3

---

Answer 4

---

Answer 5

Answer 6

**Addition and subtraction:**

$$(5 + j6) + (2 - j1) = \\ \mathbf{7 + j5}$$

$$(10 - j8) + (4 - j3) = \\ \mathbf{14 - j11}$$

$$(-3 + j0) + (9 - j12) = \\ \mathbf{6 - j12}$$

$$(3 + j5) - (0 - j9) = \\ \mathbf{3 + j14}$$

$$(25 - j84) - (4 - j3) = \\ \mathbf{21 - j81}$$

$$(-1500 + j40) + (299 - j128) = \\ \mathbf{-1201 - j88}$$

$$(25\angle 15^\circ) + (10\angle 74^\circ) = \\ \mathbf{31.35\angle 30.87^\circ}$$

$$(1000\angle 43^\circ) + (1200\angle -20^\circ) = \\ \mathbf{1878.7\angle 8.311^\circ}$$

$$(522\angle 71^\circ) - (85\angle 30^\circ) = \\ \mathbf{461.23\angle 77.94^\circ}$$

**Multiplication and division:**

$$(25\angle 15^\circ) \times (12\angle 10^\circ) = \\ \mathbf{300\angle 25^\circ}$$

$$(1\angle 25^\circ) \times (500\angle -30^\circ) = \\ \mathbf{500\angle -5^\circ}$$

$$(522\angle 71^\circ) \times (33\angle 9^\circ) = \\ \mathbf{17226\angle 80^\circ}$$

$$\frac{10\angle -80^\circ}{1\angle 0^\circ} = \\ \mathbf{10\angle -80^\circ}$$

$$\frac{25\angle 120^\circ}{3.5\angle -55^\circ} = \\ \mathbf{7.142\angle 175^\circ}$$

$$\frac{-66\angle 67^\circ}{8\angle -42^\circ} = \\ \mathbf{8.25\angle -71^\circ}$$

$$(3 + j5) \times (2 - j1) = \\ \mathbf{11 + j7}$$

$$(10 - j8) \times (4 - j3) = \\ \mathbf{16 - j62}$$

$$\frac{(3+j4)}{(12-j2)} = \\ \mathbf{0.1892 + j0.3649}$$

**Reciprocation:**

$$\frac{1}{(15\angle 60^\circ)} = \\ \mathbf{0.0667\angle -60^\circ}$$

$$\frac{1}{(750\angle -38^\circ)} = \\ \mathbf{0.00133\angle 38^\circ}$$

$$\frac{1}{(10+j3)} = \\ \mathbf{0.0917 - j0.0275}$$

$$\frac{1}{\frac{1}{15\angle 45^\circ} + \frac{1}{92\angle -25^\circ}} = \\ \mathbf{14.06\angle 36.74^\circ}$$

$$\frac{1}{\frac{1}{1200\angle 73^\circ} + \frac{1}{574\angle 21^\circ}} = \\ \mathbf{425.7\angle 37.23^\circ}$$

$$\frac{1}{\frac{1}{23k\angle -67^\circ} + \frac{1}{10k\angle -81^\circ}} = \\ \mathbf{7.013k\angle -76.77^\circ}$$

$$\frac{1}{\frac{1}{110\angle -34^\circ} + \frac{1}{80\angle 19^\circ} + \frac{1}{70\angle 10^\circ}} = \\ \mathbf{29.89\angle 2.513^\circ}$$

$$\frac{1}{\frac{1}{89k\angle -5^\circ} + \frac{1}{15k\angle 33^\circ} + \frac{1}{9.35k\angle 45^\circ}} = \\ \mathbf{5.531k\angle 37.86^\circ}$$

$$\frac{1}{\frac{1}{512\angle 34^\circ} + \frac{1}{1k\angle -25^\circ} + \frac{1}{942\angle -20^\circ} + \frac{1}{2.2k\angle 44^\circ}} = \\ \mathbf{256.4\angle 9.181^\circ}$$

Some Texas Instruments brand calculators such as the TI-84 offer an exponential key and imaginary ( $i$ ) key which allows you to enter numbers in complex exponential form (i.e.  $e^{i\theta}$ ). With the TI-84, for example, the complex number  $10 - j8$  may be entered in either of the two following forms:

$$(10 - i8) \quad \text{or} \quad (10 - 8i)$$

The result may be displayed in either rectangular or polar forms according to the complex-number display *mode* the TI-84 calculator has been set to. In rectangular mode the displayed result for  $10 - j8$  will be  $10 - 8i$ , whereas in polar mode the displayed result will be  $12.806 e^{-38.66i}$ . Note how the TI-84 uses exponential notation for polar display, where the angle ( $-38.66$  degrees, in this example) is an imaginary power of  $e$ .

If you wish to enter a complex number in polar form on a TI-84, you must unfortunately express the angle in units of *radians* (even though the calculator is able to display the result in *degrees*). For example, to enter the number  $25 \angle 15^\circ$  into a TI-84 calculator, you must type:

$$25 e^{i15\pi/180}$$

The fraction  $\pi/180$  is the conversion factor from degrees to radians, since there are  $2\pi$  radians to a full circle, or  $\pi$  radians to every 180 degrees. Thus, writing  $15\pi/180$  multiplies the desired angle (15 degrees) by the conversion factor  $\pi/180$  to yield a power in radians. The obligatory  $i$  simply makes this power an imaginary quantity, which is mathematically necessary with exponential notation for describing a complex number. It should be noted that the order of entry for the power matters little.  $i15\pi/180$  works just as well as  $15i\pi/180$  or  $15\pi/180i$ .

A time-saving step some students find useful is to save the imaginary quantity  $i\pi/180$  to a memory location in the TI-84 such as Z. That way, they can recall that imaginary factor from memory instead of typing the whole thing by hand every time they wish to enter a polar-form complex number. Supposing the memory location Z contains  $i\pi/180$ , entering the number  $25 \angle 15^\circ$  becomes as simple as:

$$25 e^{15Z} \quad \text{or} \quad 25 e^{Z15}$$

It should be understood that *any* memory location in your calculator is suitable for storing  $i\pi/180$ , not just Z. The TI-84 calculator even provides a  $\Theta$  memory location ( $\langle \text{Alpha} \rangle - \langle 3 \rangle$ ) that you may use and find easy to remember because of its common association with angles. It should also be understood that this imaginary quantity is not the same as  $i$  or  $j$ , which the calculator already provides a dedicated function for. The imaginary quantity we're storing in memory for the purpose of entering polar-notation angles contains not only  $i$  but also the  $\pi/180$  conversion factor necessary for translating your *degree* entry into *radians*.

Some calculators provide easier means of entering and displaying complex numbers in polar form. Both the Texas Instruments TI-36X Pro and TI-89 offer an angle symbol ( $\angle$ ) for this purpose, the TI-36X Pro being a much less expensive and less complex calculator than the TI-89. Entering the number  $25 \angle 15^\circ$  into one of these calculators is as easy as typing  $25 \angle 15$ , and likewise the result will be displayed in this same form when the calculator is set to "polar" complex mode.

---

Answer 7

**Partial answer:**

--	<i>R</i>	<i>L</i>	Total
<i>V</i> (polar)	501.68 V $\angle -17.14^\circ$		525 V $\angle 0^\circ$
<i>V</i> (rect.)		45.61 + j147.87 V	525 + j0 V
<i>I</i> (polar)			
<i>I</i> (rect.)			145.27 m – j44.81 mA
<i>Z</i> (polar)		1.018 k $\Omega$ $\angle 90^\circ$	
<i>Z</i> (rect.)	3.3 k + j0 $\Omega$		3.3 k + j1.018 k $\Omega$

---

Answer 8

**Partial answer:**

--	<i>L</i>	<i>C</i>	Total
<i>V</i> (polar)	600 V $\angle 0^\circ$	600 V $\angle 0^\circ$	600 V $\angle 0^\circ$
<i>V</i> (rect.)	600 + j0 V	600 + j0 V	600 + j0 V
<i>I</i> (polar)		2.398 A $\angle 90^\circ$	
<i>I</i> (rect.)	0 – j3.183 A		0 – j0.785 A
<i>Z</i> (polar)	188.5 $\Omega$ $\angle 90^\circ$		763.9 $\Omega$ $\angle 90^\circ$
<i>Z</i> (rect.)		0 – j250.2 $\Omega$	

- Conservation of Energy
  - Energy cannot be created or destroyed
- Conservation of Electric Charge
  - Electric charges cannot be created or destroyed
- Properties of a series network
  - Definition: *only one path for electric current*
  - Current the same through each component (Conservation of Electric Charge)
  - Voltages add to equal the total (Conservation of Energy)
  - Resistances add to equal to total
- Properties of a parallel network
  - Definition: *each component connected across the same two sets of electrically common points*
  - Voltage the same across each component (Conservation of Energy)
  - Currents add to equal the total (Conservation of Electric Charge)
  - Resistances diminish to equal to total
- Kirchhoff's Voltage Law (KVL)
  - A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)
- Kirchhoff's Current Law (KCL)
  - Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)
- Ohm's Law
  - The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it:  $V = IR$

Sample analysis:

- Apply property of series networks (current same) to determine 3 A through the resistor; voltage drop polarity based on the fact that resistors are always loads
- Apply Ohm's Law to calculate 6 V drop across resistor
- Apply KVL to calculate 14 V across constant current component; polarity shows it is acting as a source
- Apply property of series networks (current same) to determine 3 A through the 8 V component; polarity shows it is acting as a load

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  - Resistances diminish to equal to total
- Kirchhoff's Voltage Law (KVL)
  - A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)
- Kirchhoff's Current Law (KCL)
  - Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)
- Ohm's Law
  - The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it:  $V = IR$

Sample analysis:

- Apply property of parallel networks (voltage same) to determine 8 V drop across the resistor; current direction based on the fact that resistors are always loads
- Apply Ohm's Law to calculate 4 A current through resistor
- Apply KCL to calculate 1 A entering/exiting each node through the 8 V component; current direction shows it is acting as a source
- Apply property of parallel networks (voltage same) to determine 8 V drop across the 3 A component; polarity shows it is acting as a source

---

Answer 11

- Conservation of Energy
  - Energy cannot be created or destroyed
- Conservation of Electric Charge
  - Electric charges cannot be created or destroyed
- Properties of a series network
  - Definition: *only one path for electric current*
  - Current the same through each component (Conservation of Electric Charge)
  - Voltages add to equal the total (Conservation of Energy)
  - Resistances add to equal to total
- Properties of a parallel network
  - Definition: *each component connected across the same two sets of electrically common points*
  - Voltage the same across each component (Conservation of Energy)
  - Currents add to equal the total (Conservation of Electric Charge)
  - Resistances diminish to equal to total
- Kirchhoff's Voltage Law (KVL)
  - A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)
- Kirchhoff's Current Law (KCL)
  - Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)
- Ohm's Law
  - The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it:  $V = IR$

Sample analysis:

- Apply KCL to calculate 17 mA entering bottom node through 100  $\Omega$  resistor
- Apply Ohm's Law to calculate 1.7 V drop across 100  $\Omega$  resistor; polarity determined by the fact that a resistor is always a load
- Apply property of series networks (current same) and Ohm's Law to calculate 1 V drop across 200  $\Omega$  resistor; polarity determined by the fact that a resistor is always a load
- Apply property of series networks (current same) to determine that the 30 V component is acting as a source
- Apply KVL to calculate 2.7 V across 5 mA component; polarity shows it is acting as a source
- Apply KVL to calculate 28.3 V across 12 mA component; polarity shows it is acting as a load

---

Answer 12

- $V_{R1} = \text{increase}$
- $V_{R2} = \text{increase}$
- $V_{R3} = \text{decrease}$
- $V_{R4} = \text{decrease}$



---

Answer 13

**Series network**

100k = Coarse adjustment ; 5k = Fine adjustment

**Parallel network**

5k = Coarse adjustment ; 100k = Fine adjustment

General principles to keep in mind here are that series resistances *add* while parallel resistances *diminish*. The total resistance of a series network is always greater than any of its constituent resistances, and so the largest resistance in a series network tends to dominate. The total resistance of a parallel network is always less than any of its constituent resistances, and so the least resistance in a parallel network tends to dominate.

---

Answer 14

**First strategy:**

$$L_{total} = 1.1 \text{ H}$$

$$X_{total} = 414.7 \Omega$$

$$\mathbf{Z}_{total} = 414.7 \Omega \angle 90^\circ \text{ or } \mathbf{Z}_{total} = 0 + j414.7 \Omega$$

**Second strategy:**

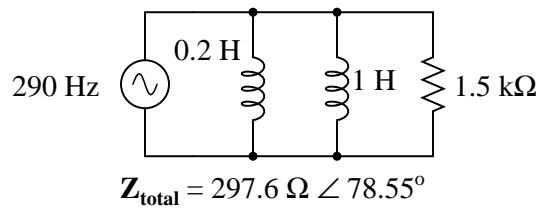
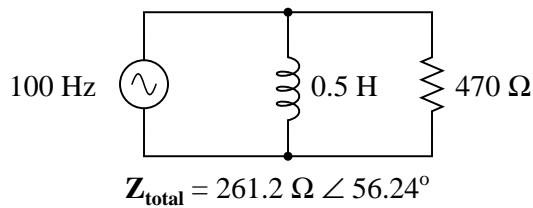
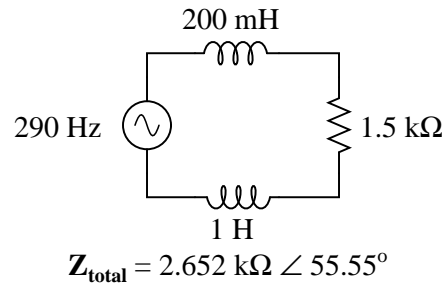
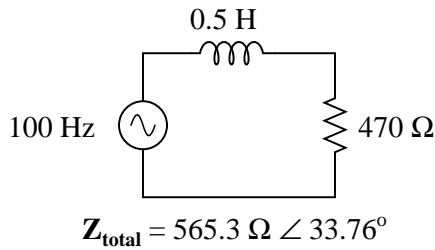
$$X_{L1} = 282.7 \Omega \quad \mathbf{Z}_{L1} = 282.7 \Omega \angle 90^\circ$$

$$X_{L2} = 131.9 \Omega \quad \mathbf{Z}_{L2} = 131.9 \Omega \angle 90^\circ$$

$$\mathbf{Z}_{total} = 414.7 \Omega \angle 90^\circ \text{ or } \mathbf{Z}_{total} = 0 + j414.7 \Omega$$

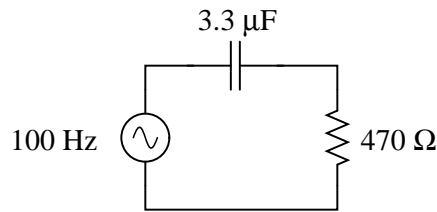
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Answer 15

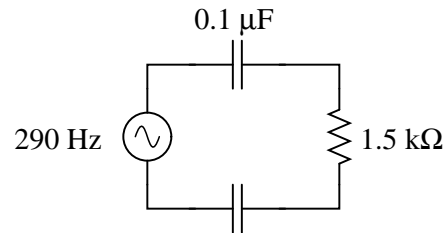


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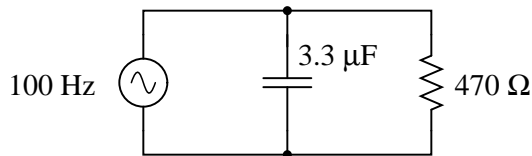
Answer 16



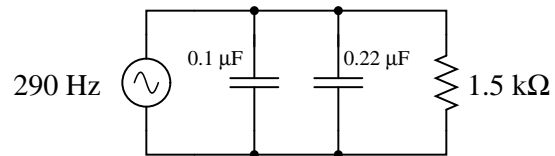
$$\mathbf{Z}_{\text{total}} = 673.4 \Omega \angle -45.74^\circ$$



$$\mathbf{Z}_{\text{total}} = 8.122 \text{ k}\Omega \angle -79.36^\circ$$



$$\mathbf{Z}_{\text{total}} = 336.6 \Omega \angle -44.26^\circ$$



$$\mathbf{Z}_{\text{total}} = 1.129 \text{ k}\Omega \angle -41.17^\circ$$

---

Answer 17

The resistor will drop more voltage.

$$Z_{\text{total}} \text{ (rectangular form)} = 5100 \Omega - j4671 \Omega$$

$$Z_{\text{total}} \text{ (polar form)} = 6916 \Omega \angle -42.5^\circ$$

---

Answer 18

$\mathbf{I} = 3.732206 \text{ mA} \angle 89.89^\circ$  for the real capacitor with ESR.

$\mathbf{I} = 3.732212 \text{ mA} \angle 90.00^\circ$  for the ideal capacitor.

---

Answer 19

The first (series) circuit's behavior is predominantly *inductive*, with 961.3 ohms of inductive reactance overshadowing 884.2 ohms of capacitive reactance, for a total circuit impedance of 77.13 ohms  $\angle +90^\circ$  (polar form) or  $0 + j77.13$  ohms (rectangular form).

The second (parallel) circuit's behavior is *capacitive*, with 1.131 millisiemens of capacitive susceptance overshadowing 1.040 millisiemens of inductive susceptance, for a total circuit admittance of 90.74 microsiemens  $\angle +90^\circ$ . This translates into a total circuit impedance of 11.02 k $\Omega \angle -90^\circ$ , the negative phase angle clearly indicating this to be a predominantly capacitive circuit.

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Answer 20

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Answer 21

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Answer 22

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Answer 23

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Answer 24

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Answer 25

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Answer 26

**Partial answer:**

This is an *instantaneous overcurrent* relay, corresponding to ANSI function code 50.

---

Answer 27

**Partial answer:**

Fault on circuit breaker #5: we will need to trip breakers 1, 2, 3, 4, and 10. This will unfortunately interrupt power to loads J, K, and L.

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  - Resistances diminish to equal to total
- Kirchhoff's Voltage Law (KVL)
  - A test charge moved from one location to any series of other locations and back to the starting location must arrive with the same amount of potential energy as it began (Conservation of Energy)
- Kirchhoff's Current Law (KCL)
  - Every charge entering a point must be balanced by a charge exiting that point (Conservation of Electric Charge)
- Ohm's Law
  - The voltage dropped across a resistance is equal to the product of its resistance and the amount of current through it:  $V = IR$

Sample analysis:

- Apply KCL to right-hand node to calculate 3 A through 3  $\Omega$  resistor
- Apply Ohm's Law to calculate 9 V drop across 3  $\Omega$  resistor; polarity determined by the fact that a resistor is always a load
- Apply property of series networks (current same) to determine that the 2  $\Omega$  resistor shares the same current as the 4 A component
- Apply Ohm's Law to calculate 8 V drop across 2  $\Omega$  resistor; polarity determined by the fact that a resistor is always a load
- Apply property of series networks (current same) to determine that both the 1  $\Omega$  resistor and the 5 V component share the same current as the 7 A component
- Apply Ohm's Law to calculate 7 V drop across 1  $\Omega$  resistor; polarity determined by the fact that a resistor is always a load
- Apply KVL to calculate 11 V drop across the 4 A component; polarity shows it is acting as a load
- Apply KVL to calculate 21 V drop across the 7 A component; polarity shows it is acting as a source

The indicators for channels 3 and 6 are lit on the input card of this PLC. This tells us channels 3 and 6 are receiving power through their respective process switches, but channel 4 is not. Since we are told the system is operating as it should (no abnormal conditions), we may assume the opposite state for each input channel will initiate a trip. Thus:

- Temperature switch (channel 6) is currently closed, and opens with a *high* temperature.
- Level switch (channel 4) is currently open, and closes with a *low* level.
- Pressure switch (channel 3) is currently closed, and opens with a *low* pressure.

Since the temperature switch channel is *de-energize to trip*, you must open that circuit in order to force the system to trip.

Since the level switch channel is *energize to trip*, you must jumper power to PLC input channel 4 in order to force the system to trip.

Since the pressure switch channel is *de-energize to trip*, you must open that circuit in order to force the system to trip.

---

Answer 30

This single-line diagram is found in Figure D.2.2 of the NFPA 70E standard (2015 edition).

- Transformers: *parallel zig-zag or hooped lines*
- Disconnects: *knife-switch symbols*
- Circuit breakers: *square boxes*
- Fuses: *rectangles with a dark band at each end*

“Tie breakers” connect the A and B segments of each bus together. They allow two busses to be powered by a single transformer.

Each percentage value is an expression of transformer *impedance*, in terms of rated load. For example, if a transformer has a full-load rating of 5 MVA (5 million volt-amperes) and an impedance of 5.5%, it means its own internal impedance is only 5.5% that of the load’s impedance drawing full power. Conversely, it means if that transformer’s secondary is short-circuited by a “bolted” fault (essentially 0 ohms for the short-circuit fault itself), the fault current will be  $\frac{1}{5.5\%}$  of the full-load current (i.e. the bolted-fault current will be 18.18 times the normal full-load current).

If the transformer feeding bus 2B fails, it should be disconnected from its 13.8 kV source by the next breaker upstream (which also feeds the transformer powering bus 3B). If the protection scheme is differential current (ANSI/IEEE type 87), then the secondary circuit breaker will be tripped by the protective relay as well. Power may be restored to bus 2B by closing the tie breaker between busses 2A and 2B.

If the transformer feeding bus 7A fails, it should be disconnected from its 13.8 kV source by the fuse on bus 1A/1. If the tie switch between bus 7A and bus 7B happens to be open at the time of the transformer fault, this is all that will happen. However, if the tie switch was closed during the fault, it is likely that the fuse on the secondary side of the *other* transformer (feeding bus 7B) will blow instead because it not only carries all the fault current but also any load current on busses 7A and 7B.

Usually tie switches and breakers are left in their open states, and so the former scenario is more likely. If this is the case, power may be restored to bus 7A by opening the disconnect switch on that transformer’s secondary winding, shutting down all loads on bus 7A, closing the tie switch, and re-starting loads on bus 7A. This sequence of operations is necessary in order to avoid closing or opening the disconnect switches while they carry substantial current.

A three-phase transformer rated at 480 volt output and 1.5 MVA, with 6% impedance, will have a bolted-fault current capacity of 30,070 amps.

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Answer 31

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Answer 32

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Answer 33

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Answer 34

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Answer 35

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Answer 36

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Answer 37

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Answer 38

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Answer 39

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Answer 40

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Answer 41

Notes:

Resistance is to reactance in an AC electrical circuit as friction is to inertia in a mechanical system. The former resists motion, while the latter resists *changes* in motion.

$$X_L = 2\pi fL$$

$$X_C = \frac{1}{2\pi fC}$$

$$X_R = 0 \quad \text{For a "pure" resistor}$$

Impedance is the combination of resistance and reactance for any component or network.

---

Answer 42

$$I_L = 530.5 \mu\text{A RMS} \angle -90^\circ$$

$$I_R = 490.2 \mu\text{A RMS} \angle 0^\circ$$

$$I_{total} = 722.3 \mu\text{A RMS} \angle -47.26^\circ$$

$$Z_{total} = 3.461 \text{ k}\Omega \angle 47.26^\circ$$

---

Answer 43

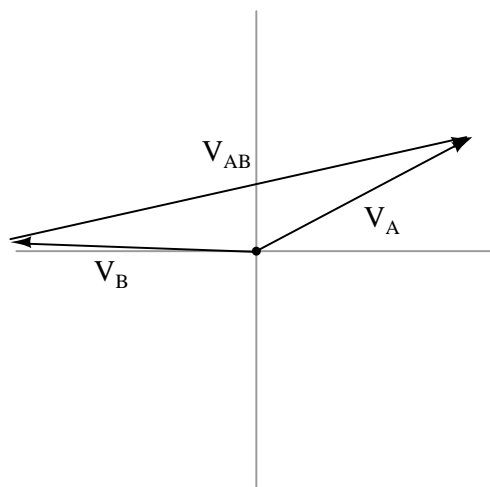
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Answer 44

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Answer 45

**Partial answer:**



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Answer 46

Partial answer:

$$V_A = 8.588 \text{ V} \angle -54.87^\circ$$

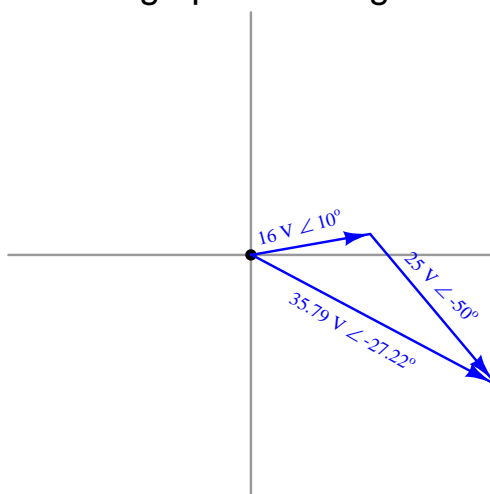
Note how the voltage between point A and ground is actually *larger* than the transformer's output voltage of 5.5 volts!

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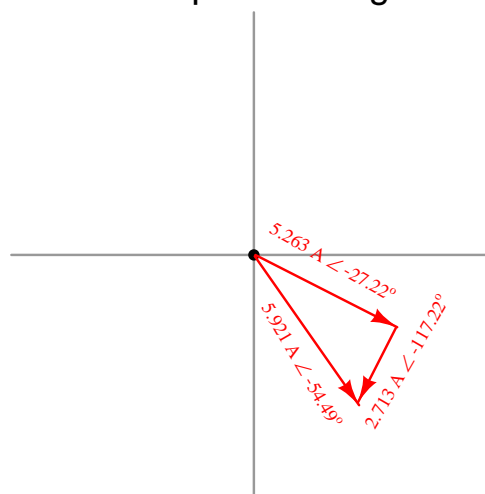
Answer 47

Partial answer:

Voltage phasor diagram

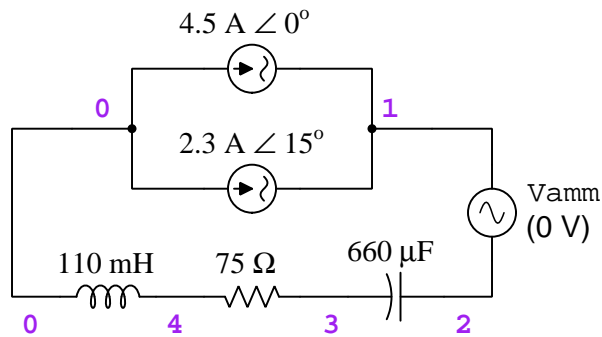


Current phasor diagram





Here we will use SPICE circuit simulation software to provide the analysis:



Circuit re-drawn with SPICE node numbers and ammeter shown:

SPICE source file (netlist):

```

*
I1 0 1 AC 4.5 0
I2 0 1 AC 2.3 15
VAMM 1 2
C1 2 3 660E-6
R1 3 4 75
L1 4 0 110E-3
.AC LIN 1 60 60
.PRINT AC I(VAMM) IP(VAMM)
.PRINT AC V(1) VP(1)
.PRINT AC V(2,3) VP(2,3)
.PRINT AC V(3,4) VP(3,4)
.PRINT AC V(4) VP(4)
.END
    
```

SPICE analysis:

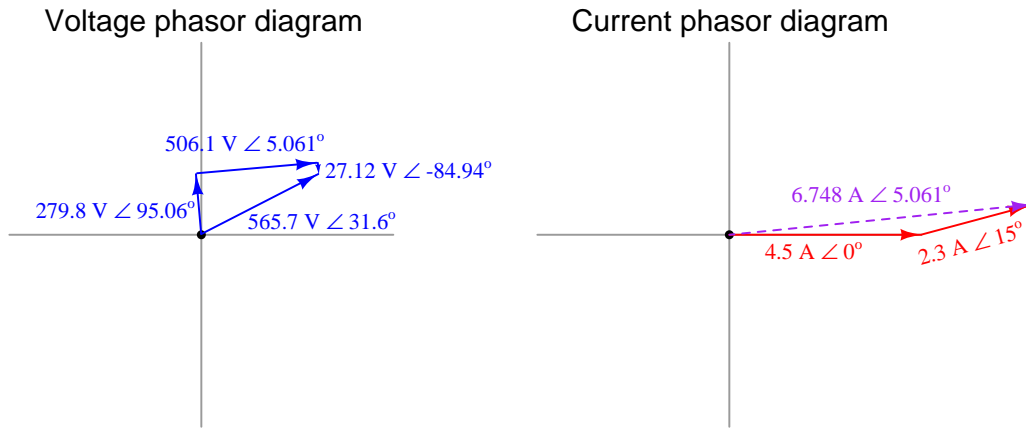
Freq	I(VAMM)	IP(VAMM)
6.000E+01	6.748E+00	5.061E+00

Freq	V(1)	VP(1)
6.000E+01	5.657E+02	3.160E+01

Freq	V(2,3)	VP(2,3)
6.000E+01	2.712E+01	-8.494E+01

Freq	V(3,4)	VP(3,4)
6.000E+01	5.061E+02	5.061E+00

Freq	V(4)	VP(4)
6.000E+01	2.798E+02	9.506E+01



Note: the voltage phasor diagram shows the vectors stacking up in a different order than the components are wired in the series circuit, simply to provide a clearer phasor diagram. If the vectors had been stacked in order as they are in the circuit (inductor, then resistor, then capacitor), the inductor and resistor voltage vectors would have practically run on top of each other which would make it more difficult to see. Since addition is a commutative operation, it really makes no difference what order it occurs in.

---

Answer 49

$$Z_{total} = 6.944 \text{ k}\Omega$$

$$I = 4.896 \text{ mA RMS}$$

$$V_L = 23.07 \text{ V RMS}$$

$$V_R = 24.97 \text{ V RMS}$$

---

Answer 50

$$V_L = 13.04 \text{ volts RMS}$$

$$V_R = 20.15 \text{ volts RMS}$$

$$I = 4.030 \text{ milliamps RMS}$$

$$\theta_Z = 32.91^\circ$$

---

Answer 51

$$V_C = 14.39 \text{ volts RMS}$$

$$V_R = 4.248 \text{ volts RMS}$$

$$I = 903.9 \mu\text{A RMS}$$

---

Answer 52

$$V_C = 47.56 \text{ volts peak}$$

$$V_R = 6.508 \text{ volts peak}$$

$$I = 1.972 \text{ milliamps peak}$$

$$\theta_Z = -82.21^\circ$$

---

Answer 53

- $I_{total} = 2.269 \text{ mA}$
- $V_{C1} = 3.041 \text{ V}$
- $V_{C2} = 5.354 \text{ V}$
- $V_{R1} = 15.43 \text{ V}$
- $V_{R2} = 2.723 \text{ V}$
- $\theta = -24.82^\circ$  (voltage lagging current)

I suggest using a dual-trace oscilloscope to measure total voltage (across the supply terminals) and voltage drop across resistor  $R_2$ . Theoretically, measuring the voltage dropped by either resistor would be fine, but  $R_2$  works better for practical reasons (oscilloscope input lead grounding). Phase shift then could be measured either in the time domain or by a Lissajous figure analysis.

---

Answer 54

The proper angle in this circuit is  $\theta$ , and it will be a positive (leading) quantity.

The reason we must focus on  $\theta$  in this problem is because this is the angle separating the resistor's voltage drop from the source's voltage. Note how in the circuit  $V_{out}$  is measured across the resistor, not across the capacitor.

---

Answer 55

$$f = 6.54 \text{ kHz}$$

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Answer 56

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Answer 57

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Answer 58

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Answer 59

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Answer 60

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Answer 61

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Answer 62

**Partial answer:**

$$V_{line} = 2400 \text{ V}$$

$$I_{phase(source)} = 2.667 \text{ A}$$

$$I_{phase(load)} = 4.619 \text{ A}$$

---

Answer 63

**Partial answer:**

$$I_{line} = 26.93 \text{ A}$$
$$V_{phase(source)} = 277 \text{ V}$$
$$V_{phase(load)} = 479.8 \text{ V}$$

---

Answer 64

**Partial answer:**

$$I_{line} = 25.88 \text{ A}$$
$$I_{phase(source)} = 14.94 \text{ A}$$
$$V_{phase(load)} = 2402 \text{ V}$$

---

Answer 65

Answer 66

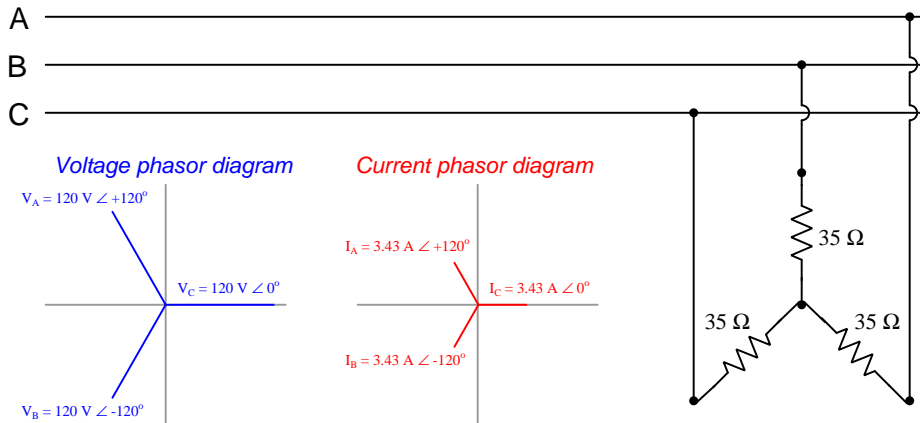
Answer 67

**Partial answer:**

Since we know resistors impart no phase shift between voltage and current, the phase angle of each phase voltage remains preserved in the respective phase currents:

$$I_A = \frac{V_A}{R_A} = \frac{120 \text{ V} \angle 120^\circ}{35 \Omega \angle 0^\circ} = 3.43 \text{ A} \angle 120^\circ$$
$$I_B = \frac{V_B}{R_B} = \frac{120 \text{ V} \angle -120^\circ}{35 \Omega \angle 0^\circ} = 3.43 \text{ A} \angle -120^\circ$$
$$I_C = \frac{V_C}{R_C} = \frac{120 \text{ V} \angle 0^\circ}{35 \Omega \angle 0^\circ} = 3.43 \text{ A} \angle 0^\circ$$

$V_{line} = 208 \text{ volts}$   
Phase rotation = CBA  
 $V_C = 120 \text{ V} \angle 0^\circ$



---

Answer 68

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Answer 69

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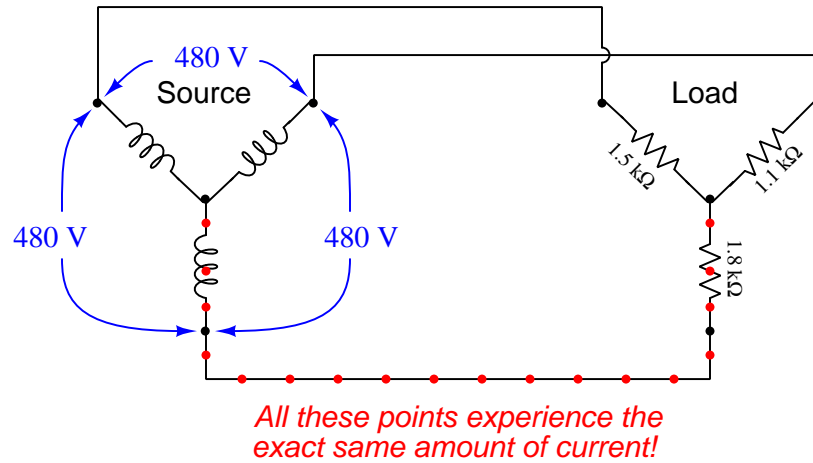
Answer 70

With switch W pressed, test point B will be equipotential with (i.e. “electrically common” to) earth ground. This ensures test point B will register 0 volts with respect to ground, because test point B *is* grounded. Test point D will now register one-half of the nominal phase voltage (i.e.  $V_D = 60$  volts), while test points A and C will register line voltage which is the same as phase voltage for a delta-connected network (120 volts).

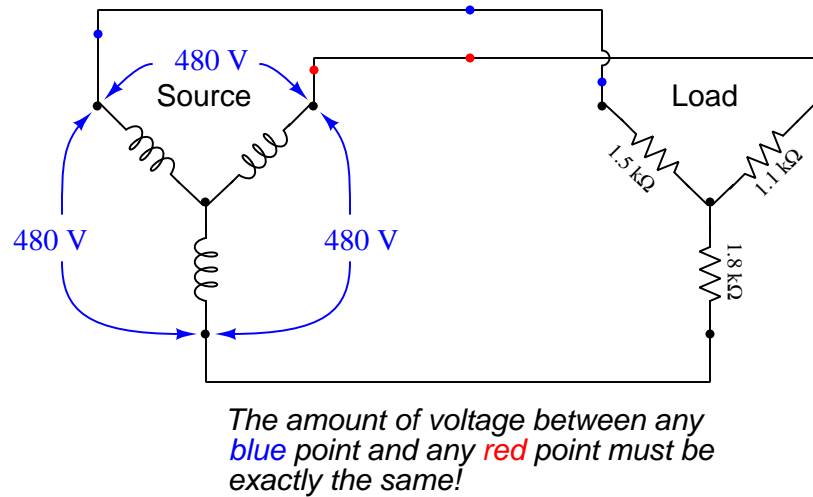
With switch Z pressed, test point A will now be grounded and register 0 volts. Test points B and C will each register 120 volts to ground: their respective phase (and line) voltages. Test point D will register 104 volts ( $120 \text{ volts} \times \cos 30^\circ = \frac{120\sqrt{3}}{2}$ ).

Pressing both pushbuttons simultaneously is a *bad idea*, because it will directly short the left-hand phase winding of the generator. This will cause excessive current to flow through that winding, most likely damaging it.

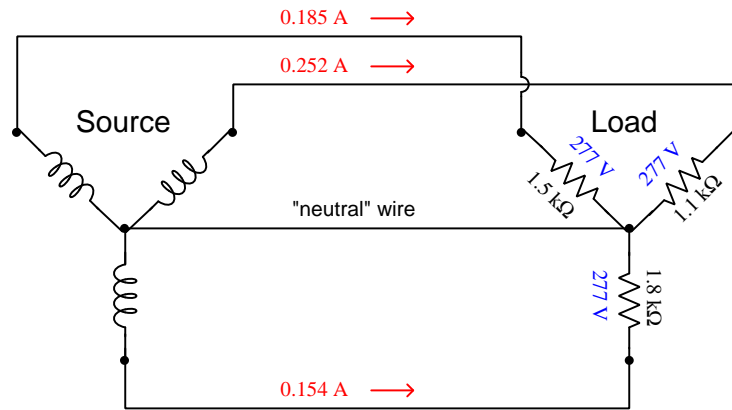
Any points lying in *series* with each other absolutely must share the same current, for the simple reason that the definition of series is having only one path for current to flow. Here is one example of multiple points (shown in red) sharing the exact same current:



Any point-pairs in *parallel* with each other absolutely must share the same voltage between them, for the simple reason that the definition of parallel is sharing a pair of equipotential point sets. Here is one example of multiple point-pairs (shown in blue/red) sharing the exact same voltage:



If we add a fourth “neutral” wire to this three-phase circuit, we force each of the load resistances to see the same amount of voltage: 277 volts from phase to neutral. Each line current will then be equal to 277 volts divided by that phase resistance. Phase voltages at the load will now be balanced, but line currents will still be imbalanced:



In case you are interested to know, the neutral wire’s current will be the *phasor sum* of these three line currents as they add together at the center node of the wye load where the neutral wire connects:

$$I_{neutral} = I_{phaseA} + I_{phaseB} + I_{phaseC}$$

$$I_{neutral} = 0.0867 \text{ A} \angle 137.9^\circ$$

---

Answer 72

The current carried by each line will be absolutely equal to the current carried by its respective phase coil within the wye-connected source, for the simple reason that each line is in *series* with each phase element of a wye network, and series components share the same current (there being only one path between those components for current to flow). If either source or load are imbalanced, we would not expect any one line’s current to equal any other line’s current, but each line’s current will be the same as the wye-coil it’s connected to.

Similarly, we may conclude that voltage measured between any pair of parallel-connected points must be equal. In this circuit, an example of that would be the voltage measured between any two lines and the voltage of the phase coil between those same lines within the delta-connected motor.

When the upper phase coil within the motor fails open, it forces the remaining two phase coils to be in series with the upper two lines (one line per coil). This means each of the functional coils within the motor will share current equally with its respective line and respective phase coil within the wye-connected source. Voltage will be unaffected, still equal between sets of parallel-connected point-pairs.

Incidentally, the motor’s new winding configuration is called *open-delta*, and it is a legitimate way to configure certain three-phase loads!

Line current is easy to calculate, after converting 100 HP into 74600 watts:

$$P = \sqrt{3}I_{line}V_{line}$$

$$I_{line} = \frac{P}{\sqrt{3}V_{line}}$$

$$I_{line} = \frac{74600 \text{ W}}{\sqrt{3}(460 \text{ V})}$$

$$I_{line} = 93.63 \text{ A}$$

However, we need to know the amount of *phase* current in each of the motor's windings, and since the motor is wound in a delta fashion we know that line current is not equal to phase current (i.e. each line current "splits" into smaller phase currents at each of the nodes where lines join the delta network, in accordance with Kirchhoff's Current Law).

Being a balanced three-phase load, this "splitting" of current will follow the ratio of  $\frac{1}{\sqrt{3}}$ :

$$I_{phase} = \frac{I_{line}}{\sqrt{3}}$$

$$I_{phase} = \frac{93.63 \text{ A}}{\sqrt{3}}$$

$$I_{phase} = 54.06 \text{ A}$$

An alternative approach to solving for phase current would be to realize that in a balanced three-phase load, each of the three phases handles exactly one-third of the total power. There is no  $\sqrt{3}$  factor in dividing power amongst the phase windings because energy is a scalar quantity and always adds directly, unlike voltage or current which are phasor quantities and must relate trigonometrically.

Since the total power in this case is 74600 watts, each of the three phase windings within the motor will convert one-third of that total electrical power (i.e. 24866.7 watts) into mechanical power. Since we can tell phase elements in a delta-connected network will experience line voltage (because each phase element is in parallel with a pair of power lines, and parallel-connected components always share the same voltage), we may treat each of the phase windings as a single-phase load. Calculating current for a single-phase load given power and voltage:

$$P = IV$$

$$I = \frac{P}{V}$$

$$I = \frac{24866.7 \text{ W}}{460 \text{ V}}$$

$$I = 54.06 \text{ A}$$



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Answer 74

With switch W pressed, test point B will be equipotential with (i.e. “electrically common” to) earth ground. This ensures test point B will register 0 volts with respect to ground, because test point B *is* grounded. Test point D will now register one phase voltage (120 volts), while test points A and C will register line voltage (208 volts).

With switch Z pressed, test point D will now be grounded and register 0 volts. Test points A, B, and C will each register 120 volts to ground: their respective phase voltages.

Pressing both pushbuttons simultaneously is a *bad idea*, because it will directly short the phase B winding of the generator. This will cause excessive current to flow through that winding, most likely damaging it.

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Answer 75

- $V_{phase} \text{ (source)} = \underline{574.2 \text{ V}}$
- $I_{phase} \text{ (source)} = \underline{0.589 \text{ A}}$
- $V_{phase} \text{ (load)} = \underline{331.5 \text{ V}}$
- $I_{phase} \text{ (load)} = \underline{1.02 \text{ A}}$
- $V_{line} = \underline{574.2 \text{ V}}$
- $I_{line} = \underline{1.02 \text{ A}}$
- $P_{total} = \underline{1014.4 \text{ W}}$

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Answer 76

- $V_{phase} \text{ (source)} = \underline{341.6 \text{ V}}$
- $I_{phase} \text{ (source)} = \underline{13.663 \text{ A}}$
- $V_{phase} \text{ (load)} = \underline{591.6 \text{ V}}$
- $I_{phase} \text{ (load)} = \underline{7.888 \text{ A}}$
- $V_{line} = \underline{591.6 \text{ V}}$
- $I_{line} = \underline{13.663 \text{ A}}$

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Answer 77

Perhaps the simplest approach to this problem is to calculate the power dissipation of each resistor inside of each three-resistor array. Since power is a scalar quantity (i.e. it adds directly, not trigonometrically), the 15 kW total heat output of each array means each resistor inside of each array must dissipate 5 kW of power.

In the delta-connected heater, each resistor sees full line voltage (480 VAC), therefore the resistance may be calculated as such:

$$R = \frac{V^2}{P} = \frac{480^2}{5000} = 46.08 \Omega$$

In the wye-connected heater, each resistor sees  $\frac{1}{\sqrt{3}}$  of the full line voltage (480 VAC), which is 277.1 VAC. Therefore the resistance may be calculated as such:

$$R = \frac{V^2}{P} = \frac{277.1^2}{5000} = 15.36 \Omega$$

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Answer 78

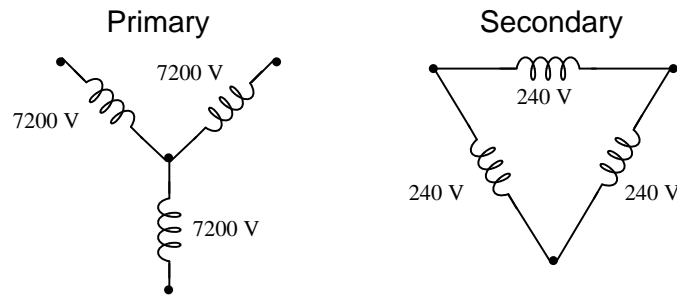
$$P_{elec} = 198.146 \text{ kVA} = 265.61 \text{ HP}$$

$$P_{mech} = 244.36 \text{ HP}$$

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Answer 79

The transformer primary windings are connected in a Wye configuration, which means each primary winding receives the 7.2 kV phase voltage. The secondary windings are connected in a Delta configuration, making the secondary line voltage equal to 240 volts.



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Answer 80

In the direct-connected load, each resistor sees  $\frac{1}{\sqrt{3}}$  of the 13.8 kV line voltage (7967.4 volts), therefore, each resistor current is equal to:

$$I = \frac{V}{R} = \frac{7967.4}{1240} = 6.425 \text{ amps}$$

Since each resistor sees 7967.4 volts and carries 6.425 amps, the power for each resistor will be:

$$P = IV = (6.425)(7967.4) = 51.194 \text{ kW}$$

The power for this load is simply the power of all resistors combined:

$$P_{total} = 153.58 \text{ kW}$$

The three transformers have their primary windings connected in a Wye configuration, and their secondary windings in a Delta configuration. Thus, each transformer primary sees 7967.4 volts, stepping it down by a 16.67:1 ratio into 477.95 volts. The secondary windings, being Delta-connected, make this 477.95 volt value the line voltage for the load. The load is Delta-connected as well, and so each resistor in that load sees 477.95 volts, giving a resistor current of:

$$I = \frac{V}{R} = \frac{477.95}{950} = 0.5031 \text{ amps}$$

Since each resistor sees 477.95 volts and carries 0.5031 amp, the power for each resistor will be:

$$P = IV = (0.5031)(477.95) = 240.46 \text{ W}$$

The power for this load is simply the power of all resistors combined:

$$P_{total} = 721.38 \text{ W}$$

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Answer 81

This is a graded question – no answers or hints given!

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Answer 82

This is a graded question – no answers or hints given!

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Answer 83

This is a graded question – no answers or hints given!

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Answer 84

This is a graded question – no answers or hints given!

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Answer 85

This is a graded question – no answers or hints given!

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Answer 86

This is a graded question – no answers or hints given!

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Answer 87

This is a graded question – no answers or hints given!

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Answer 88

This is a graded question – no answers or hints given!

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Answer 89

This is a graded question – no answers or hints given!

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Answer 90

This is a graded question – no answers or hints given!

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Answer 91

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Answer 92

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Answer 93

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