

Lab

Protective Relay system: *Question 61*, **completed objectives due by the end of day 3**

Miniature AC power grid documentation: *Question 62*, generator schematic diagrams

Miniature AC power grid documentation: *Question 63*, substation schematic diagrams

Exam

Day 3 – **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
-

Recommended daily schedule

Day 1

Theory session topic: Lockout and auxiliary relays

Questions 1 through 20; answer questions 1-6 in preparation for discussion (remainder for practice)

Day 2

Theory session topic: Review, part 1

Questions 21 through 40; answer questions 21-30 in preparation for discussion (remainder for practice)

Today’s morning lab session will be spent completing any remaining lab objectives as well as doing general clean-up, team tool locker inspection, reorganization, equipment repair, and other tasks necessary for the maintenance of our lab facility. See question 64 for a list of necessary tasks to complete.

If teams complete their labwork prior to today, it is highly recommended to spend that lab time practicing AC circuit analysis (phasor calculations, phasor diagrams, transformer connections, CT wire sizing, etc.). This is also a good opportunity to apply SPICE to the analysis of AC circuits, using examples from the *SPICE Modeling of Power Circuits* learning module:

http://www.ibiblio.org/kuphaldt/socratic/model/mod_spice_power.pdf

Day 3

Theory session topic: Review, part 2 (morning)

Questions 41 through 60; answer questions 41-45 in preparation for discussion (remainder for practice)

Exam (afternoon)

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 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.

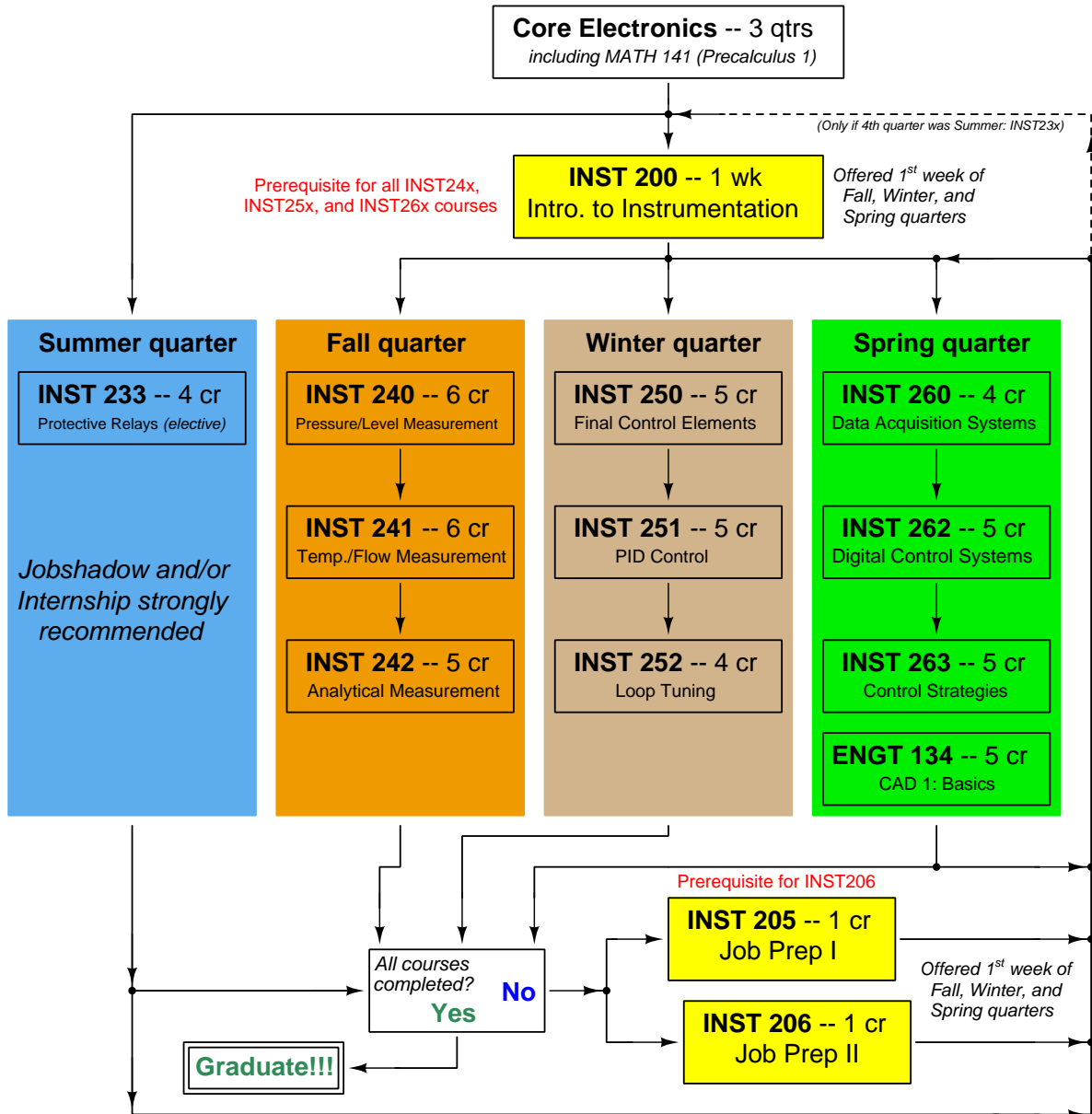
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INST 233 Course Outcomes

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]

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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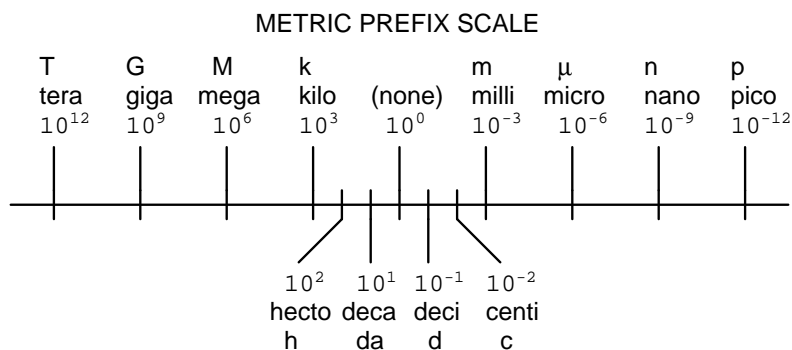
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Metric prefixes and conversion constants

- **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: μ
- 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 (in³) = 4 quarts (qt) = 8 pints (pt) = 128 fluid ounces (fl. oz.) = 3.7854 liters (l)

1 milliliter (ml) = 1 cubic centimeter (cm³)

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 (ft²) = 4840 square yards (yd²) = 4046.86 square meters (m²)

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 10¹⁰ 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/s²) = 32.1740 feet per second per second (ft/s²)

Physical constants

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

Avogadro's number (N_A) = 6.022×10^{23} per mole (mol^{-1})

Electronic charge (e) = 1.602×10^{-19} Coulomb (C)

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

Stefan-Boltzmann constant (σ) = 5.67×10^{-8} Watts per square meter-Kelvin⁴ ($\text{W}/\text{m}^2 \cdot \text{K}^4$)

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°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°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

Read and outline the Simplified Tutorial of the *Auxiliary Protective Relays* 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 i02845

Question 2

Read selected portions of the “SEL-RS Rotary Switch” instruction manual (document SEL-RS Rotary Switch Family Instruction Manual, May 2013) and answer the following questions:

A typical SEL-RS rotary hand switch is comprised of different modules stacked on a common rotary shaft. Table 1 on page 5 lists four different module types. Identify what these modules are called and explain what each of them do:

-
-
-
-

Identify what the “A” wire terminals are used for in this switch (e.g. A1+, A1–, A2+, A2–, etc.).

Figure 13 on page 8 shows common connections for the optional *tripping module*. In the right-hand diagram we see a pair of LEDs connected along with the tripping coil. From this diagram identify the purpose of LED1 and LED3 – under what condition(s) will they illuminate?

SEL sells three different types of switch contact modules for the SEL-RS86 rotary switch (“lockout” applications). Identify these different module types, and explain where each one might be used.

SEL-RS rotary switches are typically used for three major types of application, reflected in the model numbers following “RS”: SEL-RS86, SEL-RS52, and SEL-RS43. Identify these applications, and determine what the model numbers refer to.

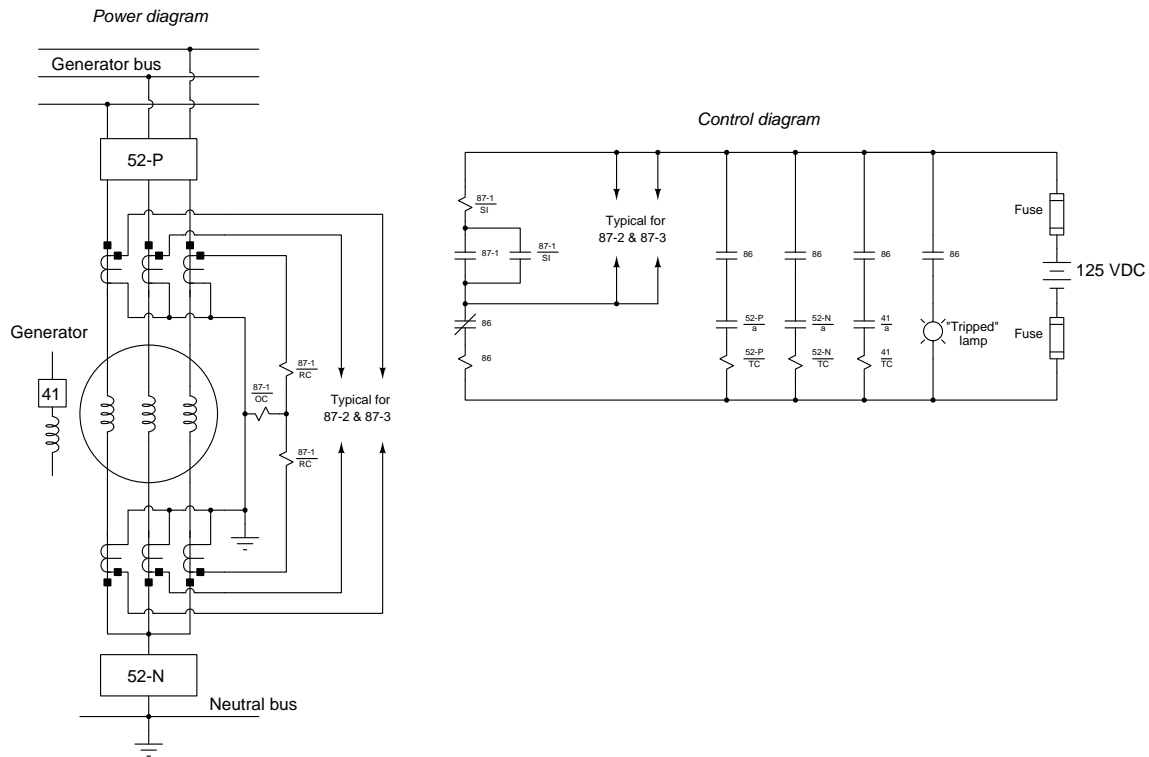
Suggestions for Socratic discussion

- This design of panel-mounted switch is called *modular* or *stackable*. Explain what these terms refer to, and why this design feature is very useful for industrial control applications.
- A feature available on some models of this switch is a *target*. Explain what a “target” is and what purpose it might serve in an electrical protection system.

[file i00825](#)

Question 3

The following power and trip circuit diagrams show the differential current (87) protection for a large three-phase generator:



Suppose one day the 86 relay trips, opening all three circuit breakers (52-P, 52-N, and 41) and illuminating the “Tripped” lamp. Electricians subsequently perform continuity and high-voltage insulation tests of the stator windings within the generator but find no faults at all.

Identify the likelihood of each specified fault for this system. 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
Dead DC station power supply		
Fault in generator field winding		
CT failed open		
86 trip coil failed open		
86 trip coil failed shorted		
Any 87/SI coil failed open		
Any 87/SI coil failed shorted		
Any 87/RC coil failed open		
Any 87/RC coil failed shorted		
Any 87/OC coil failed open		
Any 87/OC coil failed shorted		

file i03070

Question 4

Read selected portions of the “Lessons Learned From Commissioning Protective Relay Systems” whitepaper (written by Karl Zimmerman and David Costello of Schweitzer Engineering Labs) and answer the following questions:

In Application Example “A” (pp. 7-8) we are shown a case where a pair of line differential relays are protecting a short transmission line. Figure 10 shows a single-line diagram of the system and Figure 11 shows a “live” phasor diagram of currents measured by these two relays. Describe what the problem was in this case, and explain how the phasor diagram reveals this to be so. It may be helpful to sketch a “corrected” phasor diagram showing what the phasors ought to have looked like during initial testing.

In Application Example “H” (pp. 14-15) a case is explored involving a differential current relay installed on a step-down transformer. Figure 34 on page 15 shows the current phasor diagram for transformer primary and secondary sides. Identify the problem by careful examination of this phasor diagram. Also, identify how we can tell which winding (W1 or W2) of this transformer is the high-voltage side based on the phasor diagram alone.

Appendix C beginning on page 22 describes a test called *primary current injection*. Describe what would be necessary to perform this kind of commissioning test, and identify the different elements of the protective relay system verified by it.

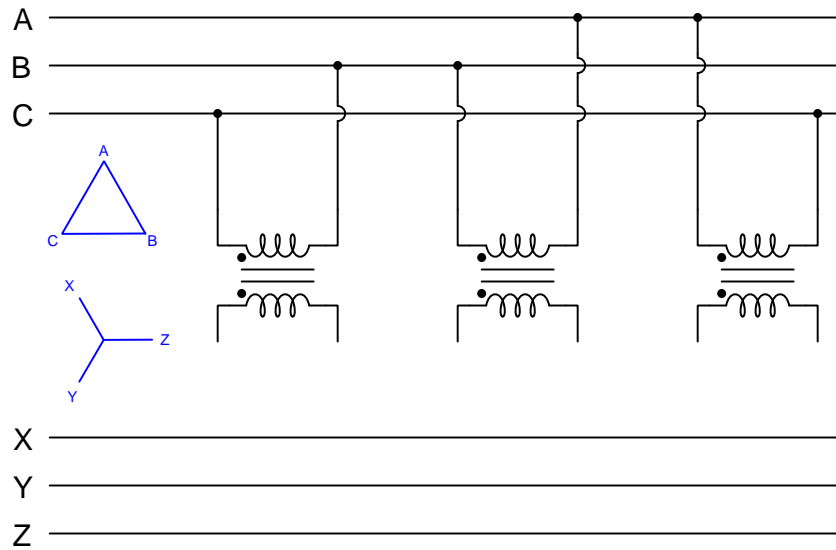
Suggestions for Socratic discussion

- Figure 10 in Application Example “A” shows *operate* and *restrain* labels on the single-line diagram. Explain what these terms mean in the context of this system’s protection scheme.
- Application Example “H” describes conductors being *rolled*. What do you think this term means, in the context of this problem?
- Application Example “C” on page 9 cites the use of *synchrophasors* to commission instrument transformers. Explain what “synchrophasors” are and how they were used in this case to verify proper VT function.

[file i03089](#)

Question 5

Sketch the necessary wire connections to create a three-phase transformer bank fulfilling the phasor diagrams shown to the left of the transformers, where ABC is the primary bus and XYZ is the secondary bus:



Hint: each transformer faithfully translates the phase angle of its primary winding voltage to the secondary winding, which means each line segment (vector) in the primary phasor diagram will have the same phase angle as one of the line segments (vectors) in the secondary phasor diagram. *For example, note how line segment A-B has the exact same phase angle as X-(ground) in the two phasor diagrams.* These identical angles for A-B and X-(ground) tell you the middle transformer must connect to line X in the secondary bus.

After sketching correct wire connections, write the phase sequences (phase rotations) for both 3-phase busses, and identify whether the lower bus *leads*, *lags*, or is *in-phase* with the upper bus.

file i02103

Question 6

Match the following ANSI/IEEE codes with their corresponding device or function descriptions:

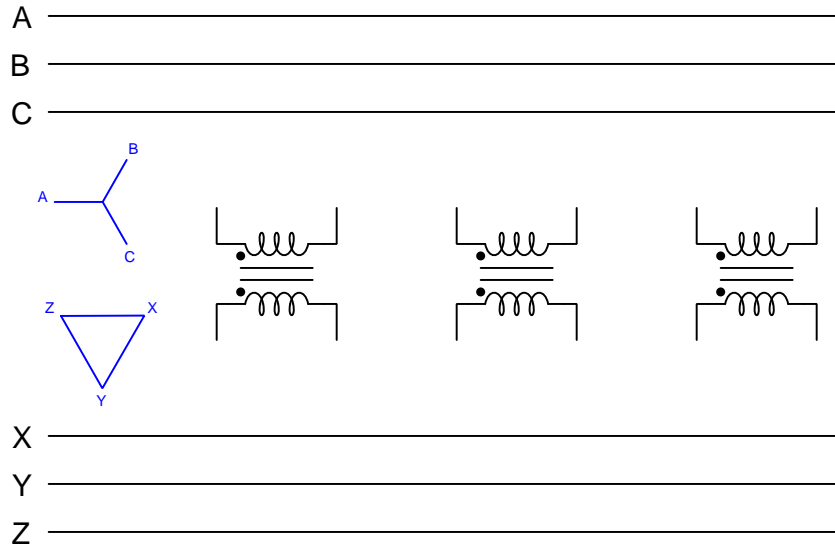
- Overcurrent (instantaneous)
- Automatic reclose
- Frequency
- Loss of excitation
- AC circuit breaker
- Lockout or Auxiliary
- Differential
- Overcurrent (time)

- 40
- 51
- 50
- 87
- 79
- 52
- 86
- 81

[file i03019](#)

Question 7

Sketch the necessary wire connections to create a three-phase transformer bank fulfilling the phasor diagrams shown to the left of the transformers:

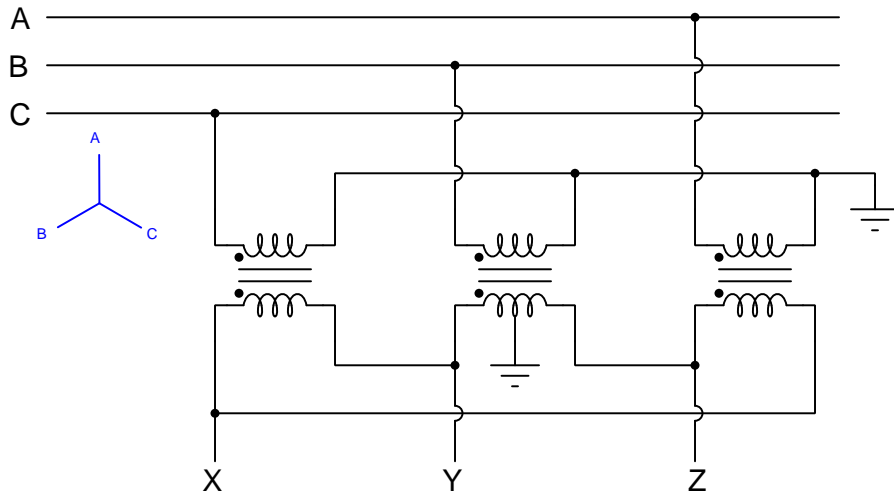


Also, write the phase sequences (phase rotations) for both 3-phase busses, and identify whether the lower bus *leads*, *lags*, or is *in-phase* with the upper bus.

[file i02104](#)

Question 8

Calculate the following voltages (in polar form) for this transformer bank, given $V_A = 120 \text{ V} \angle 90^\circ$ and a transformer turns ratio of 1:1.



$V_X = \underline{\hspace{2cm}}$

$V_{AB} = \underline{\hspace{2cm}}$

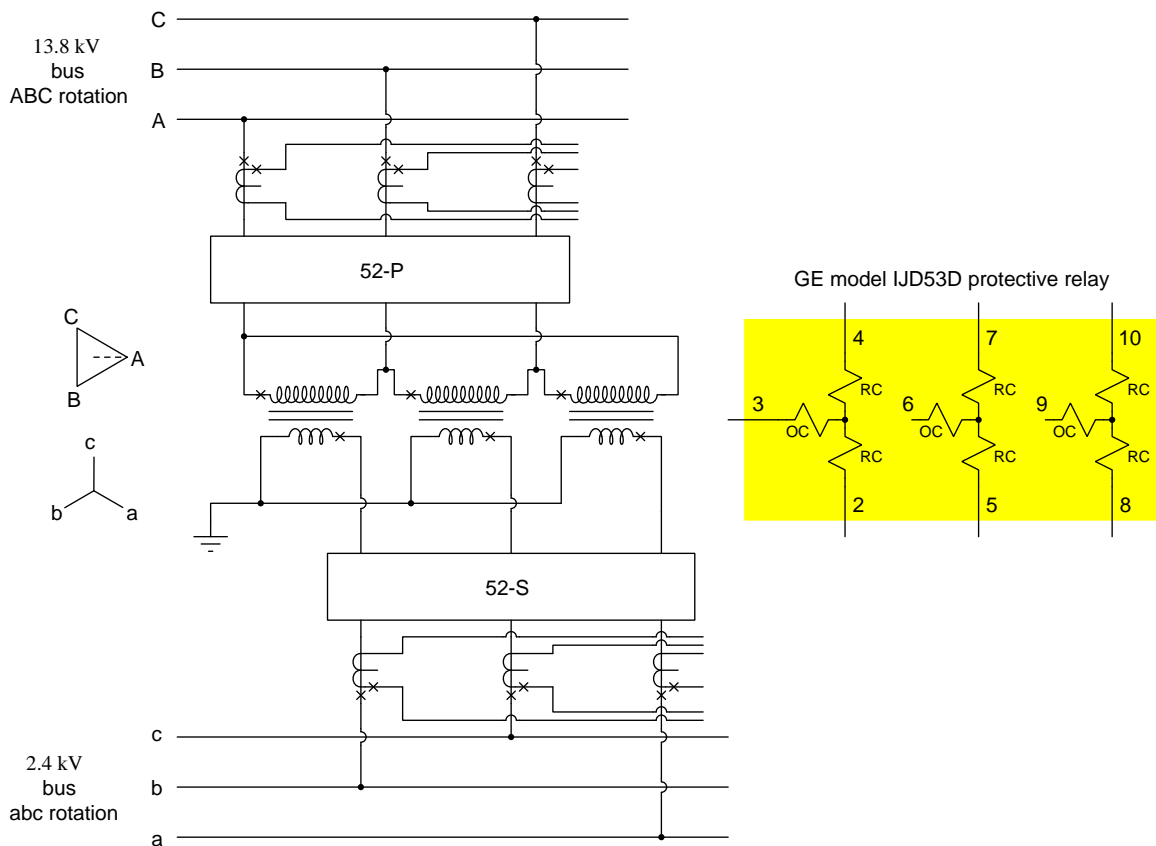
$V_{ZY} = \underline{\hspace{2cm}}$

$V_{XC} = \underline{\hspace{2cm}}$

file i02105

Question 9

Sketch the proper wire connections to connect CTs to a General Electric model IJD53D differential current protective relay in order to properly protect this three-phase power transformer bank:



Assuming the use of 600:5 CTs on the 13.8 kV lines, what should the CT ratios be on the 2.4 kV lines?

Suggestions for Socratic discussion

- Is this power transformer *additive* or *subtractive* in polarity? How can you tell?

[file i03069](#)

Question 10

Question 11

Question 12

Question 13

Question 14

Question 15

Question 16

Question 17

Question 18

Question 19

Question 20

Question 21

Read the one-line electrical diagram of a substation for a large wastewater treatment plant, contained in Appendix B of the “West Point Flooding Investigation – preliminary findings report” (page 44 of the PDF document), and answer the following questions:

Identify where electrical power enters this substation from Seattle City Light, and at what line voltage level.

Identify all protection schemes wired to trip the vacuum switch feeding power to each of the transformers supplying the substation.

Two “Station Type Surge Arrestors” are included in this system. Explain in detail how they are designed to function in order to protect the substation against surges such as lightning strikes.

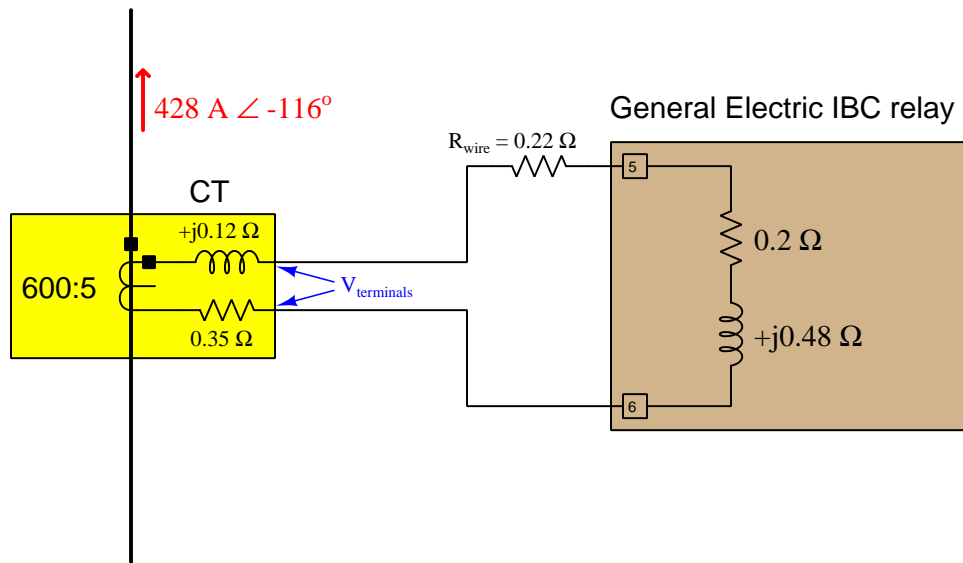
One circuit breaker in this substation fulfills a special function, and is called a *tie breaker*. This label has nothing to do with breaking a tied score, but rather refers to the circuit breaker’s purpose of tying two parts of the system together. Locate this circuit breaker (52-9) in the one-line diagram and explain its purpose in the substation.

One of the circuit breakers in this substation (52-3) tripped during the flooding emergency this plant experienced in February of 2017, and is highlighted by the word “Tripped” in large red print. Identify all protective relay schemes which could have tripped this particular breaker.

[file i01289](#)

Question 22

A General Electric model IBC directional overcurrent relay is connected to a current transformer, with the following circuit values. Note in particular the R and X_L values internal to the CT, representing secondary winding resistance and leakage inductance, respectively:



Calculate the amount of current in the CT secondary circuit, as well as the voltage output by the CT, assuming a perfect 600:5 current ratio for the CT:

$$I_{\text{sec}} = \underline{\hspace{2cm}}$$

$$V_{\text{CT-terminals}} = \underline{\hspace{2cm}}$$

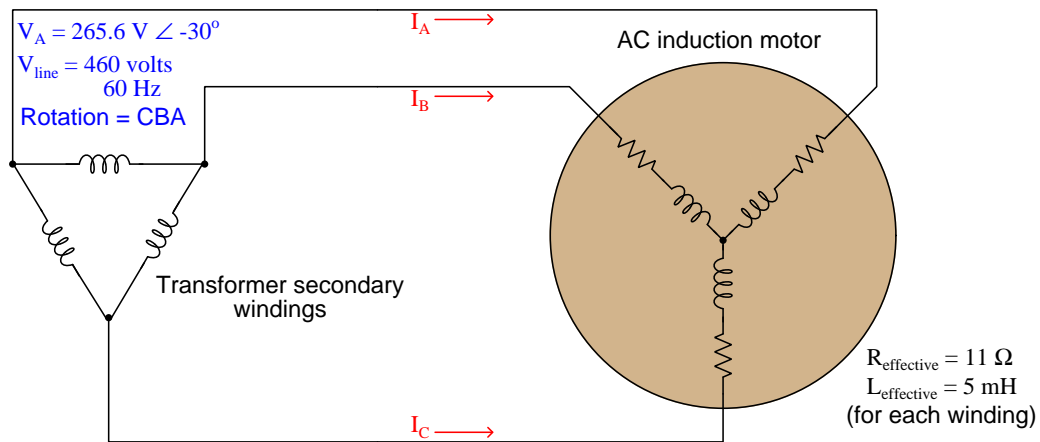
Suggestions for Socratic discussion

- Calculate the C-class required of this CT to avoid undue error under fault conditions, assuming a maximum fault current of 9 kA.

file i00829

Question 23

Calculate the line currents for this three-phase motor:



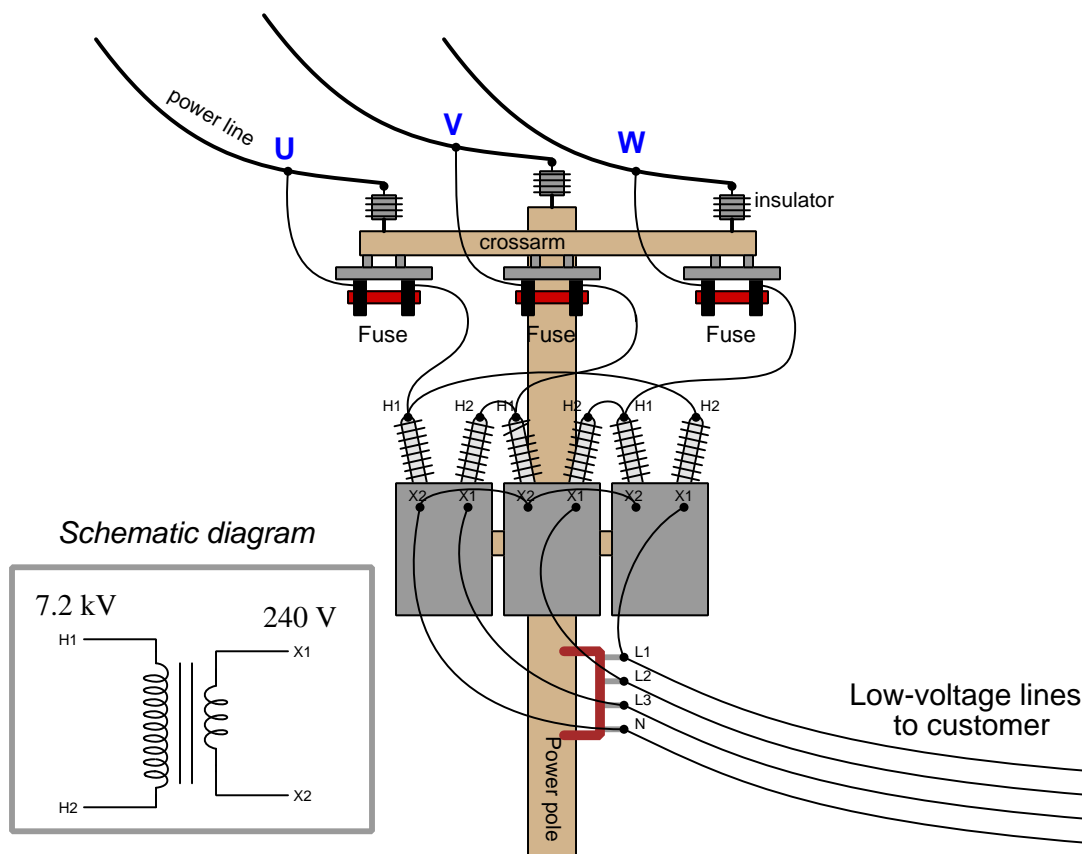
Suggestions for Socratic discussion

- 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.

[file i00830](#)

Question 24

This bank of pole-mounted power transformers steps 7.2 kVAC line power down to 240 VAC power to service a small business:



Given the following power line voltages (measured phase-to-ground), calculate the phase angles of the specified secondary-side voltages:

- $V_U = 4160 \text{ V} \angle 0^\circ$
- $V_V = 4160 \text{ V} \angle -120^\circ$
- $V_W = 4160 \text{ V} \angle -240^\circ$

- $V_{L1-N} = \text{___} \angle \text{___}$
- $V_{L2-N} = \text{___} \angle \text{___}$
- $V_{L3-N} = \text{___} \angle \text{___}$
- $V_{L1-L3} = \text{___} \angle \text{___}$

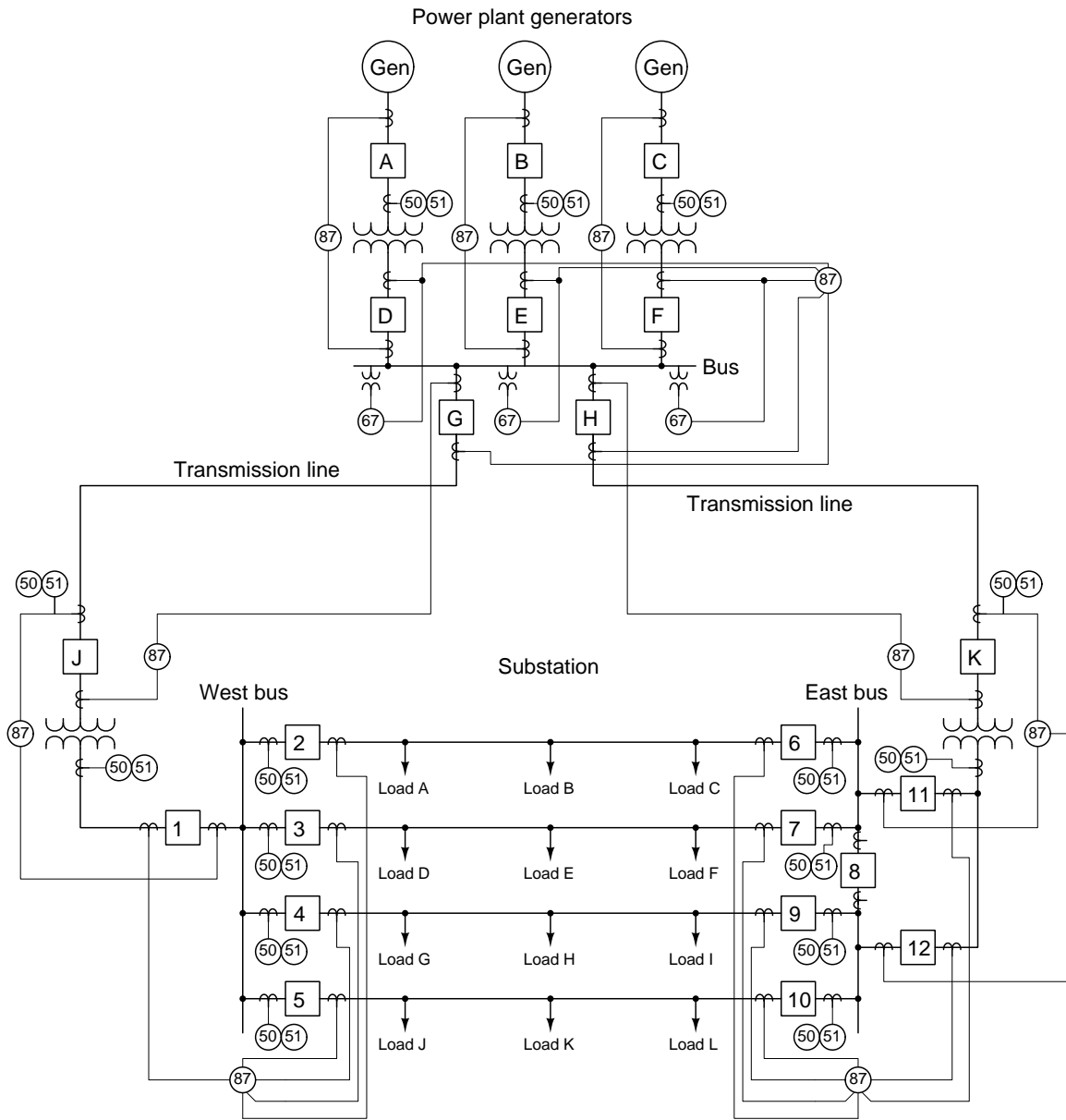
Suggestions for Socratic discussion

- Do these power transformers have *additive* or *subtractive* polarities? How can you tell?
- Identify the phase sequence (a.k.a. phase *rotation*) of this power system based on the given phase-to-ground power line voltage values.

[file i00826](#)

Question 25

Examine this single-line diagram of a power distribution system, showing transformers, generators, circuit breakers, power lines, and some of the protective relays that would make a complete system. In particular, pay close attention to *protection zones* for each relay, noting which pieces of equipment in this power system are protected by which relay:



Identify which relay(s) would command which circuit breakers to trip given the following faults:

- Phase-to-ground fault on the left-hand transmission line
- Phase-to-phase fault on the right-hand transmission line
- Loss of mechanical driving power for the middle generator
- Internal winding fault in right-hand generator transformer
- Phase-to-phase fault on the generator bus

[file i03099](#)

Question 26

Current transformers ideally act as *current sources* to whatever instruments or protective relays they drive, and in so doing are able to output surprisingly high amounts of voltage if necessary to push the intended current through the load(s). However, they definitely have voltage limits, and these limits are primarily defined by the iron core's magnetic saturation.

For example, an ideal 800:5 ratio CT with 800 amps of primary (power line) current going through it should push 5 amps of current out of its secondary winding to the protective relay it's wired to, no matter if that relay's burden is 1 ohm or 100 ohms – the only difference being 5 volts versus 500 volts output by the CT in order to overcome that relay burden. However, a *real* CT might not be able to source 500 volts to a relay burden, and so the magnitude of that burden definitely matters.

How can we know the amount of voltage any particular CT is capable of outputting? Are there any conditions that would cause a real CT's output voltage to become *derated* (i.e. cause the CT's maximum output voltage to fall below its normal rating)? How do we take these factors into consideration when sizing CT secondary wires for a real installation?

[file i02107](#)

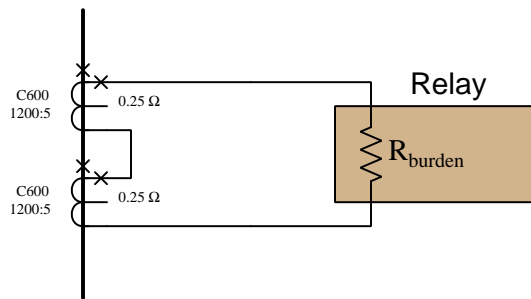
Question 27

An electrical engineer calculates that the following CT will not be able to adequately drive the protective relay under fault conditions:

- CT class = C600
- CT ratio = 1200:5
- CT secondary winding resistance = 0.25 ohms
- CT secondary wire size = 10 AWG
- CT secondary wire loop length (total) = 480 feet
- Protective relay burden = 2.5 + j0 ohms
- Maximum symmetrical fault current = 15000 amps AC
- System reactance/resistance ratio = 4

First, verify that the engineer has correctly assessed the inadequacy of this CT circuit. Do you concur that there is a problem here, or do you think the engineer erred and this system will work fine after all?

Suppose the engineer proposes a solution to this problem consisting of connecting *two* CTs in series for each line of the system, the two CTs both sensing the same line current with their secondary windings connected in series-aiding fashion like such:



Will this solution work or not? Explain your reasoning.

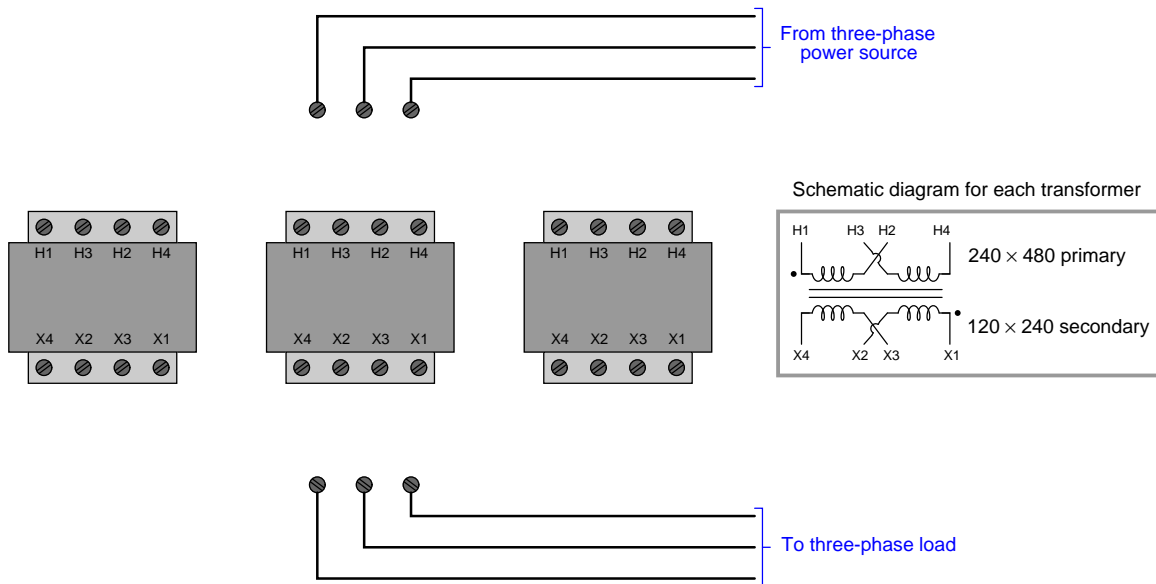
Suggestions for Socratic discussion

- Does the polarity of the two series-connected CTs matter? What would happen if you connected the two windings so their polarity marks opposed one another?
- Will connecting two CTs in series affect how the protective relay must be set? Why or why not?
- Would connecting two CTs in *parallel* achieve the same result? Why or why not?

[file i03097](#)

Question 28

Suppose you need to connect jumper wires to configure these three transformers to step up 240 VAC three-phase line power to 415 VAC three-phase load power:

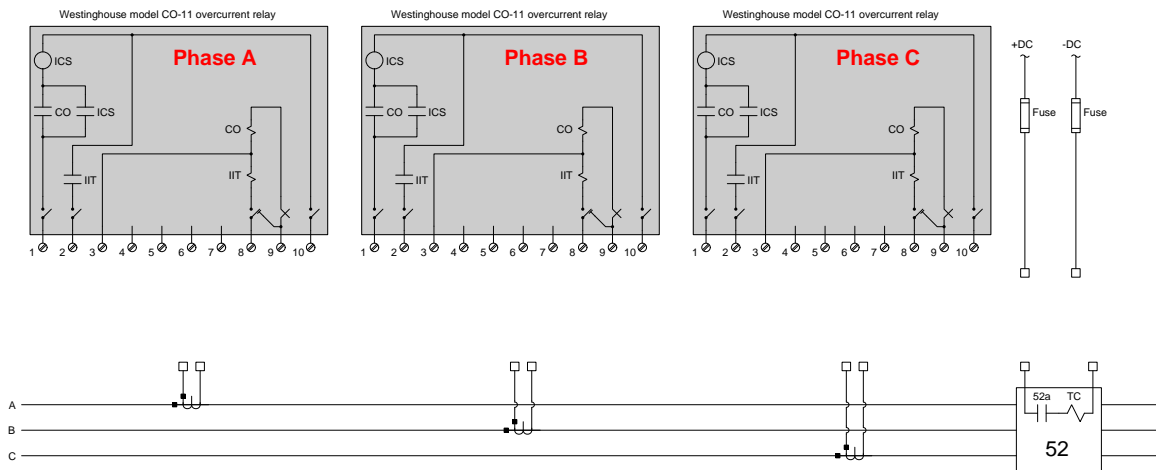


Sketch all necessary connections to achieve this goal.

[file i02903](#)

Question 29

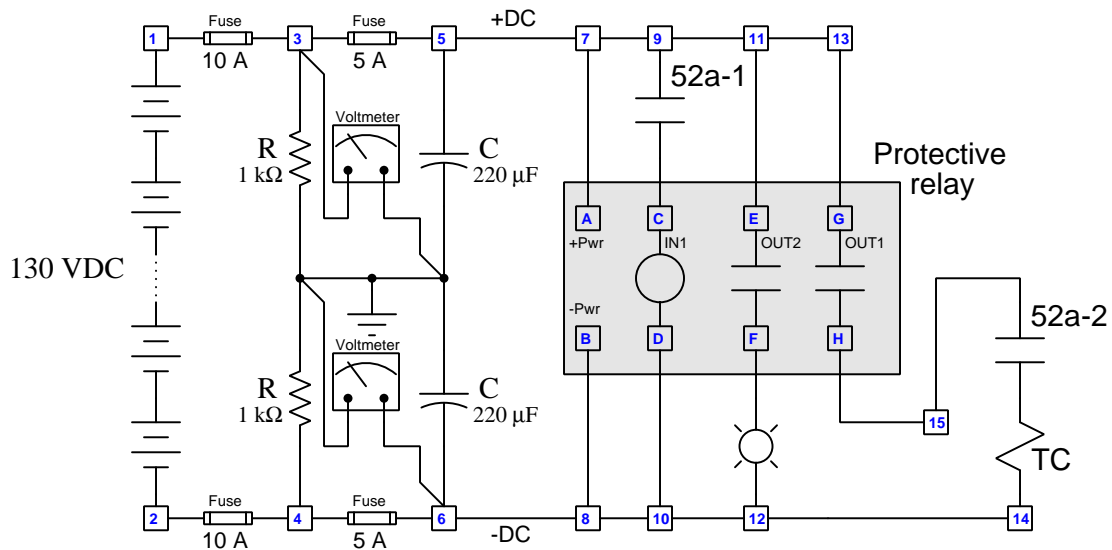
Sketch all the necessary wire connections for this set of three Westinghouse model CO-11 overcurrent relays to fulfill both the 50 and 51 ANSI/IEEE protective functions. Note that Westinghouse refers to the time-overcurrent element as “CO” and the instantaneous overcurrent element as “IIT”:



[file i00831](#)

Question 30

This protective relay circuit has a problem. During the last fault, it successfully tripped the circuit breaker, but the relay never registered the change in breaker status (from closed to tripped) – both the relay’s front-panel display and the indicator lamp continued to show the breaker as remaining in the *closed* state.



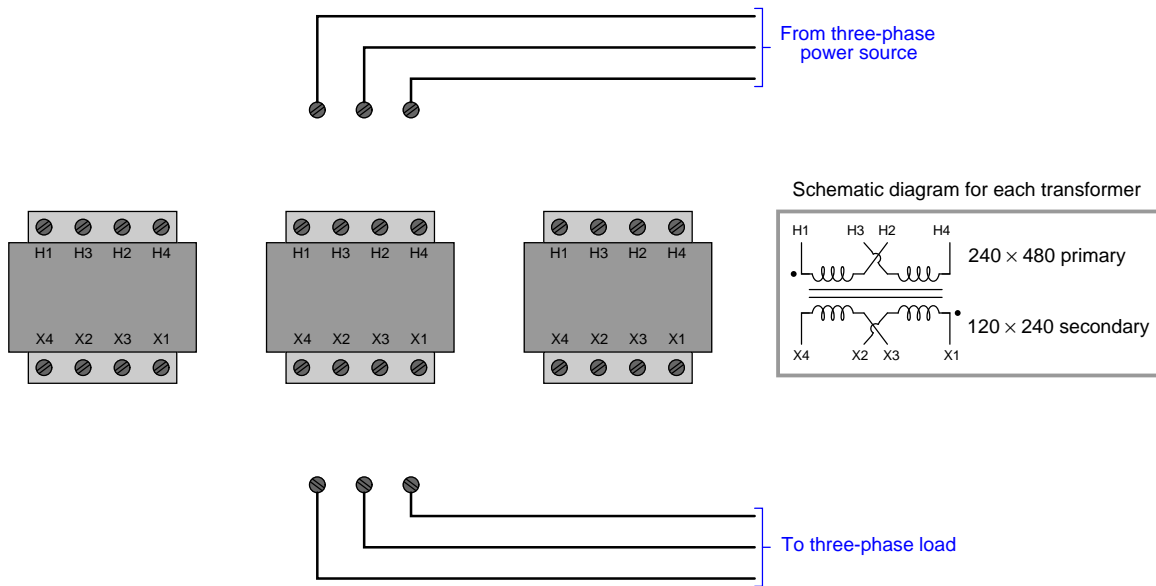
Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
Battery bank voltage low		
52a-1 contact failed open		
52a-1 contact failed shorted		
Failed relay input IN1		
Trip coil failed open		
Trip coil failed shorted		
Wire between terminals 5 and 7 failed open		
Wire between terminals 9 and 11 failed open		
Wire between terminals 10 and D 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 i03100](#)

Question 31

Suppose you need to connect jumper wires to configure these three transformers to step down 480 VAC three-phase line power to 208 VAC three-phase load power:



Sketch all necessary connections to achieve this goal.

[file i02904](#)

Question 32

Question 33

Question 34

Question 35

Question 36

Question 37

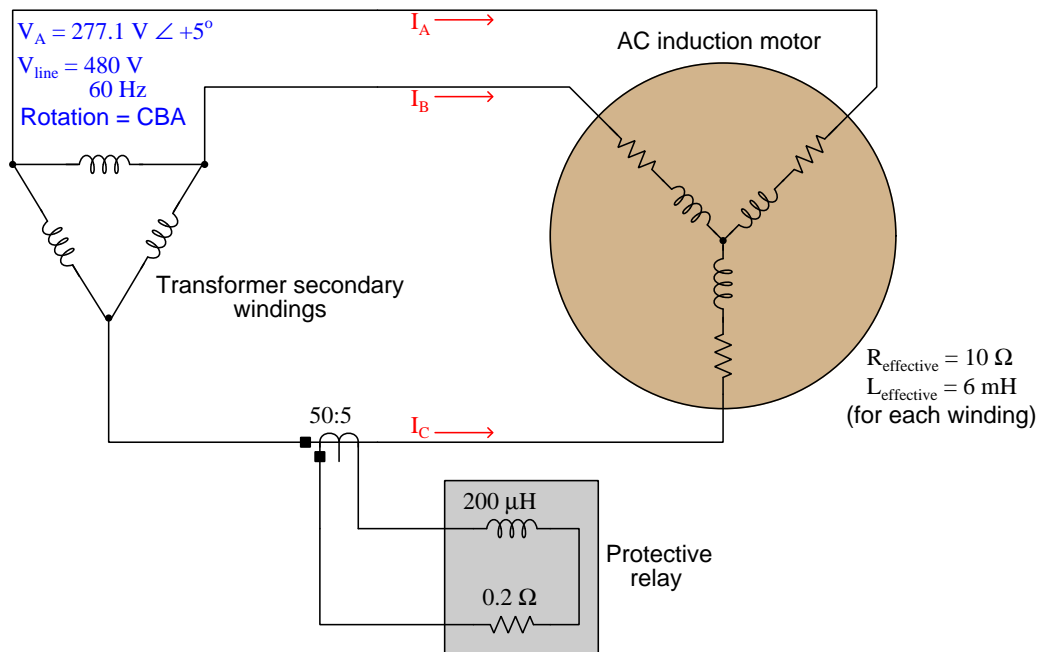
Question 38

Question 39

Question 40

Question 41

Calculate voltage dropped across the terminals of the protective relay during normal operation of this three-phase motor, being sure to express it as a phasor quantity. Assume a perfectly balanced system.



[file i00787](#)

Question 42

A current transformer with a C100 class rating and a 300:5 ratio is used to measure current through a power line where the maximum symmetrical fault current is 5 kA and the relay burden is 0.8 ohms (resistive). The CT's secondary winding resistance is 0.2 ohms. Assume no DC transients in this power system and 200 feet of distance between the CT and the relay (400 feet total wire length).

Calculate the maximum amount of resistance for the wire connecting the CT to the relay not exceeding the CT's rated capability, and then choose the *smallest* copper wire gauge size satisfying this criterion:

$$R_{\text{wire}} (\text{maximum}) = \text{_____} \Omega$$

- 6 AWG
- 8 AWG
- 10 AWG
- 12 AWG
- 14 AWG

[file i03315](#)

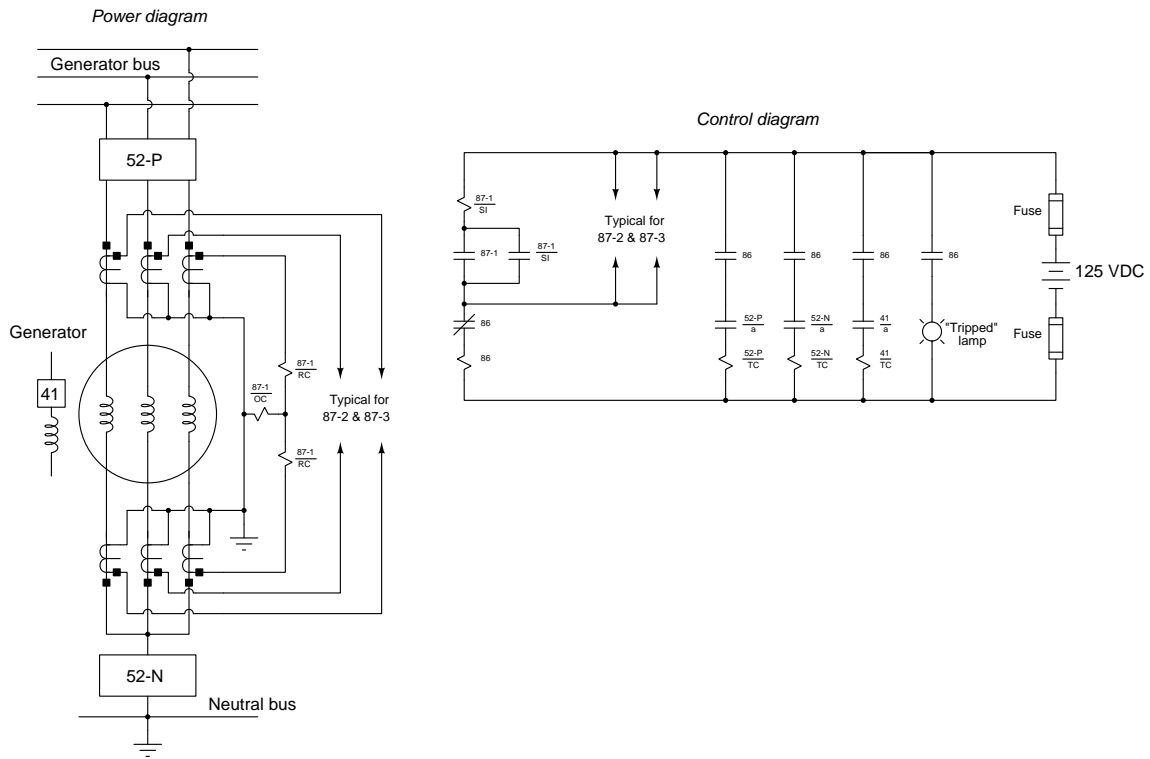
Question 43

A current transformer with a ratio of 1000:5 senses line current in a system where the reactance-to-resistance ratio is 6-to-1. The CT has a rating of C800, an internal winding resistance of 0.2 ohms, and is connected to a protective relay having a burden of 0.65 ohms (resistive) through 12 gauge copper wire. Sketch an equivalent schematic diagram of this circuit, and calculate the maximum cable length connecting this CT to the relay so that it does not become excessively burdened with a symmetrical fault current of 3.8 kA.

[file i02608](#)

Question 44

The following power and trip circuit diagrams show the differential current (87) protection for a large three-phase generator:



Suppose one day relay 87-3 trips, tripping the 86 lockout relay and opening all three circuit breakers (52-P, 52-N, and 41).

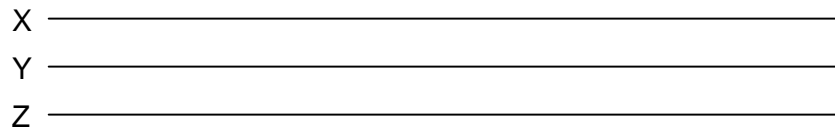
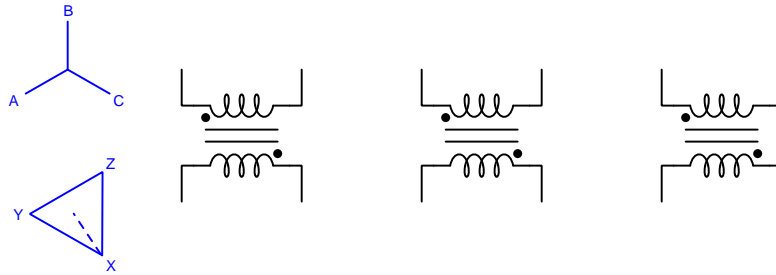
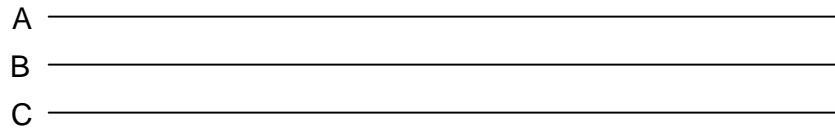
Identify the likelihood of each specified fault for this system. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault could independently account for *all* measurements and symptoms in this circuit.

Fault	Possible	Impossible
Dead DC station power supply		
Fault in generator field winding		
CT failed open		
86 trip coil failed open		
86 trip coil failed shorted		
87-3/OC coil failed open		
87-3/OC coil failed shorted		
87-3/RC coil failed open		
87-3/RC coil failed shorted		

file i01028

Question 45

Sketch the necessary wire connections to create a three-phase transformer bank fulfilling the phasor diagrams shown to the left of the transformers:



Also, write the phase sequences (phase rotations) for both 3-phase busses, and identify whether the lower bus *leads*, *lags*, or is *in-phase* with the upper bus.

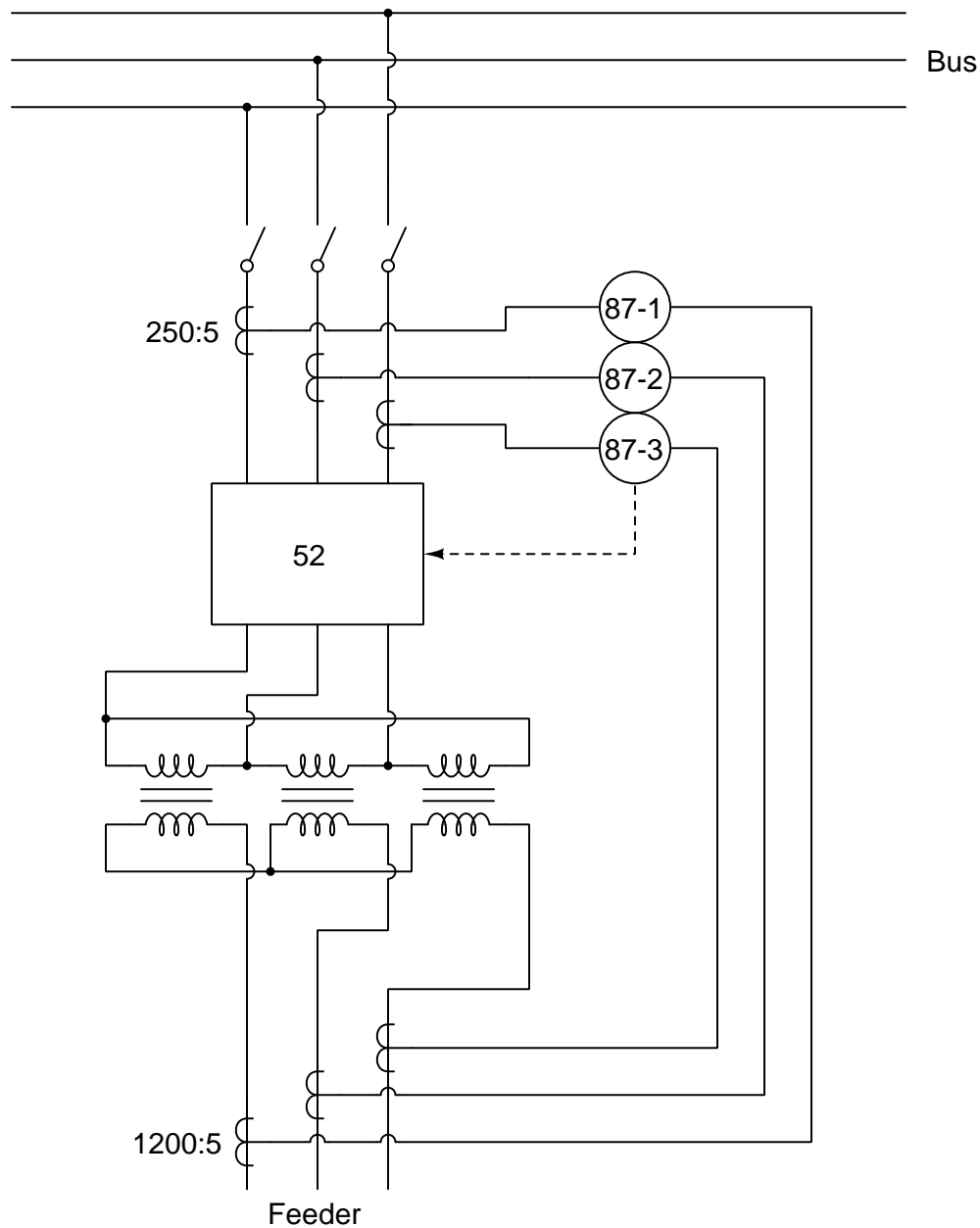
Suggestions for Socratic discussion

- A key piece of information in the lower phasor diagram is the dashed vector. What does this vector represent, and why is it important?

[file i00848](#)

Question 46

Examine this differential current protection system for a transformer, supplying three-phase power to a feeder from a substation bus:



Suppose the cable connecting feeder phase 2's CT to the 87-2 relay fails shorted, such that the relay no longer senses current from the secondary winding of the transformer through that phase. Will the other two differential current relays continue to provide adequate protection for the transformer? Explain why or why not, in detail.

[file i02563](#)

Question 47

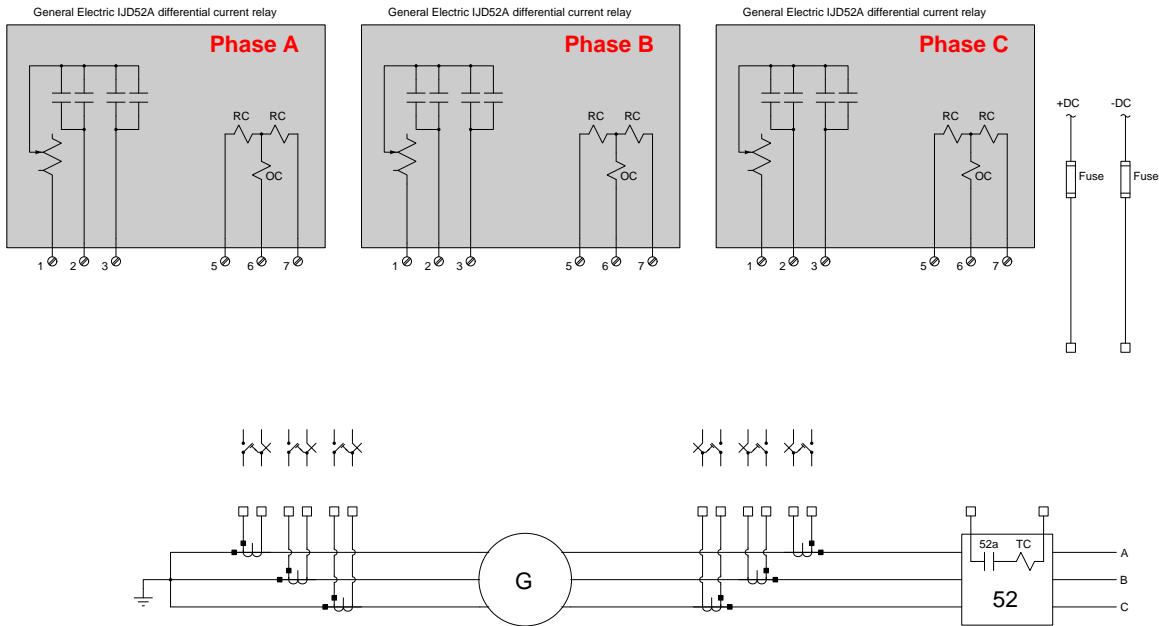
Suppose a pair of three-phase AC generators are preparing to be synchronized and connected to the same bus. One of them is outputting 485 volts (line), while the other is outputting 478 volts (line), both at the exact same frequency (60 Hz). However, at the present moment they are 18° out of phase with each other.

A set of three synchronization lamps connected across the open circuit breaker contacts (one lamp connected across each contact) indicates the two generators' readiness to synchronize. Calculate the voltage across each of the lamps in this out-of-phase condition, as well as the frequency of that lamp voltage.

[file i03328](#)

Question 48

Sketch all the necessary wire connections for this set of three General Electric model IJD52A differential current relays to protect the generator against internal faults:

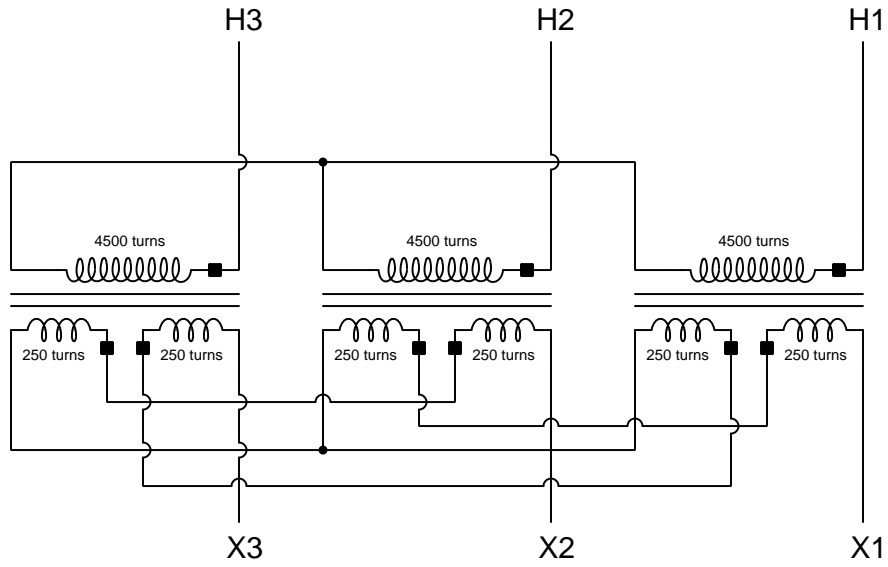


Don't forget to safely ground all the CT secondary circuits!

[file i00832](#)

Question 49

This three-phase transformer configuration is called a Wye-Zigzag:



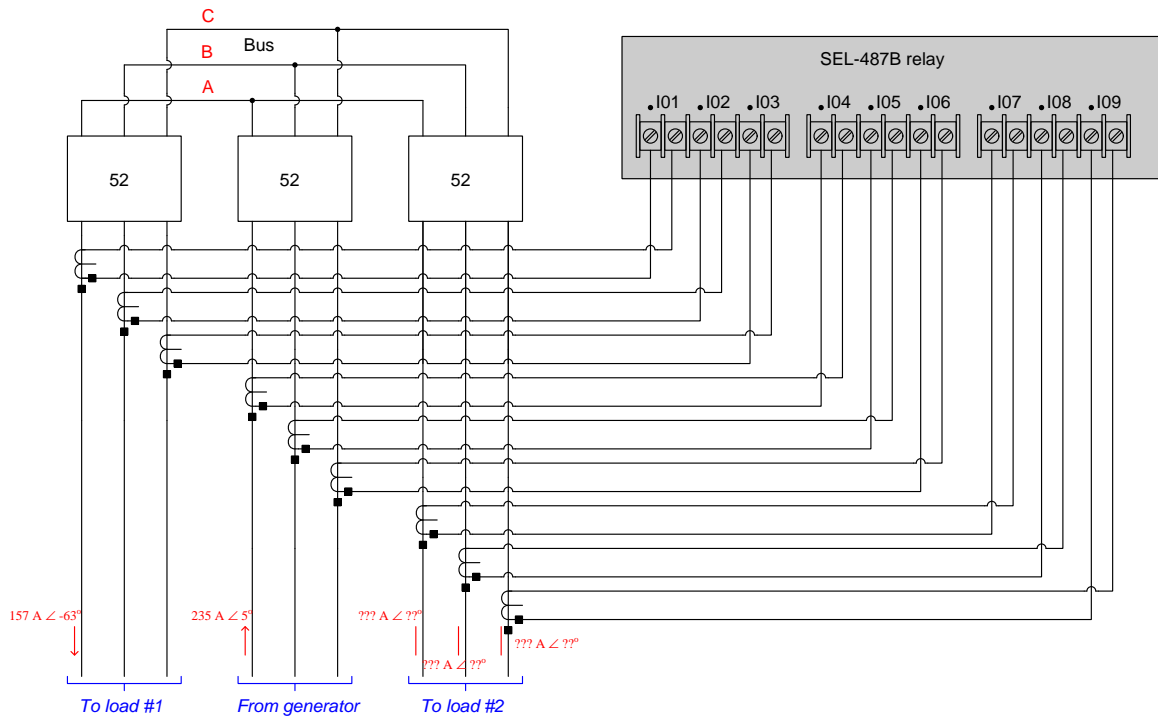
Calculate the magnitude and phase angle of V_{X1} assuming V_{H1} is $7.2 \text{ kV} \angle 0^\circ$ and the phase rotation is H1-H2-H3.

$V_{X1} = \underline{\hspace{2cm}}$

[file i00837](#)

Question 50

An SEL-487B differential current protective relay is used to provide protection for a three-terminal bus at an industrial facility substation:



Calculate the magnitudes and phase angles for all three line currents feeding load #2, assuming the generator and both loads are balanced, the bus is not faulted, and the phase rotation is ABC. Be sure to place arrowheads on the current arrows for load #2 in addition to expressing the currents in complex (polar) form.

[file i02565](#)

Question 51

Question 52

Question 53

Question 54

Question 55

Question 56

Question 57

Question 58

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:

Performance objective	Grading	1	2	3	4	Team
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° 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° phase shift is indicated by the needle pointing straight down.

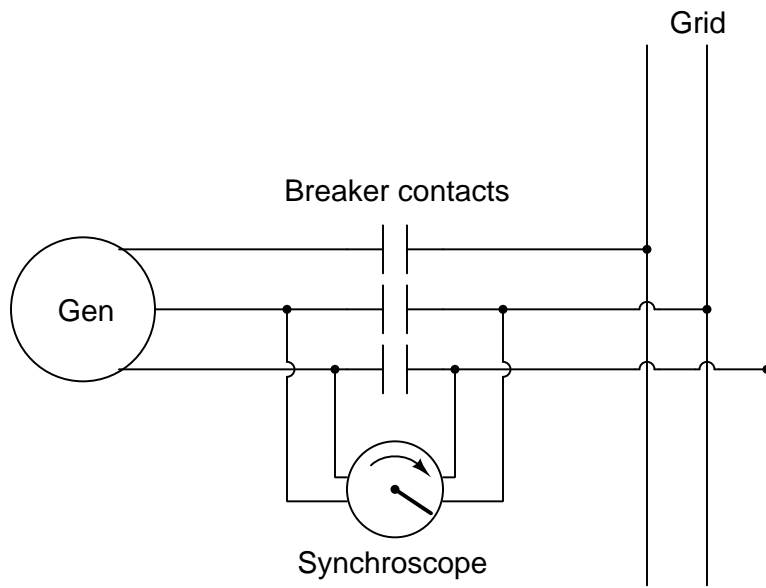
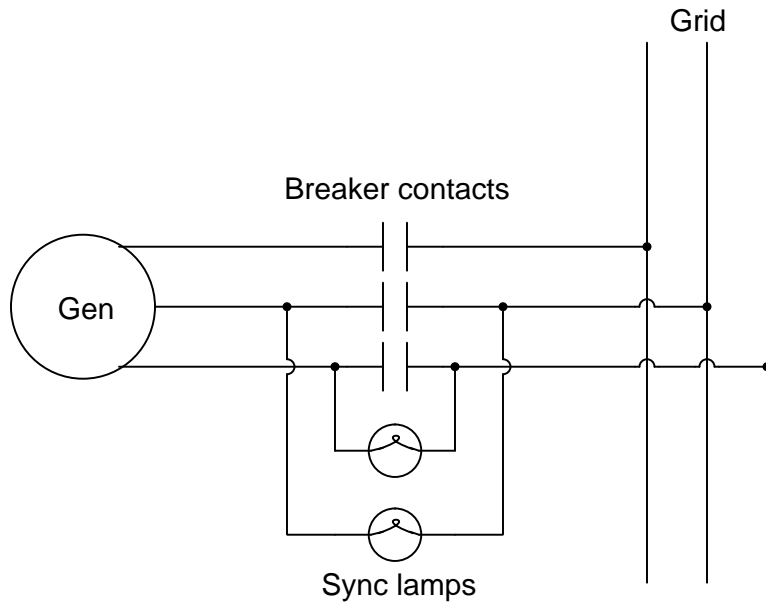
If the generator and power grid are at different frequencies, the sync lamps will oscillate in brightness at a frequency equal to the difference in generator and line frequencies. A synchroscope's needle will rotate at a speed equal to this difference frequency.

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.

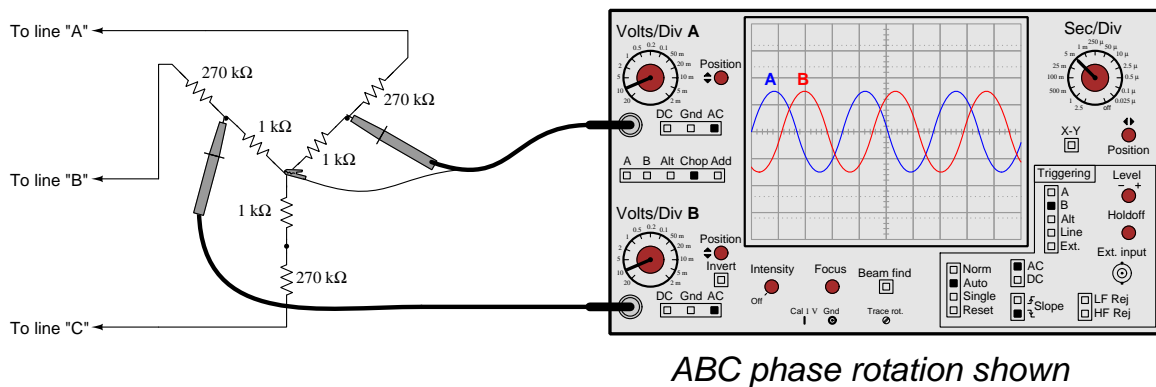
Common mistakes:

- 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.

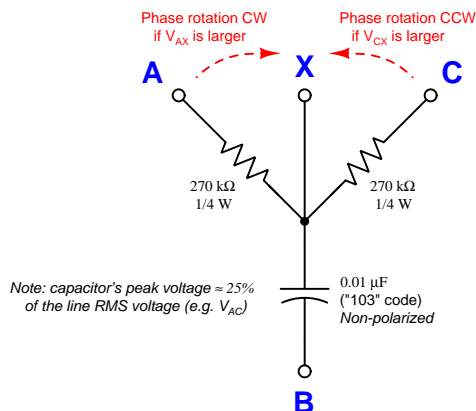
Lab Exercise – phase rotation (sequence) testing

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 = Ω Phase B = Ω Phase C = Ω
CT secondary circuit insulation resistance <i>(quantitative) – insulation tester</i>	Phase A = Ω Phase B = Ω Phase C = Ω
Protective relay input burden (all phases) <i>(quantitative) – ohmmeter</i>	Phase A = Ω Phase B = Ω Phase C = Ω
CT circuit ground resistance (all phases) <i>(quantitative) – ohmmeter</i>	Phase A = Ω Phase B = Ω Phase C = Ω
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 = Ω
Breaker close coil circuit loop resistance <i>(quantitative) – ohmmeter</i>	52/CC = Ω

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 `AcSELeator 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.

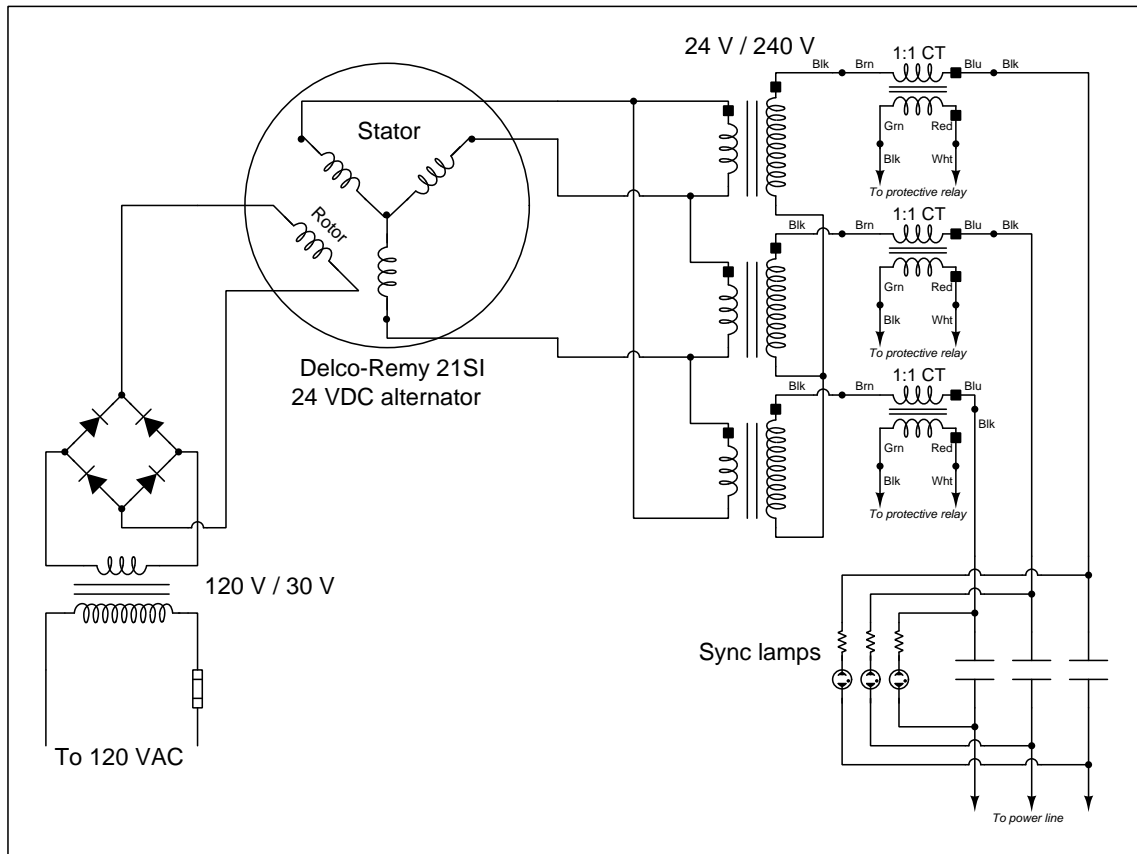
If your team's protective relay provides oscillography and/or phasor diagram displays in addition to text-based fault reports (as do SEL relays), you must show these as well. **AcSELeRator QuickSet SEL-5030** software is necessary to generate and display oscillographs and phasor diagram animations for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

file i03020

Question 62

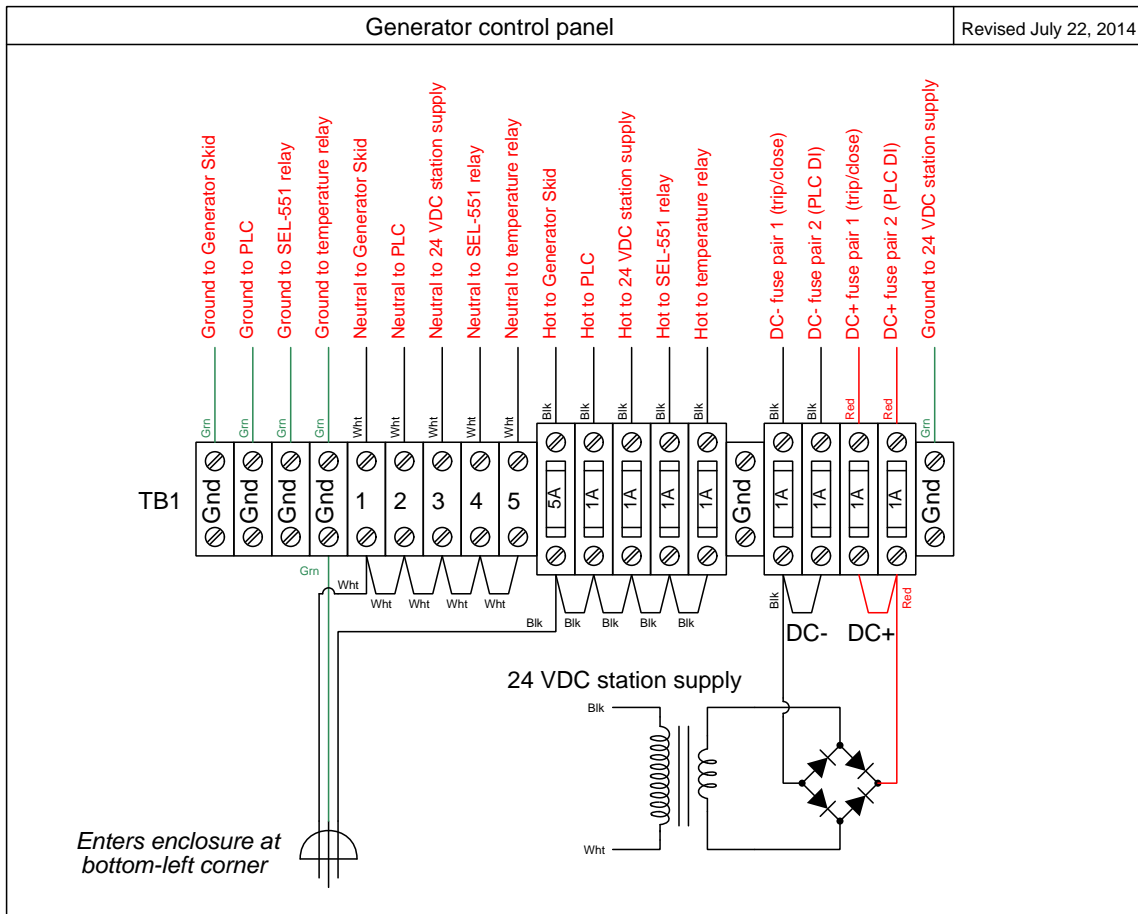
In the Instrumentation lab at Bellingham Technical College there exists a miniature three-phase AC power grid consisting of multiple generators and multiple substations. This question serves as a reference for a number of the schematic diagrams documenting each generating station in this system.

Generator field and power wiring



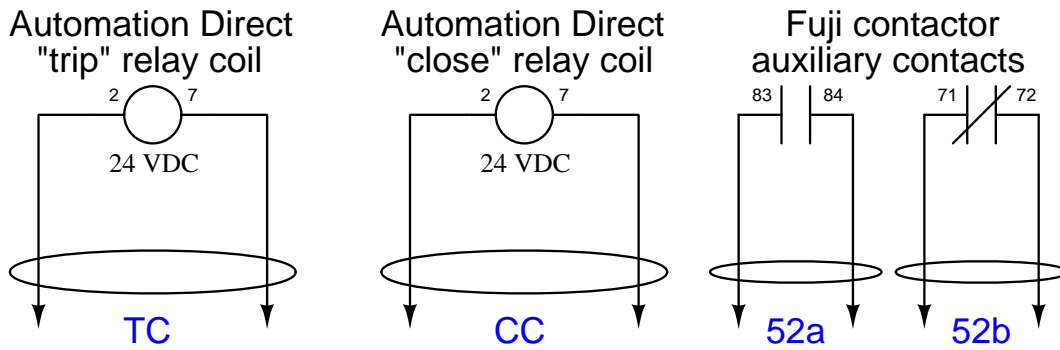
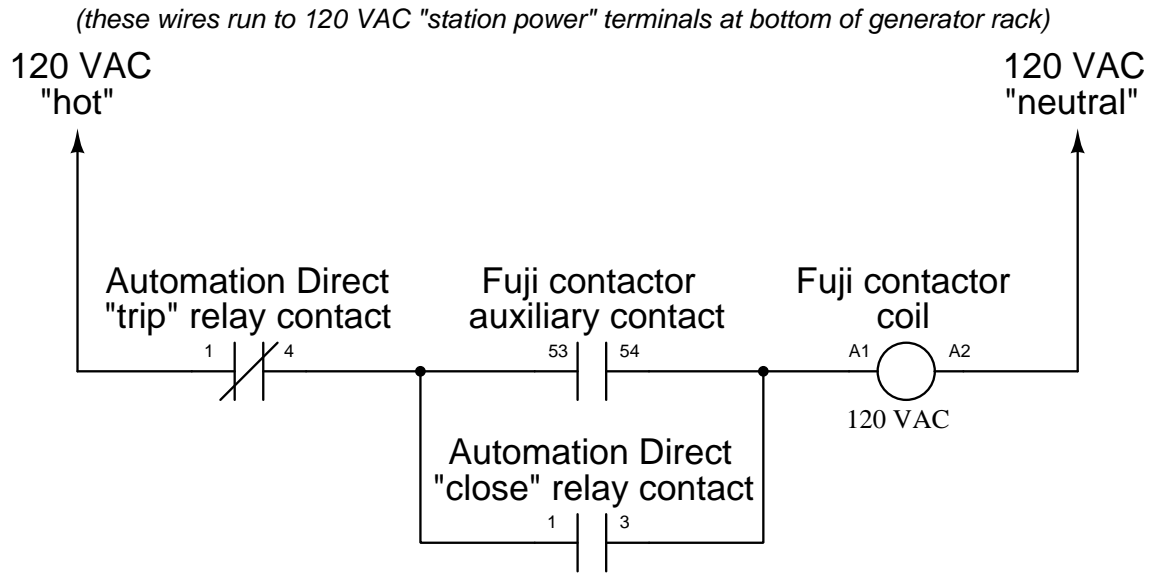
This is typical of each generator skid. At full speed (600 RPM, 60 Hz output frequency) each generator only outputs about 8 Volts AC because this is a much slower speed than it was designed to run when spun by a truck or boat engine. We run it this slow in order to achieve the standard grid frequency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

120 VAC and DC station control power distribution



Located in the generator control panel.

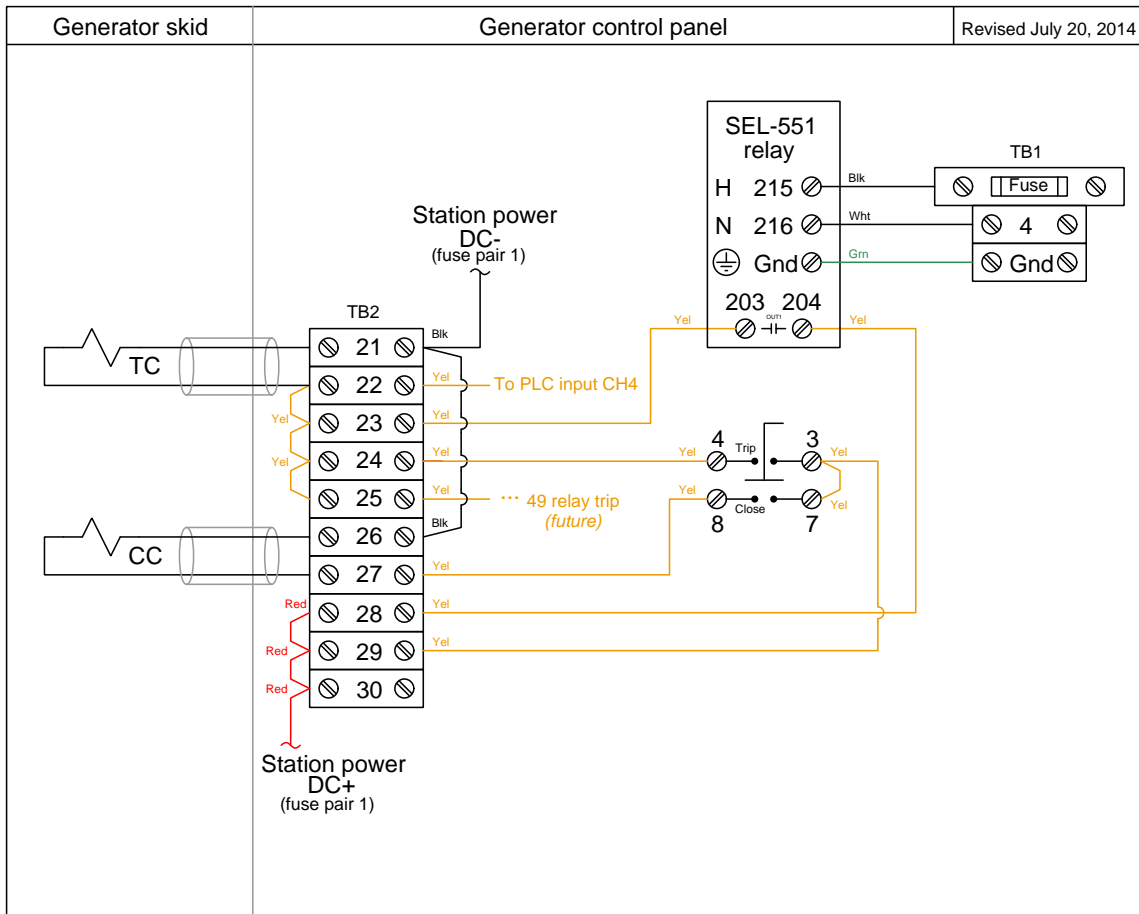
Generator circuit breaker details



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

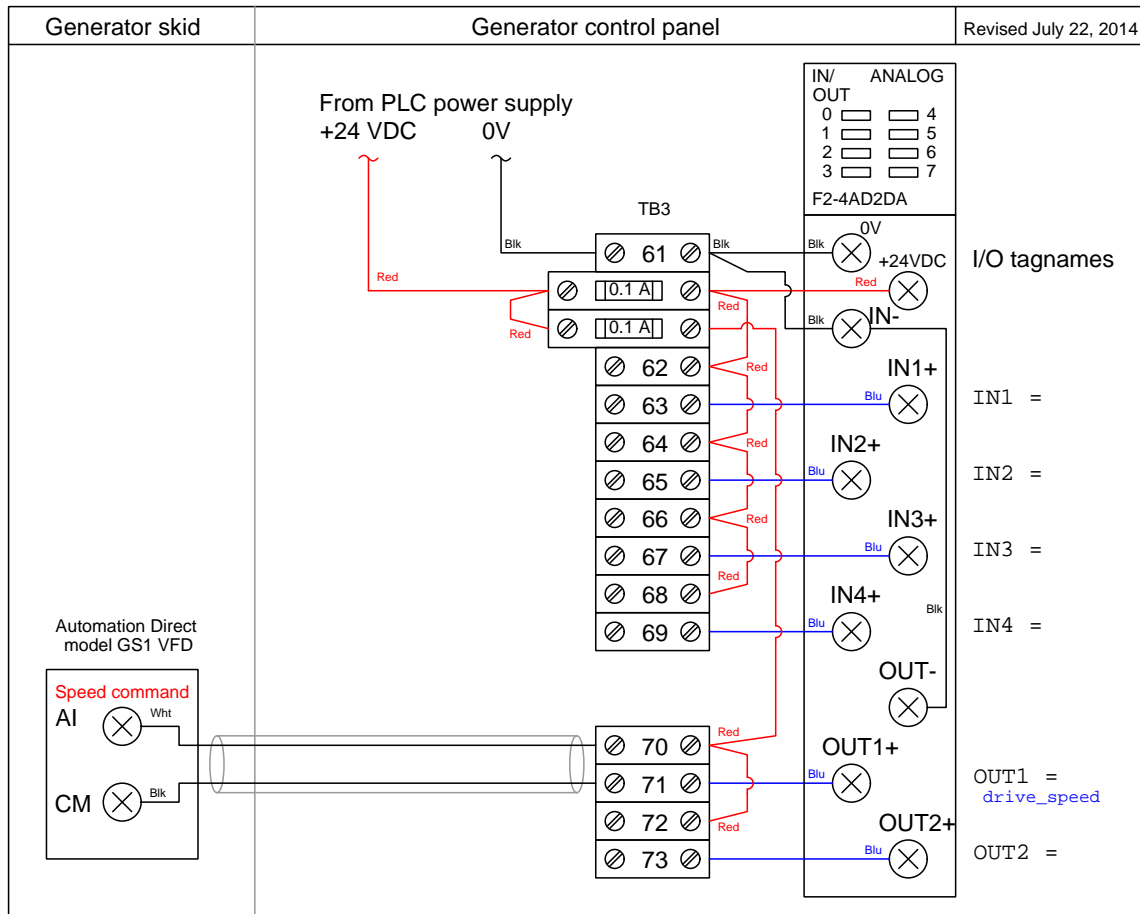
Located on the generator skid, near the very top where the three-phase AC power exits. We are using a standard Fuji 3-phase motor contactor as the circuit breaker element, and a pair of ice-cube style relays wired to latch the contactor on and off, so that the contactor mimics the behavior of a spring-actuated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

Trip/close wiring



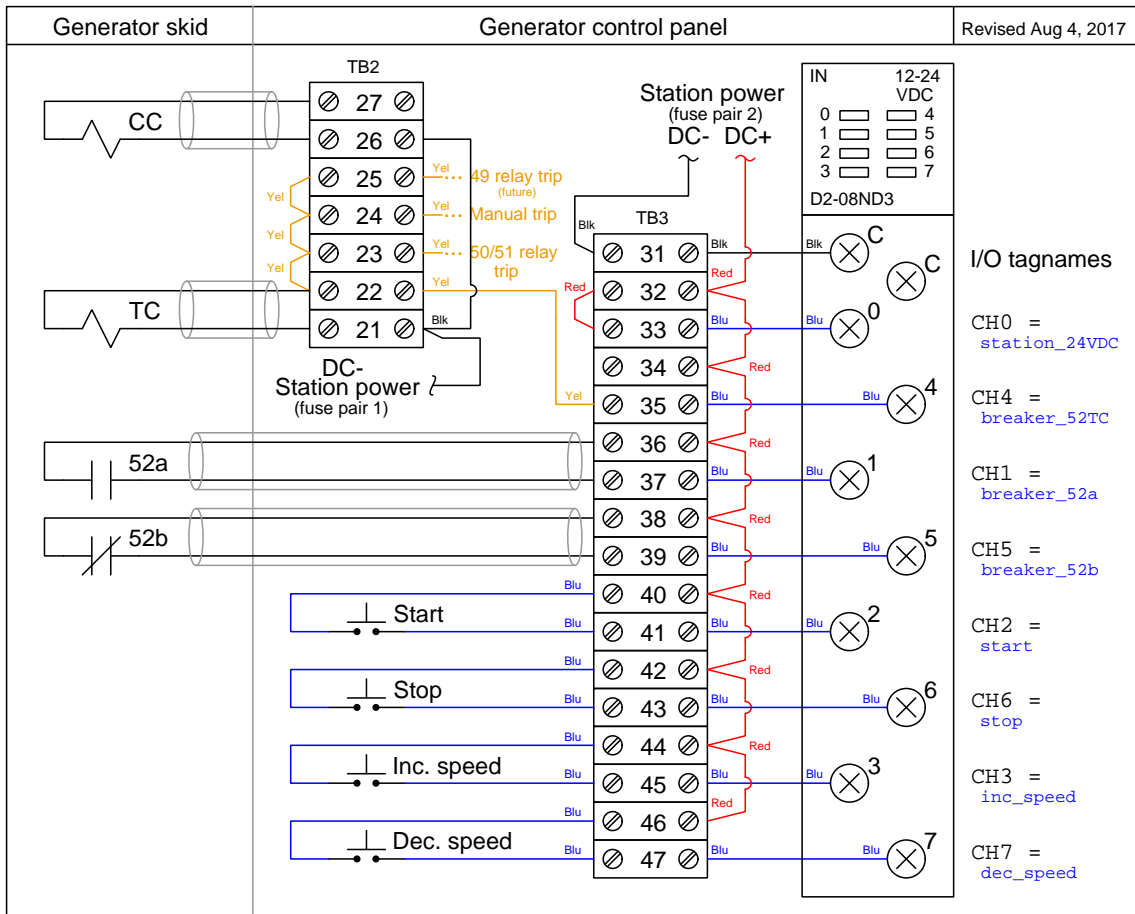
Located in the generator control panel.

PLC analog inputs/outputs



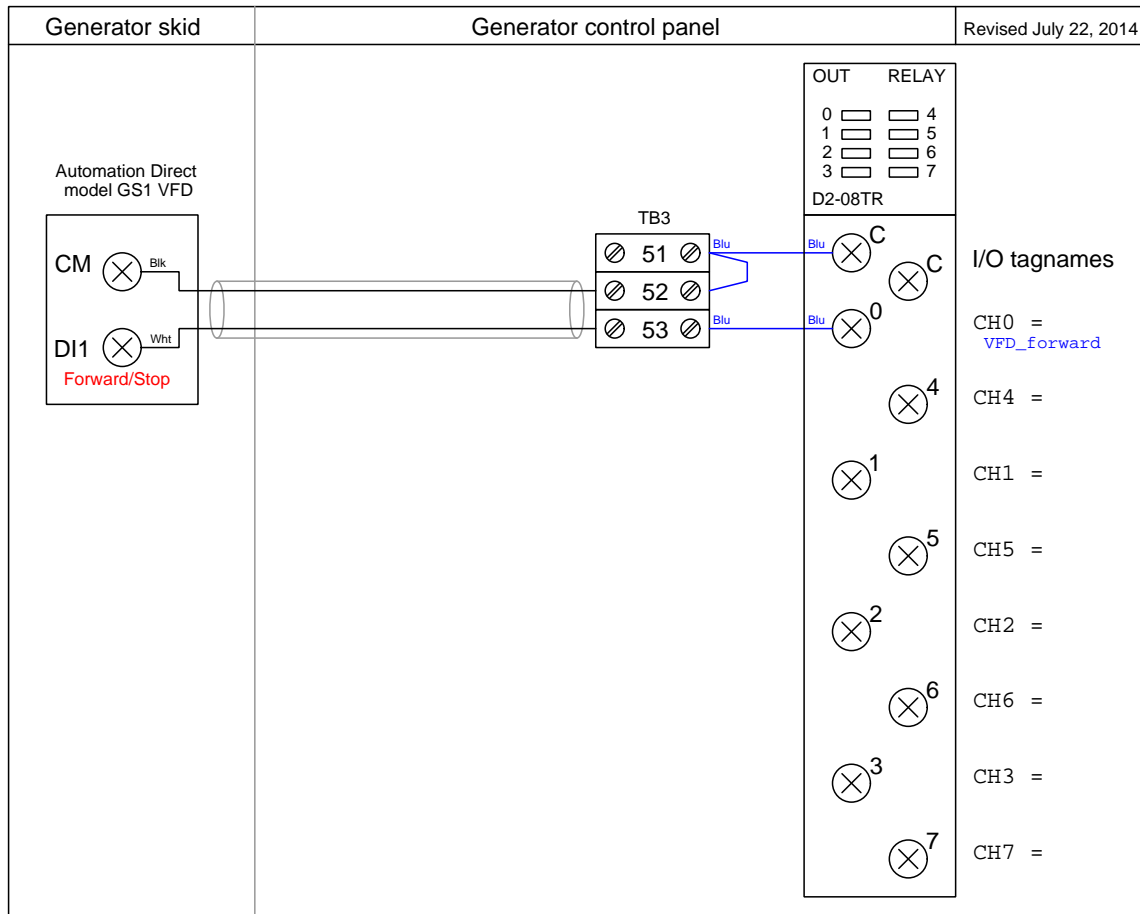
Located in the generator control panel. The one analog output sends a 4-20 mA speed control signal to the VFD, which then drives a three-phase motor to spin the generator. This VFD-controlled motor mimics a prime mover such as a hydro turbine or steam engine which would ordinarily be the mechanical driver 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](#)

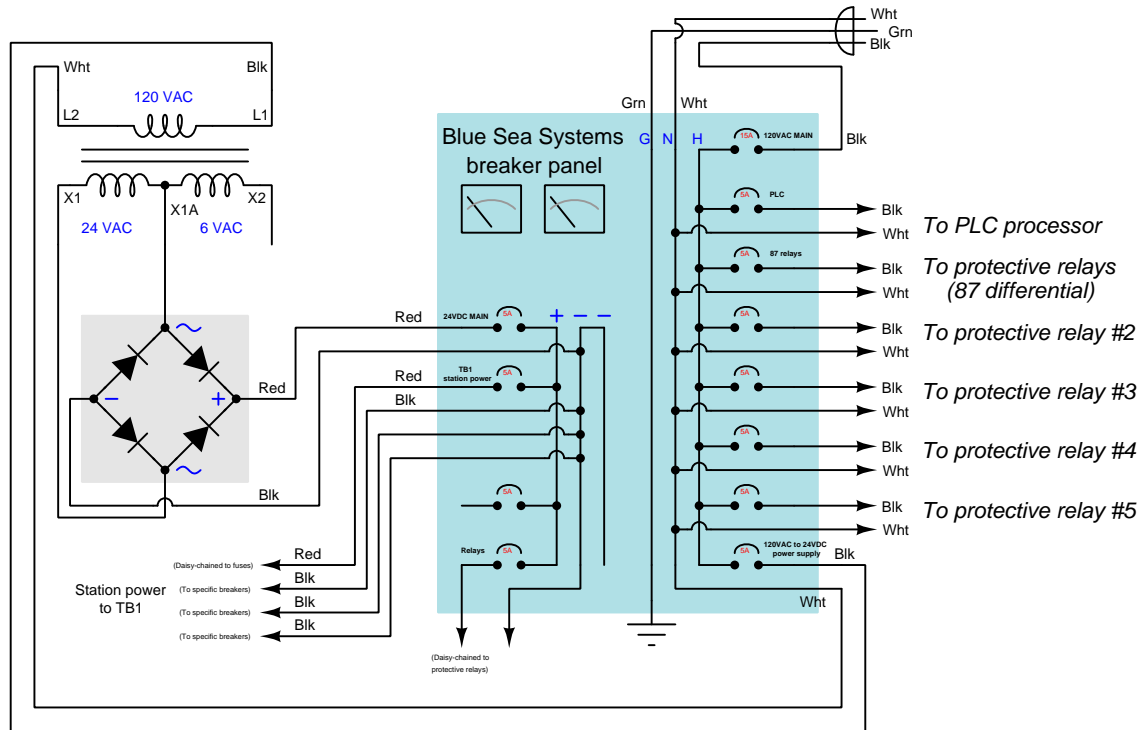
Question 63

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.

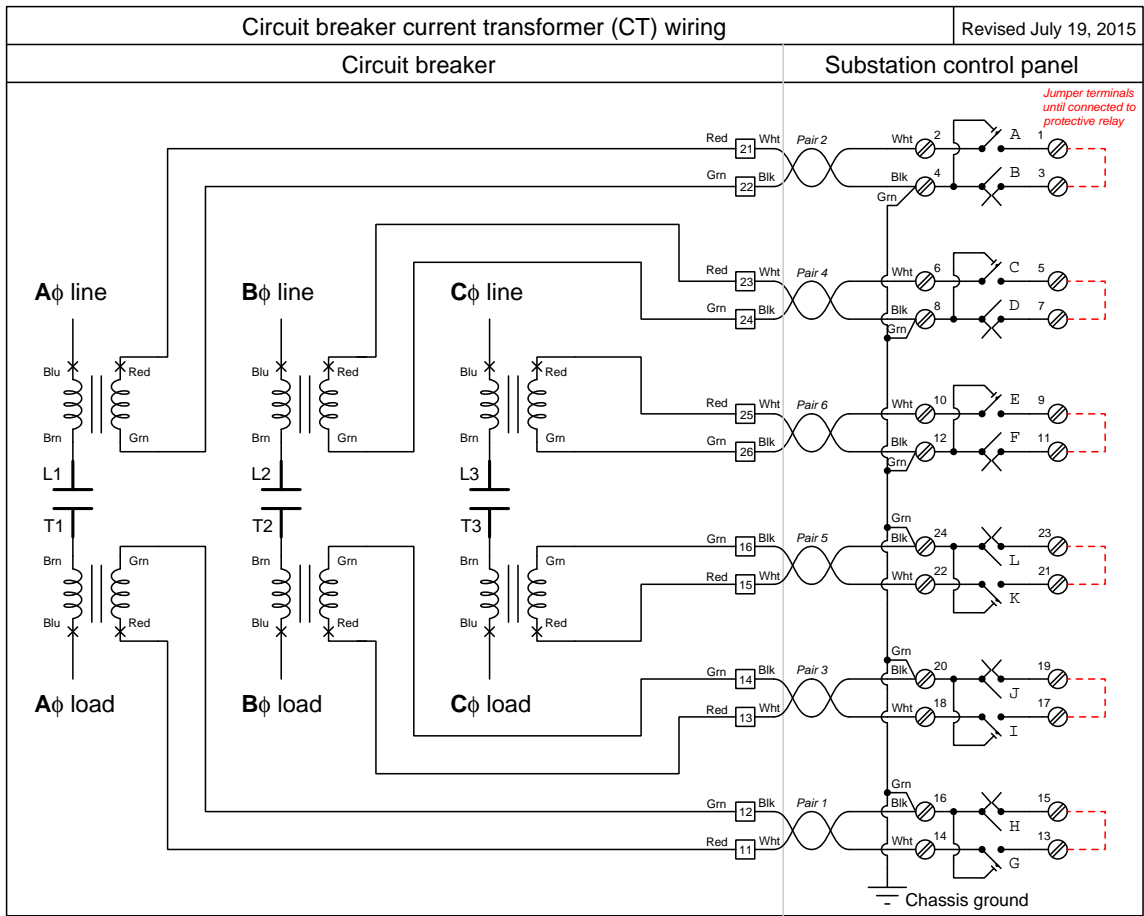
Station power diagram

Station power wiring diagram

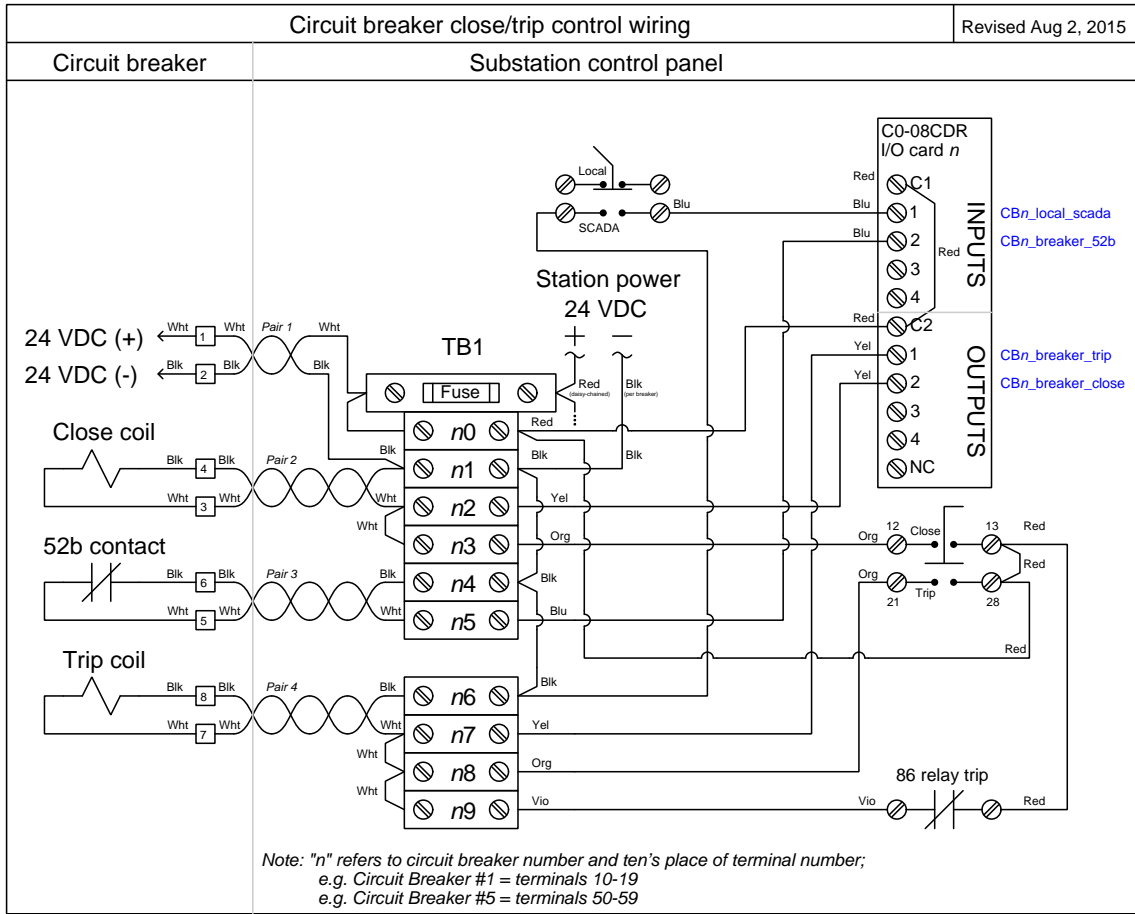
Revised August 19, 2015



Circuit breaker current transformer (CT) wiring



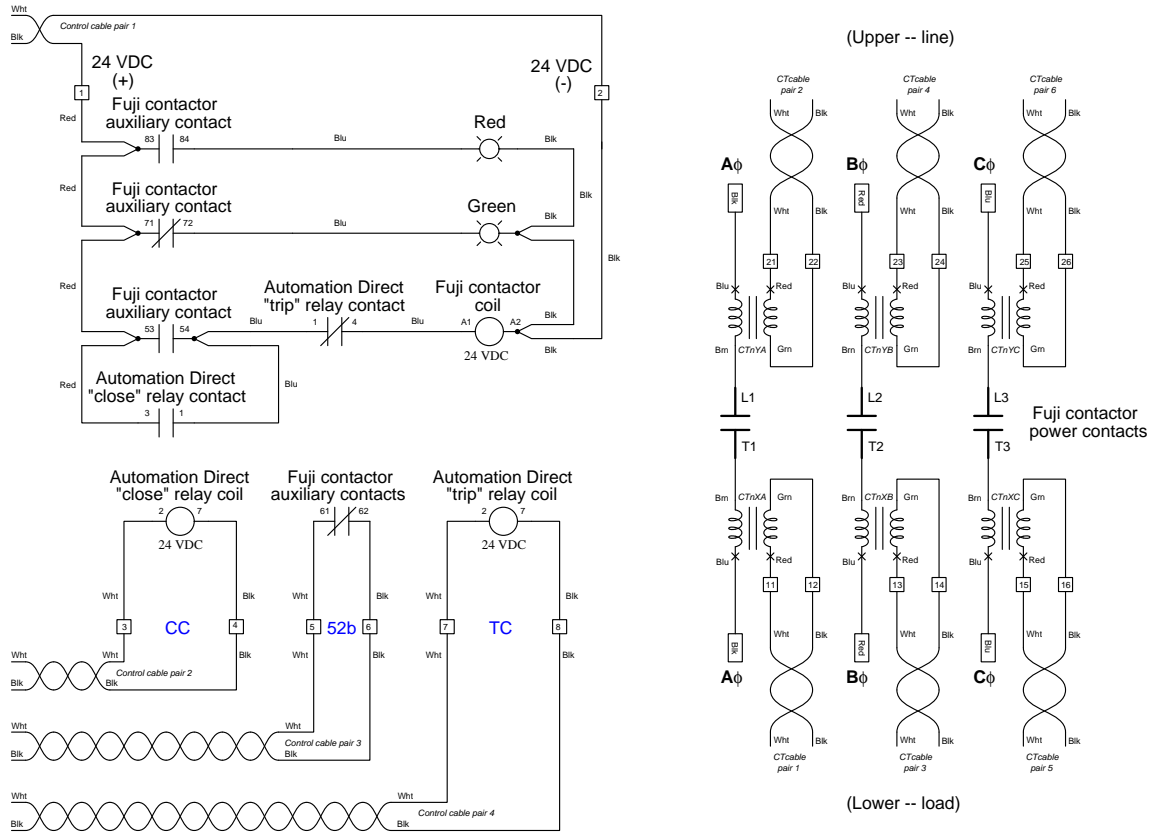
Circuit breaker trip/close wiring



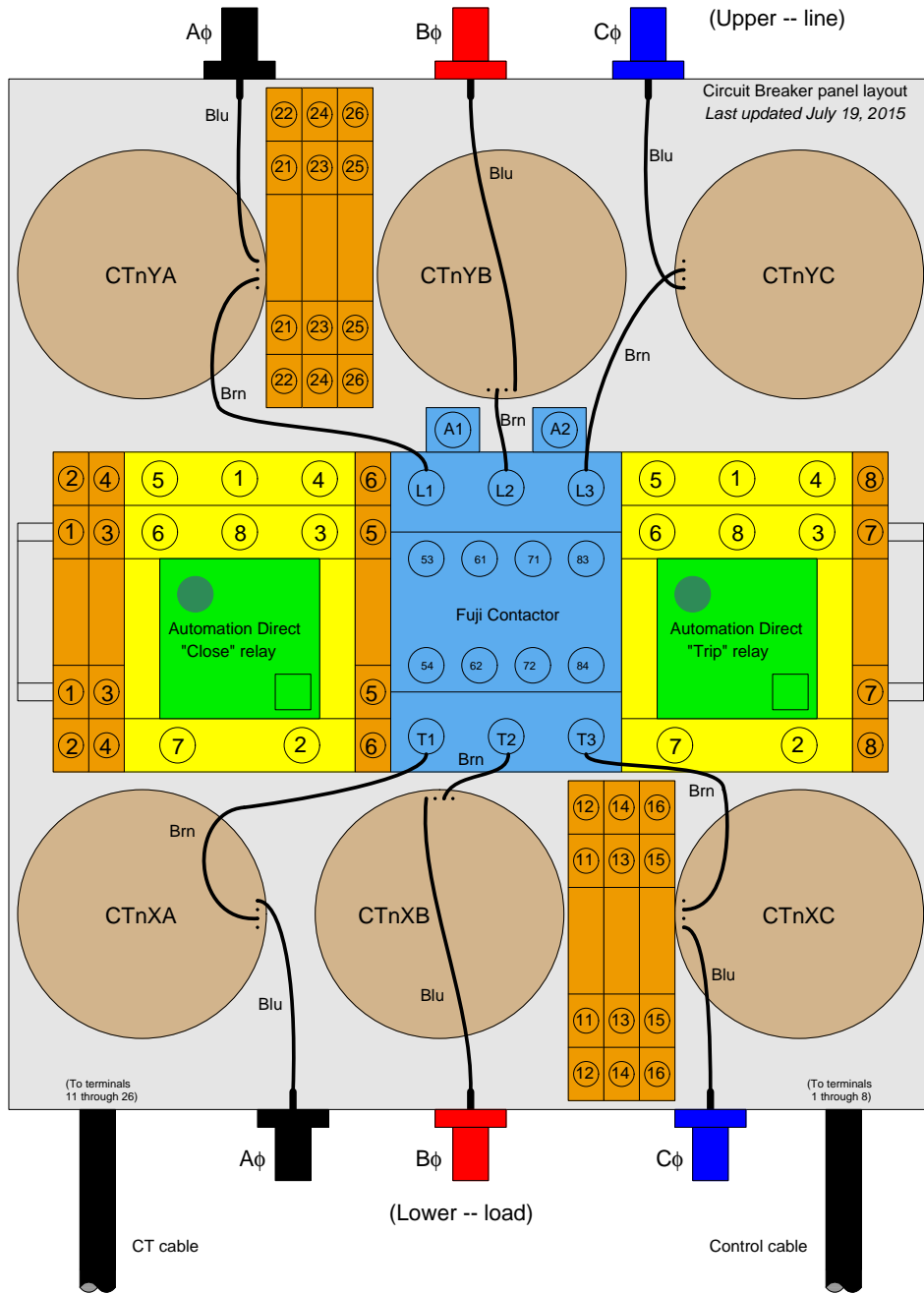
Circuit breaker internal wiring diagram

Circuit Breaker internal wiring diagram

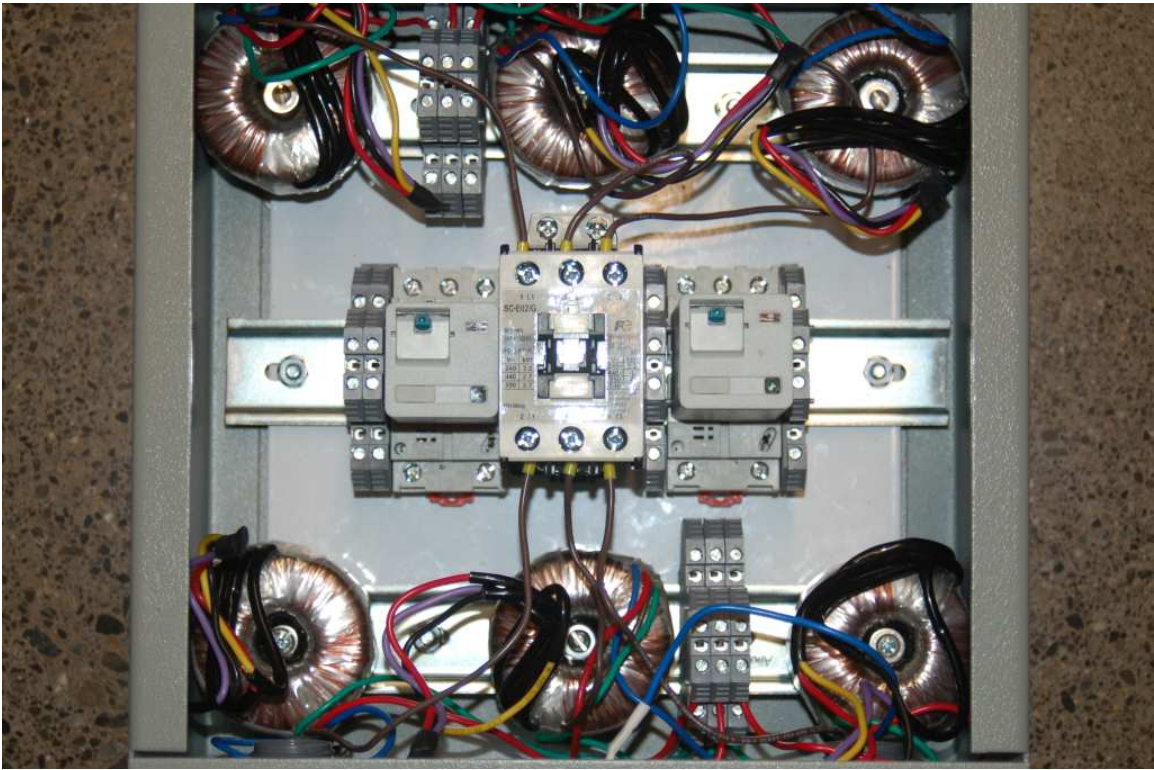
Last updated July 19, 2015



Circuit breaker internal layout

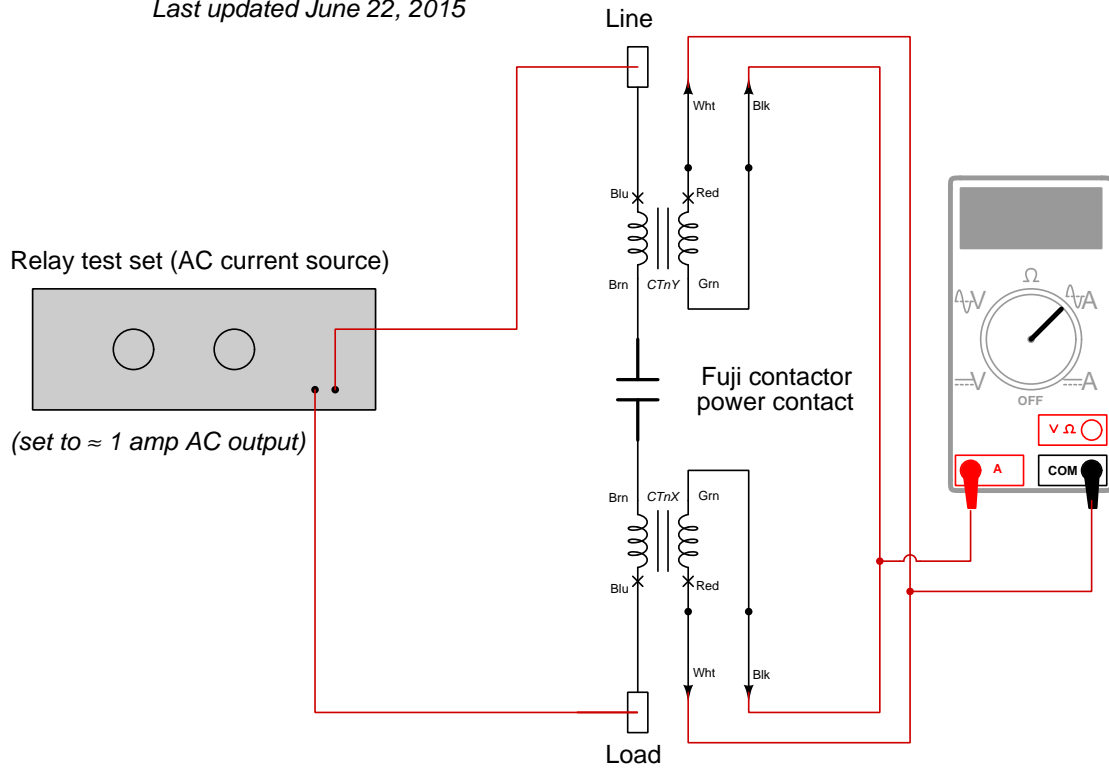


Photograph of typical circuit breaker



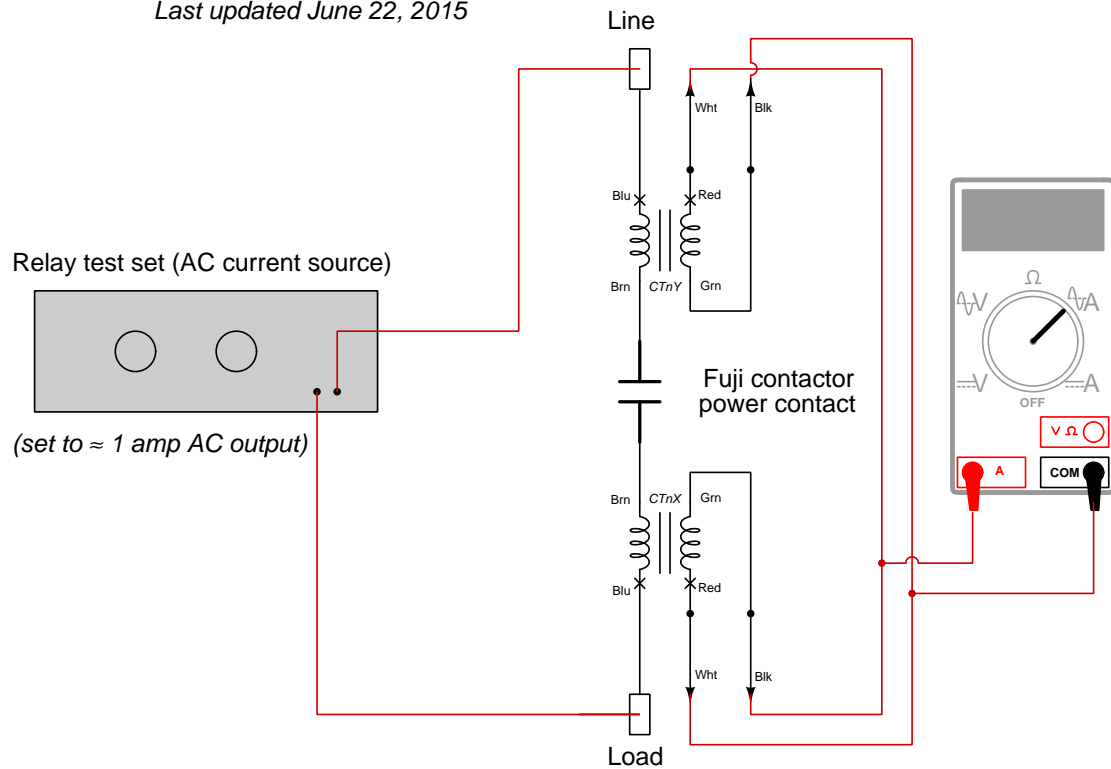
Current transformer polarity test setup current transformer secondary windings aiding

Last updated June 22, 2015

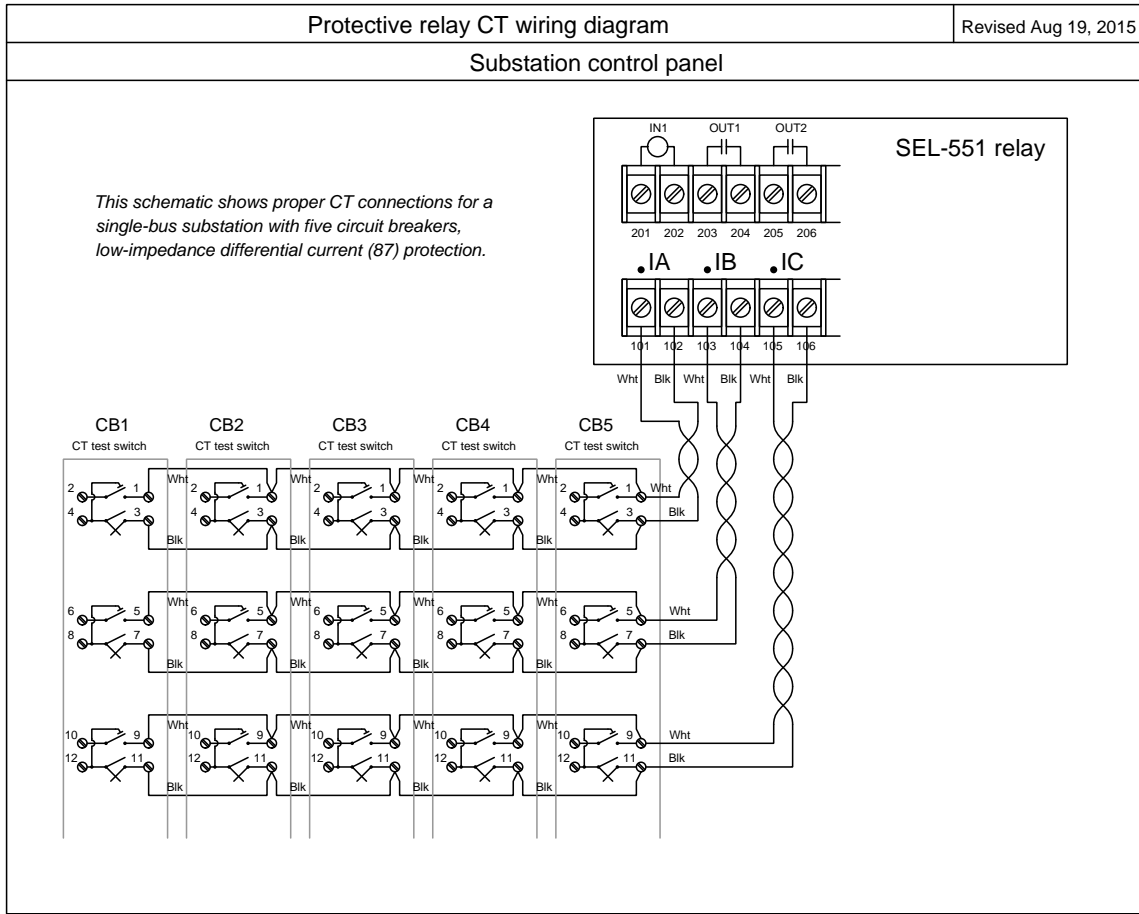


Current transformer polarity test setup current transformer secondary windings opposing

Last updated June 22, 2015

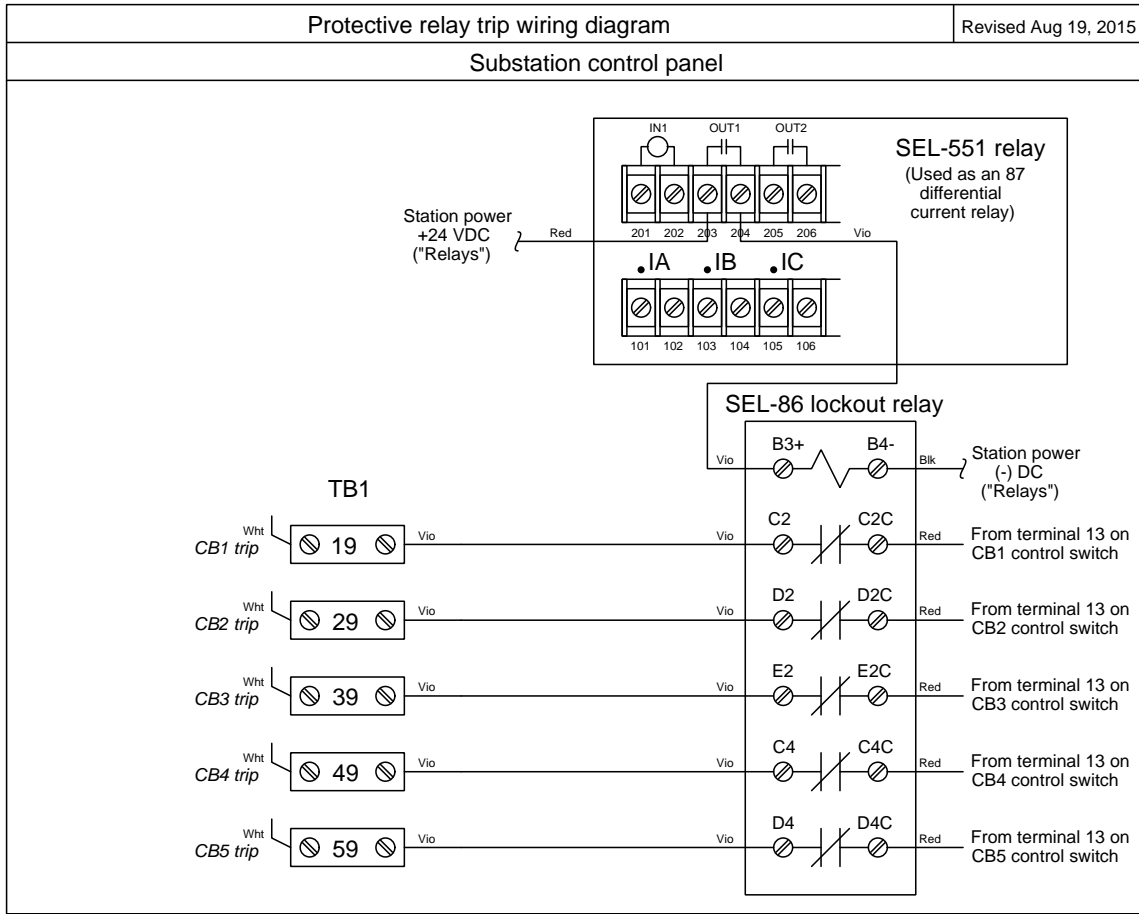


Protective relay CT wiring



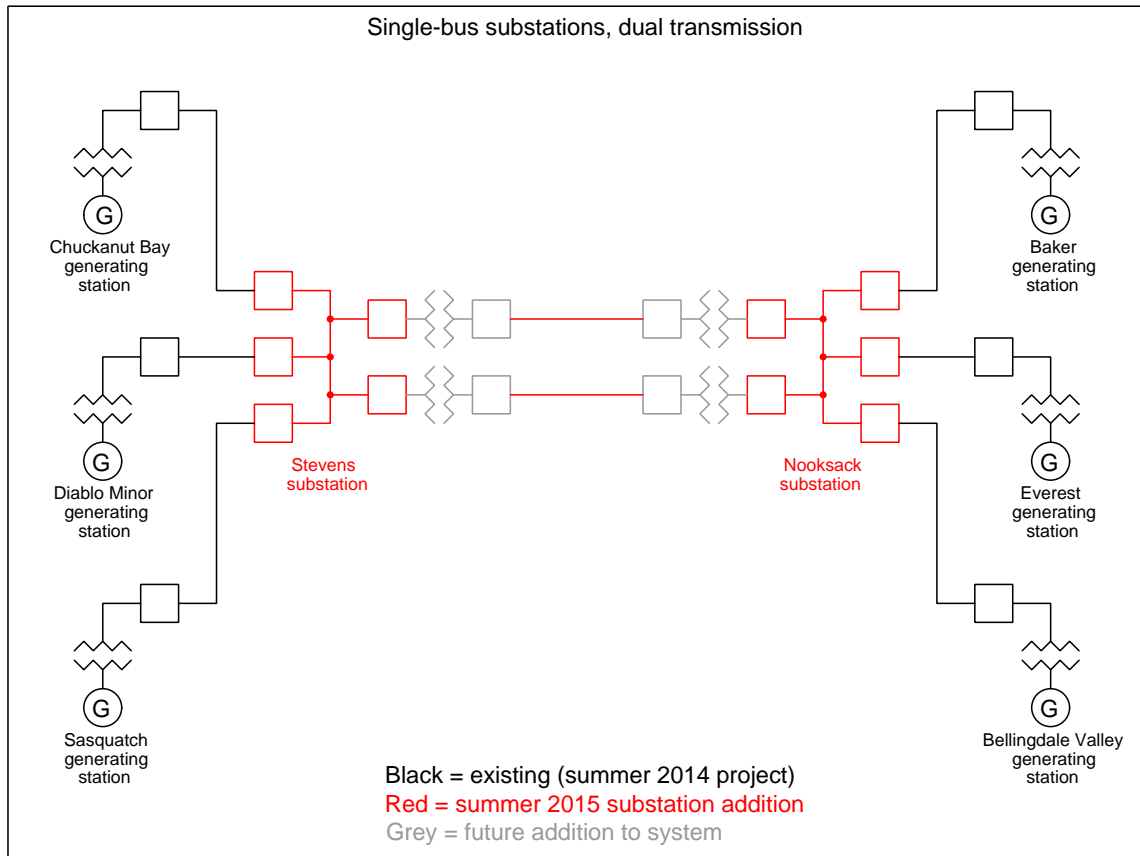
This scheme parallels all the CT secondary windings, to form a crude low-impedance version of differential current (IEEE/ANSI number code 87) protection.

Protective relay trip wiring

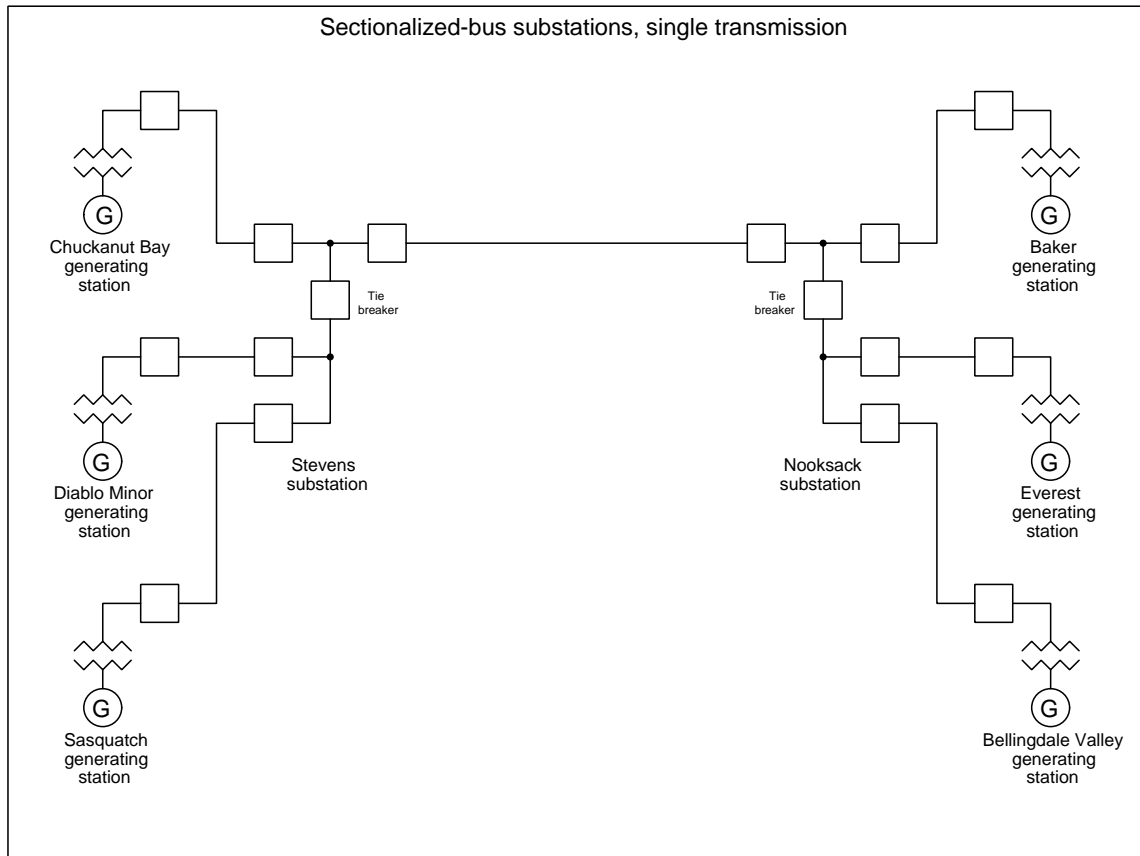


This scheme parallels all the CT secondary windings, to form a crude low-impedance version of differential current (IEEE/ANSI number code 87) protection.

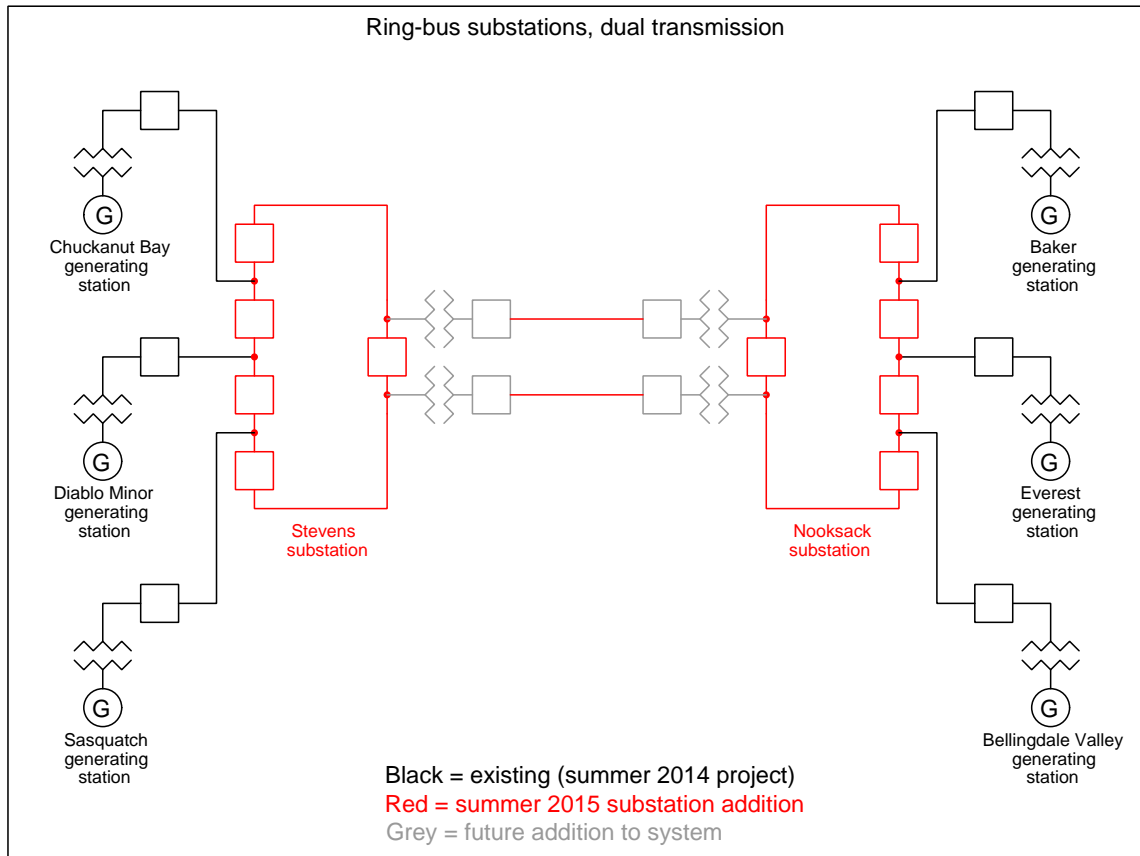
Substation configuration option: single bus



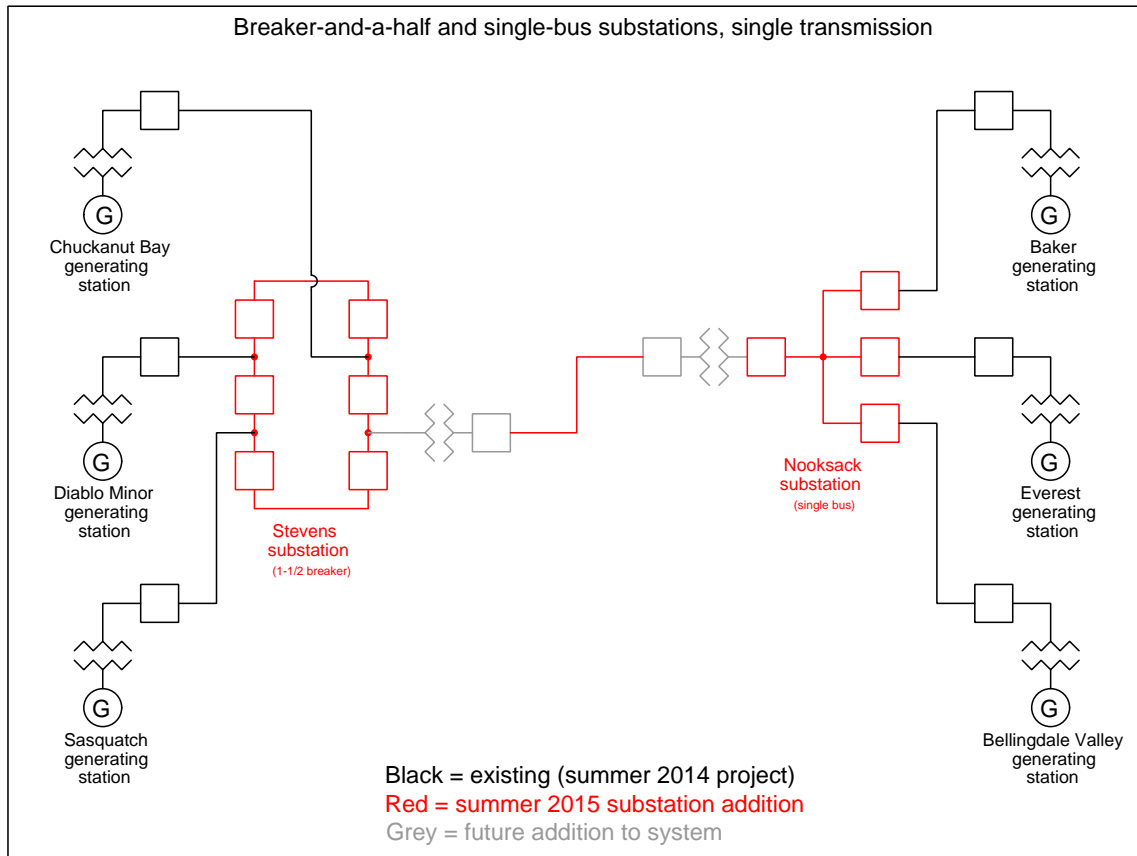
Substation configuration option: sectionalized bus



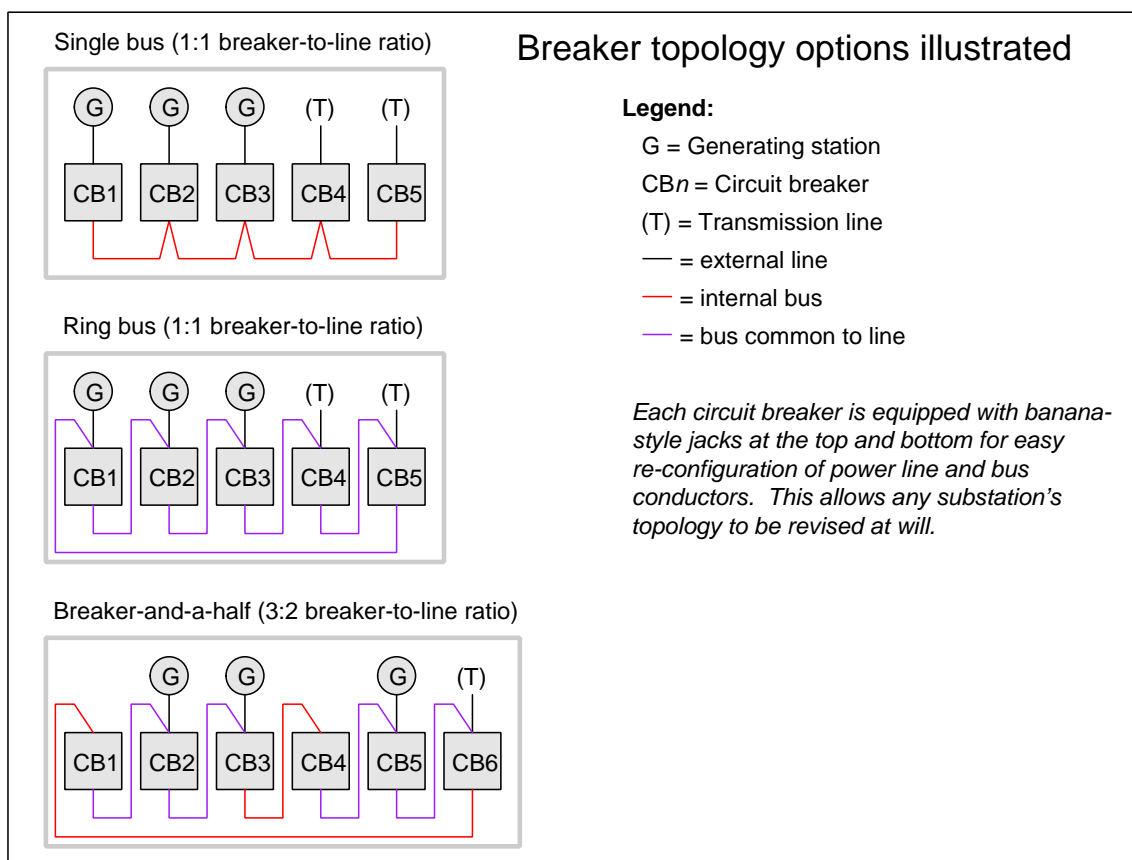
Substation configuration option: ring bus



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](#)

The maintenance of a working lab facility is extensive, especially for a program such as Instrumentation, where most of the equipment comes in the form of donations which must be pieced together, and where many of the systems are custom-built for the purpose. Every student bears a responsibility for helping maintain the lab facility, because every student benefits from its provisions.

On the last day of every quarter, time is allocated to the clean-up and re-organization of the lab facility. This is a full work day, with attendance enforced as per usual. In order to help students focus on the tasks that need to be done, the following list documents some of the work necessary to make the lab ready for next quarter. Tasks preceded by a blank line will be assigned to lab teams for completion.

Lab tasks

- Check to see that all small items bearing BTC inventory tags are painted a bright color to make them easy to spot for each year's inventory check.
- _____ Sweep all lab floor areas, recycling or discarding any waste material.
- _____ Sweep all storage room floor areas, recycling or discarding any waste material. Place items found on floor back on shelves where they belong.
- _____ Collect all copper tube segments and place them in the copper/brass recycling receptacle.
- _____ Collect all aluminum, stainless steel, brass, and copper wire scrap (pieces shorter than 1 foot) in the scrap metal buckets near the north-west exit door.
- _____ Haul recyclable metals to a local scrap dealer, and return with cash to buy pizza for today's lunch.
- _____ Organize storage bins for danger tags and masking tape. Collect any unused danger tags from around the lab room and place them in that bin.
- _____ Help search for any missing Team Tool Locker items.
- _____ Clean all workbench and table surfaces.
- _____ Remove items from the compressor room, sweep the floor, and make sure there is no junk being stored there.
- _____ Collect lengths of cable longer than 1 foot and place in the storage bins inside the DCS cabinets for future use.
- _____ Re-organize wire spool storage area: remove any empty spools from the rack, ensure all boxes and unmounted spools are neatly stacked on the floor.
- _____ Collect all plastic tubes and return them to the appropriate storage bin.
- _____ Re-organize tube fitting drawers (north-west corner of lab room), ensuring no pipe fittings are mixed in, that all fittings are found in the proper drawers, and that all drawers are properly labeled (these drawers should have sample fittings attached to the fronts).
- _____ Re-organize pipe fitting drawers (north-west corner of lab room), ensuring no tube fittings are mixed in.
- _____ Re-organize hose fitting drawers (north-west corner of lab room).
- _____ Re-organize terminal block and ice-cube relay drawers (north end of lab room).
- _____ Drain condensed water out of air compressor tank (in the compressor room).
- _____ Return all books and manuals to bookshelves.
- _____ Inspect each and every control panel in the lab, removing all wiring except for those which should be permanently installed (120 VAC power, signal cables between junction boxes). Ensure that each junction box's power cords are securely fastened and grounded.
- _____ Inspect each and every signal wiring junction box in the lab, removing all wiring except for those which should be permanently installed (e.g. 120 VAC power, signal cables between junction boxes.). Ensure that each junction box's power cords are securely fastened and grounded.
- _____ Check condition of labels on all junction boxes and control panels, making new labels if the old labels are missing, damaged, or otherwise hard to read.
- _____ Check condition of labels on all permanently-installed cables (e.g. between junction boxes), making new labels if the old labels are missing, damaged, or otherwise hard to read.

- _____ Check condition of labels on all terminal blocks inside control panels and junction boxes, making new labels if the old labels are missing or otherwise hard to read.
- _____ Remove all debris left in control panels and junction boxes throughout the lab room, using a vacuum cleaner if necessary.
- _____ Clean up deadweight testers (they tend to leak oil). *Hint: WD-40 works nicely as a solvent to help clean up any leaked oil.*
- _____ Maintenance on turbocompressor system: (safety tag-out, check oil level, repair any oil leaks, repair any poor wire connections, clean debris out of control cabinet, re-tighten all power terminal connections).
- _____ Return all shared tools (e.g. power drills, saws) to the proper storage locations (hand tools to the tool drawer in the north-east corner of the lab room, and power tools to the tool shelf in the upstairs storage area).
- _____ Remove items from all storage cabinets on the north end of the lab room, cleaning all shelves of junk (e.g. pH probes that have been left dry) and returning all items to their proper places. Install covers on all transmitters missing them, especially on pneumatic transmitters which are vulnerable to damage without their covers attached.
- _____ Visually inspect all general-purpose pressure regulators stored in the north storage shelves for missing adjustment bolts, missing tube connectors, damaged port threads, etc. Make repairs as necessary.
- _____ Test all pressure transmitters not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. Check for stripped screw heads and replace screws if necessary. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all temperature transmitters not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. Check for stripped screw heads and replace screws if necessary. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all I/P converters not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. Check for stripped screw heads and replace screws if necessary. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all precision pressure gauges not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all precision pressure regulators not labeled “good” to see if they are indeed defective. Repair if possible, salvage parts and discard if not. *Do not discard any instrument with a BTC inventory tag!*
- _____ Test all hand air pumps used for pressure calibration work. If a pump leaks, disassemble the pump to clean and inspect its internal parts. Repair if possible, salvage parts and discard if not. *Do not discard any instrument with a BTC inventory tag!*
- _____ Return all field instruments (e.g. transmitters) and miscellaneous devices (e.g. pressure gauges and regulators) to their proper storage locations. *Note that I/P transducers and valve positioners should remain near their respective control valves rather than be put away in storage!*
- _____ Store all 2×2 foot plywood process boards in secure locations, ensuring each one is ready to use next quarter.
- _____ Ensure that each and every control valve mounted on the racks in the lab room has an I/P transducer mounted nearby, complete with Swagelok tube connectors in good condition for connecting compressed air supply and signal to the valve.
- _____ Check to make sure that each valve is securely mounted to the rack, and if there is a positioner attached that the feedback arm is properly connected to the valve stem (e.g. no missing tension springs, bent linkages, obvious misalignments).
- _____ Remove all items from the flammables cabinet, wipe all shelves of liquid and residue, then re-stock in a neat and safe manner.
- _____ Clean all bar-be-que grills of residue left over from lunches and fundraisers. *Note: you may need to take the grill racks and grease drip trays to a car wash station and use the engine degreaser solution to clean them thoroughly enough!*

- _____ Re-set all function block parameters in the DCS “Generic Loops” to their default settings. See the documentation on the main BTC_PPlus workstation for instructions on parameter values.
- _____ Check manometers on the calibration bench, ensuring those filled with red fluid are at their fluid levels and that all the others (normally filled with distilled water) are completely drained.
- _____ Turn on compressed air to the calibration bench, checking for leaks and ensuring every pressure regulator is functioning as it should.
- _____ Clean refrigerators, throwing away any food items remaining within.
- _____ Thoroughly clean all food ovens and any other cooking tools.
- _____ Return all shelf boards to their appropriate places on the racks.
- _____ Clean and re-organize all shelves in classroom DMC 130 storing components for the hands-on mastery assessments. Throw away any damaged jumper wires, battery clips, etc. Discard any batteries whose terminal voltages are less than 80% of their rating (e.g. less than 7.2 volts for a 9-volt battery).
- _____ Shut off power to all control systems except for the DCS.
- _____ Store any donated components in the proper locations.
- _____ Clean all whiteboards using Windex, so they actually look white again!

• *Instructors may add items to this list as necessary:*

- _____
- _____
- _____
- _____
- _____
- _____
- _____

Personal tasks

- Apply “sick hours” to missed time this quarter (remember, this is *not* automatically done for you!).
- Donate unused “sick hours” to classmates in need.
- Take any quizzes missed due to classroom absence this quarter (remember, a quiz not taken will be counted as a failed quiz!).

file i01229

Answers

Answer 1

Answer 2

Partial answer:

The model numbers refer to the ANSI/IEEE code for the application:

- SEL-RS86 = auxiliary lockout relay
 - SEL-RS52 = circuit breaker manual trip/close
 - SEL-RS43 = manual transfer or selector
-

Answer 3

Partial answer:

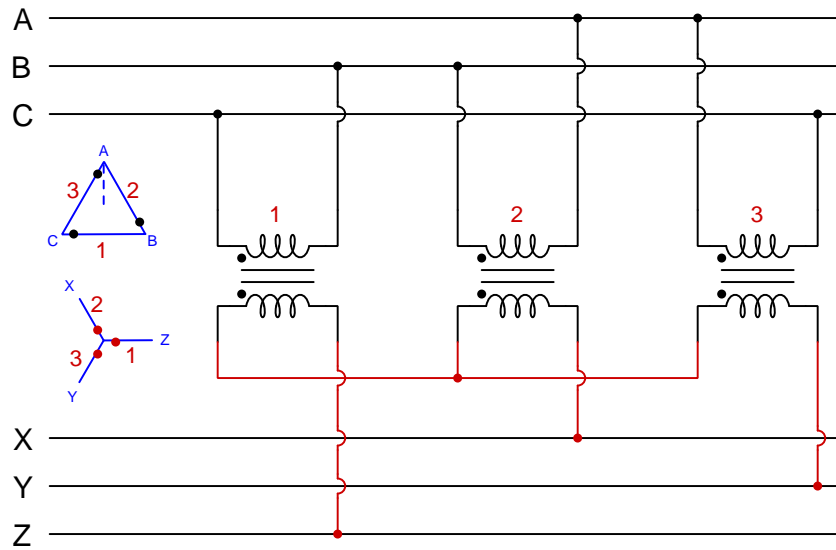
Fault	Possible	Impossible
Dead DC station power supply		
Fault in generator field winding		
CT failed open		
86 trip coil failed open		√
86 trip coil failed shorted		
Any 87/SI coil failed open		
Any 87/SI coil failed shorted		
Any 87/RC coil failed open	√	
Any 87/RC coil failed shorted		
Any 87/OC coil failed open		
Any 87/OC coil failed shorted		

Answer 4

Answer 5

Partial answer:

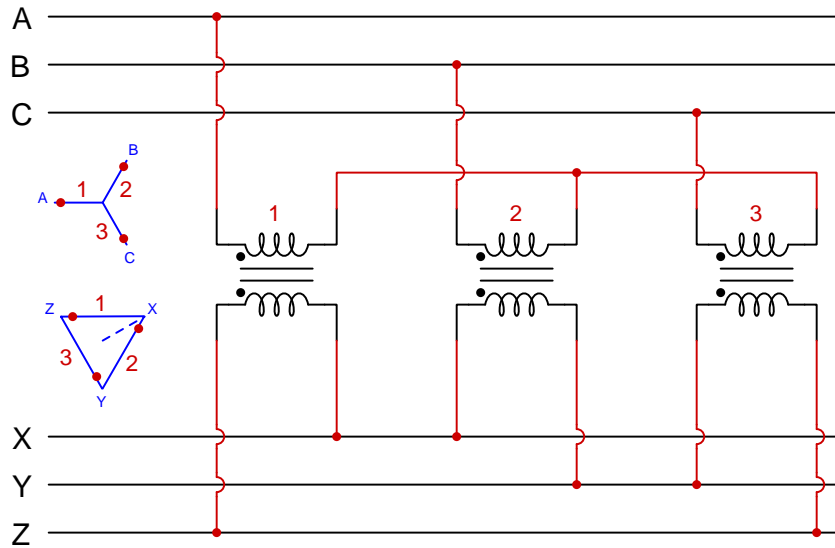
Note the dots and numbers placed on the phasor diagrams to keep track of which transformers and which polarities are used:



Answer 6

Answer 7

This is not the only solution, but it will work. Note the dots and numbers placed on the phasor diagrams to keep track of which transformers and which polarities are used:



The upper bus phase rotation is ABC.

The lower bus phase rotation is XYZ.

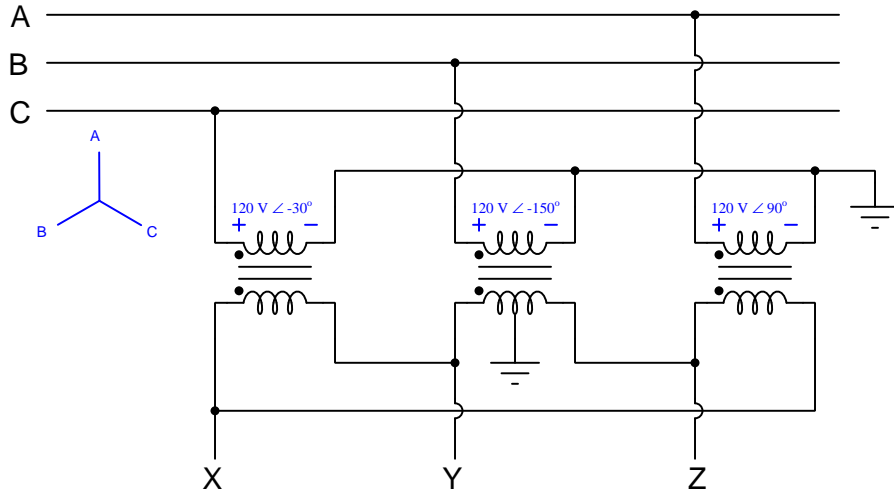
The phase shift between the two busses (comparing V_A with V_X) is 150° , with the lower bus *lagging behind* the upper bus: $V_A = \angle 180^\circ$ and $V_X = \angle 30^\circ$

Answer 8

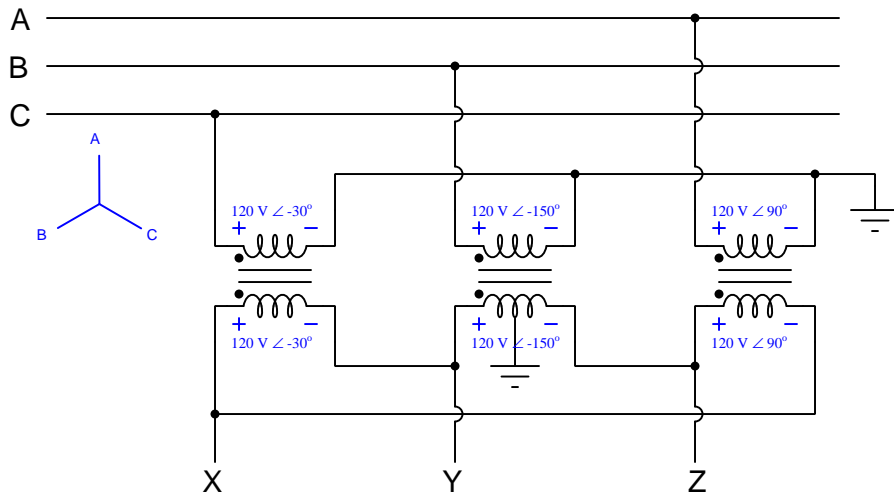
First, let us list the upper bus phase voltages based on the Wye phasor diagram:

- $V_A = 120 \text{ V} \angle 90^\circ$
- $V_B = 120 \text{ V} \angle -150^\circ$
- $V_C = 120 \text{ V} \angle -30^\circ$

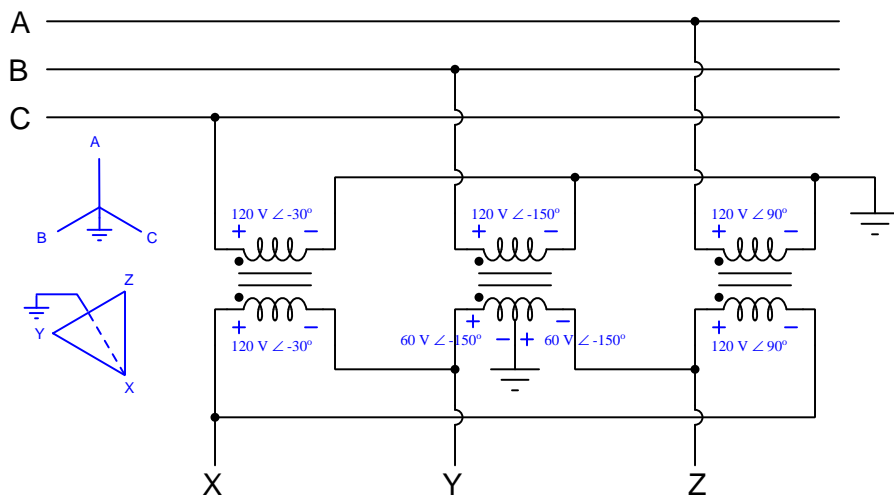
Now, we can annotate these voltages on the schematic diagram:



We know that transformers faithfully reproduce the same phase angle from primary to secondary, and so we may simply transfer these annotations to the secondary windings like this:



The middle transformer's secondary winding is center-tapped, and so we will split its 120 V value into two equal halves, with additive polarity. We may also sketch a phasor diagram for the secondary voltages:



Now we are ready to calculate the requested voltages!

$$V_X \text{ (measured from X to ground)} = (120 \text{ V } \angle -30^\circ) + (60 \text{ V } \angle -150^\circ) = 103.923 \text{ V } \angle -60^\circ$$

$$V_{AB} \text{ (measured from A to B)} = V_A - V_B = (120 \text{ V } \angle 90^\circ) - (120 \text{ V } \angle -150^\circ) = 207.846 \text{ V } \angle 60^\circ$$

$$V_{ZY} \text{ (measured from Z to Y)} = V_Z - V_Y = -(60 \text{ V } \angle -150^\circ) - (60 \text{ V } \angle -150^\circ) = 120 \text{ V } \angle 30^\circ$$

(equivalent to $(-120 \text{ V } \angle -150^\circ)$; the full secondary voltage measured “backwards”)

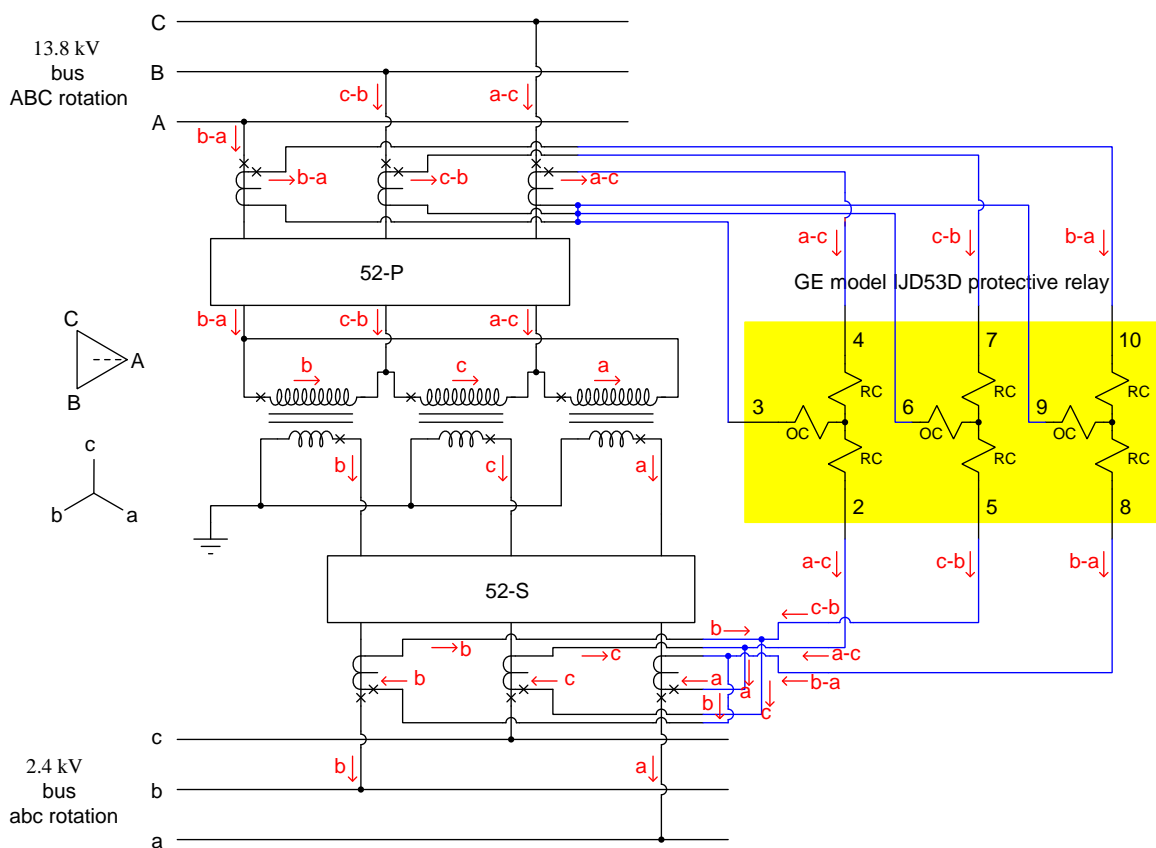
$$V_{XC} \text{ (measured from X to C)} = V_X - V_C = (103.923 \text{ V } \angle -60^\circ) - (120 \text{ V } \angle -30^\circ) = 60 \text{ V } \angle -150^\circ$$

Answer 9

This is not an easy task. Here are a few hints on how to figure out the CT connections:

- Remember that the CTs must be connected in complementary fashion to the windings of the power transformer (i.e. CTs on the Wye-connected side of the power transformer must be connected in Delta, and vice-versa)
- Annotate phase currents for each of the *Wye-connected* power transformer windings with arrows. Choose the Wye side first because there are no nodes where currents mesh in a Wye configuration!
- Label those same phase currents on the other side of the transformer (ignore turns ratio for the sake of simplicity). Remember that currents on the primary and secondary sides of any transformer (power or CT) always flow in opposite directions with reference to the polarity markings, because one winding is functioning as a source while the other is functioning as a load.
- Use Kirchhoff's Current Law to label all currents at nodes where transformer windings join to form a Delta configuration.

Here is my solution, with connecting wires shown in blue and current annotations shown in red. CT test switches have been omitted for simplicity:



I'll let you figure out the proper secondary-side CT ratios to make this system work.

Answer 10

Answer 11

Answer 12

Answer 13

Answer 14

Answer 15

Answer 16

Answer 17

Answer 18

Answer 19

Answer 20

Answer 21

Answer 22

$$I_{sec} = \underline{3.56667 \text{ A } \angle -116^\circ}$$

$$V_{CT\text{-terminals}} = \underline{2.275 \text{ V } \angle -67.19^\circ}$$

If you attempted to calculate terminal voltage ($V_{CT\text{-terminals}}$) by multiplying current and CT winding impedance ($[3.56667 \text{ A } \angle -116^\circ] \times [0.35 \Omega + j0.12 \Omega]$), you are making a serious mistake. What this calculation does is calculate the amount of voltage *dropped across the winding impedance*, not the voltage seen between the two terminals of the CT. Bear in mind that the CT winding is the only source in the secondary circuit, everything else in that circuit is a load.

Answer 23

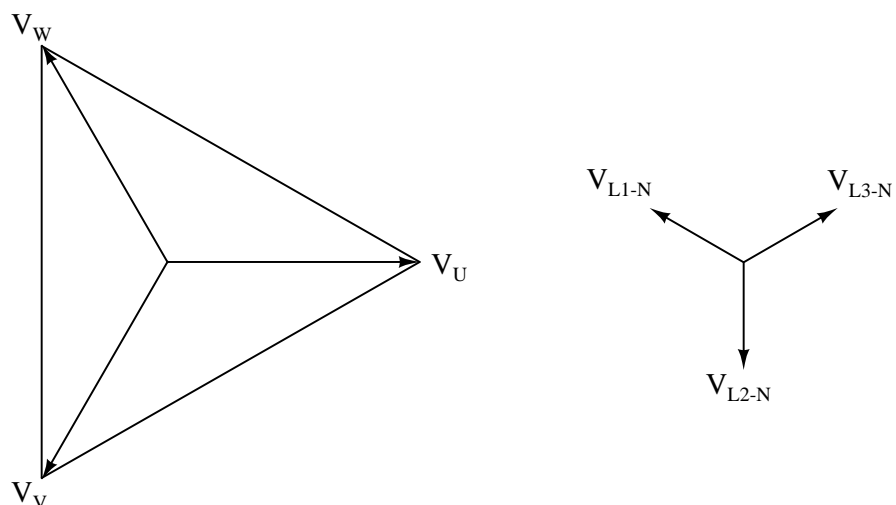
$$I_A = 23.79 \text{ A } \angle -39.72^\circ$$

$$I_B = 23.79 \text{ A } \angle -279.72^\circ$$

$$I_C = 23.79 \text{ A } \angle -159.72^\circ$$

Answer 24

Partial answer:



Answer 25

Answer 26

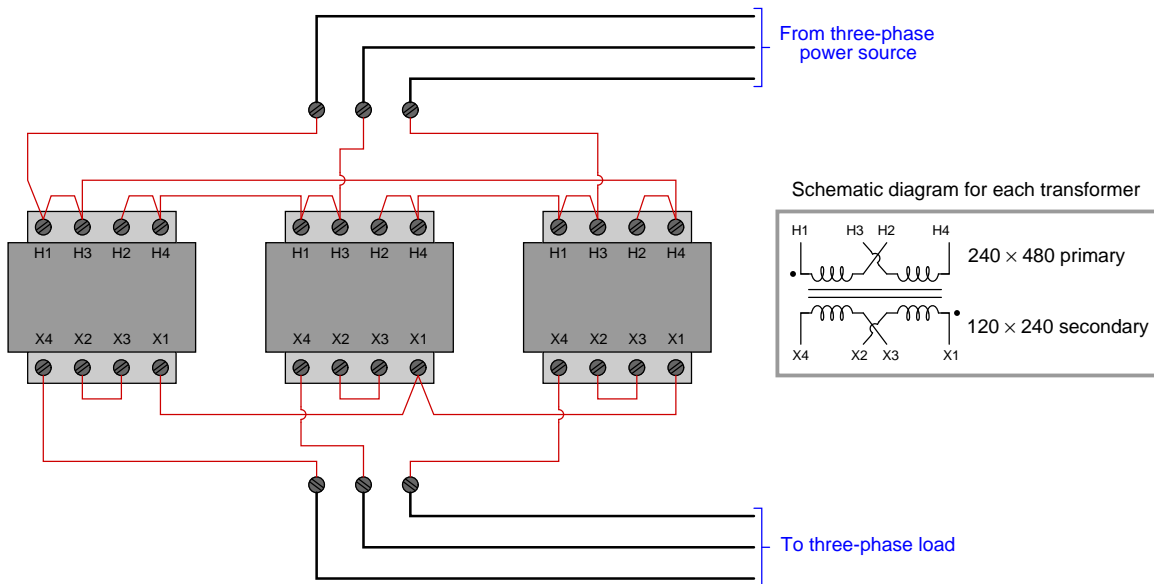
Hint: the “C” or “T” rating of a current transformer is critical here. For example, “C400” means 400 volts under specific test conditions. I’ll let you research/determine the rest of the details!

Answer 27

The engineer is correct on both counts: the CT circuit as designed will not adequately source the relay’s burden successfully under maximum fault conditions, and the series-connected CT solution will work.

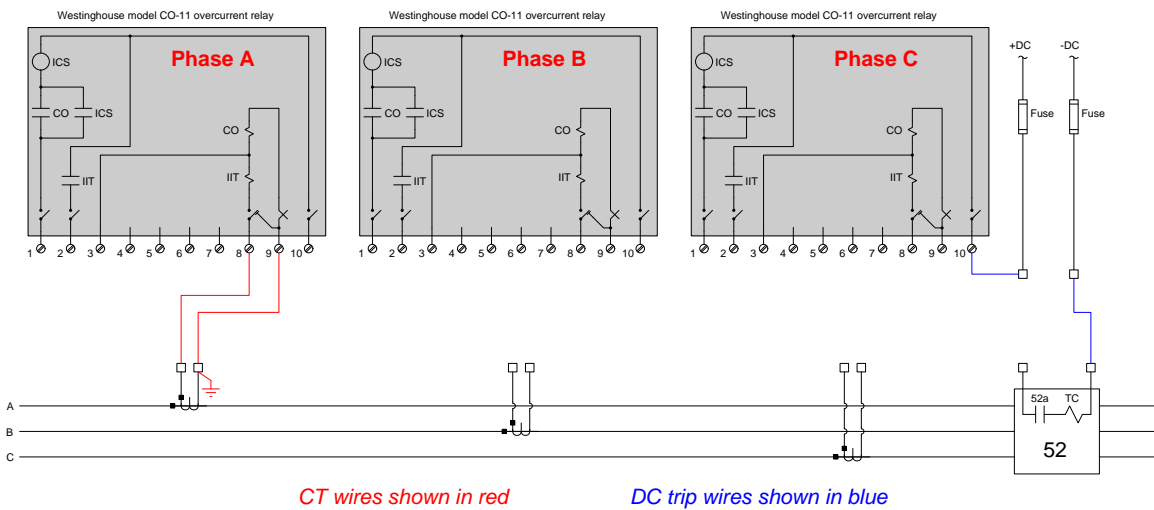
Answer 28

This is one possible solution, wiring the transformer primaries as a 240 VAC Delta network and the transformer secondaries as a 240/415 VAC Wye network:



Answer 29

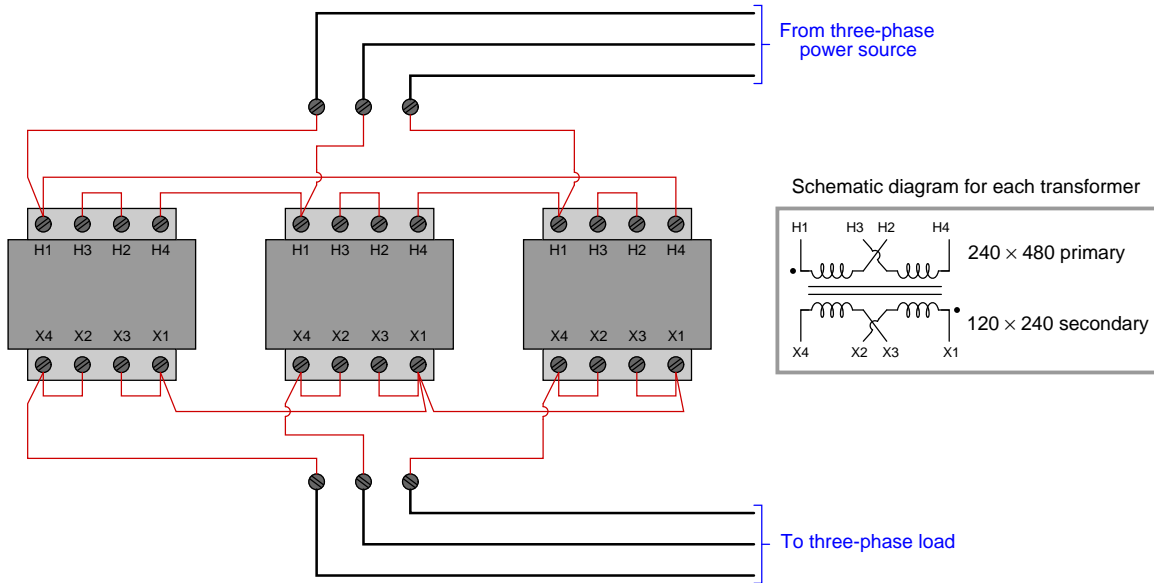
Partial answer:



Answer 30

Answer 31

This is one possible solution, wiring the transformer primaries as a 480 VAC Delta network and the transformer secondaries as a 120/208 VAC Wye network:



Answer 32

Answer 33

Answer 34

Answer 35

Answer 36

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Here is a SPICE analysis of the system, using a single AC voltage source to model V_C (-120° behind V_A which has a phase angle of 5°). **Lpri** and **Lsec** comprise the primary and secondary windings of a 50:5 CT (having an inductance ratio of 100:1, which is a 10:1 turns ratio). A “dummy” resistor connects node 5 to ground (node 0) in order to satisfy SPICE’s demand that a DC path for current always exists to ground on the secondary side of the CT.

SPICE source file (netlist):

```
* SIMULATION
V1 3 0 AC 277.1 -115
R1 1 2 10
L1 2 0 6e-3
Lpri 3 1 1
Lsec 4 5 100
Kct Lpri Lsec 0.9999
Rrelay 4 6 0.2
Lrelay 6 5 200e-6
Rdummy 5 0 1e-3
.AC LIN 1 60 60
.PRINT AC V(4,5) VP(4,5)
.END
```

SPICE analysis summary:

Freq	v(4,5)	vp(4,5)
6.000E+01	5.766E-01	-1.075E+02

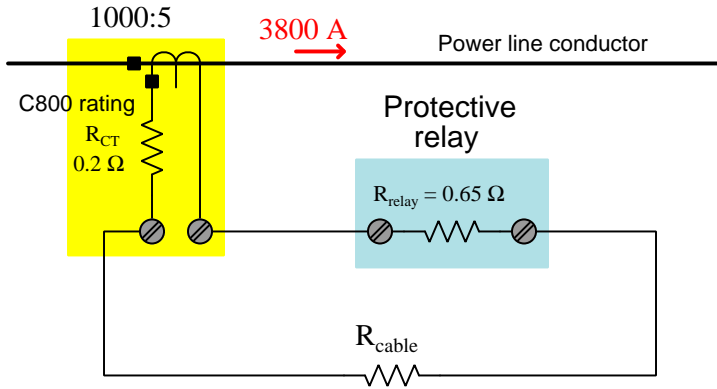
Answer 42

$$R_{wire} (\text{maximum}) = \underline{\mathbf{0.440}} \Omega$$

10 AWG is the minimum wire size for this application.

Answer 43

Partial answer:



Answer 44

Answer 45

Partial answer:

The upper bus phase rotation is ABC. The lower bus phase rotation is XYZ.

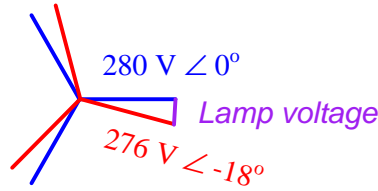
The phase shift between the two busses (comparing V_A with V_X) is 90° , with the lower bus *leading ahead of* the upper bus: $V_A = \angle -150^\circ$ and $V_X = \angle -60^\circ$

Answer 46

With one CT circuit failed (*any* one for that matter!), the corresponding 87 relay will immediately detect an imbalanced current condition for any amount of line current and trip the circuit breaker as designed. To put it simply, the system will falsely trip and refuse to operate.

Answer 47

You can solve this by sketching two phasor diagrams (one for each generator), with an 18° shift between the two sets of phasors, and calculate the distance between any one pair of corresponding phasor tips. With line voltages of 485 volts and 478 volts, the phase voltages will be $\frac{1}{\sqrt{3}}$ of those values, or 280 volts and 276 volts, respectively:

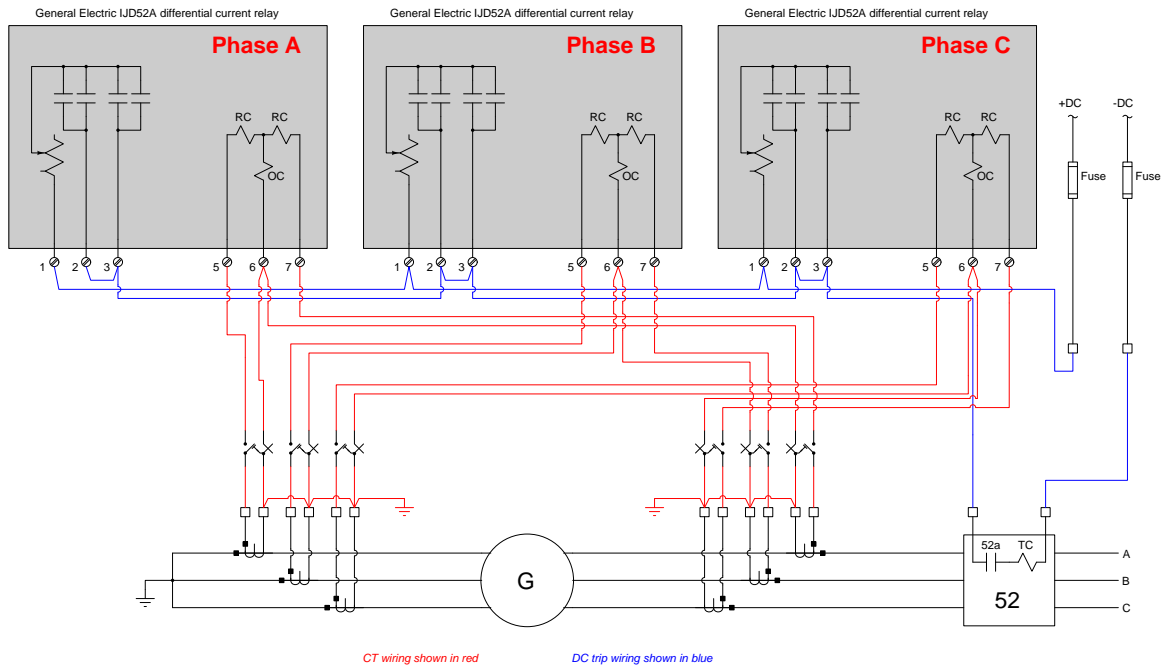


$$V_{lamp} = (280 \text{ V} \angle 0^\circ) - (276 \text{ V} \angle -18^\circ)$$

$$V_{lamp} = 87.1 \text{ V} \angle 78.4^\circ$$

Since lamps care not for phase angle, the voltage across each lamp will be 87.1 volts. The frequency of this voltage across the lamp will be the same as the generators: 60 Hz.

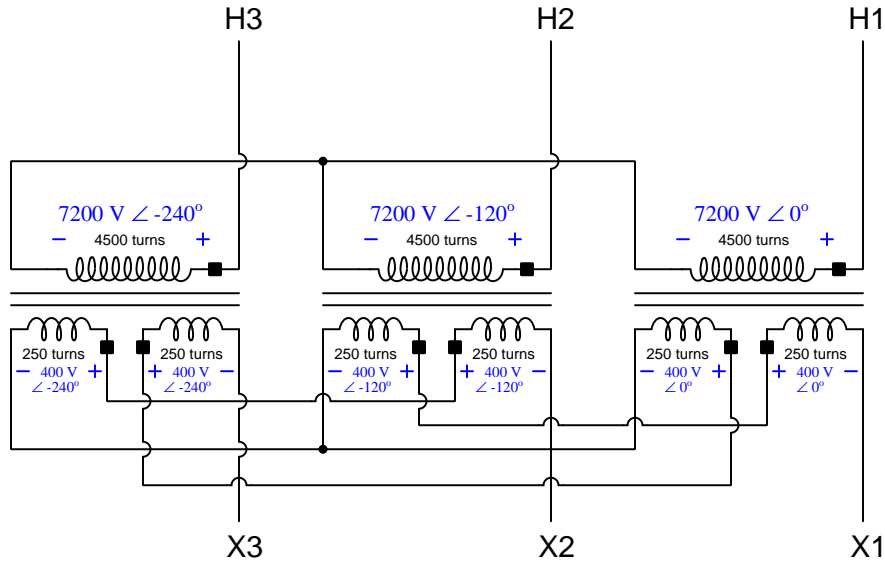
Answer 48



If $V_{H1} = 7200 \text{ V} \angle 0^\circ$, and the rotation is H1-H2-H3, then the primary phase voltages must be:

- $V_{H1} = 7200 \text{ V} \angle 0^\circ$
- $V_{H2} = 7200 \text{ V} \angle -120^\circ$
- $V_{H3} = 7200 \text{ V} \angle -240^\circ$

The 4500:250 turns ratio (18:1) from each primary winding to each secondary winding yields secondary winding voltages of 400 volts each. At this point it becomes useful to mark the schematic with + and - polarity symbols (as though we were analyzing a DC circuit) with the known voltages:

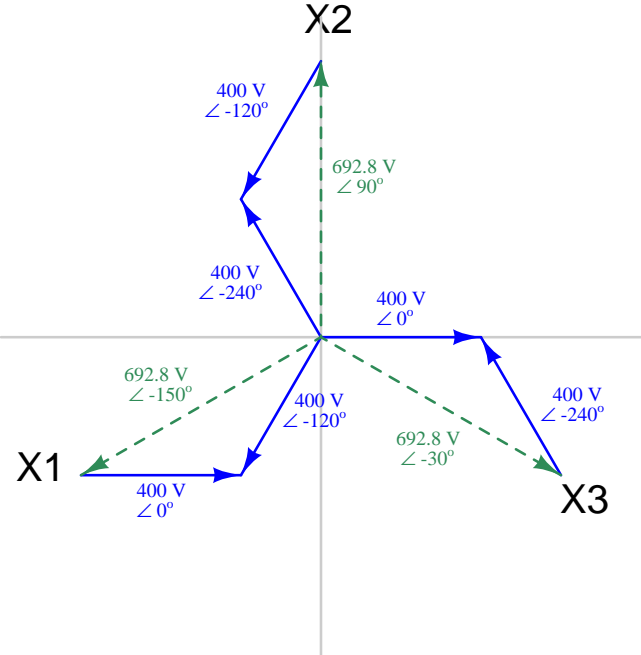


Note how all the secondary winding voltages bear the same angle as their respective primary winding voltages, because we are working on the assumption that there is negligible phase shift inherent to the transformer. Note also how all of our + and - polarity marks follow the same pattern as the "square" polarity markings on the transformer windings: every "polarity" terminal is positive while every "nonpolarity" terminal is negative.

At this point we may simply add up the winding pair voltages for each secondary line, respecting polarity as we go:

- $V_{X1} = (400 \text{ V} \angle -120^\circ) - (400 \text{ V} \angle 0^\circ) = 692.8 \text{ V} \angle -150^\circ$
- $V_{X2} = (400 \text{ V} \angle -240^\circ) - (400 \text{ V} \angle -120^\circ) = 692.8 \text{ V} \angle 90^\circ$
- $V_{X3} = (400 \text{ V} \angle 0^\circ) - (400 \text{ V} \angle -240^\circ) = 692.8 \text{ V} \angle -30^\circ$

The phasor diagram showing secondary winding voltages makes it clear why this is called a “zigzag” configuration. The arrowheads on each winding voltage phasor shows the subtraction at work, with phasor tips meeting at each vertex in the “zigzag” shape:



The resultant phasors V_{X1} , V_{X2} , and V_{X3} are shown in green, while the secondary winding phasors are shown in blue.

Answer 50

The arrowhead directions are arbitrary, but since the generator's phase A arrow is pointing upward (toward the substation bus) and load #1's phase A arrow is pointing downward (away from the substation bus), it makes sense to sketch load #2's phase A arrow downward as well.

With load #2 phase A current arrow pointing down, we may apply Kirchhoff's Current Law to phase A at the substation bus. The sum of the two currents exiting that node of the bus must equal the one current entering that node of the bus. Therefore, for phase A:

$$I_{gen} = I_{load1} + I_{load2}$$

$$I_{load2} = I_{gen} - I_{load1}$$

$$I_{load2} = (235 \text{ A } \angle 5^\circ) - (157 \text{ A } \angle -63^\circ)$$

$$I_{load2} = 228.5 \text{ A } \angle 44.56^\circ$$

If the entire system is balanced (i.e. all phase and line quantities equal in magnitude with phase angles displaced by exactly 120 degrees), then the other two line currents for load #2 must have the same magnitude but with different angles. Given the ABC phase rotation, phase B's current must lag behind phase A by 120 degrees, while phase C's current must lag another 120 degrees (or lead phase A by 120 degrees):

$$I_{load2(A)} = 228.5 \text{ A } \angle 44.56^\circ$$

$$I_{load2(B)} = 228.5 \text{ A } \angle -75.44^\circ$$

$$I_{load2(C)} = 228.5 \text{ A } \angle 164.56^\circ$$

Answer 51

Answer 52

Answer 53

Answer 54

Answer 55

Answer 56

Answer 57

Answer 58

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Answer 64