

Lab

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

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

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

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
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Recommended daily schedule

Day 1

Theory session topic: Instrument and power transformers

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

Day 2

Theory session topic: Instrument transformers

Questions 21 through 40; answer questions 21-27 in preparation for discussion (remainder for practice)

Feedback questions (*61 through 66*) are optional and may be submitted for review at the end of the day

Day 3

Theory session topic: Overcurrent (50/51) protection

Questions 41 through 60; answer questions 41-49 in preparation for discussion (remainder for practice)

Day 4

Theory session topic: Differential current (87) protection

Questions 61 through 80; answer questions 61-68 in preparation for discussion (remainder for practice)

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

How To . . .

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

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

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

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

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

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

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

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

Receive extra instructor help: ask during lab time, or during class time, or by appointment. Tony may be reached by email at tony.kuphaldt@btc.edu 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.

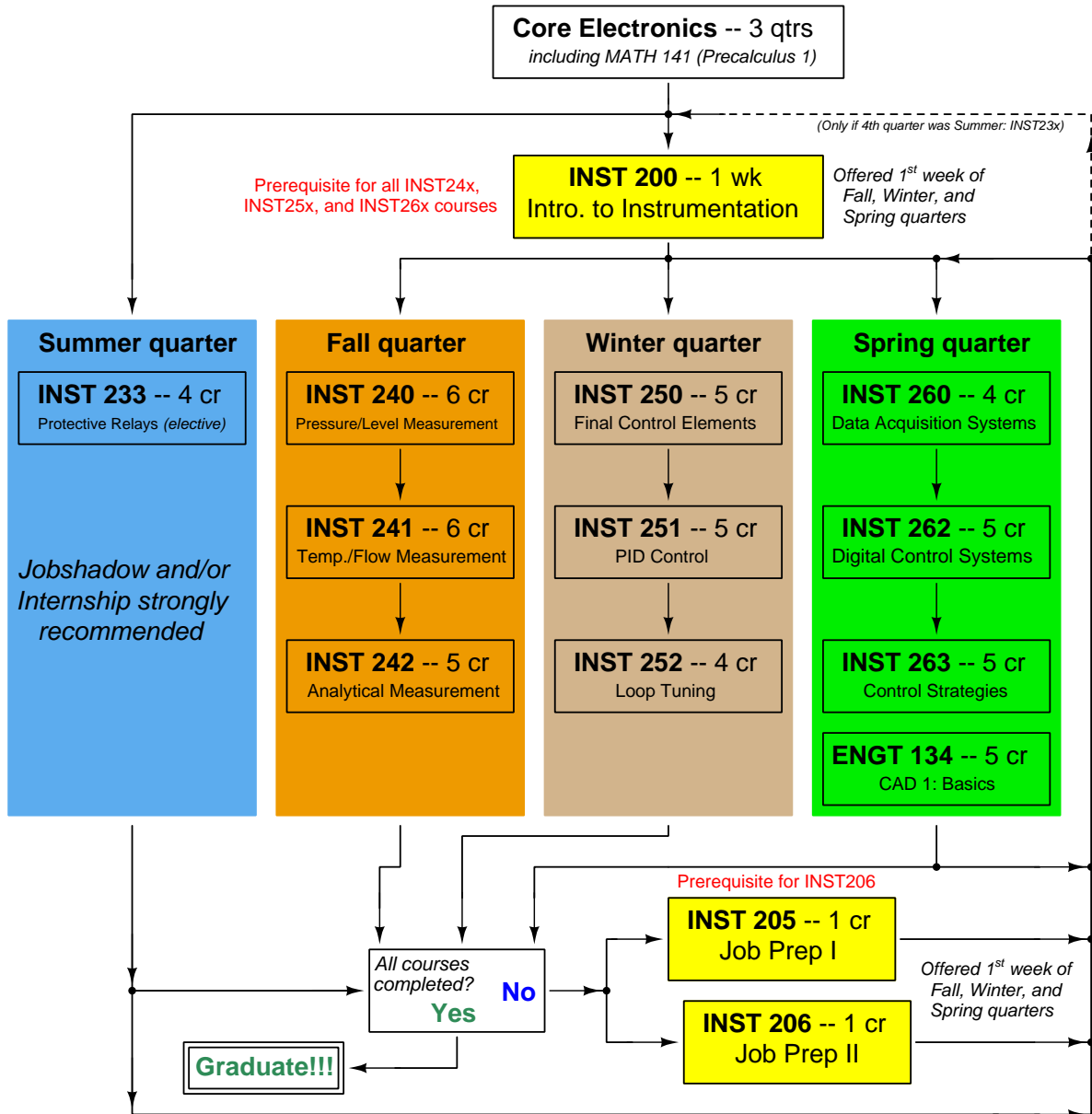
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INST 233 Course Outcomes

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



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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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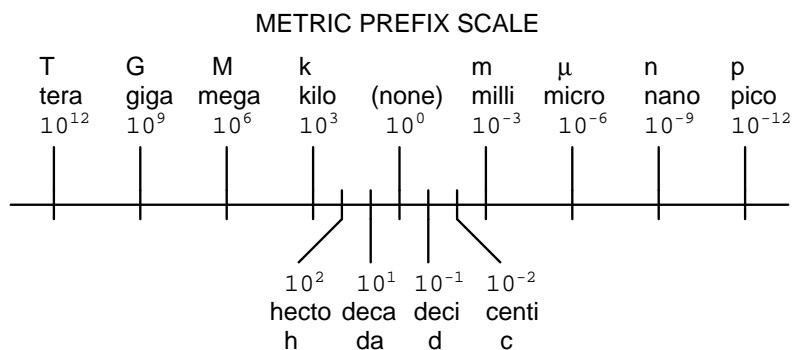
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Metric prefixes and conversion constants

- **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 [Full Tutorial](#) of the *Transformers* learning module of the Modular Electronics Learning Project. This document is freely available online as a PDF file, indexed on the MODEL Project home page at the following URL:

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

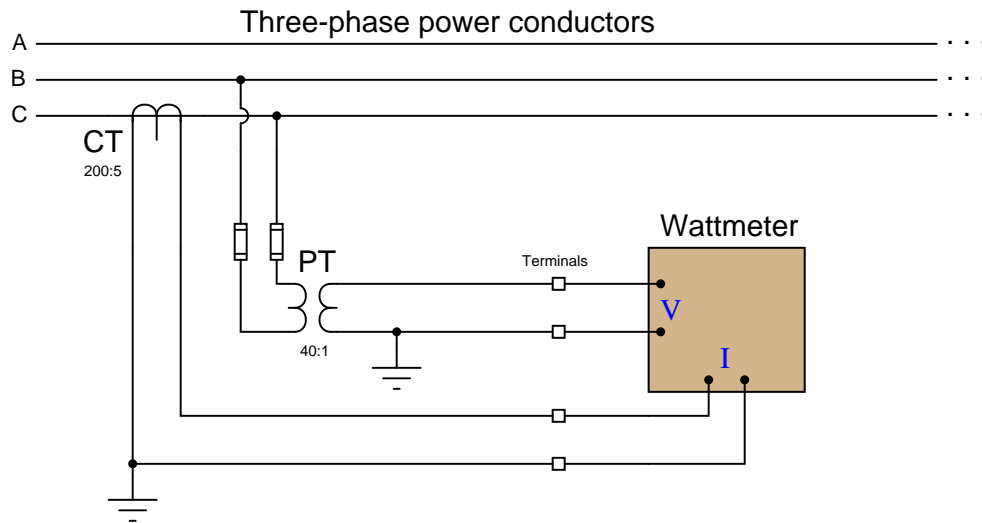
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- (1) Your written summary of all major points of the text, expressed as simply as possible in your own words. A “Table of Contents” format works well for this.
- (2) Active helpful reading strategies (e.g. verbalizing your thoughts as you read, simplifying 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 i02840](#)

Question 2

This wattmeter measures power on one phase of a three-phase power system by sensing both line voltage and line current through instrument transformers. The nominal line voltage of this power system is 4160 volts AC, while the current may extend upwards of 180 amps AC under full-load conditions:



What would you have to do in order to check the calibration of this wattmeter? Specifically, devise a step-by-step procedure that you could give to another technician telling them what they would have to do in order to simulate precise amounts of electrical power to the wattmeter's input, keeping safety in mind as the first priority. Note: you are not allowed to shut power off in the three-phase system to do your test – it must be done “live.”

The power of a balanced three-phase system is given by the following formula:

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

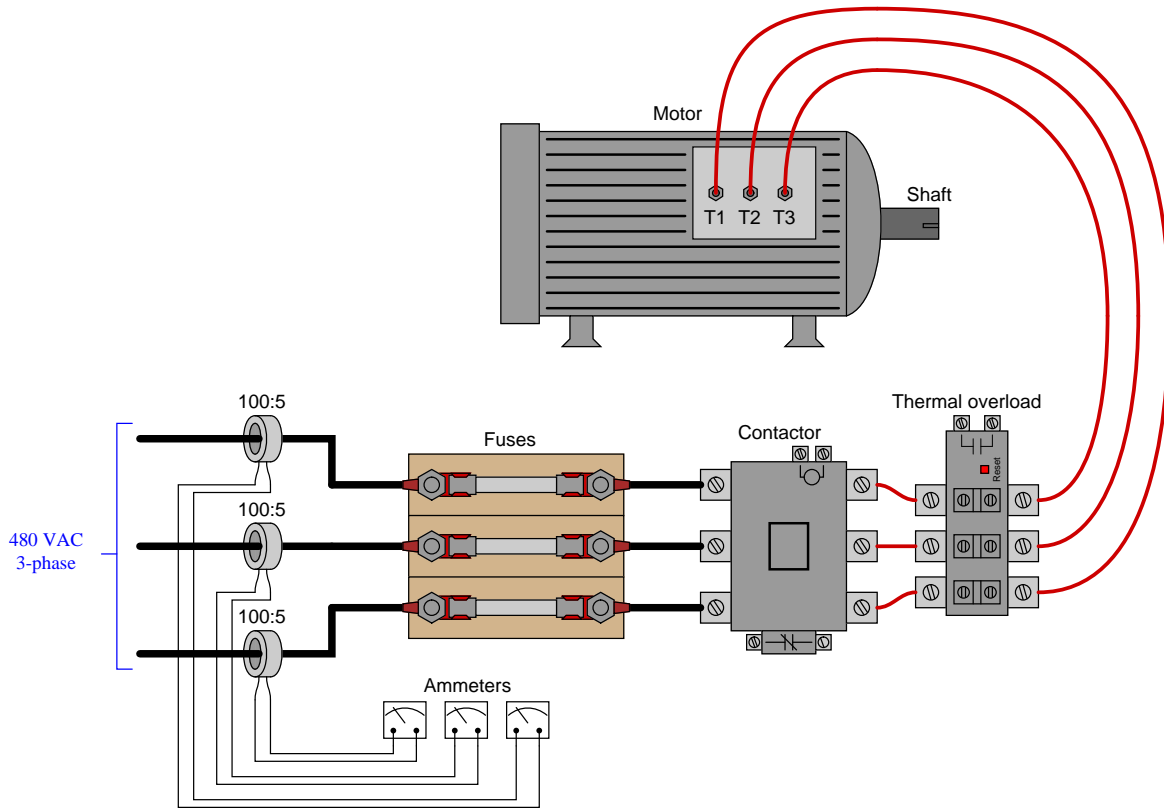
Suggestions for Socratic discussion

- An important safety rule to apply when working with live circuit is the “one-hand rule.” Explain what this rule is, and how it is applied to a scenario such as this.
- When loosening the screws on a terminal block to remove wires for the PT signal, should you remove the wires from the left-hand side of the terminals (as shown in the diagram) or from the right-hand side, or does this matter at all?
- The task of disconnecting a wattmeter from live instrument transformers presents significant hazard. Devise a way to make this procedure safer, using special “test switches” installed on the signal wires at the time of construction, so that a technician may simply throw the switches' levers to isolate the wattmeter instead of putting a screwdriver on “live” terminals and removing wires from terminal blocks.
- Suppose the PT's output signal were 113.6 volts RMS, and the CT's output signal were 2.9 amps RMS. How much power does this represent flowing through the three-phase lines?
- Why are both instrument transformers' secondary circuits grounded?
- Suppose the potential transformer has a reliability rating of 0.9995 and the current transformer has a reliability rating of 0.9998. Calculate the probability that the wattmeter will receive good information from which to calculate power.

[file i01212](#)

Question 3

Suppose the current through each of the ammeters is 2.81 amps, and the ratio of each current transformer is 100:5. Calculate the horsepower output of this AC motor, assuming a power factor of 1 and an efficiency of 88%:

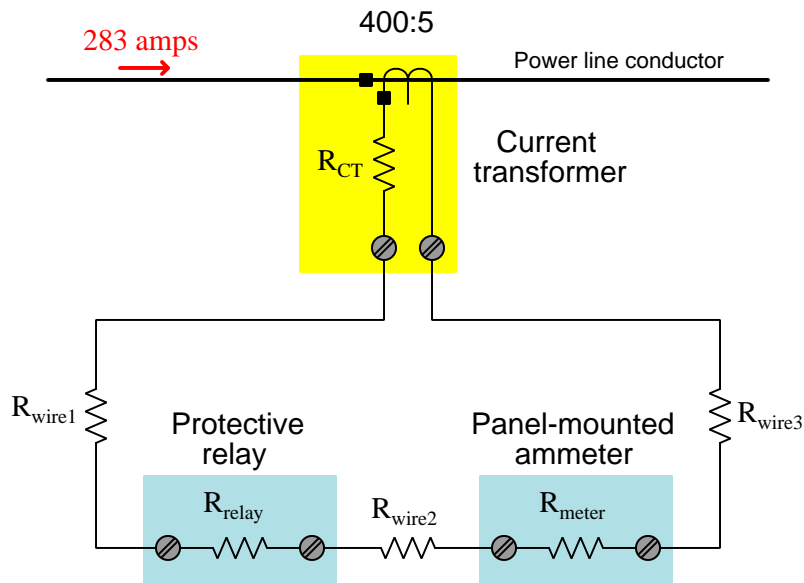


$P =$ _____ horsepower

file i01045

Question 4

Suppose a current transformer with a ratio of 400:5 sends its output signal to a protective relay and a panel-mounted ammeter as shown in this schematic diagram:



- $R_{CT} = 0.3 \Omega$ (this is the internal resistance of the CT's secondary winding)
- $R_{wire1} = 0.4 \Omega$
- $R_{wire2} = 0.1 \Omega$
- $R_{wire3} = 0.4 \Omega$
- $R_{relay} = 2.5 \Omega$
- $R_{meter} = 1.0 \Omega$

Calculate the following voltage drops in this current transformer circuit, from the given information:

- $V_{relay} = \underline{\hspace{2cm}}$ volts
- $V_{meter} = \underline{\hspace{2cm}}$ volts
- Total voltage dropped across all wires = $\underline{\hspace{2cm}}$ volts
- Voltage output at CT terminals = $\underline{\hspace{2cm}}$ volts
- Voltage generated by CT secondary winding (before any R_{CT} losses) = $\underline{\hspace{2cm}}$ volts

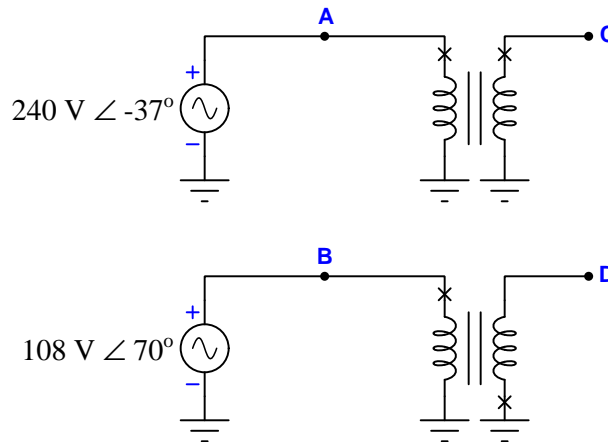
Suggestions for Socratic discussion

- Explain why the two instruments (the relay and the meter) are connected in *series* with each other and not in *parallel*.
- Predict the effects of wire 1 failing open in this circuit.
- Predict the effects of the power line conductor failing open in this circuit.
- Predict the effects of the protective relay failing shorted in this circuit.
- Predict the effects of the panel-mounted ammeter failing open in this circuit.
- Predict the effects of the panel-mounted ammeter failing shorted in this circuit.

[file i02873](#)

Question 5

Calculate V_{AB} and V_{CD} in this circuit and sketch phasor diagrams for these voltages, assuming both sources and transformers share a common ground and that both transformers have 1:1 winding ratios:



Hint: since all transformers have a 1:1 turns ratio, the secondary voltage must be identical to the primary voltage for each one. This means the phasor representing a transformer's secondary winding voltage must be exactly the same length and have exactly the same angle as the phasor representing that same transformer's primary voltage. Treat each phasor as a line segment you are free to move around so long as you do not alter its length or direction, and you can see how they "stack up" onto each other according to how the windings are electrically connected to form a complete phasor diagram.

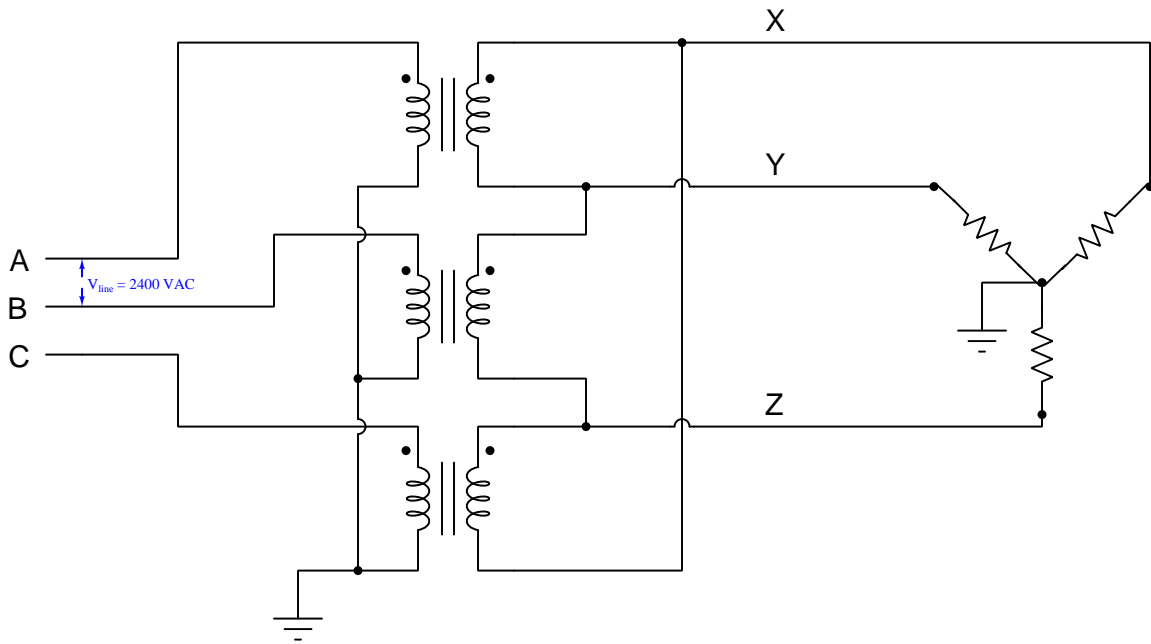
Suggestions for Socratic discussion

- Sketch the phasor for V_{BA} .
- Sketch the phasor for V_{DC} .
- Predict the effects of the upper transformer's primary winding failing open on the phasor diagram.
- Predict the effects of the lower transformer's primary winding failing open on the phasor diagram.

[file i00819](#)

Question 6

Sketch phasor diagrams of both the input phase voltages (V_A , V_B , and V_C) and the output phase voltages (V_X , V_Y , and V_Z) for this Wye-Delta transformer bank powering a resistive load, assuming 1:1 transformer turns ratios, an input line voltage of 2400 volts, an A-B-C phase sequence, and using phase A as the reference voltage (0 degree phase angle with reference to ground):



Hint: since all transformers have a 1:1 turns ratio, the secondary voltage must be identical to the primary voltage for each one. This means the phasor representing a transformer's secondary winding voltage must be exactly the same length and have exactly the same angle as the phasor representing that same transformer's primary voltage. Treat each phasor as a line segment you are free to move around so long as you do not alter its length or direction, and you can see how they "stack up" onto each other according to how the windings are electrically connected to form a complete phasor diagram.

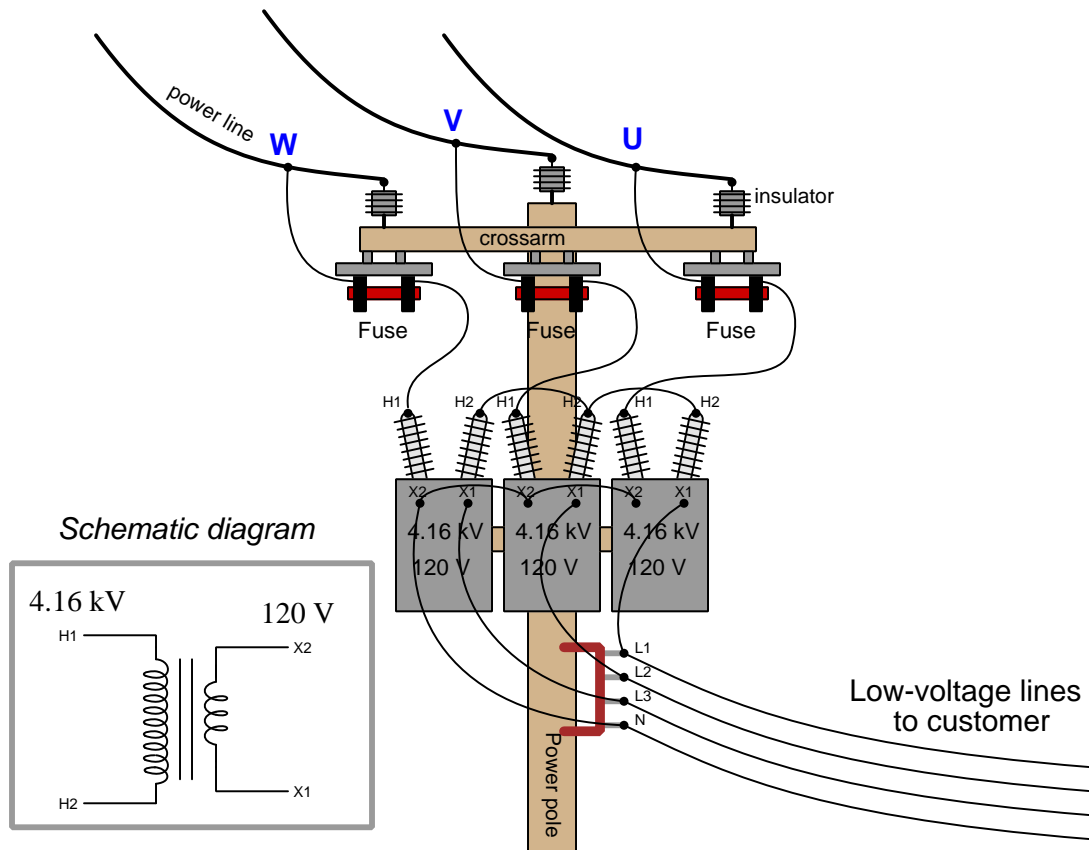
Suggestions for Socratic discussion

- 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 i00820](#)

Question 7

This bank of pole-mounted power transformers steps 7.2 kVAC line power down to 120/208 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 i00821](#)

Question 8

Identify the ANSI/IEEE code for each of the following devices or functions:

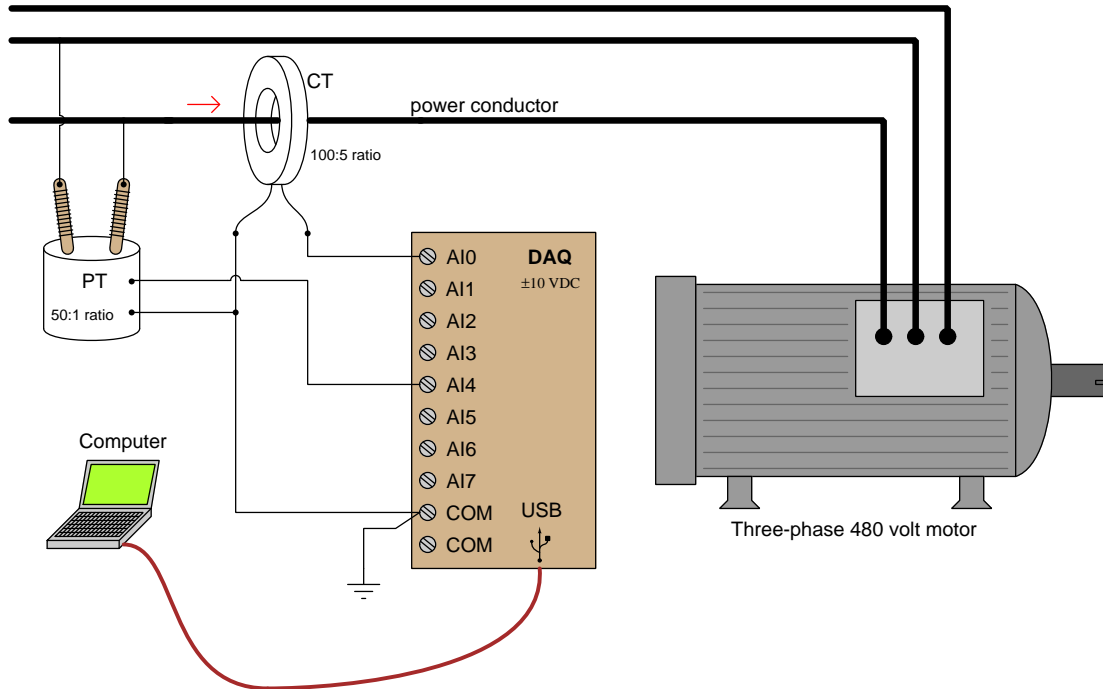
- Differential = _____
- AC circuit breaker = _____
- Lockout or Auxiliary = _____
- Loss of excitation = _____
- Overcurrent (instantaneous) = _____
- Automatic reclose = _____
- Overcurrent (time) = _____
- Frequency = _____

file i03018

Question 9

A technician connects a DAQ (Data Acquisition) module to one phase of a 480 VAC three-phase electric motor in order to measure and record that motor's voltage and current simultaneously on a laptop computer. The DAQ functions as a high-speed data recorder, allowing the computer to display and record a time-based graph of motor voltage and motor current over time.

Knowing that the phase-to-phase voltage of approximately 480 volts and the line current of approximately 25 amps will be far too great for the DAQ to directly measure, the technician uses *instrument transformers* (a "PT" potential transformer and a "CT" current transformer) to step these voltages and currents to more reasonable values:



Unfortunately, as soon as the motor is energized, the DAQ disappears in a bright flash of light and cloud of smoke. The destruction also propagated to the PC the DAQ was connected to (through the USB cable)! What went wrong, and how should the technician correct his mistake? Assume we must use the same model of DAQ unit having the same ± 10 volt input limits.

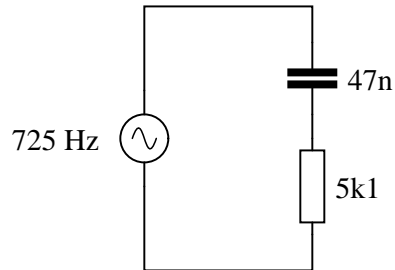
Suggestions for Socratic discussion

- What exactly does an *instrument transformer* do?
- Could this system be made to work with a differential-input DAQ? Why or why not?
- Suppose we were free to select a different DAQ for this application. What specifications would we be looking for in the new DAQ to make it function properly in the circuit as shown?

[file i02035](#)

Question 10

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

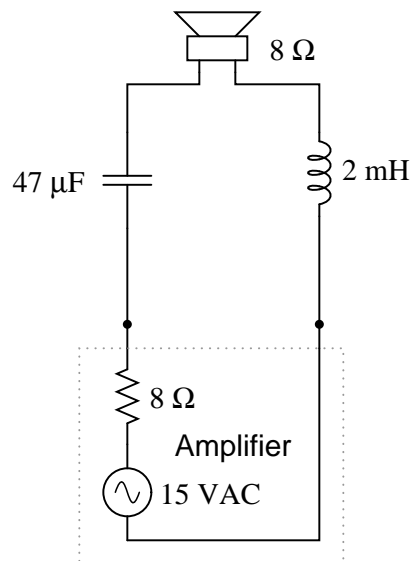


Also, calculate the total impedance (Z_{total}) of this circuit, expressing it in both rectangular and polar forms.

[file i01039](#)

Question 11

Calculate the voltage dropped across the inductor, the capacitor, and the 8-ohm speaker in this sound system at the following frequencies, given a constant source voltage of 15 volts:



- $f = 200$ Hz
- $f = 550$ Hz
- $f = 900$ Hz

Regard the speaker as nothing more than an 8-ohm resistor.

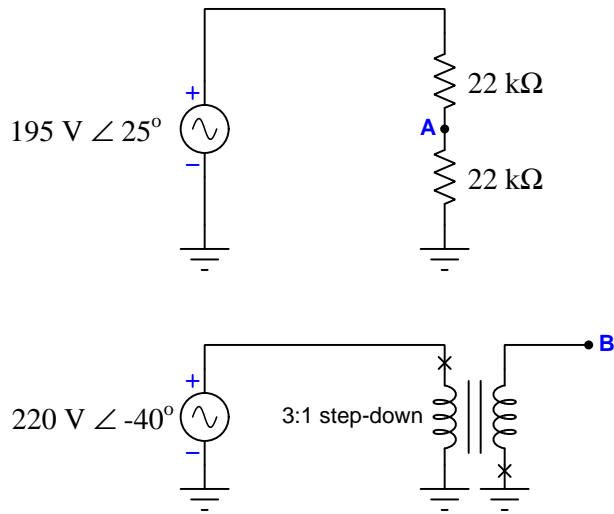
Suggestions for Socratic discussion

- As part of an audio system, would this LC network tend to emphasize the *bass*, *treble*, or *mid-range* tones?

[file i01075](#)

Question 12

Calculate the amount of voltage between points A and B in this circuit, and also sketch a phasor diagram showing how all the voltages relate to each other in this circuit:



[file i00834](#)

Question 13

Question 14

Question 15

Question 16

Question 17

Question 18

Question 19

Question 20

Question 21

Read and outline the Full Tutorial of the *Instrument Transformers* 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>

Note that this particular Full Tutorial is lengthy, and as such you should feel free to skip to the “*Instrument Transformer Safety*” section and read from there to the Tutorial’s end.

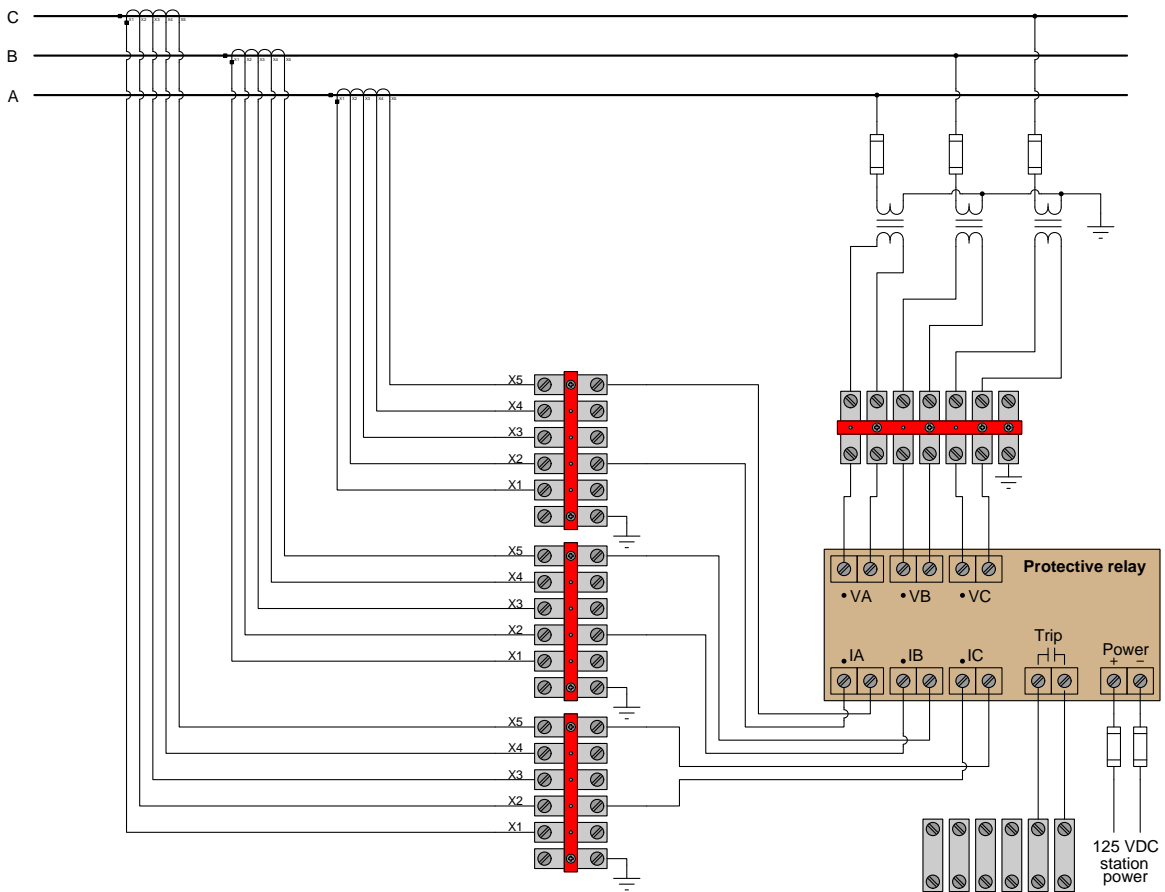
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- (6) Any points of confusion, and precisely why you found the text confusing.

[file i02841](#)

Question 22

Explain how to isolate the protective relay from all PTs and all CTs prior to testing the relay:



[file i02883](#)

Question 23

Suppose an 800:5 current transformer with an internal winding resistance of 0.25 ohms is connected to a protective relay presenting a purely resistive burden of 0.7 ohms. The wire used to connect the CT to the relay is 12 gauge, 1500 feet total circuit length (i.e. 750 feet cable length for a 2-conductor cable).

From this information, determine both the voltage dropped across the relay's terminals at a fault current value of 4.5 kA (power line current), as well as the voltage dropped across the CT's terminals at that same current, and finally the amount of voltage the CT secondary must produce internally to overcome both the total circuit burden (i.e. relay plus wiring plus the CT's own winding resistance) during this same fault condition.

$$V_{relay} = \text{_____} \text{ volts}$$

$$V_{CT-terminals} = \text{_____} \text{ volts}$$

$$V_{CT-internal} = \text{_____} \text{ volts}$$

Suggestions for Socratic discussion

- The Fluke brand 80-series digital multimeters are advertised as exhibiting 1.8 mV/mA of burden when measuring current in the low range (up to 400 mA maximum), and 0.03 V/A burden when measuring current in the high range (up to 10 amps maximum). How do these specifications compare to the burden of the protective relay in this question's scenario? Would a Fluke 80-series DMM present a lesser or greater burden to the CT than the specified relay? Would you recommend using a digital multimeter to interpret current from the CT in this application?

file i03088

Question 24

A set of current transformers located in the bushings of a substation circuit breaker are C200 class with 800:5 ratios and winding resistance values of 0.15 ohms each. Each CT secondary connects to a digital protective relay having an input resistance of 6 milliohms. The wire used for this CT secondary circuit is 12 AWG and the distance between the circuit breaker and the relay is 150 feet.

An electrical engineer performs a “system study” analysis and determines the maximum fault current for this power circuit to be 11,000 amps. Given these parameters, will the CTs be able to deliver accurate representations of fault current to the protective relay? Consider only AC current (not DC transients) in your analysis of this system, for simplicity.

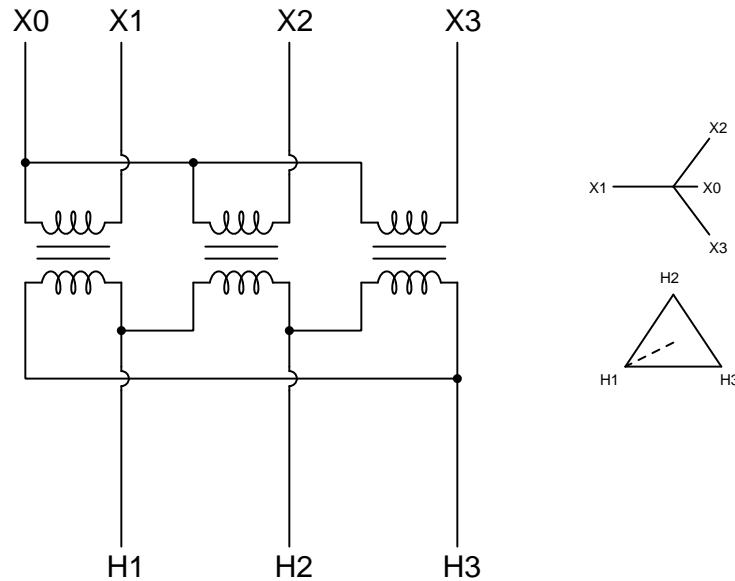
Suggestions for Socratic discussion

- A useful problem-solving technique is to sketch a simple diagram of the system you are asked to analyze. This is useful even when you already have some graphical representation of the problem given to you, as a simple sketch often reduces the complexity of the problem so that you can solve it more easily. Draw your own sketch showing how the given information in this problem inter-relates, and use this sketch to explain your solution.
- Quantitative problems requiring many calculations to arrive at a result are good candidates for solution using a computer spreadsheet program such as Microsoft Excel. Try creating a spreadsheet to solve this problem, and you will have a tool useful for solving other problems like it!
- Suppose the $\frac{X}{R}$ ratio of this power system were significant enough that certain faults could produce DC transients worthy of consideration for CT performance. Calculate the maximum $\frac{X}{R}$ ratio we could tolerate with this CT circuit as specified.
- Suppose the wire resistance in this circuit happened to be excessive for the fault conditions and CT capability specified. What could we alter in this system to improve matters?
- The Fluke brand 80-series digital multimeters are advertised as exhibiting 1.8 mV/mA of burden when measuring current in the low range (up to 400 mA maximum), and 0.03 V/A burden when measuring current in the high range (up to 10 amps maximum). How do these specifications compare to the burden of the protective relay in this question’s scenario? Would a Fluke 80-series DMM present a lesser or greater burden to the CT than the specified relay? Would you recommend using a digital multimeter to interpret current from the CT in this application?

[file i03090](#)

Question 25

Examine these schematic and phasor diagrams found on the side of a power transformer, and answer the following questions:



Which is the high-voltage side and which is the low-voltage side of this transformer? How can you tell?

Is the high-voltage side of this transformer *leading*, *lagging*, or *in-phase with* the low-voltage side? How can you tell?

Suppose the turns ratio for each winding pair in this three-phase transformer is 4:1 and the line voltage H1-H2 is 480 volts. Calculate the line voltage X1-X2.

Mark polarity dots for the primary and secondary windings of this transformer in order to produce the phasors shown in the phasor diagram.

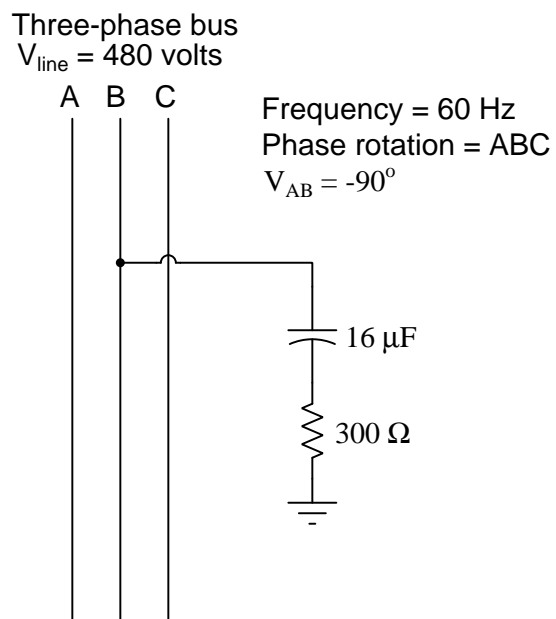
Suggestions for Socratic discussion

- Explain how it would be possible to determine the polarity of the individual transformer windings using simple tools.
- Explain how it would be possible to determine the step ratio of the individual transformer windings using simple tools (but with no access to AC power).
- 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 i03068](#)

Question 26

Calculate the voltage across the resistor in this circuit, as well as its power dissipation:



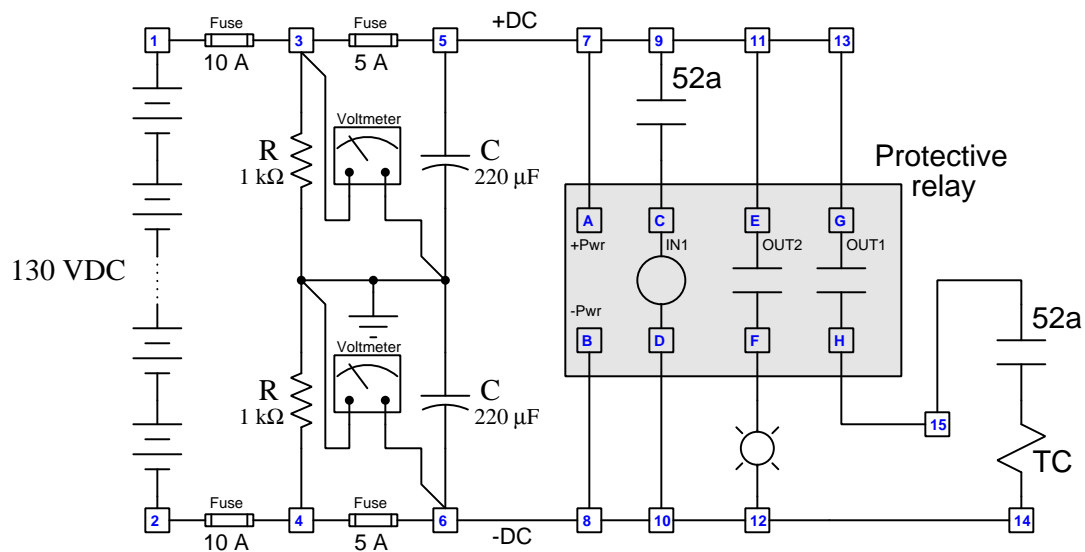
$V_R =$ _____

$P_R =$ _____

[file i00827](#)

Question 27

Identify the effects of the following faults in this protective relay DC trip circuit. Note the omission of all instrument transformer (e.g. PT, CT) wiring and an exclusive focus on DC trip wiring in this diagram. Also note the resistive voltage divider and dual voltmeters used to detect any ground faults in the DC station power wiring:



- Upper resistor failing open
- Upper capacitor failing shorted
- Loose connection on left side of terminal 12
- Broken wire between terminals D and 10
- Broken wire between terminals E and 11
- Ground fault at terminal 7
- Simultaneous ground faults at terminals 9 and 6

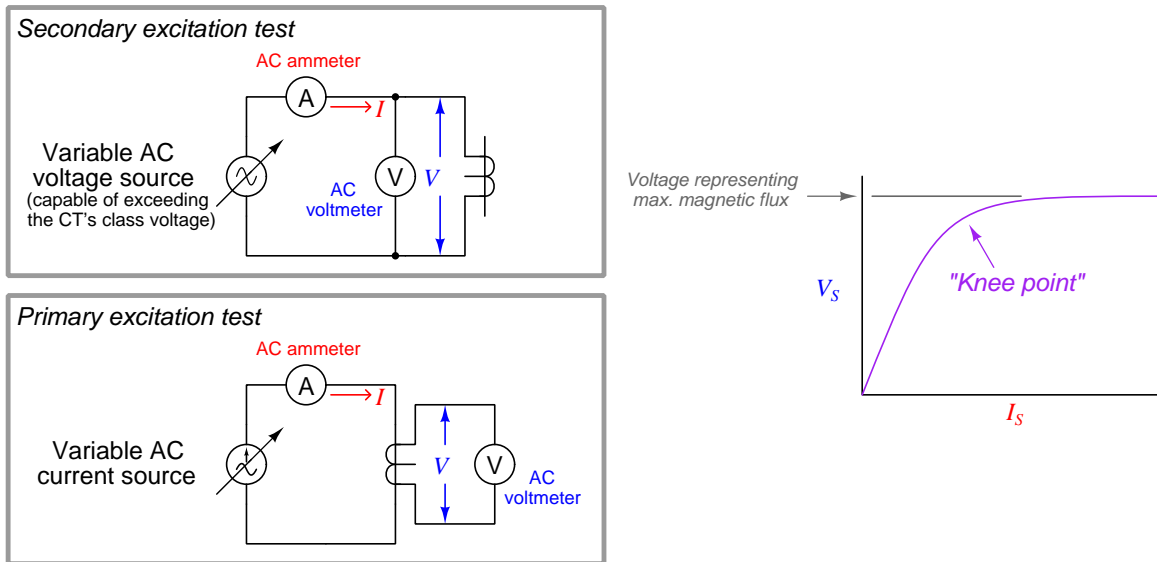
Suggestions for Socratic discussion

- What is the point of having both 5 amp and 10 amp fuses in this circuit?
- What should a voltmeter register between terminal 3 and ground? Between terminal 4 and ground? If we permanently installed two voltmeters to register these voltages, could their indications help us pinpoint certain faults before they become serious?
- Can we tell what ANSI/IEEE function this protective relay implements? Why or why not?

[file i03098](#)

Question 28

Set up a current transformer, a set of multimeters, and an adjustable AC power supply to perform a saturation test on a current transformer. If your adjustable AC power supply cannot produce a voltage equal to or greater than the “class” rating of the CT (e.g. at least 200 volts to test a C200 current transformer), you may be able to perform a similar test using a high-current AC source such as a protective relay test set to drive current through the primary of the CT:



Identify the relevant data you will need to collect in this experiment to determine the CT’s saturation point (i.e. the “knee point” voltage). Use a computer spreadsheet if you wish to plot this data and show it in graphical form.

Lastly, determine a test by which you could determine the *polarity* of the CT, supposing it is not already marked.

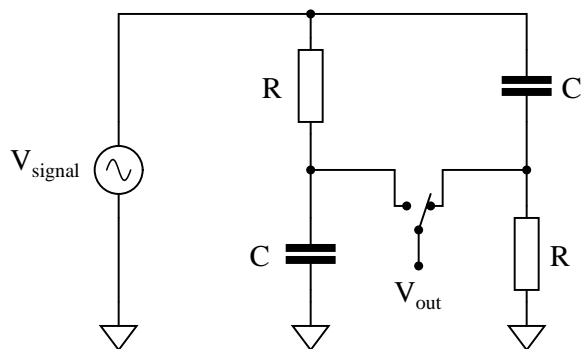
Suggestions for Socratic discussion

- Explain in detail *why* the voltage output by an open-circuited CT does not linearly follow excitation current, but instead “falls off” with diminishing returns. What, exactly, is happening inside the CT to make it behave as such?
- Suppose you could re-design a CT to have a greater knee-point voltage. What would you alter about the CT’s construction to achieve this design goal?

[file i03087](#)

Question 29

Determine the magnitude and phase shift of the output voltage (V_{out}) with reference to the source voltage (0°) for each of the two switch positions, assuming the source frequency is such that $X_C = R$:

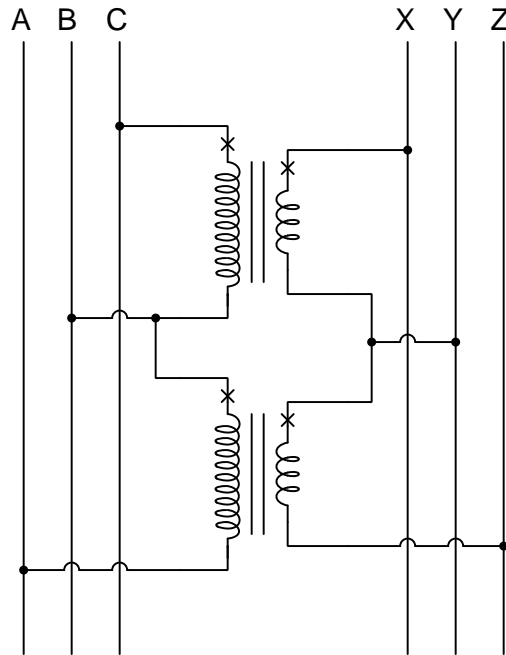


Note: you should be able to do the phase shift calculation mentally, without the aid of a calculating device! It is also possible to determine the output voltage magnitude without the aid of a calculating device if you are familiar enough with the values of common trigonometric functions.

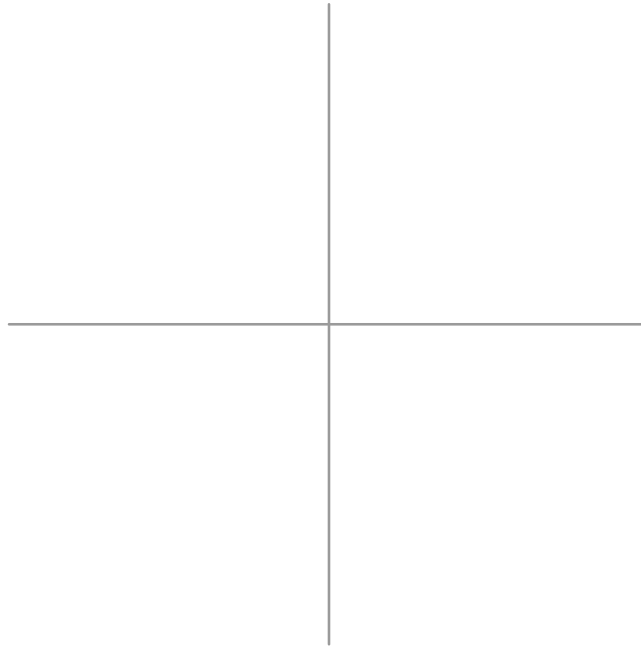
[file i00845](#)

Question 30

The following three-phase transformer configuration is called an *open-delta*:



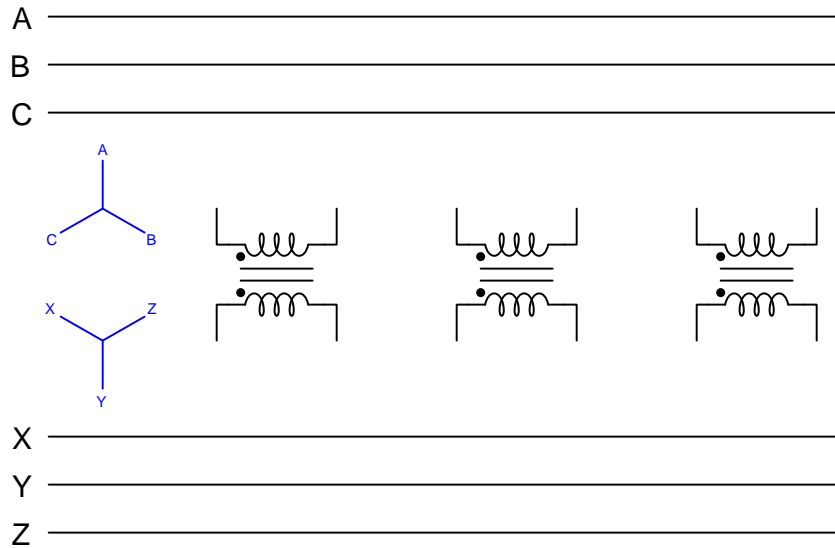
Sketch a phasor diagram showing V_X , V_Y , and V_Z assuming 4:1 step-down ratios for each transformer, an *ACB* phase rotation, and $V_A = 277 \text{ volts } \angle 0^\circ$.



file i00838

Question 31

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

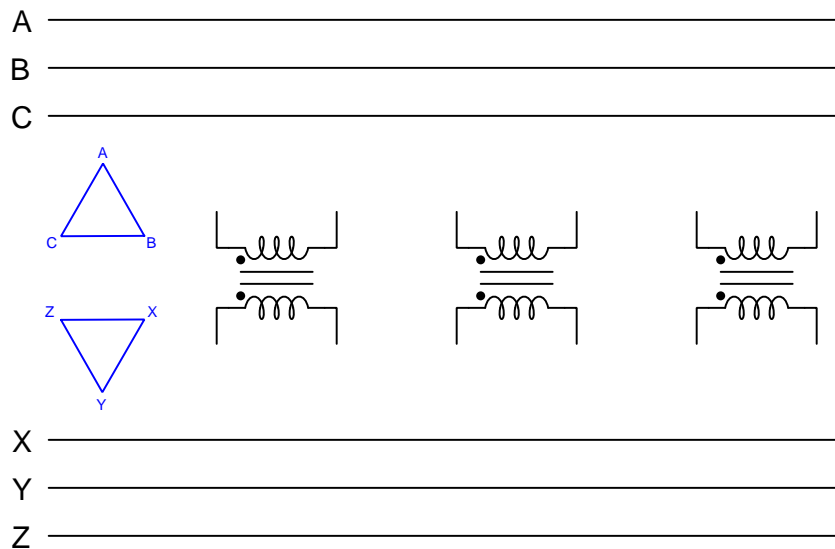


Also, write the phase sequences (phase rotations) for both 3-phase busses, and identify whether the lower bus *leads*, *lags*, or is *in-phase* with the upper bus.

[file i02564](#)

Question 32

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

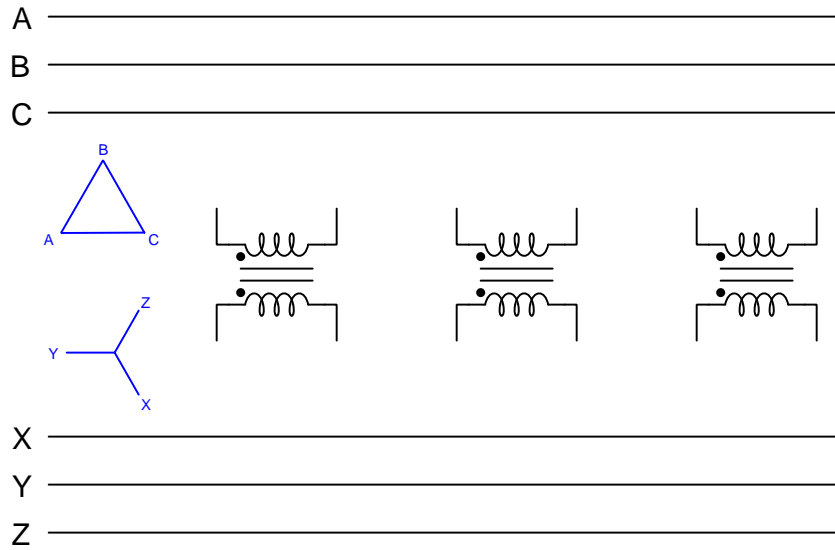


Also, write the phase sequences (phase rotations) for both 3-phase busses, and identify whether the lower bus *leads*, *lags*, or is *in-phase* with the upper bus.

[file i03331](#)

Question 33

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.

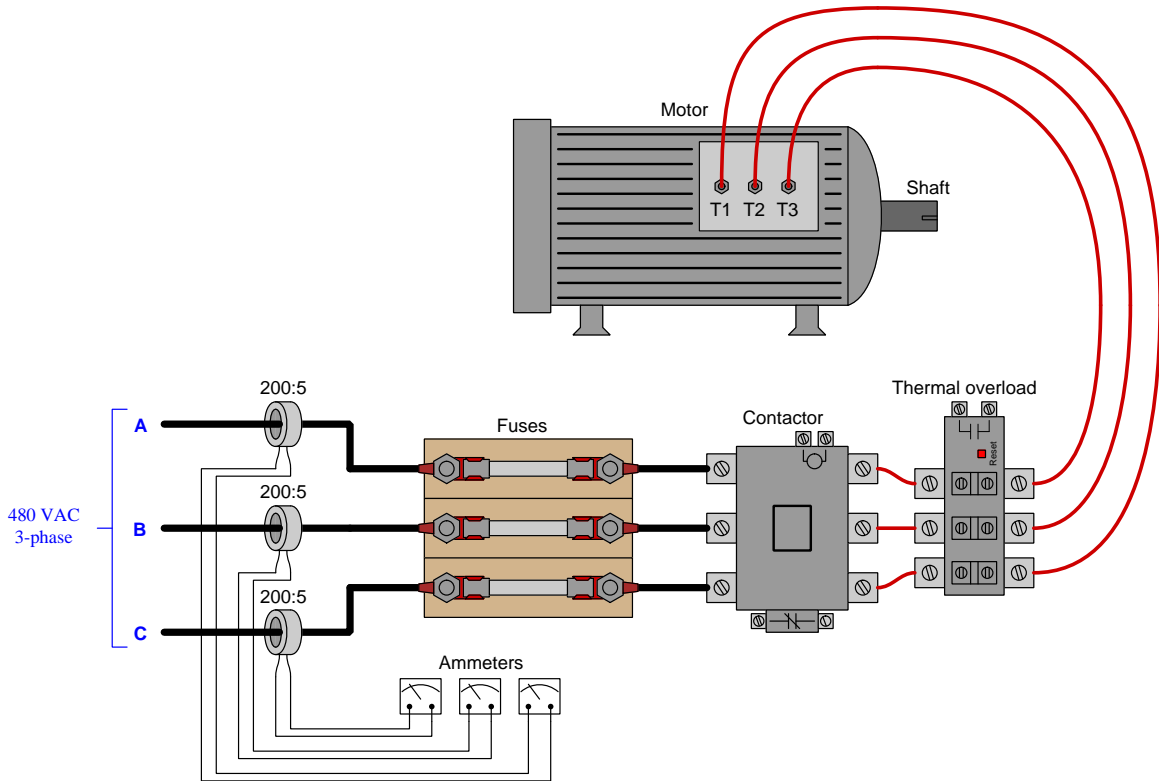
Suggestions for Socratic discussion

- 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 i00847](#)

Question 34

Calculate the current measured by each ammeter assuming the motor's power consumption is 95 kW with a perfect power factor (1), the phase rotation is CBA, and $V_A = 277\angle -20^\circ$. Be sure to express each current value in polar form:



Ammeter "A" current = _____

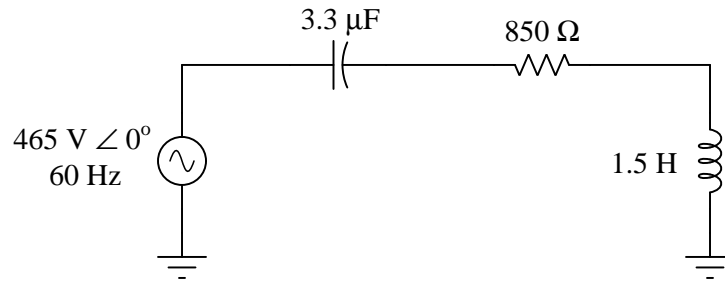
Ammeter "B" current = _____

Ammeter "C" current = _____

file i00849

Question 35

Solve for all voltages, currents, and impedances in this circuit. Express all answers in both polar and rectangular forms:



--	<i>C</i>	<i>R</i>	<i>L</i>	Total
<i>V</i>				465 V ∠ 0° 465 + j0 V
<i>I</i>				
<i>Z</i>				

file i03096

Question 36

Question 37

Question 38

Question 39

Question 40

Question 41

Read and outline the [Full Tutorial](#) of the *Overcurrent Protection 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:

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- (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 i02842](#)

Question 42

Examine an electromechanical time-overcurrent (51) relay, identifying the following:

- Induction disk
- Time dial
- Tap connections (for pick-up coarse adjustment)
- Seal-in unit
- Connecting plug and “brush” contacts
- Drag magnet
- Target (indicator flag) unit
- Instantaneous overcurrent unit (if present)
- Terminal connections to connect the current transformer (*confirm using your multimeter!*)
- Terminal connections for the trip contact (*demonstrate using your multimeter!*)



Be very careful when handling one of these relays! The induction disk shaft rests in two jeweled bearings, and may be damaged if the unit is dropped or the disk forcibly turned. When you rotate the disk by hand, please use only your fingertips, and touch the disk very lightly!

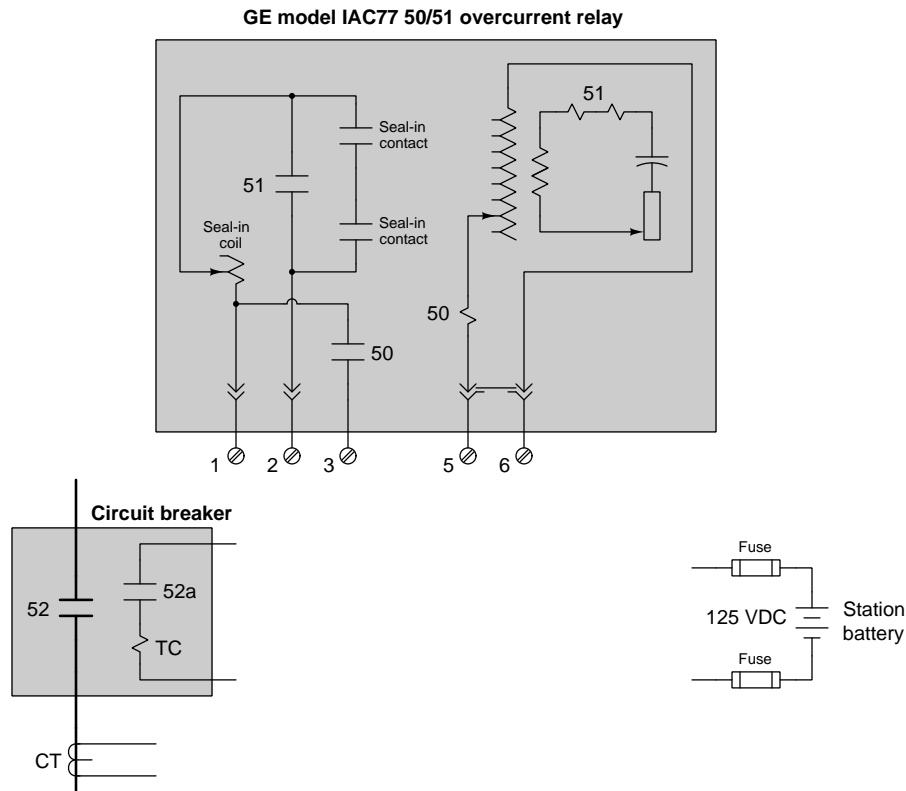
Partner with your classmates to drive current into the CT terminals of a time-overcurrent relay using a *relay test set* or some other suitable source of adjustable alternating current. Apply slightly more current to the relay than what the tap setting is set for, and measure the trip contact status using a multimeter. Ask your instructor for assistance with the relay test set, as it is capable of generating significant AC voltage and current values for input into protective relays.

Suggestions for Socratic discussion

- Demonstrate how setting the “time dial” to different positions affects the time required for the 51 relay to trip. Is a small time dial number or a large time dial number needed to make the relay more sensitive (i.e. trip sooner)?
- Suppose you were to remove the drag magnet from a 51 relay. How would the relay’s behavior be altered as a result of this component loss?
- Suppose you were to remove the restraint spring from a 51 relay (the spiral spring responsible for applying a restraining torque to the induction disk). How would the relay’s behavior be altered as a result of this component loss?

Question 43

The following is an electrical schematic diagram for a General Electric model IAC77 electromechanical instantaneous/time-overcurrent protective relay:



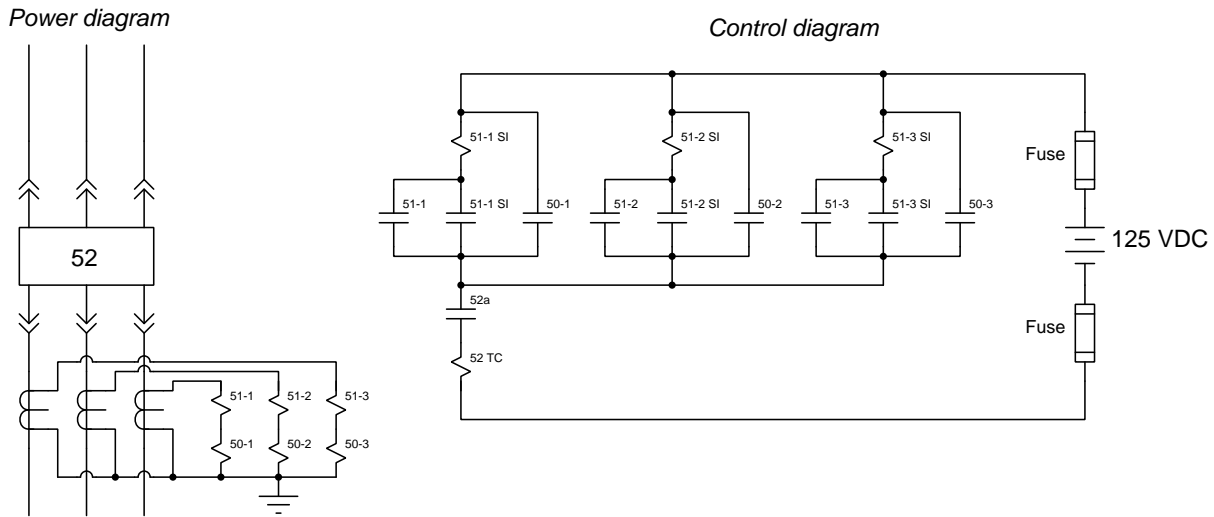
Identify the following:

- What type of symbol represents a coil of wire in this schematic
- What type of symbol represents a relay contact in this schematic
- What type of symbol represents a resistor in this schematic
- What type of symbol represents a capacitor in this schematic
- Where to connect the current transformer to the relay
- How to make coarse adjustments of the pick-up value for the 51 (time-overcurrent) function
- How to make fine adjustments of the pick-up value for the 51 (time-overcurrent) function
- How to make adjustments of the pick-up value for the 50 (instantaneous overcurrent) function
- Whether or not 50 and 51 pickup adjustments are *interactive* (i.e. adjusting one affects the adjustment of the other)
- The purpose of having a seal-in unit
- How to wire the relay so it only functions as a “50” (instantaneous overcurrent) unit
- How to wire the relay so it only functions as a “51” (time overcurrent) unit
- How to wire the relay so it performs both “50” and a “51” protective functions
- Why the circuit breaker has an auxiliary contact (52a) connected in series with the trip coil (note: this contact opens and closes simultaneously with the breaker’s main power contacts, being operated by the same mechanism)

file i01970

Question 44

The following is an electrical schematic diagram for a three-phase 50/51 overcurrent protective relay circuit, where three overcurrent relays (one for each phase of the power circuit) trip a single breaker in the event of an overcurrent fault. The power diagram on the left shows all the high-voltage components, while the control diagram on the right shows the circuitry associated with the breaker's trip coil:



Examine this schematic diagram, and then explain how the circuit breaker may be tripped by *any one* of the three overcurrent relays. Also, identify at least one circuit fault in either the power diagram or the control diagram that could prevent the circuit breaker from tripping when it needs to.

Finally, calculate the amount of voltage dropped by the instantaneous sensing coil of one of the relays (coil 50-1, coil 50-2, or coil 50-3) when line current is 1300 amps at 60 Hz, assuming a 2000:5 CT ratio for each line, and given a coil resistance of 31.35 milliohms and a coil inductance of 27.33 microhenrys:

$$V_{coil} = \text{_____} \text{ volts}$$

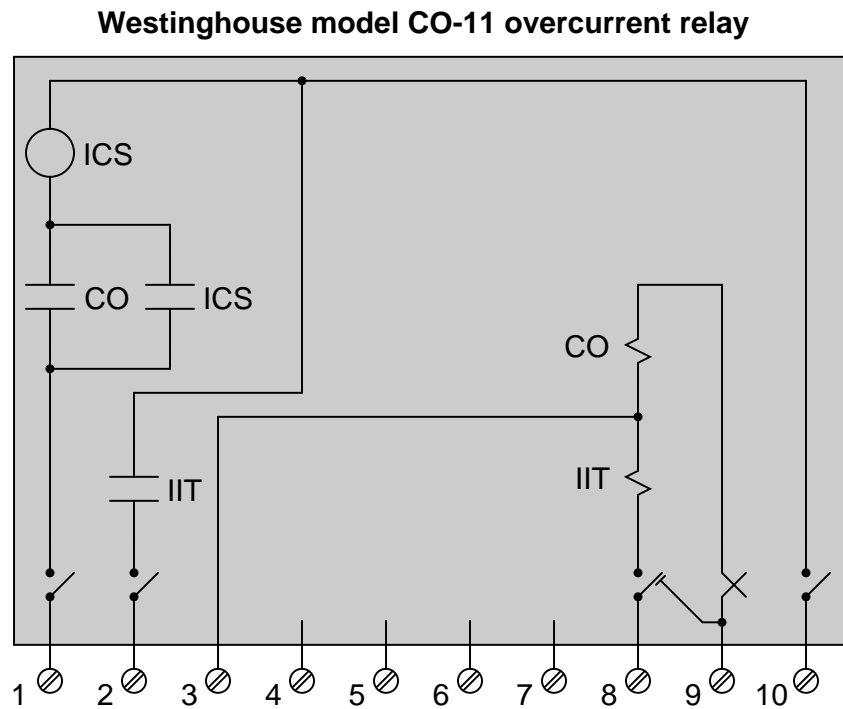
Suggestions for Socratic discussion

- Explain the purpose of the circuit breaker's *52a* contact shown in the control diagram.

[file i01971](#)

Question 45

The following schematic diagram shows a Westinghouse model CO-11 overcurrent protective relay, complete with time-overcurrent (“CO”), instantaneous overcurrent (“IIT”), and seal-in (“ICS”) elements. The relay as shown has been removed from service:



Suppose you were asked to test this relay to ensure it performs both the “50” and the “51” protective functions as designed. When in service, this relay is connected to a current transformer having a ratio of 400:5 amps, and it is supposed to trip the breaker if the power line current exceeds 950 amps (for any length of time), or trip the breaker in 4.6 seconds if the power line current is at a value of 376 amps. Explain in detail how you would bench-test this relay to ensure it is properly calibrated and functional for this application.

Suggestions for Socratic discussion

- Supposing you had no access to any precision protective relay calibration equipment, how could you build a simple circuit to generate the precise amounts of AC current needed to simulate overload conditions?

[file i02057](#)

Question 46

Read selected portions of the “SEL-551 Relay” protective relay manual (document PM551-01, April 2011) and answer the following questions:

Identify three different ANSI/IEEE protective relay functions implemented by this one device. Hint: the *Settings Sheet* section of the manual may be helpful in identifying its functions.

Figure 1.1 on page 1.2 shows some typical applications for the SEL-551 protective relay. Identify at least two applications shown. Also, identify the direction of power flow in this single-line diagram.

A very useful feature of this relay is *event reporting*. This particular model provides a detailed report on a 15-cycle time frame surrounding a trip event. An example of this is shown on page 7.12. Based on the current data shown in this example, when did the fault condition occur, and on which phase of the three-phase system did it occur?

The latter portion of the event report shown on page 7.13 shows the CT ratio for each phase being 120 (120:1, or 600:5) and the pickup value for the phase time-overcurrent being 6 amps. How many amps of line current (RMS) does this translate to, for a pickup value? How many amps of line current (peak) does this pickup value represent?

Suggestions for Socratic discussion

- Note which side of each power circuit breaker the CTs are located: on the *line* side or on the *load* side? Explain the rationale behind this consistent placement of overcurrent protection CTs.
- What do you suppose a *fast bus trip scheme* is, as suggested in the single-line diagram of Figure 1.1?
- Some digital protective relays provide real-time phasor diagrams of line current for visual analysis of a fault. Using data from the 15-cycle event report shown in this manual, describe what the live phasor diagram of line currents would appear to do before, during, and after this particular fault event.
- Figure 7.3 on page 7.15 shows the method by which the SEL-551 relay calculates RMS values for current based on instantaneous samples of each phase current (8 times per cycle), which is one sample every 45 degrees of phasor rotation. Explain how this method works.
- In the latter portion of the event report shown on page 7.13, a section called “SELogic Control Equations” defines the variables able to initiate a trip. Figure 3.13 on page 3.17 shows a logic gate diagram of the “Trip Logic” for this relay. Based on the information contained in the trip logic diagram and in the event report’s summary of the SELogic equations, explain how trip conditions are defined in this particular protective relay, and how the flexibility of SELogic allows a relay technician to do far more with this than could be done with simple electromechanical relay technology.

[file i01202](#)

Question 47

Suppose a 51 (time-overcurrent) protective relay is used to provide protection for a large (3000 horsepower) electric motor. The motor runs on a line voltage of 4160 volts, and has a full-load efficiency of 88%. The relay obtains its line current data from a set of three 400:5 current transformers on the motor's T1, T2, and T3 leads.

Based on this information, identify the *pick-up* current value for this protective relay, in secondary CT amps:

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

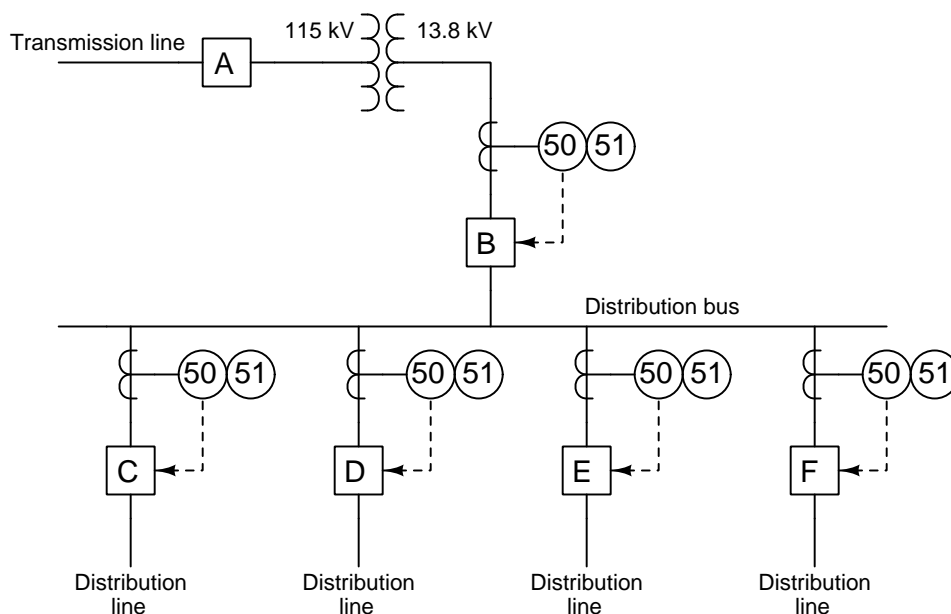
Also, explain what other factor(s) will dictate the time dial setting and time-current curve type for this 51 relay to provide sufficient protection for the motor.

file i00851

Question 48

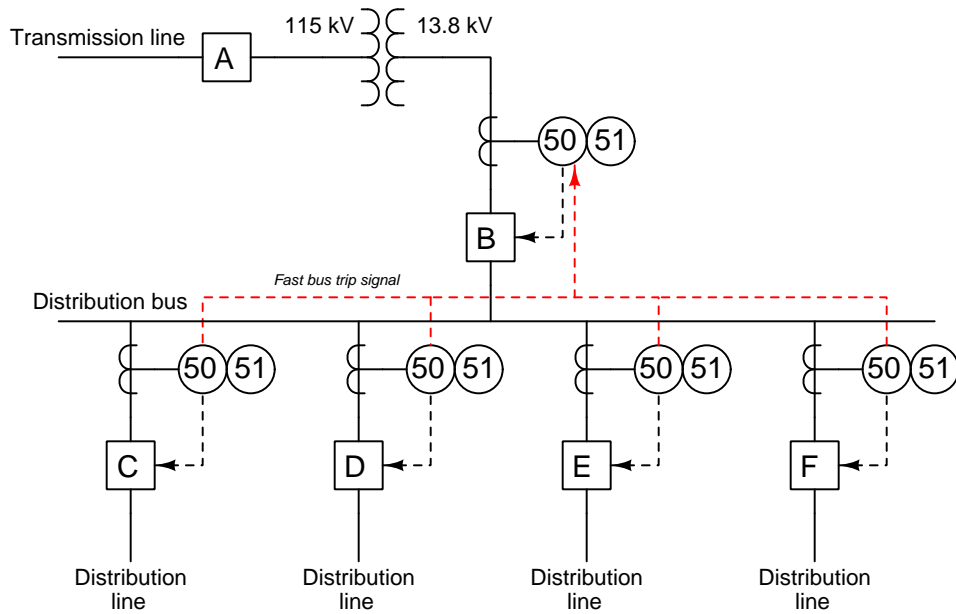
A very important concept in overcurrent protection is something called *coordination*. This is where overcurrent-protection devices (e.g. fuses, circuit breakers, reclosers, protective relays) closer to the power source have trip thresholds greater than protection devices farther away from the source. The rationale behind coordination is to trip the smallest portion of the power grid necessary to clear the fault.

Examine this single-line diagram of a single-bus substation where incoming power arrives through a transmission line and exits to customer loads through four identical distribution feeder lines:



Identify which of the protective relays should have the highest pickup value and/or longest tripping time value, and which of the protective relays should have the lowest pickup/time values. Describe a “thought experiment” whereby these different pickup values help clear a distribution line fault most effectively.

Now, consider the following modification to this substation, incorporating a protection strategy known as *fast bus trip* scheme, also known as a *reverse interlocking* or *zone interlocking* scheme (shown in red):

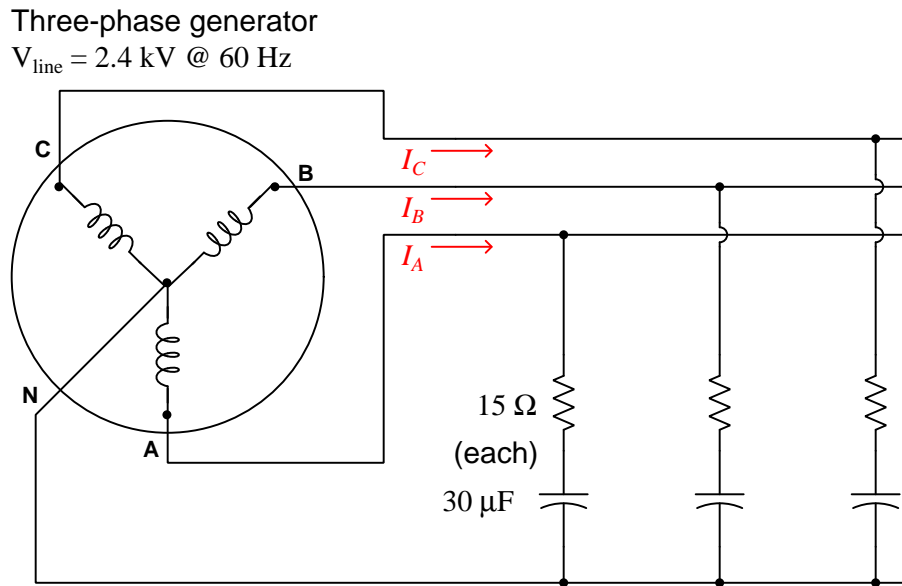


The purpose of a fast bus trip scheme is to detect and clear any faults on the substation bus by means of overcurrent relays faster than they would be cleared by the incoming line relay's regular action. The "fast bus trip signal" informs breaker B's relays whether or not high current is being sensed by any of the distribution breaker relays. Explain how this protection scheme uses information sent to the bus relay from the feeder relays to accomplish faster tripping. Again, describe a "thought experiment" that will illustrate the effectiveness of this protection scheme.

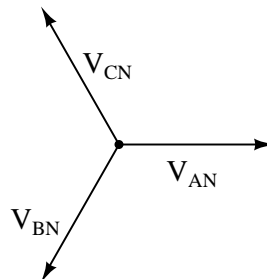
[file i01194](#)

Question 49

Calculate the amount of current in each line of this balanced three-phase circuit. Capacitance and resistance values are typical for each phase:



State your answers both in symbolic form (e.g. ??? volts \angle ?? degrees) as well as in a phasor diagram along with these generator voltage phasors:



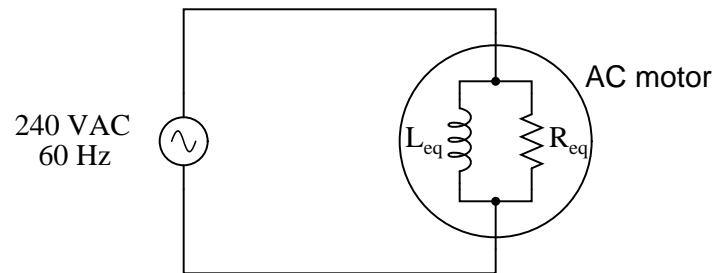
Suggestions for Socratic discussion

- Predict how the phasor diagram of voltage and current would change if one of the capacitors failed open.
- Predict how the phasor diagram of voltage and current would change if one of the capacitors failed shorted.
- Predict how the phasor diagram of voltage and current would change if one of the resistors failed open.
- Predict how the phasor diagram of voltage and current would change if one of the resistors failed shorted.

[file i03041](#)

Question 50

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

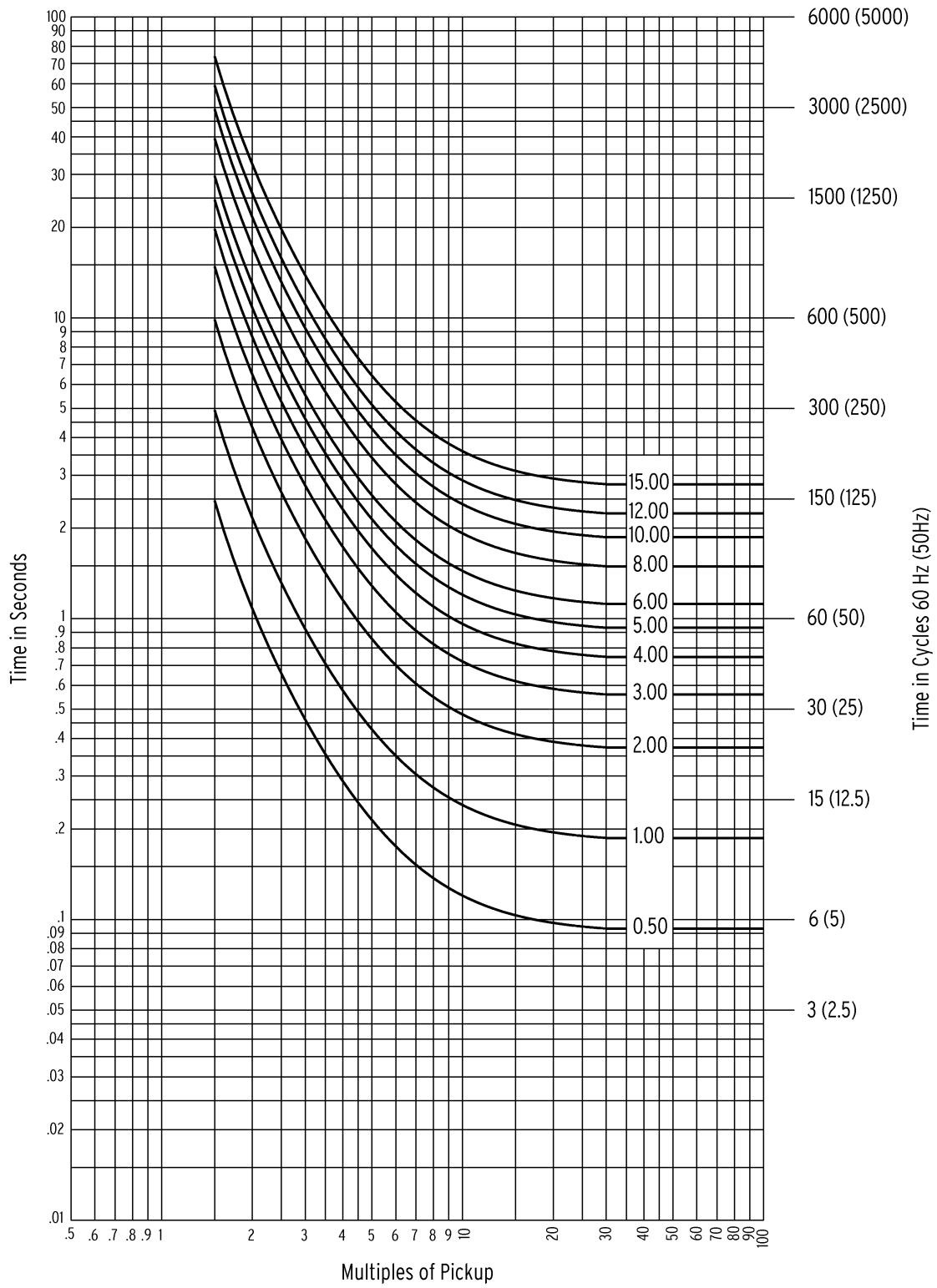


Calculate the current necessary to power this motor if the equivalent resistance and inductance is 20Ω and 238 mH , respectively.

[file i01058](#)

Question 51

Use these graphs to determine the time it will take for a 51 relay to trip given a 600:5 CT ratio, a fault current of 7500 amps, a time-dial setting of 3, and a pick-up current setting (“tap setting”) of 4.0 amps:



Question 52

Calculate the necessary time-dial setting for a 51 protective relay with an “extremely inverse” characteristic assuming a pick-up (tap setting) of 5 amps, a CT ratio of 1200:5, and a desired trip time of 10 seconds for a fault current value of 3.6 kA.

Time dial setting = _____

Question 53

Question 54

Question 55

Question 56

Question 57

Question 58

Question 59

Question 60

Question 61

Read and outline the Full Tutorial of the *Differential Generator, Line, and Bus Protection 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:

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Question 62

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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 i02844](#)

Question 63

Read selected portions of the “SEL-387L Line Current Differential Relay” protective relay data sheet (document SEL-387L Data Sheet, October 2009) and answer the following questions:

The model 387L is billed as a “No Settings” relay. Explain what this means, and why it is possible for this application when modern digital protective relays typically have *lots* of important parameters which must be set.

Explain why differential current protection for a power line requires the use of *two* model 387L relays, and also how the relay pair communicates with each other.

Reference is made within this data sheet to “local” and “remote” current measurements. Describe what is meant by these two terms.

A useful feature provided by this relay is a pair of *transfer contacts*. Explain what these do, and how they are similar to discrete I/O in PLCs.

Suggestions for Socratic discussion

- Can a pair of 387L relays be used to provide differential current protection on a *transformer*? Explain why or why not.
- A concept referenced within this document is that of a *transfer trip* signal. Locate an instance of this concept expressed within the document, and explain its application to the protection of a power line. What exactly does the “transfer trip” signal do, and which device initiates that signal?
- Sketch a simple circuit showing how the T1 input on one relay could be used to trigger the R1 output on a second relay to perform some useful function.

[file i00823](#)

Question 64

Read selected portions of the “SEL-387A Current Differential Relay” protective relay instruction manual (document SEL-387A Instruction Manual, January 2014) and answer the following questions:

Identify common applications for this model of protective relay.

Like many other modern digital protective relays, the model 387A is capable of providing more than one ANSI/IEEE protection function. Identify some of the functions offered by this particular relay other than 87 (differential).

Figure 2.7 on page 2-10 shows a sample application where the 387A relay protects a transformer. Identify the winding configuration of the power transformer (e.g. Delta/Wye) as well as the configuration of the primary and secondary circuit current transformers as they connect to the relay. How does this CT connection scheme differ from traditional (electromechanical) differential current relays?

Based on the power transformer configuration shown in Figure 2.7, how much phase shift is there between the primary and secondary phases?

One of the major considerations when implementing differential current protection on power transformers is *phase shift compensation* from primary to secondary, if the power transformer being protected has Wye-Delta or Delta-Wye windings. With electromechanical relays this compensation takes the form of different CT wiring configurations on the primary and secondary sides (i.e. Delta-connected CTs on the power transformer’s Wye side, and Wye-connected CTs on the power transformer’s Delta side). However, digital 87 relays such as the model 387A offer “connection compensation” which is based on digital math calculations rather than electrical wiring. Pages 3-17 through 3-21 discuss the application of this feature in the model 387A relay. Read this section and explain in your own words how connection compensation works for the two examples shown in figures 3.9 and 3.10.

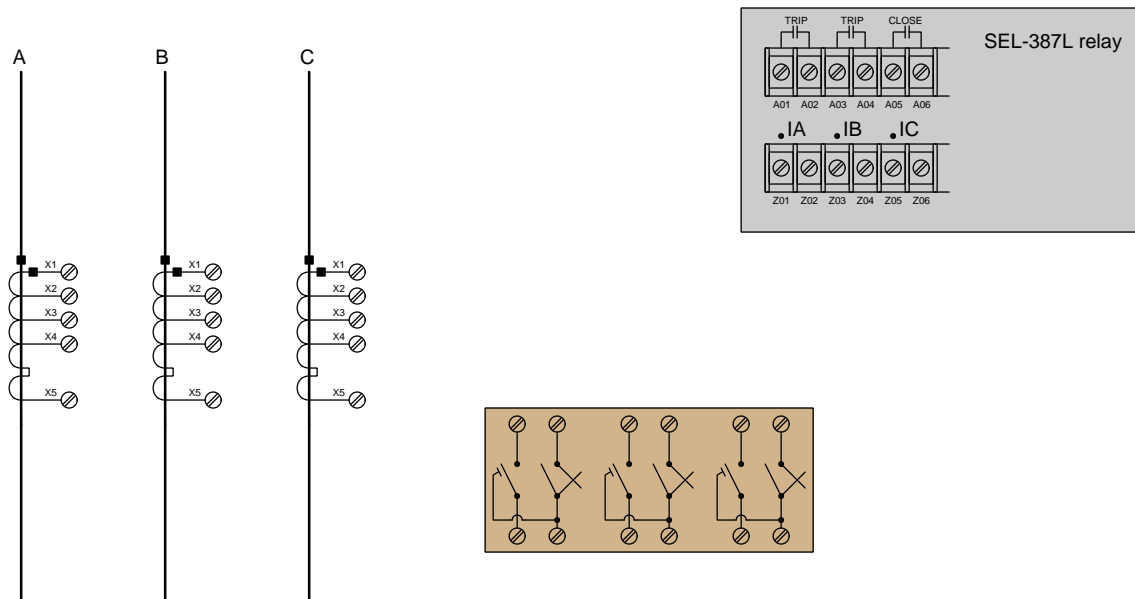
Suggestions for Socratic discussion

- The winding compensation parameter must be set to a particular value on the Wye-connected side of the power transformer, if the CTs for that side are also Wye-connected. Explain why this is, and what the particular $WnCTC$ value must be set to.
- Examine each of the phasor diagrams shown for each of the $WnCTC$ selection examples on pages 3-19 (figure 3.9) and 3-20 (figure 3-10). Which phasor diagrams show the phase shift of the power transformer? How are the CT phase shifts represented? What does the dashed line in each phasor diagram represent? How do the $WnCTC$ values fit into the phasor diagrams?

[file i00824](#)

Question 65

Sketch wire connections to complete wiring between this SEL-387L differential current relay and a set of three line CTs. Note that only a few of the available terminals on the SEL-387L relay are shown, and that the line CTs are *multi-ratio current transformers* with different “taps” to choose from:



Assume we wish to have the CT ratios be 1200:5 each. The number of CT secondary winding turns between adjacent terminals are as follows:

Terminals	Turns
X1 – X2	80
X2 – X3	160
X3 – X4	60
X4 – X5	100

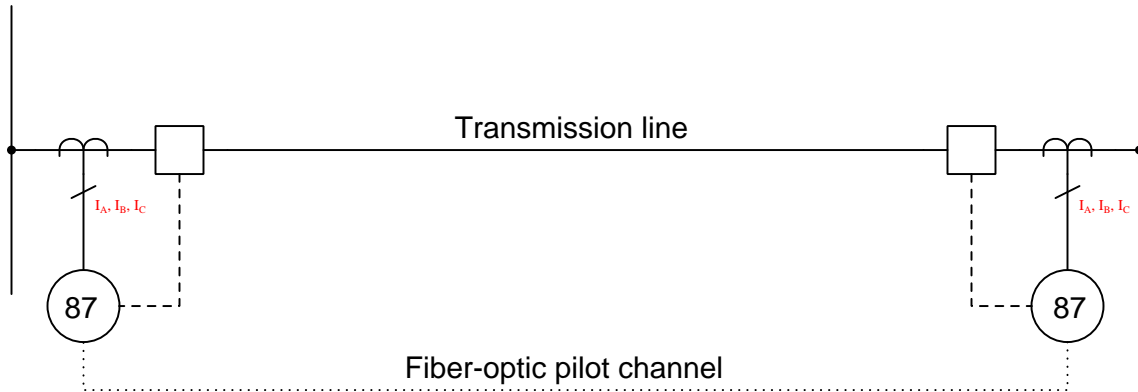
Suggestions for Socratic discussion

- Since we only need two terminals on the secondary of each CT, should the other (unused) terminals be shorted together for safety? Why or why not?

[file i03086](#)

Question 66

In this system, a pair of line current differential relays (87) provide protection for a power line, each relay sensing current through the three line conductors at each end. The optional slash mark and “ I_A , I_B , I_C ” notations emphasize the fact that the relays are monitoring all three phases:

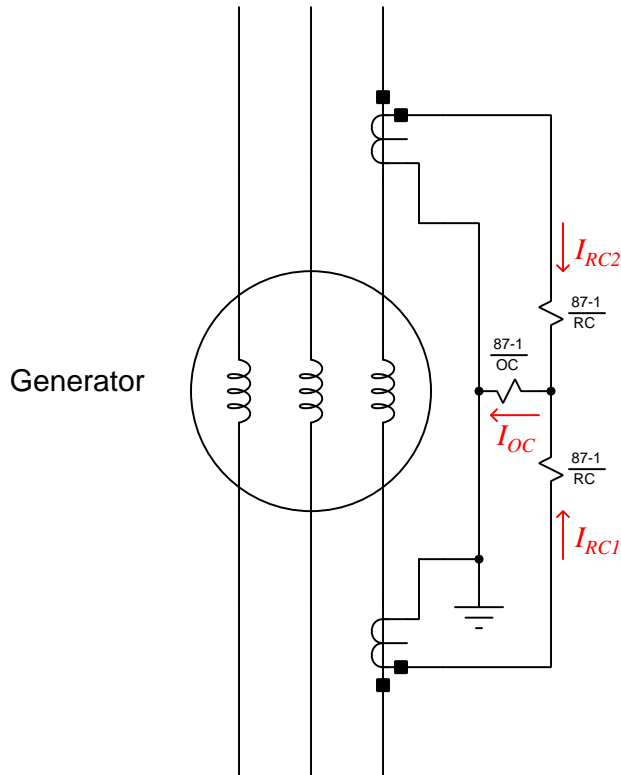


Suppose a line-to-line fault develops between phases A and B of this power line, with no connection whatsoever to earth ground. Determine whether or not the 87 relays will trip, and explain why.

[file i00852](#)

Question 67

Calculate the current passing through this 87 relay's operate coil (87/OC) given the two currents sent through the restraint coils (87/RC):



Differential current measurement is only shown here on one phase of the generator, for simplicity

$$I_{RC1} = 4.72 \text{ A } \angle 21^\circ$$

$$I_{RC2} = 4.68 \text{ A } \angle -160^\circ$$

In addition to calculating a symbolic answer for I_{OC} , sketch a phasor diagram showing how the three currents (I_{RC1} , I_{RC2} , and I_{OC}) relate to one another.

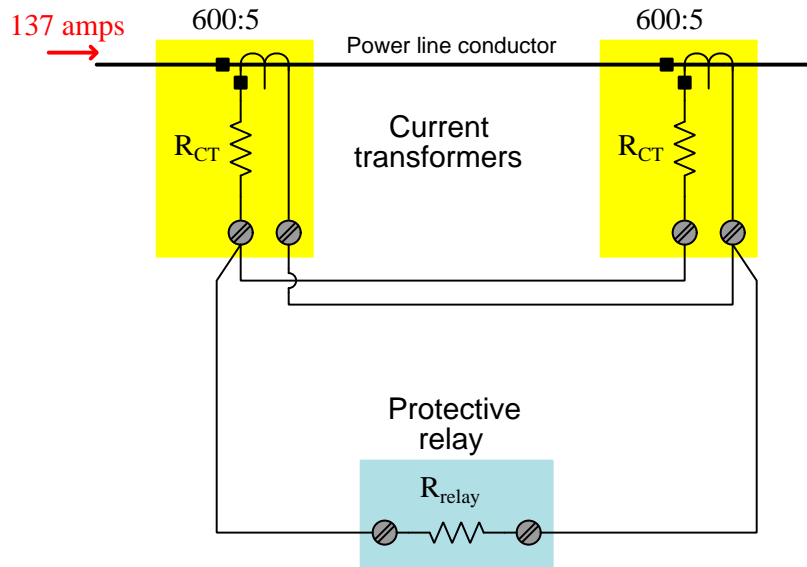
Suggestions for Socratic discussion

- Identify factors which could account for these two currents not perfectly canceling each other at the differential current relay.

[file i02607](#)

Question 68

Suppose a pair of current transformers with 600:5 ratios are parallel-connected to feed their output signals to a protective relay as shown in this schematic diagram:



- $R_{CT} = 0.5 \Omega$ (this is the internal resistance of each CT's secondary winding)
- $R_{relay} = 1.8 \Omega$

Calculate the following voltage drops in this current transformer circuit, from the given information:

- $V_{relay} = \underline{\hspace{2cm}}$ volts
- Voltage output at each CT's terminals = $\underline{\hspace{2cm}}$ volts
- Voltage generated by each CT's secondary winding (before any R_{CT} losses) = $\underline{\hspace{2cm}}$ volts

Suggestions for Socratic discussion

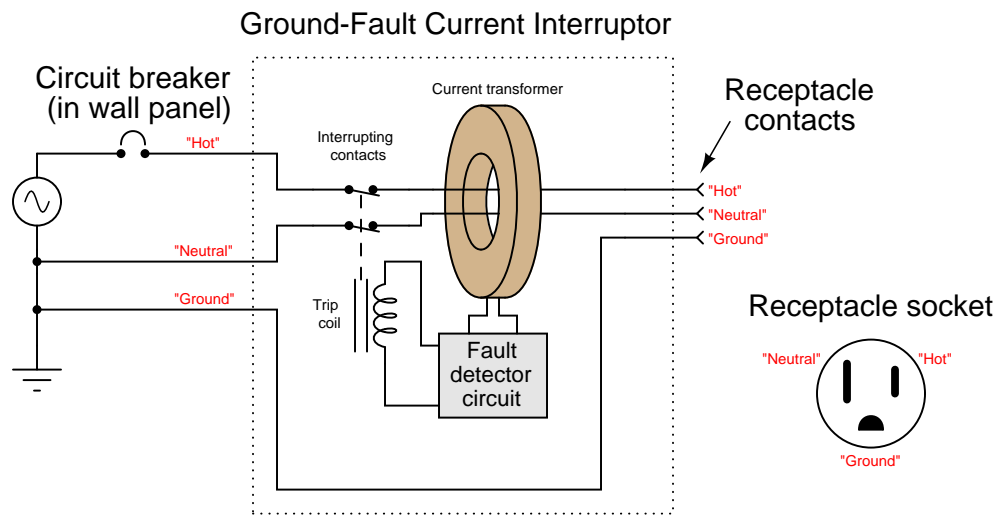
- Sketch current arrows showing the direction of each CT's secondary current relative to the direction shown for the 137 amp primary current.
- Explain why the two CT secondary windings must be paralleled as shown, and not parallel-connected with one of the CT's polarity reversed.

[file i02872](#)

Question 69

Protective relays are typically found only in electric power grid applications, or at industrial facilities where exceptionally large loads are operated (e.g. huge motors for ball mills, compressors, pumps, etc.). However, there is a type of circuit protective device that is so common, it exists within almost every home in the United States: a *Ground Fault Current Interruptor*, or *GFCI*.

The basic idea behind a GFCI is represented in this simplified schematic diagram:



A GFCI receptacle uses a single current transformer (CT) to measure the *difference* in electric current through the “hot” and “neutral” conductors of any electrical appliance plugged into the receptacle. If even a slight difference is detected, the interruptor contacts open, stopping power to the appliance.

Explain how a single CT is able to detect a difference in current between two conductors. Also, explain how a difference in current would ever arise between the “hot” and “neutral” conductors of an appliance. Finally, explain how you could test the proper operation of a GFCI by introducing a real ground fault.

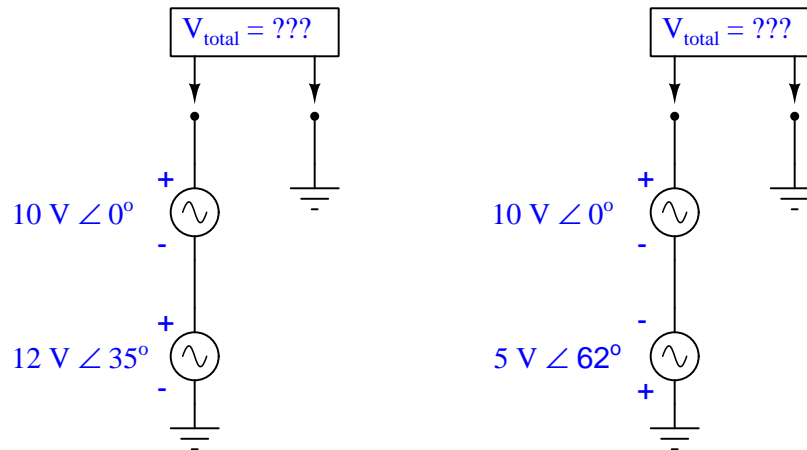
Suggestions for Socratic discussion

- The National Electrical Code requires GFCI receptacles be used in household areas where exposure to water is likely, such as in bathrooms and outside. Explain why the presence of water is a factor in applying GFCI safety technology.
- Which ANSI/IEEE protective relay function code best fits the safety function performed by a GFCI?

[file i01201](#)

Question 70

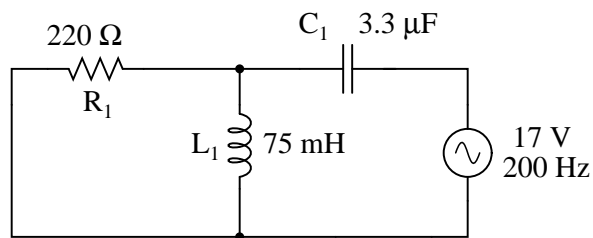
Determine the total voltage in each of these examples, drawing a phasor diagram to show how the total (resultant) voltage geometrically relates to the source voltages in each scenario:



[file i00841](#)

Question 71

Complete the table of values for this circuit, representing all quantities in *polar* form:

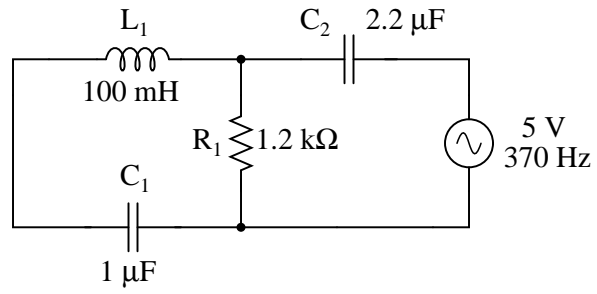


	R_1	L_1	C_1	Total
V				
I				
Z				

[file i00842](#)

Question 72

Complete the table of values for this circuit, representing all quantities in *polar* form:

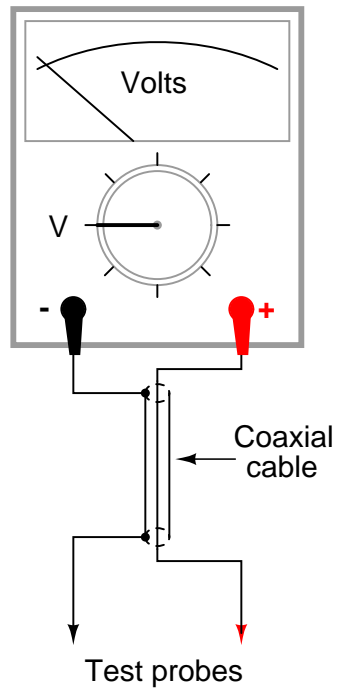


	R_1	L_1	C_1	C_2	Total
V					
I					
Z					

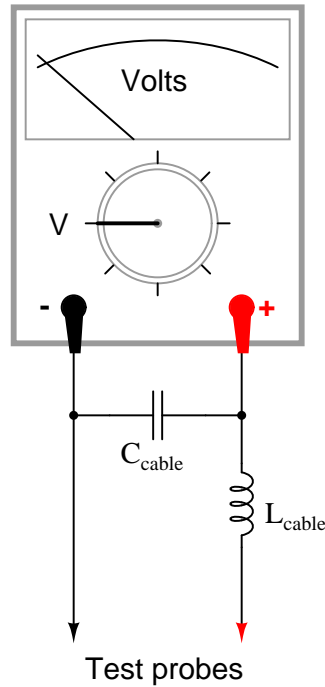
[file i00843](#)

Question 73

Test leads for DC voltmeters are usually just two individual lengths of wire connecting the meter to a pair of probes. For highly sensitive instruments, a special type of two-conductor cable called *coaxial cable* is generally used instead of two individual wires. Coaxial cable – where a center conductor is “shielded” by an outer braid or foil that serves as the other conductor – has excellent immunity to induced “noise” from electric and magnetic fields:



When measuring high-frequency AC voltages, however, the parasitic capacitance and inductance of the coaxial cable may present problems. We may represent these distributed characteristics of the cable as “lumped” parameters: a single capacitor and a single inductor modeling the cable’s behavior:



Typical parasitic values for a 10-foot cable would be 260 pF of capacitance and 650 μH of inductance. The voltmeter itself, of course, is not without its own inherent impedances, either. For the sake of this example, let’s consider the meter’s “input impedance” to be a simple resistance of 1 M Ω .

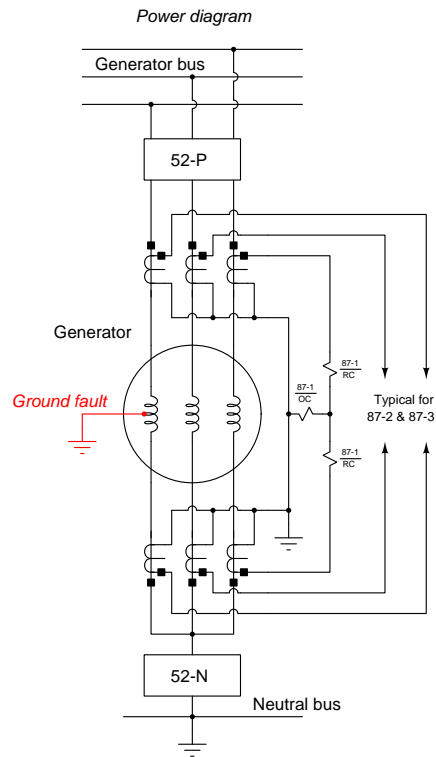
Calculate what voltage the meter would register when measuring the output of a 20 volt AC source, at these frequencies:

- $f = 1 \text{ Hz}$; $V_{\text{meter}} =$
- $f = 1 \text{ kHz}$; $V_{\text{meter}} =$
- $f = 10 \text{ kHz}$; $V_{\text{meter}} =$
- $f = 100 \text{ kHz}$; $V_{\text{meter}} =$
- $f = 1 \text{ MHz}$; $V_{\text{meter}} =$

file i00844

Question 74

Suppose this generator suffers a ground fault in its left-hand winding. Assuming a balanced line current of 150 amps through each phase of the 52-P circuit breaker, a ground fault current magnitude of 10 amps, and CT ratios of 200:5, calculate the amount of current going through each coil (RC and OC) of the 87-3 relay:



file i00853

Question 75

Question 76

Question 77

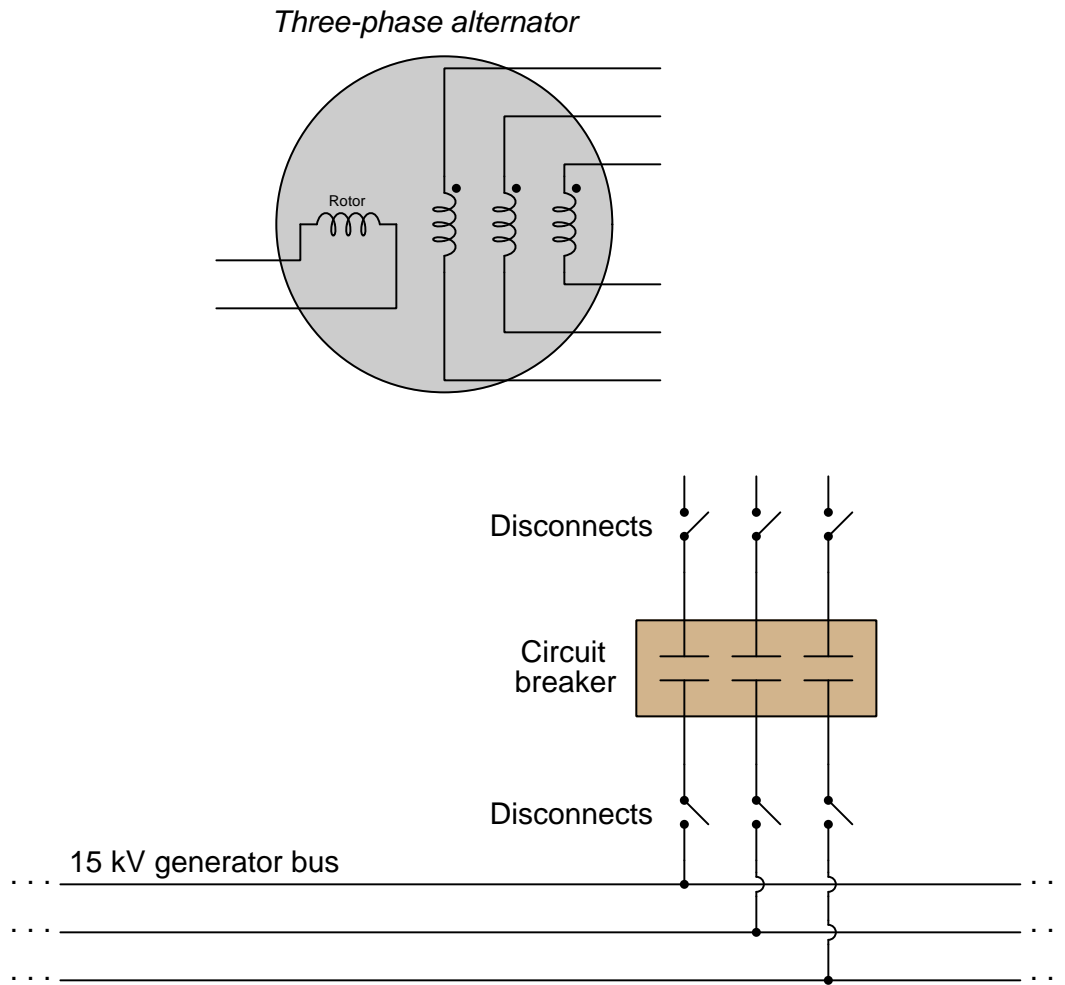
Question 78

Question 79

Question 80

Question 81

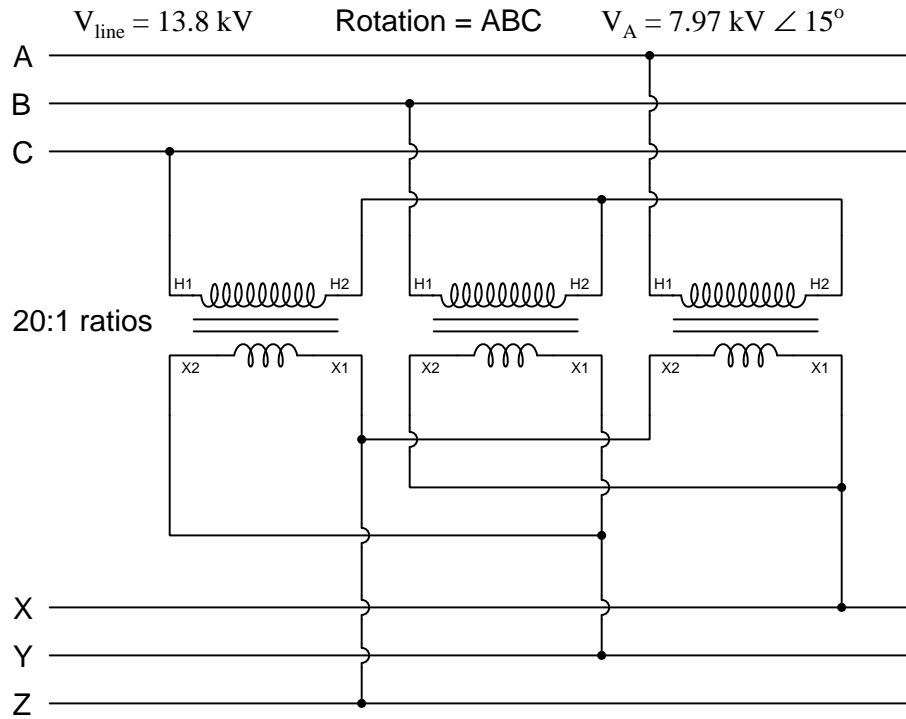
A 15 kV three-phase alternator needs to have its windings connected properly to prepare it to send power to a “bus” shared by other alternators in a power plant. This bus operates at a line voltage of 15 kV:



Each phase winding on the alternator is rated at 15 kV. The rotor winding is rated at 220 VDC. Sketch all necessary connections to make this alternator work as intended.

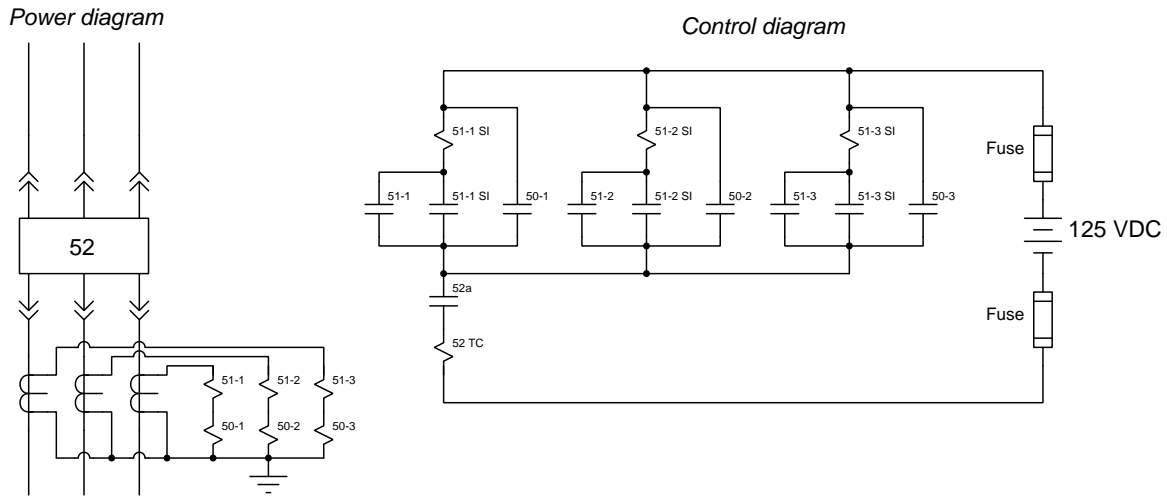
Question 82

Sketch a phasor diagram for this transformer bank's output voltages, and determine their phase rotation:



Question 83

The following diagrams document the overcurrent protection system for a feeder supplying three-phase AC power to an industrial load:



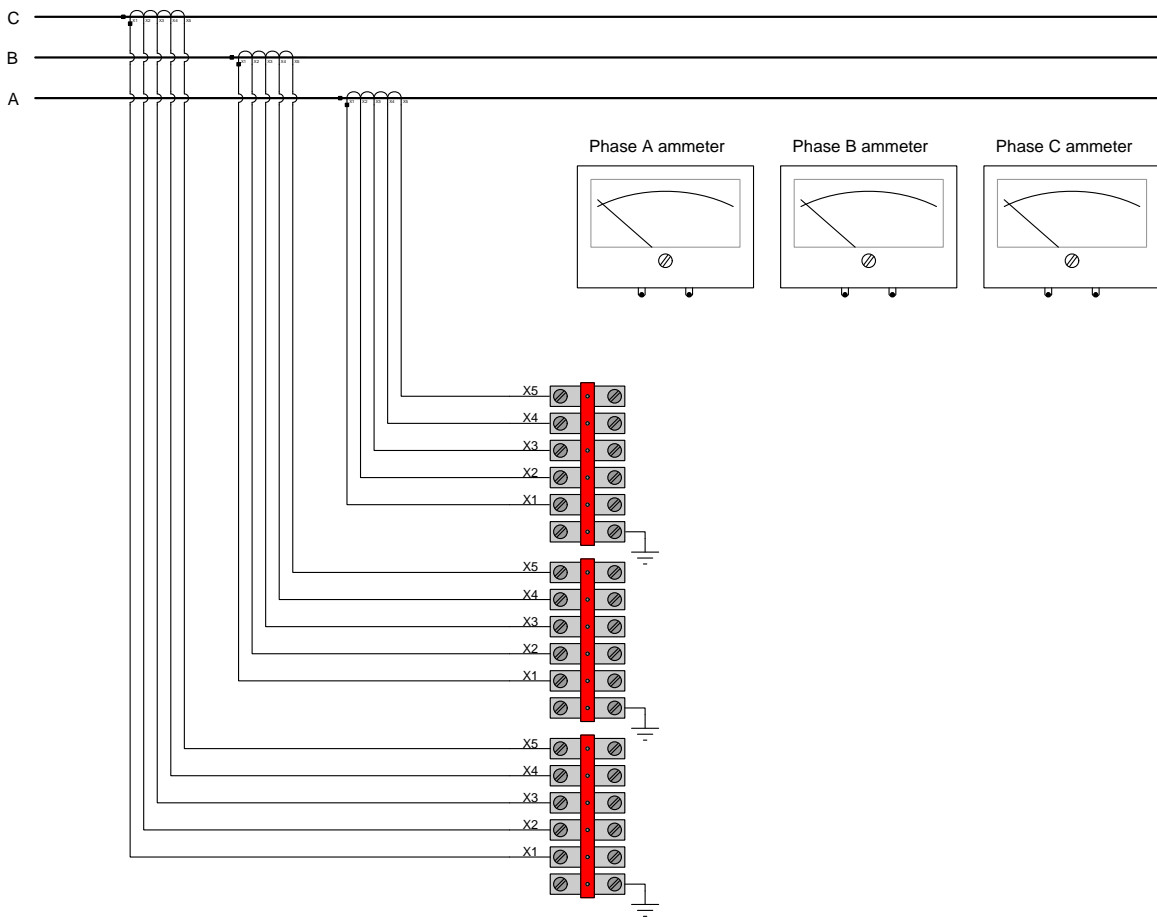
Suppose one day the circuit breaker (52) trips for no apparent reason. None of the brightly-colored “target” flags on the electromechanical protective relay are visible, as one would normally expect following a relay trip event. Identify the likelihood of each specified fault for this system. Consider 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		
52/TC coil failed shorted		
51-3/SI coil failed shorted		
50-1 contact failed open		
50-1 contact failed shorted		
50-2 coil failed shorted		
50-2 coil failed open		

Also, identify which side of the 52 circuit breaker should be the “line” (supply) and which side should be the “load” in order for the 50/51 relay to provide maximum protection in this system.

Question 84

Sketch wires connecting these multi-ratio CTs to the three ammeters, and also insert screws into the shorting terminal blocks as appropriate, in order to provide a 200:5 CT ratio on each phase:

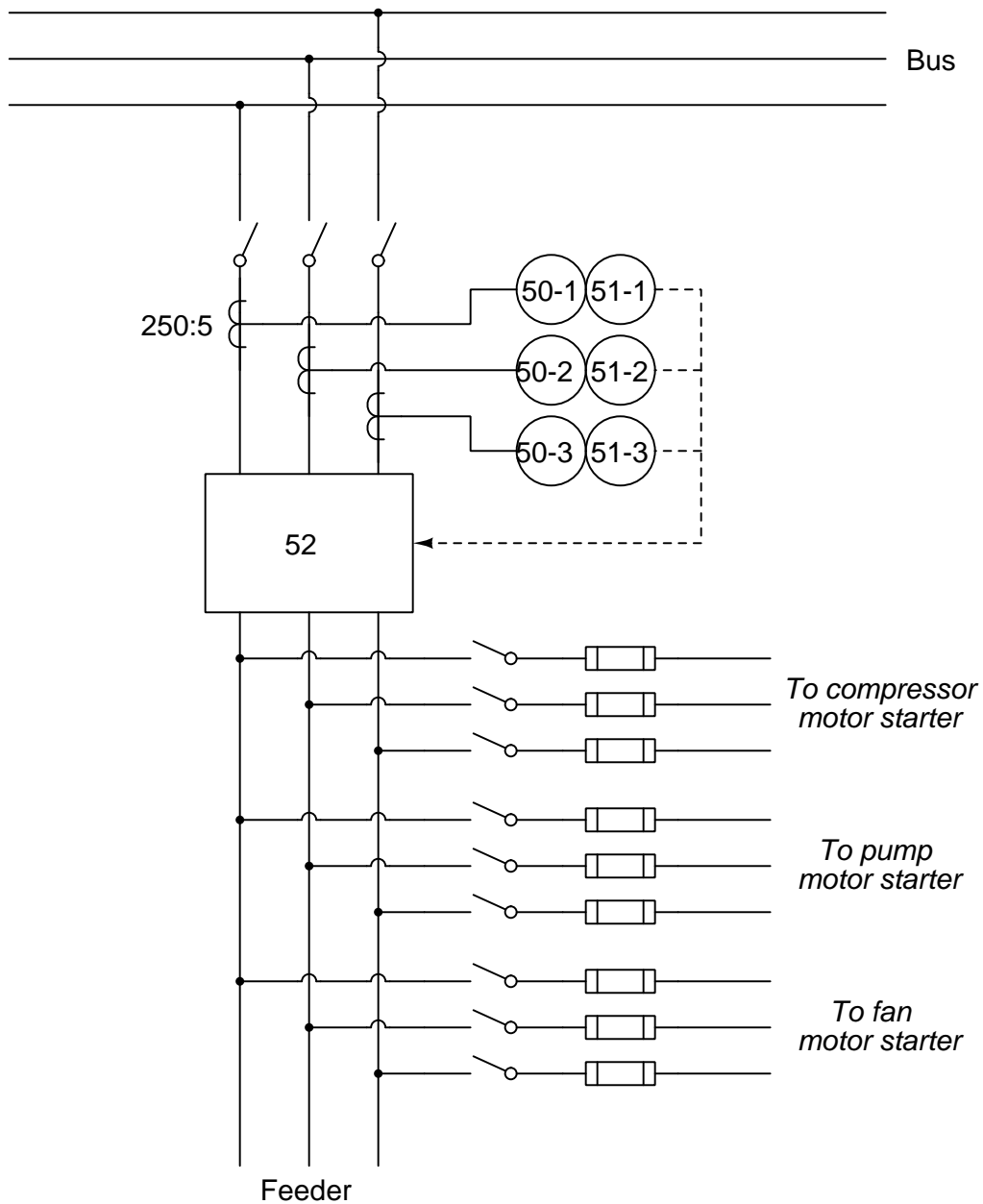


Assume each of the multi-ratio CTs has the following number of wire turns between terminal pairs:

- 10 turns between X1 and X2
- 5 turns between X2 and X3
- 25 turns between X3 and X4
- 20 turns between X4 and X5

Question 85

Examine this overcurrent protection system for a feeder, supplying three-phase power to a set of industrial loads from a substation bus:



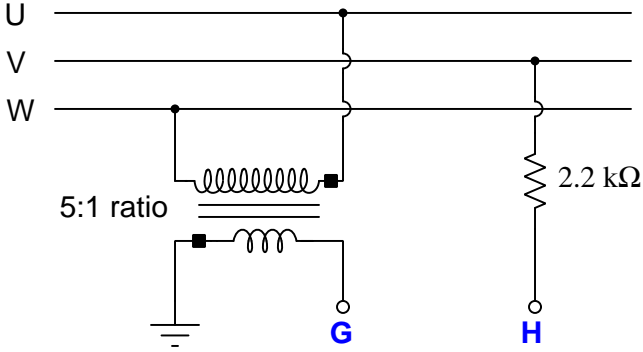
Explain why 50/51 overcurrent protection is necessary at all, since each of the loads has its own set of fuses to protect against overcurrent conditions.

Suppose the cable connecting phase 2 CT to the 50-2/51-2 relay fails shorted, such that the relay no longer senses current through that phase. Will the other two overcurrent relays continue to provide adequate protection? Explain why or why not, in detail.

[file i02562](#)

Question 86

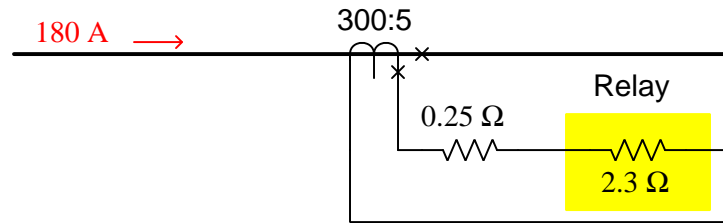
Calculate the V_{GH} in this circuit, expressing your answer in polar form. Assume an UVW phase rotation with $V_U = 277$ volts $\angle -15^\circ$:



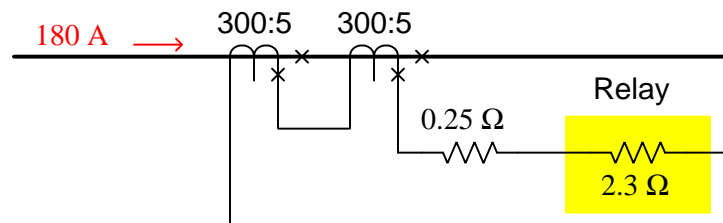
$V_{GH} = \underline{\hspace{2cm}}$

Question 87

Calculate all currents and voltages in this current transformer (CT) circuit:



Now, calculate all currents and voltages in this current transformer circuit, with two identical CTs connected in series:



Finally, sketch the direction of current through each CT assuming the direction shown by the 180 amp arrow at one particular instant in time.

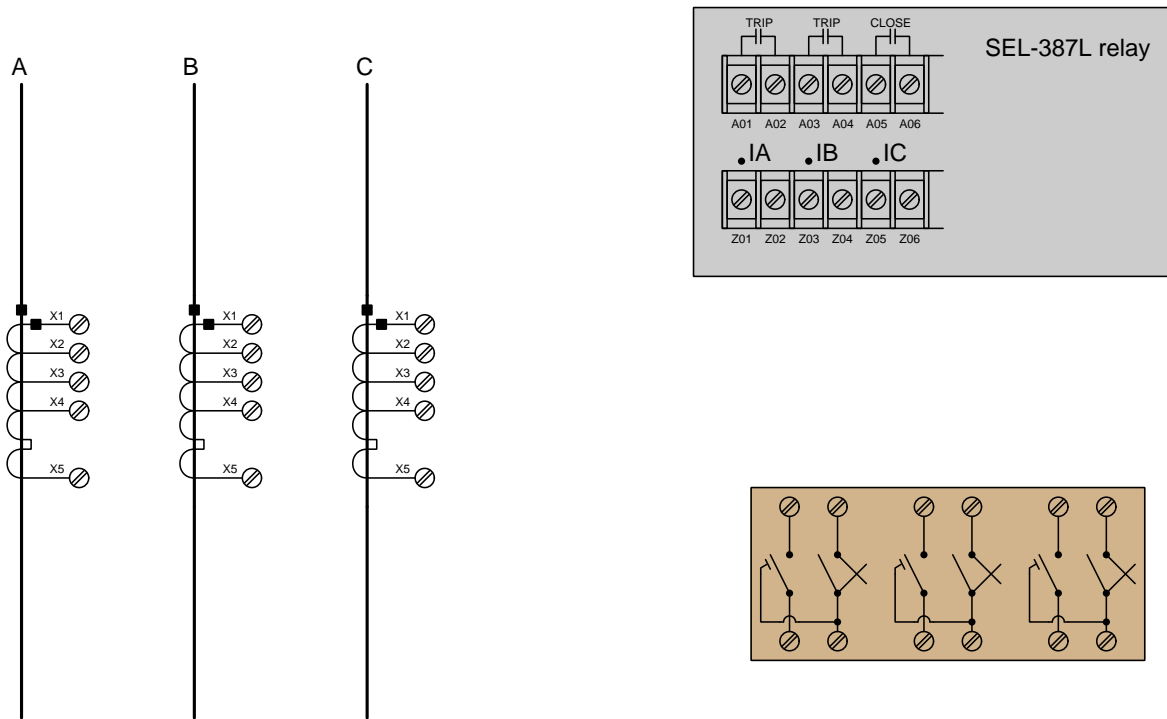
Question 88

Every protective relay or measuring device presents a *burden* to the instrument transformer(s) driving signal into it. The greater a relay's burden, the more power is demanded from the instrument transformer and the less accurate the system will tend to be. For this reason, burden is a very important parameter to consider when wiring a protective relay system.

The datasheet for a General Electric model CEB52 "distance" protective relay (ANSI/IEEE code 21) shows the burden for its "polarizing coil" PT input to be $1540 - j162$ ohms. Calculate the current through this coil when the PT's output signal is 103 volts $\angle -6^\circ$.

Question 89

Sketch wire connections to complete wiring between this SEL-387L differential current relay and a set of three line CTs. Note that only a few of the available terminals on the SEL-387L relay are shown, and that the line CTs are *multi-ratio current transformers* with different “taps” to choose from:

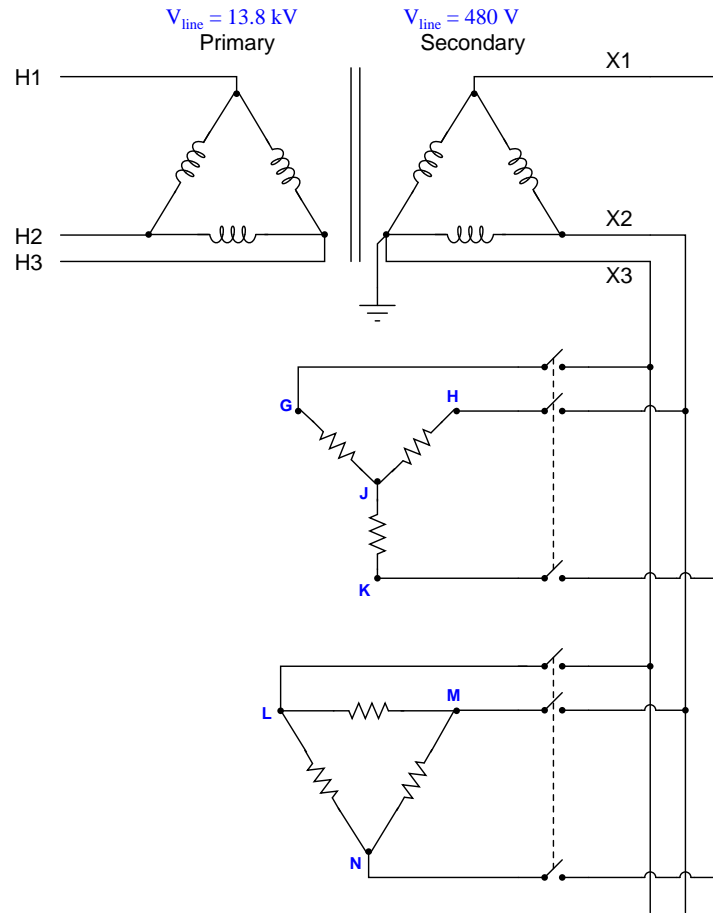


Assume we wish to have the CT ratios be 1100:5 each. The number of CT secondary winding turns between adjacent terminals are as follows:

Terminals	Turns
X1 - X2	80
X2 - X3	160
X3 - X4	60
X4 - X5	100

Question 90

A three-phase step-down transformer supplies 480 VAC to a pair of resistive loads. The secondary winding is “corner-grounded” on the X2 leg:



Determine the following phase-to-ground voltages in this system while both loads are energized:

- $V_G =$ _____ volts
- $V_H =$ _____ volts
- $V_J =$ _____ volts
- $V_K =$ _____ volts
- $V_L =$ _____ volts
- $V_M =$ _____ volts
- $V_N =$ _____ volts

Supposing the upper load has a total power dissipation of 8.4 kW and the lower load has a total power dissipation of 3.9 kW, calculate the amount of current through line H2.

[file i00966](#)

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.

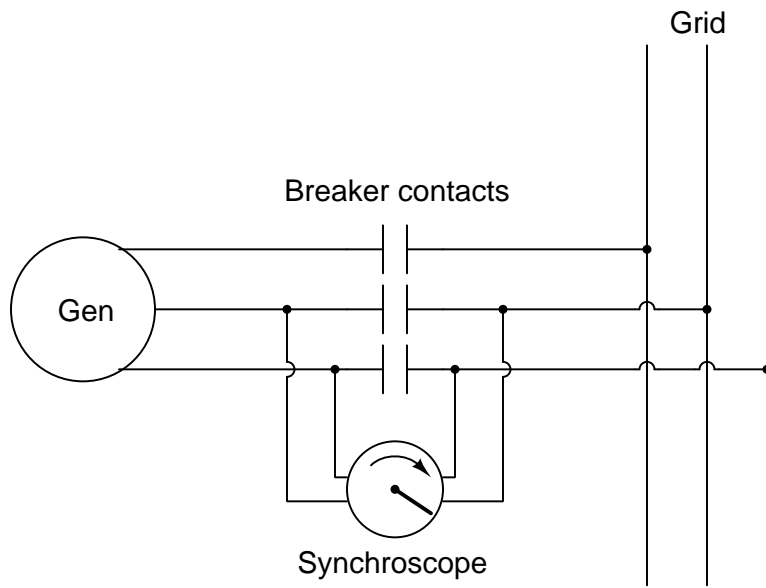
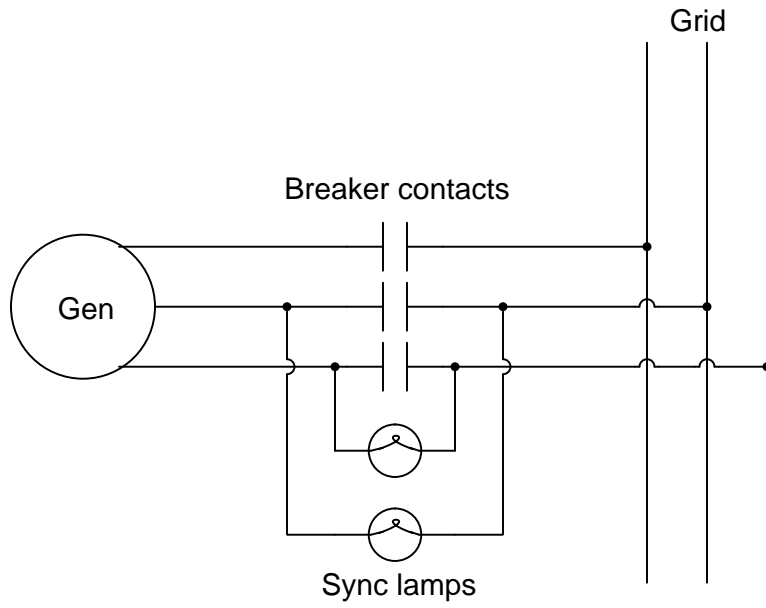
If the generator and power grid are at different frequencies, the sync lamps will oscillate in brightness at a frequency equal to the difference in generator and line frequencies. A synchroscope's needle will rotate at a speed equal to this difference frequency.

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.

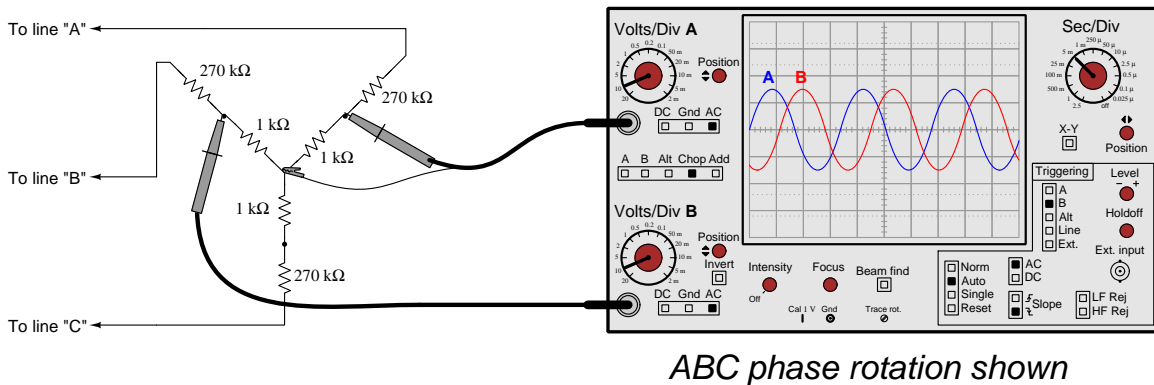
Common mistakes:

- 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.

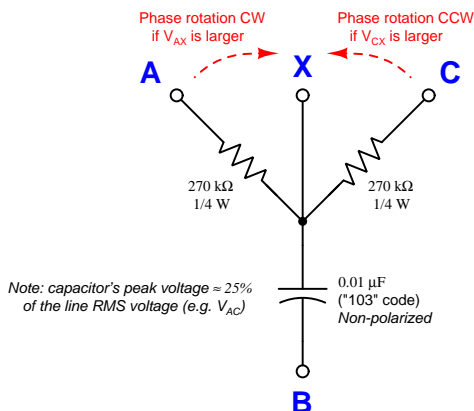
Lab Exercise – phase rotation (sequence) testing

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.

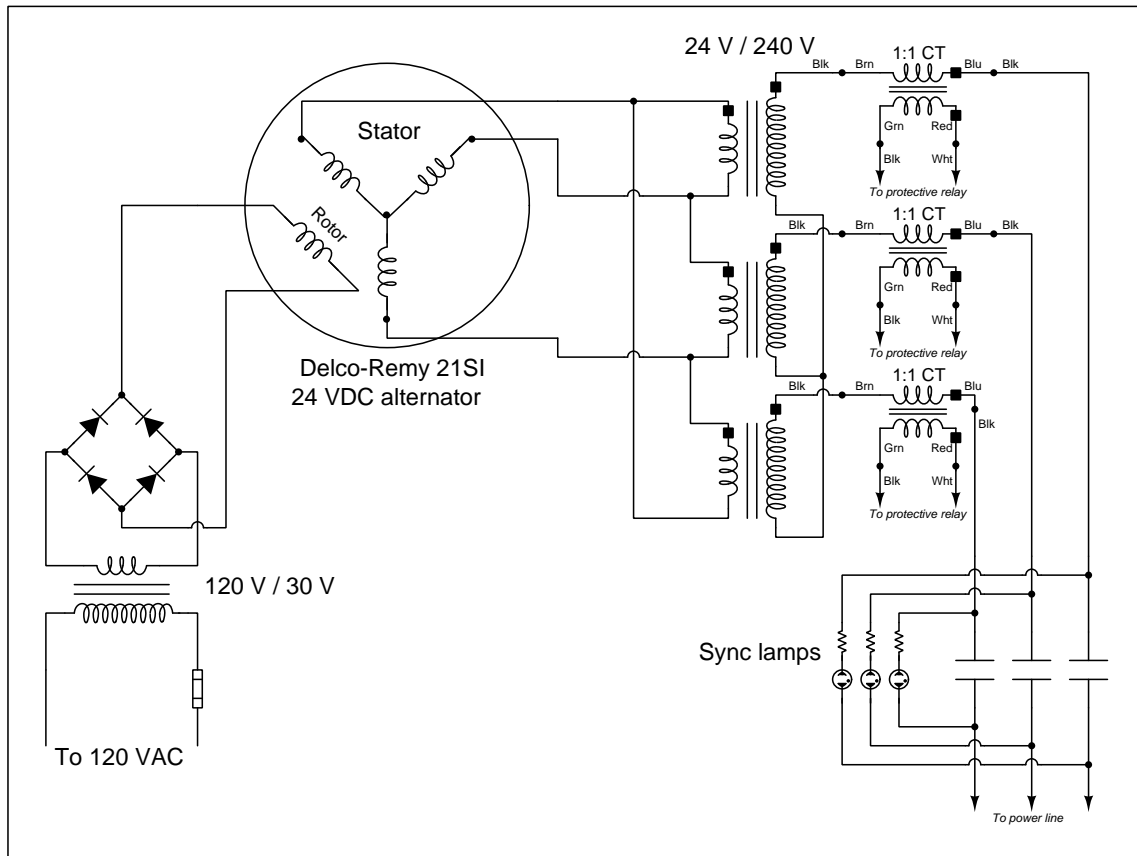
If your team’s protective relay provides oscillography and/or phasor diagram displays in addition to text-based fault reports (as do SEL relays), you must show these as well. **AcSELeRator QuickSet SEL-5030** software is necessary to generate and display oscillographs and phasor diagram animations for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

file i03020

Question 92

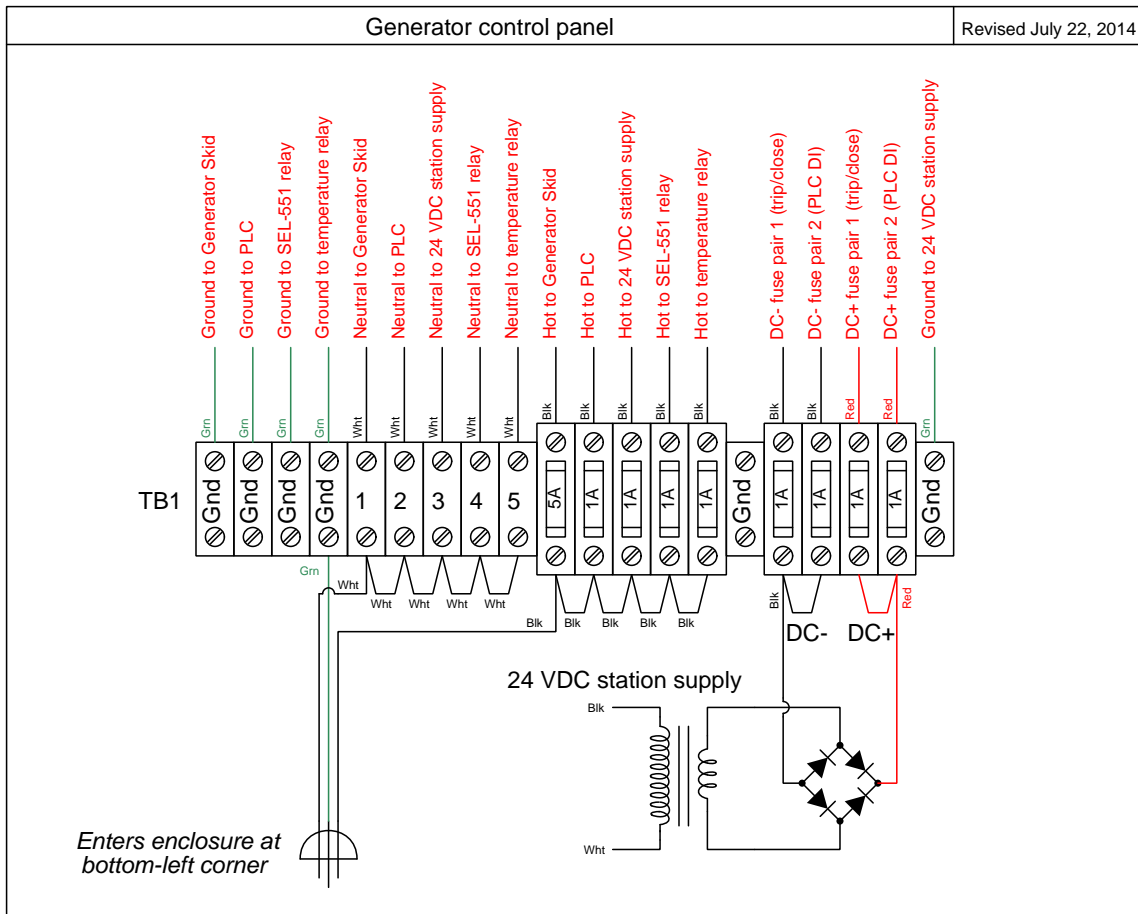
In the Instrumentation lab at Bellingham Technical College there exists a miniature three-phase AC power grid consisting of multiple generators and multiple substations. This question serves as a reference for a number of the schematic diagrams documenting each generating station in this system.

Generator field and power wiring



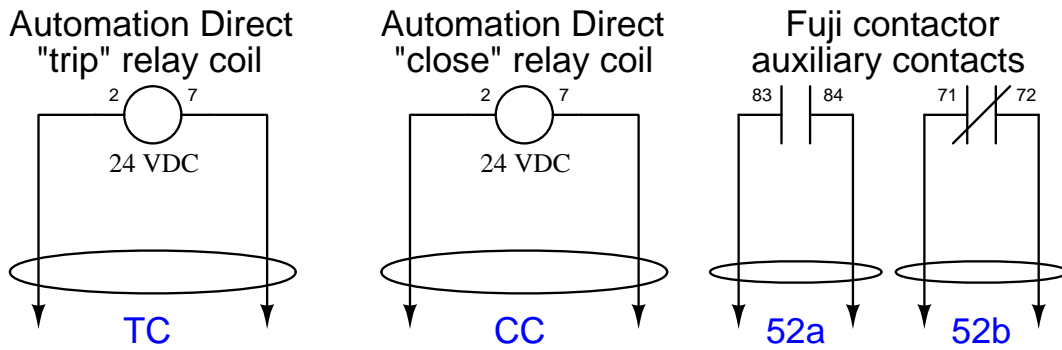
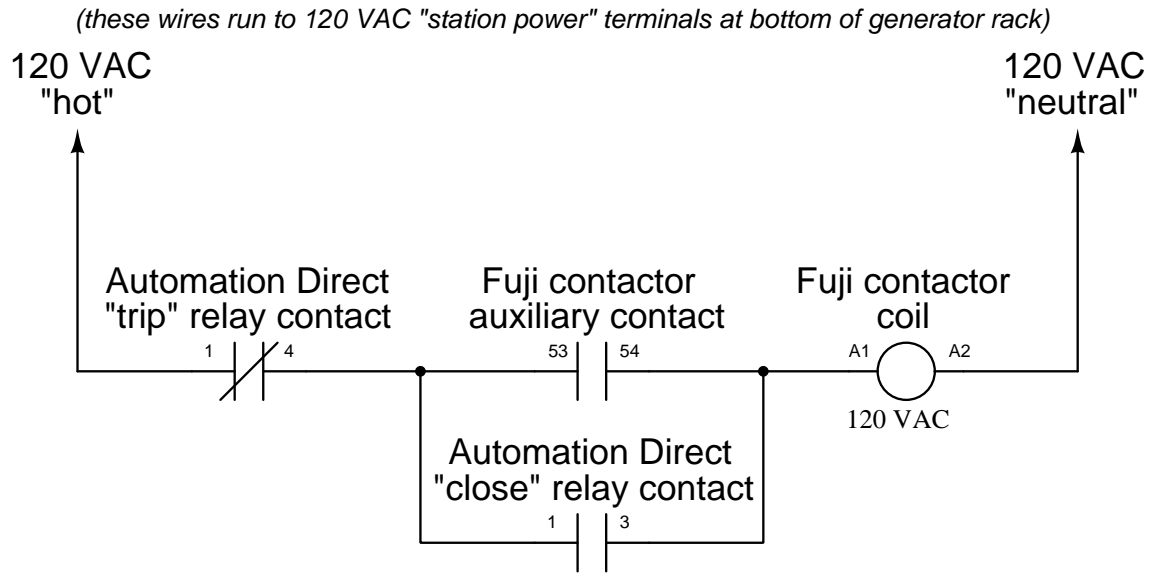
This is typical of each generator skid. At full speed (600 RPM, 60 Hz output frequency) each generator only outputs about 8 Volts AC because this is a much slower speed than it was designed to run when spun by a truck or boat engine. We run it this slow in order to achieve the standard grid frequency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

120 VAC and DC station control power distribution



Located in the generator control panel.

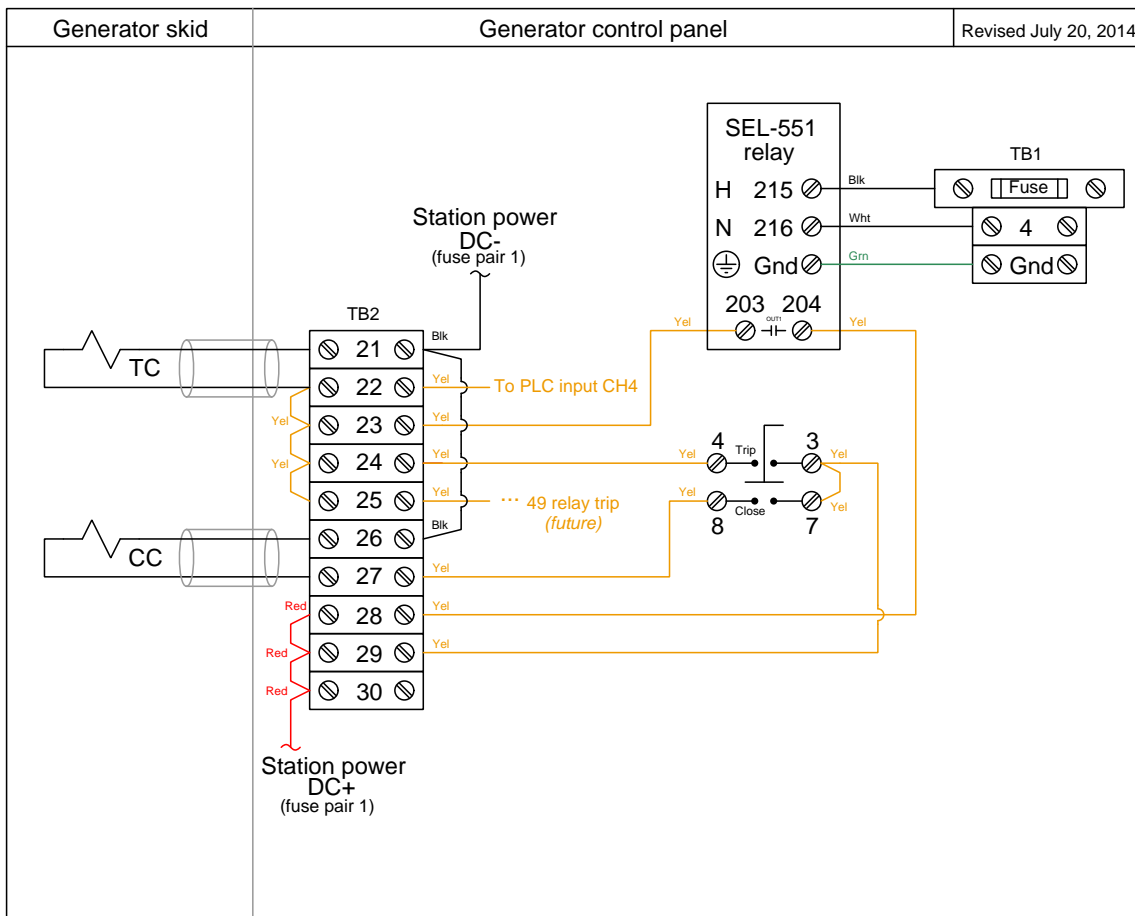
Generator circuit breaker details



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

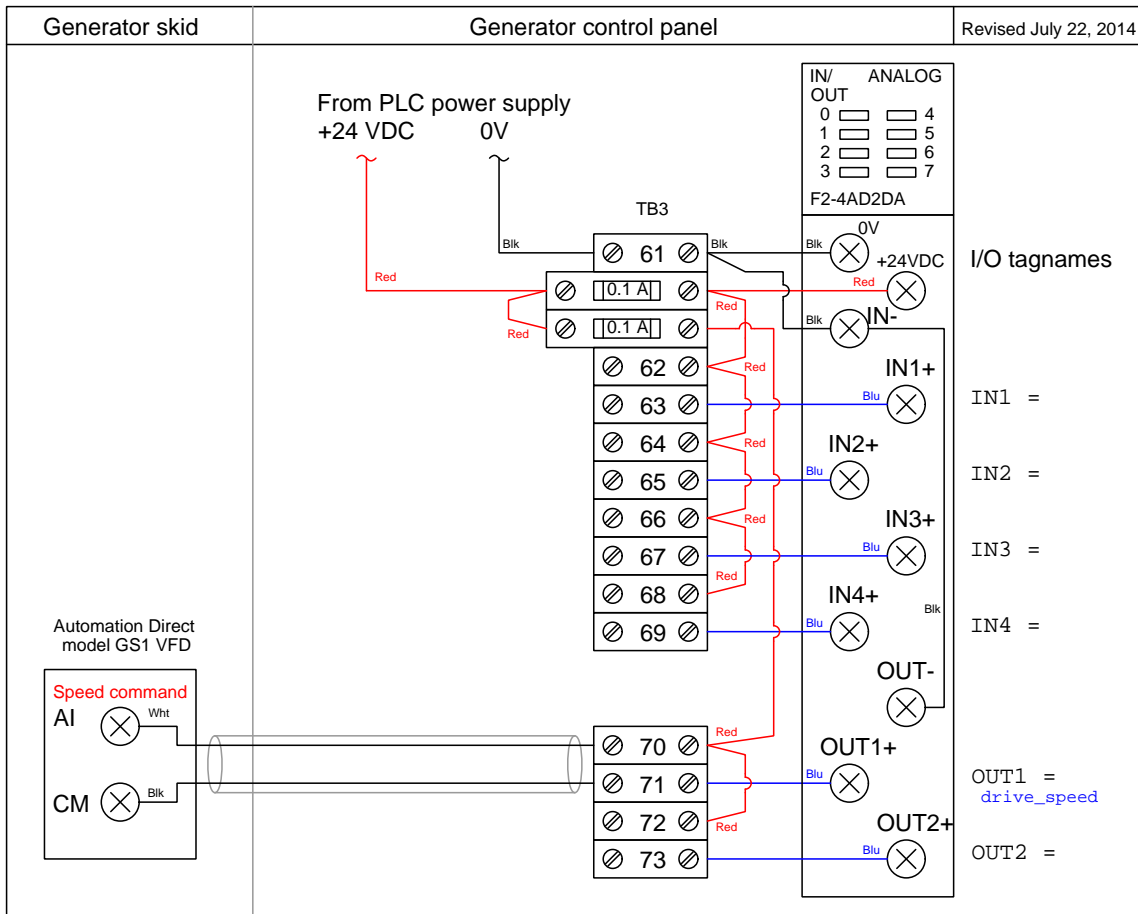
Located on the generator skid, near the very top where the three-phase AC power exits. We are using a standard Fuji 3-phase motor contactor as the circuit breaker element, and a pair of ice-cube style relays wired to latch the contactor on and off, so that the contactor mimics the behavior of a spring-actuated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

Trip/close wiring



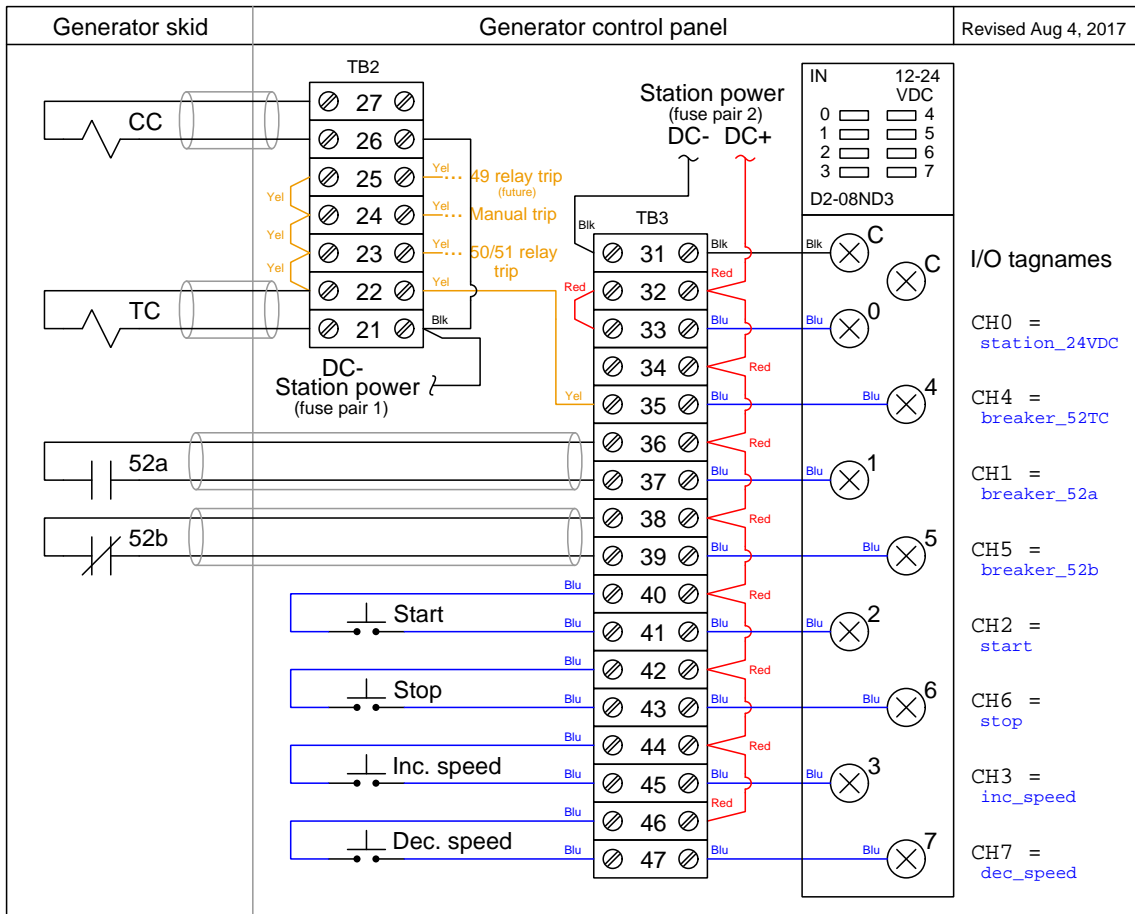
Located in the generator control panel.

PLC analog inputs/outputs



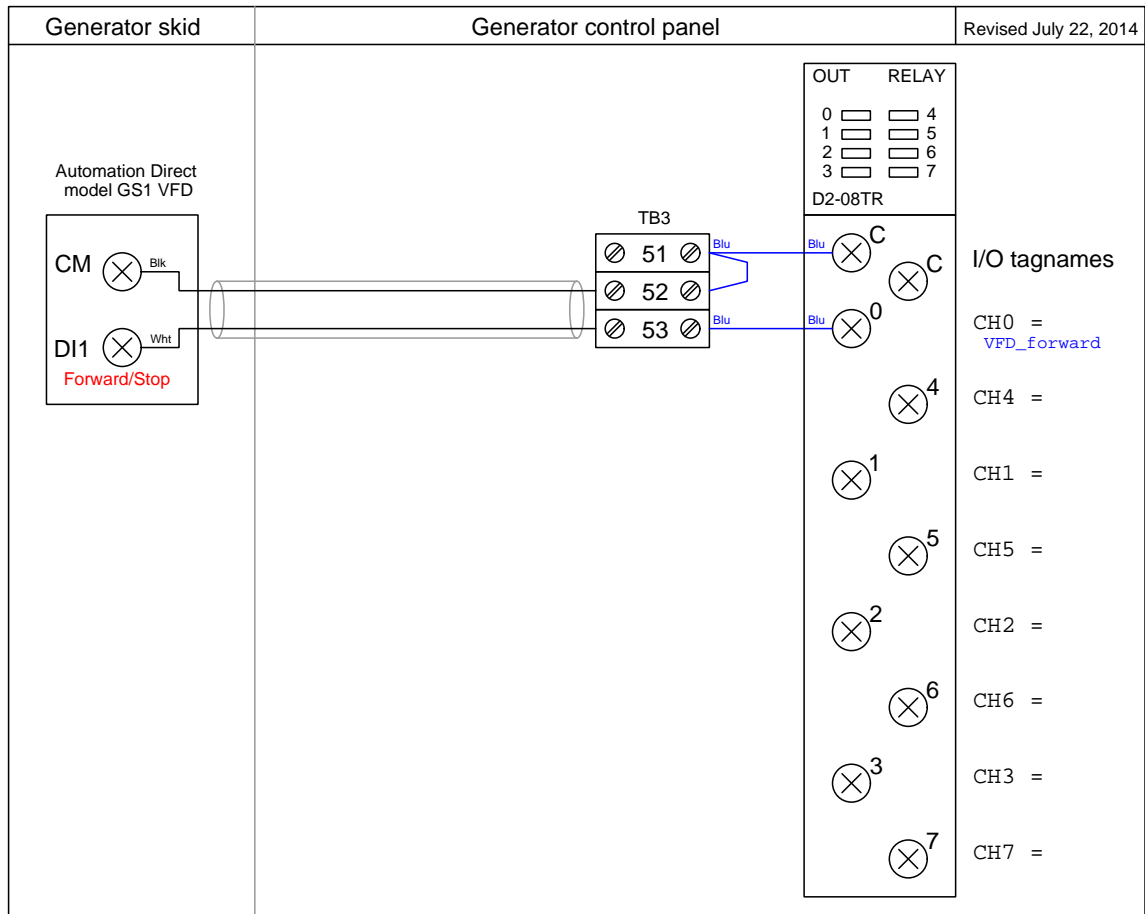
Located in the generator control panel. The one analog output sends a 4-20 mA speed control signal to the VFD, which then drives a three-phase motor to spin the generator. This VFD-controlled motor mimics a prime mover such as a hydro turbine or steam engine which would ordinarily be the mechanical driver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

PLC discrete inputs



Located in the generator control panel.

PLC discrete outputs



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

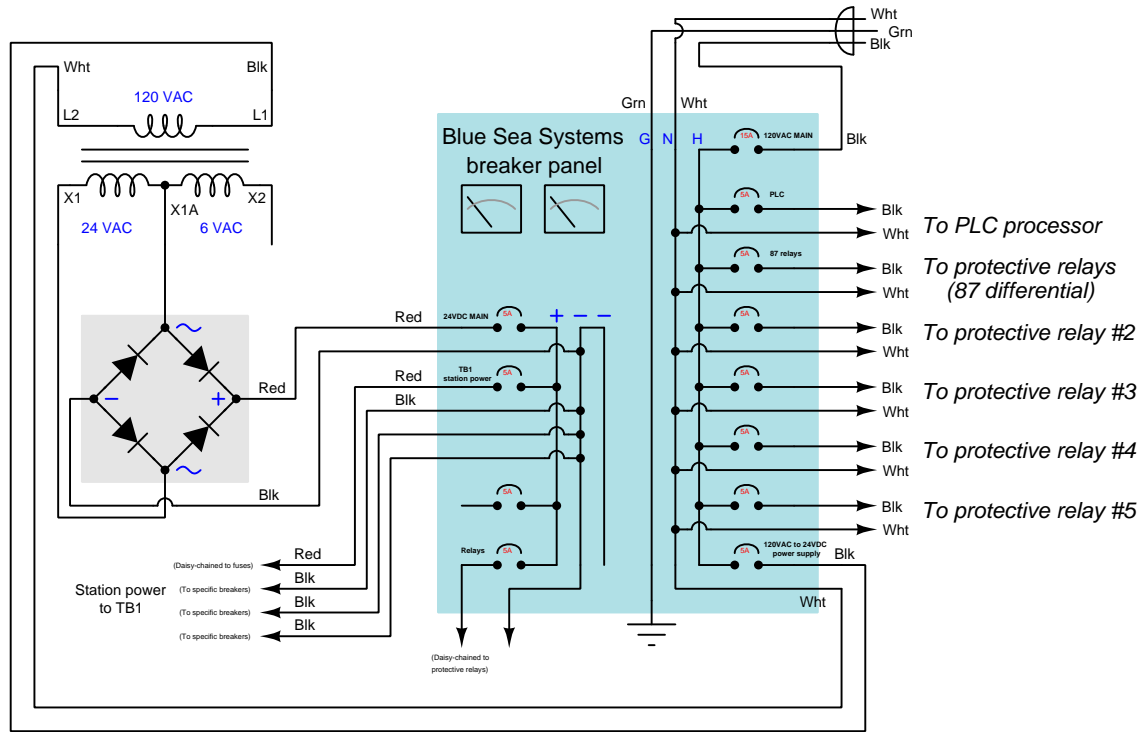
Question 93

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

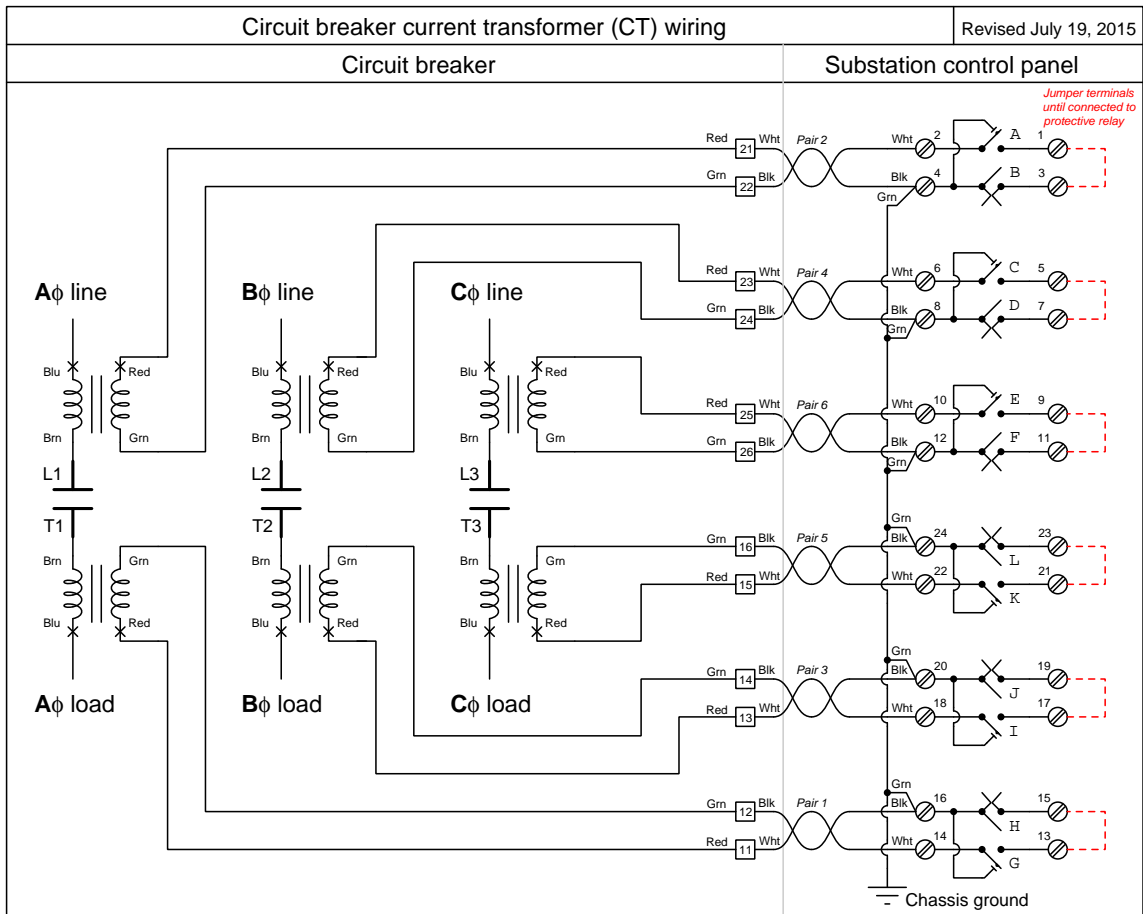
Station power diagram

Station power wiring diagram

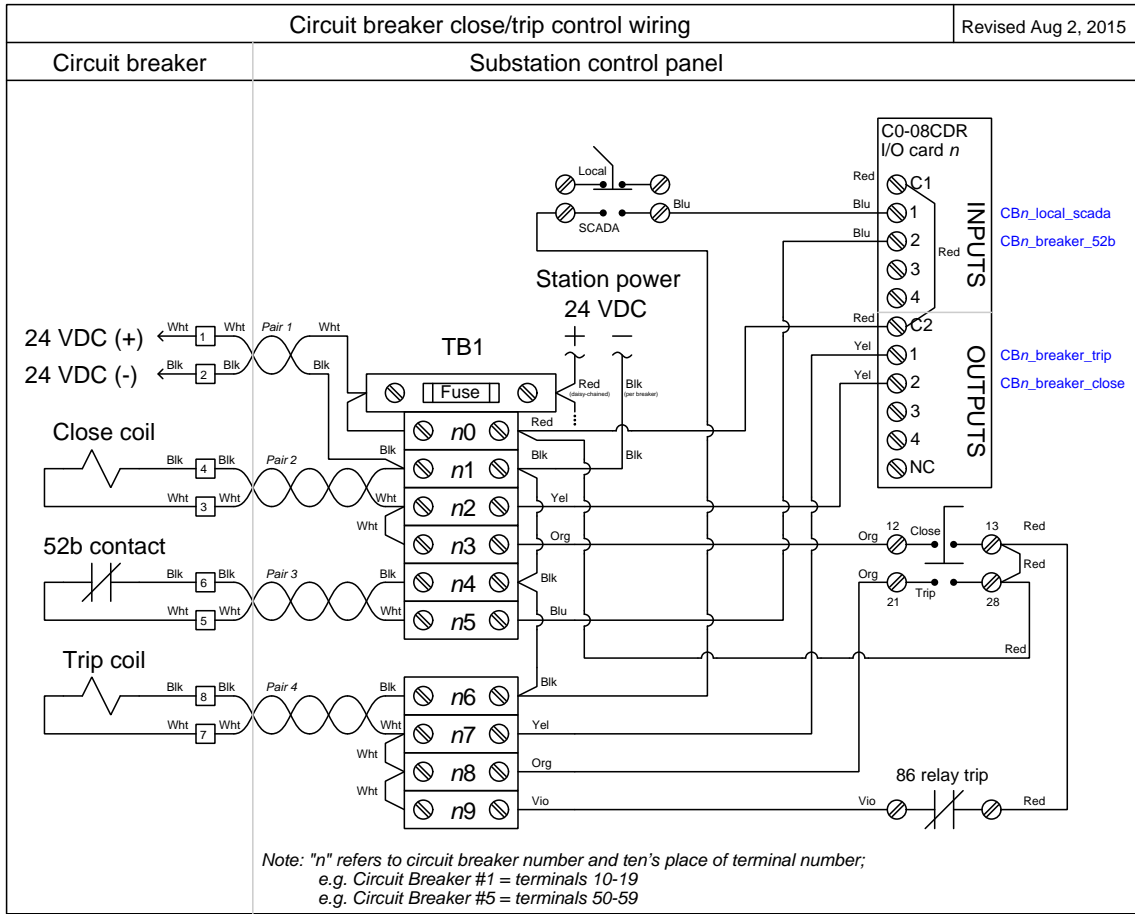
Revised August 19, 2015



Circuit breaker current transformer (CT) wiring



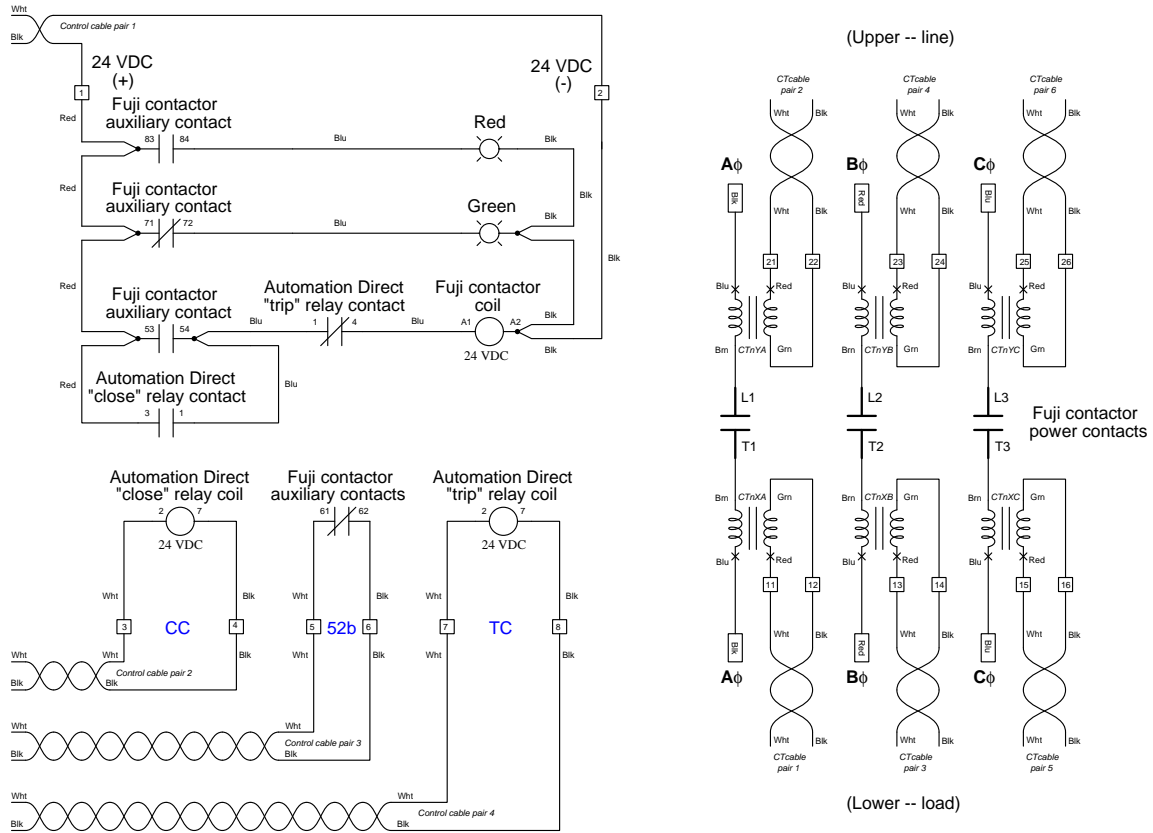
Circuit breaker trip/close wiring



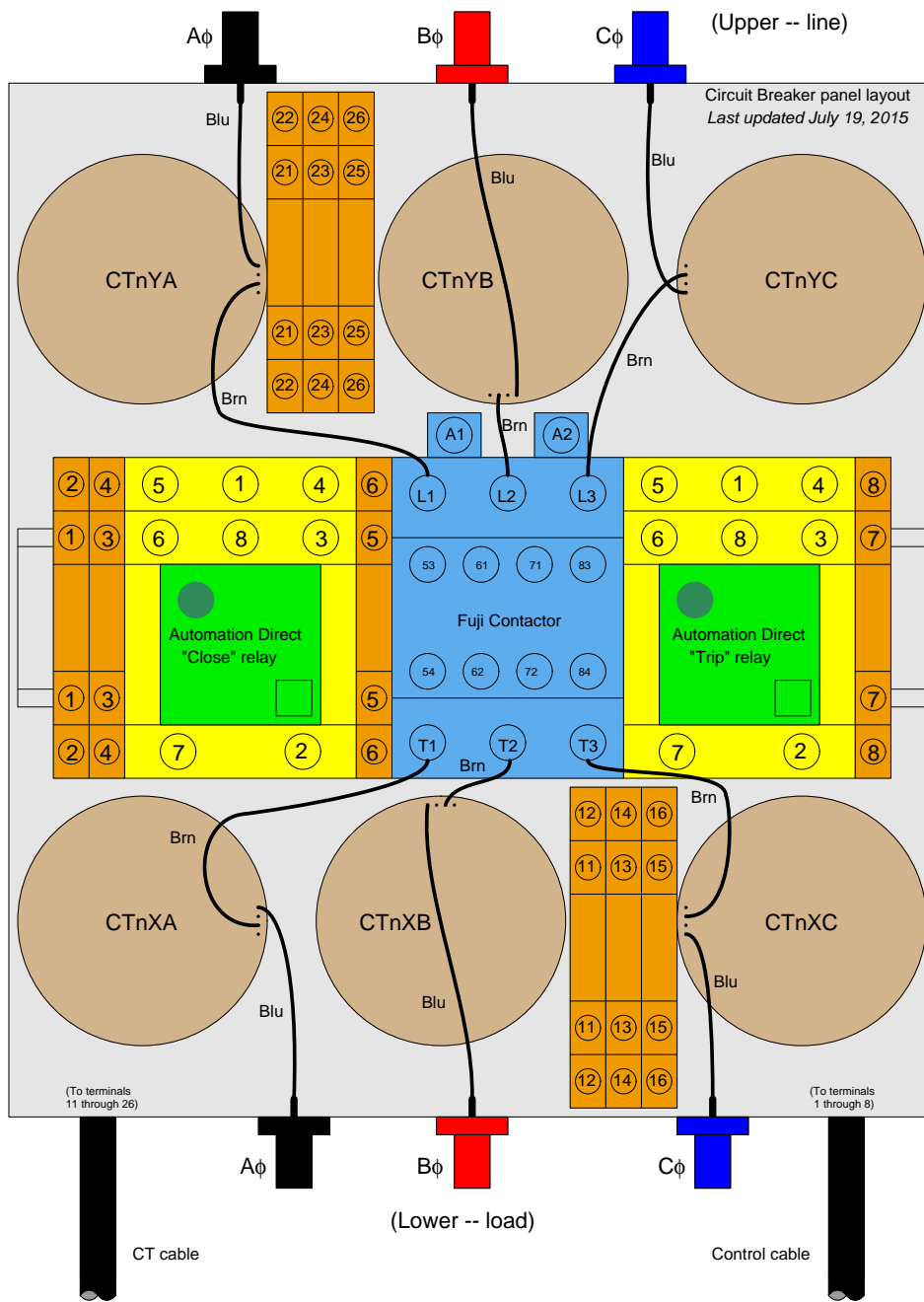
Circuit breaker internal wiring diagram

Circuit Breaker internal wiring diagram

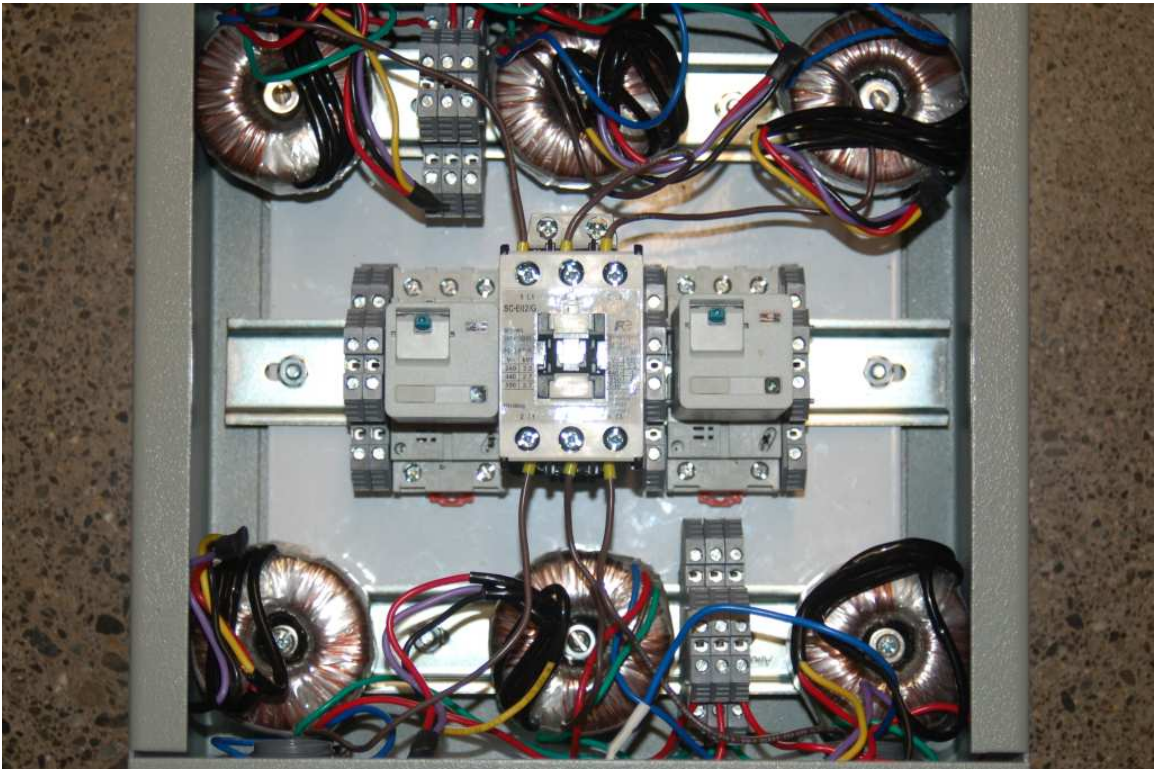
Last updated July 19, 2015



Circuit breaker internal layout

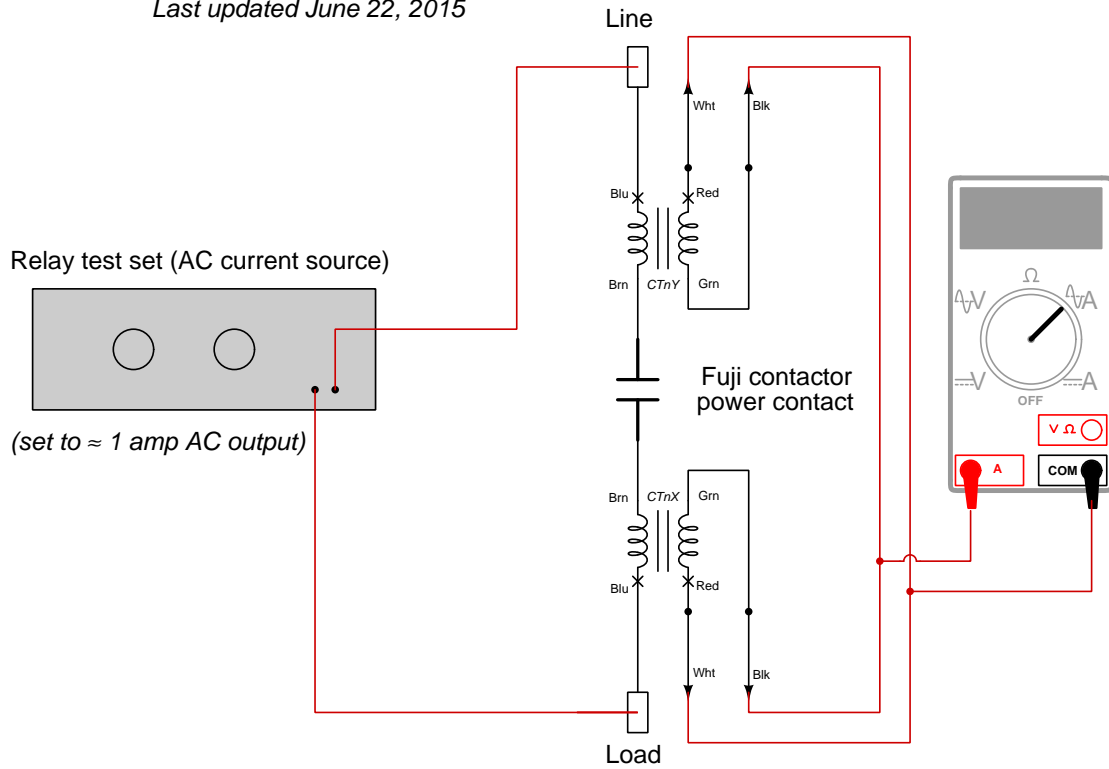


Photograph of typical circuit breaker



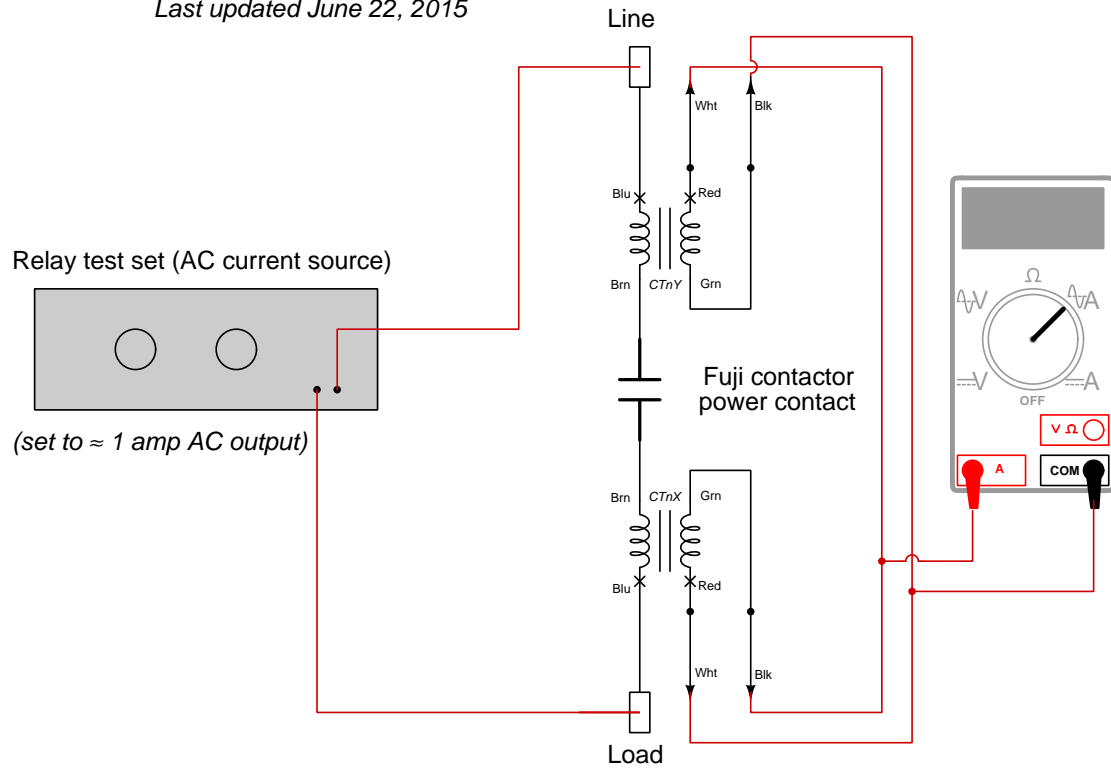
Current transformer polarity test setup current transformer secondary windings aiding

Last updated June 22, 2015

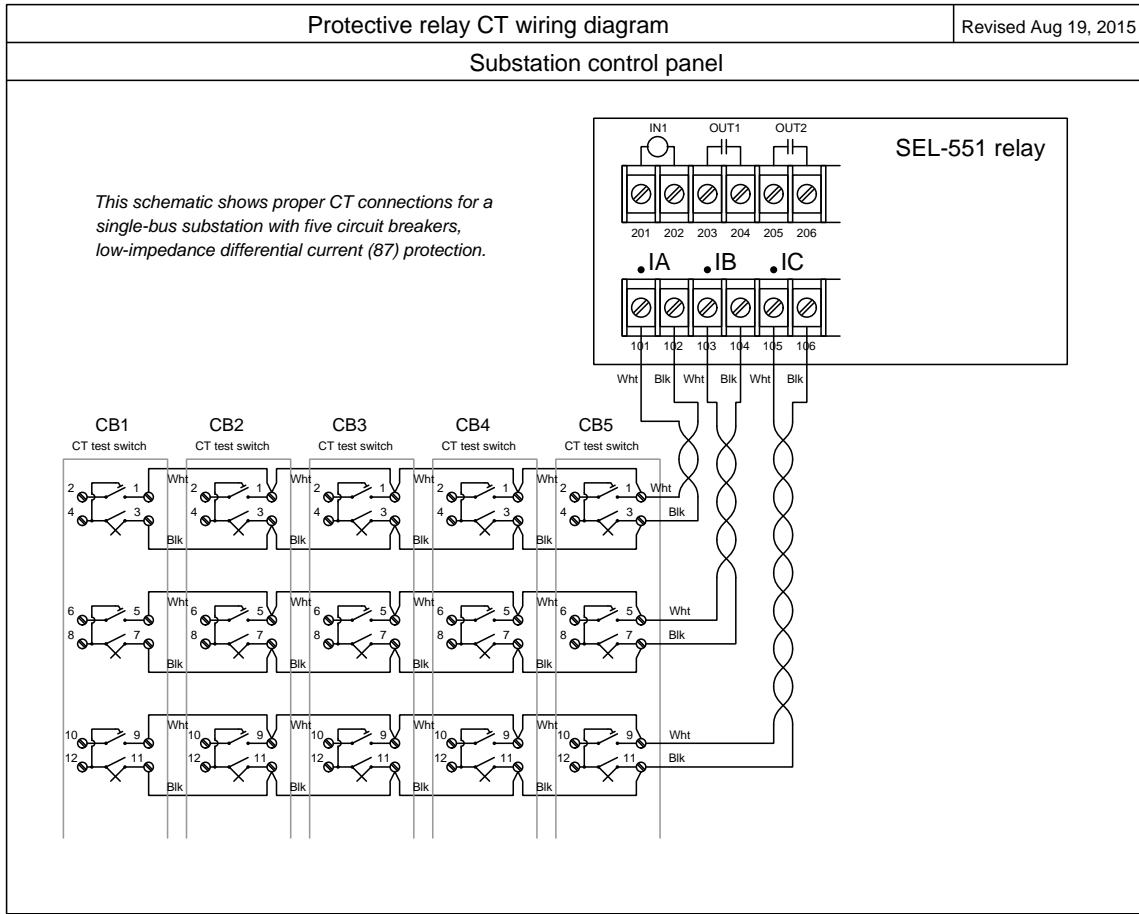


Current transformer polarity test setup current transformer secondary windings opposing

Last updated June 22, 2015

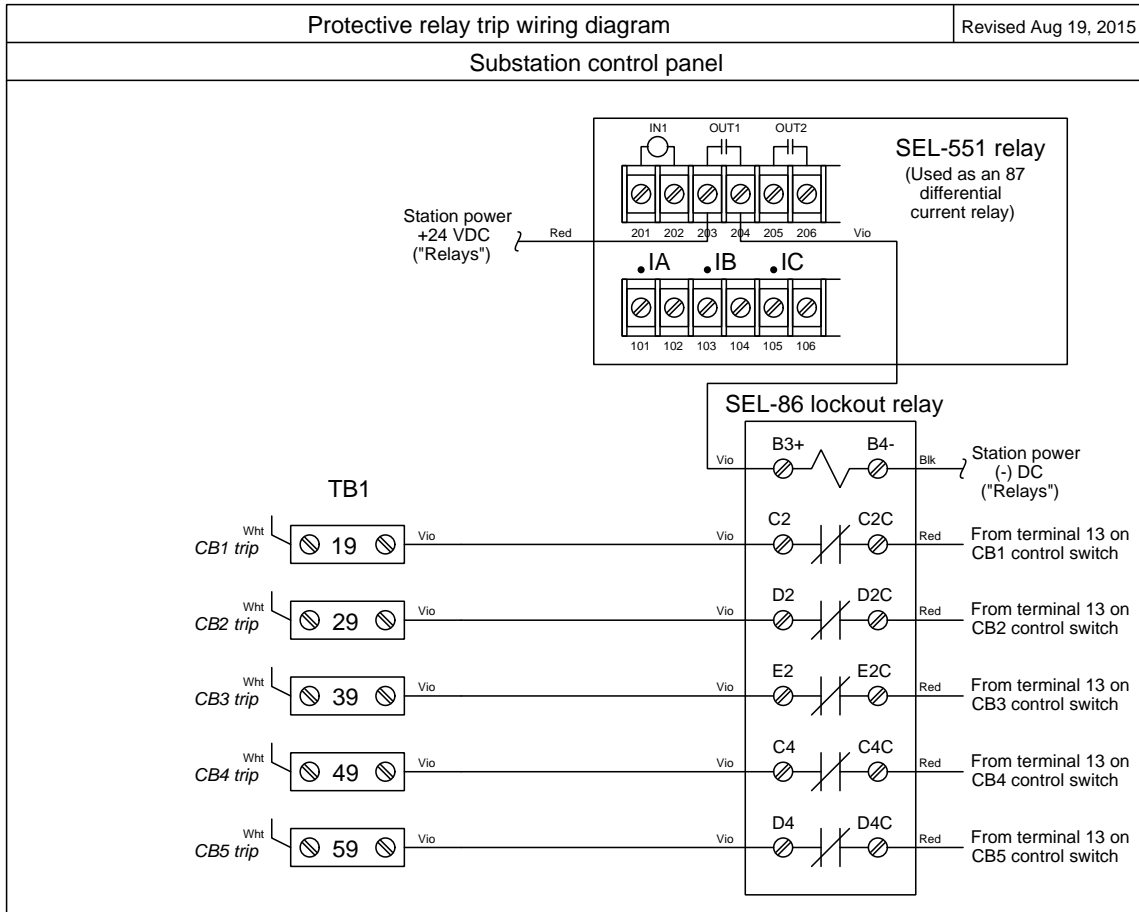


Protective relay CT wiring



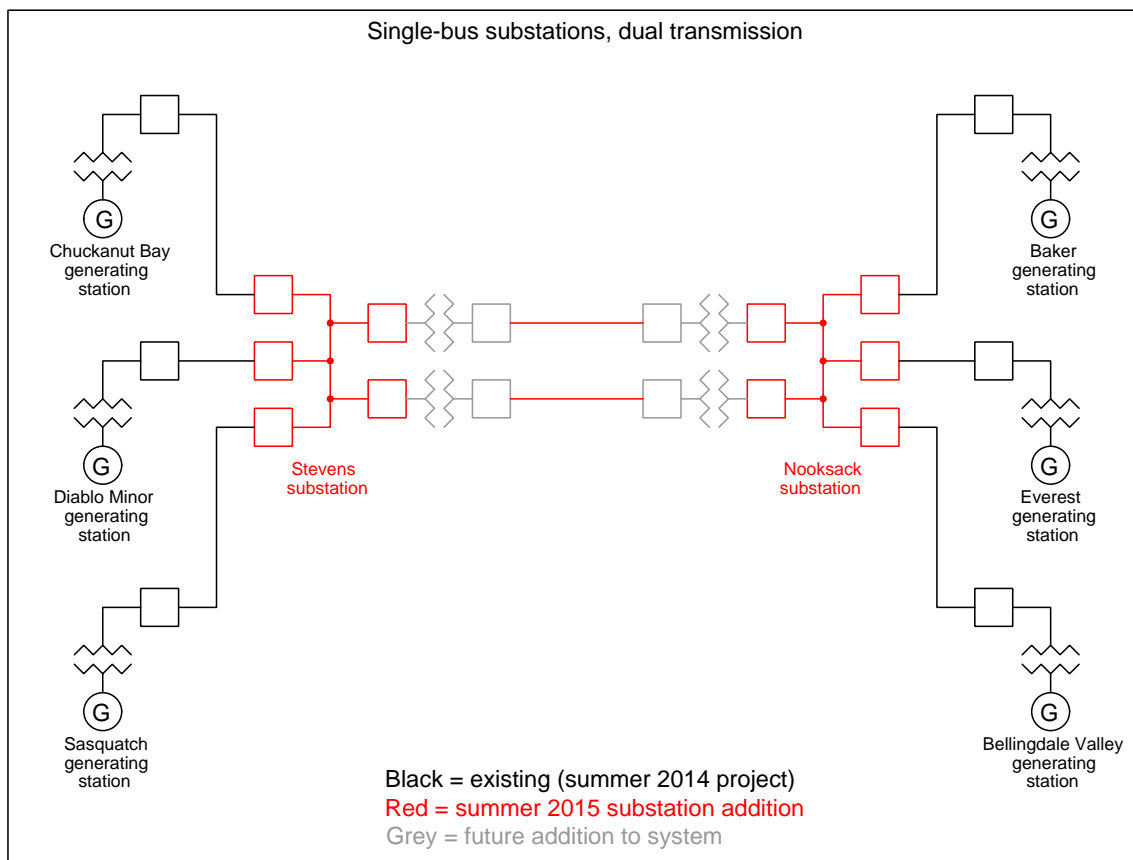
This scheme parallels all the CT secondary windings, to form a crude low-impedance version of differential current (IEEE/ANSI number code 87) protection.

Protective relay trip wiring

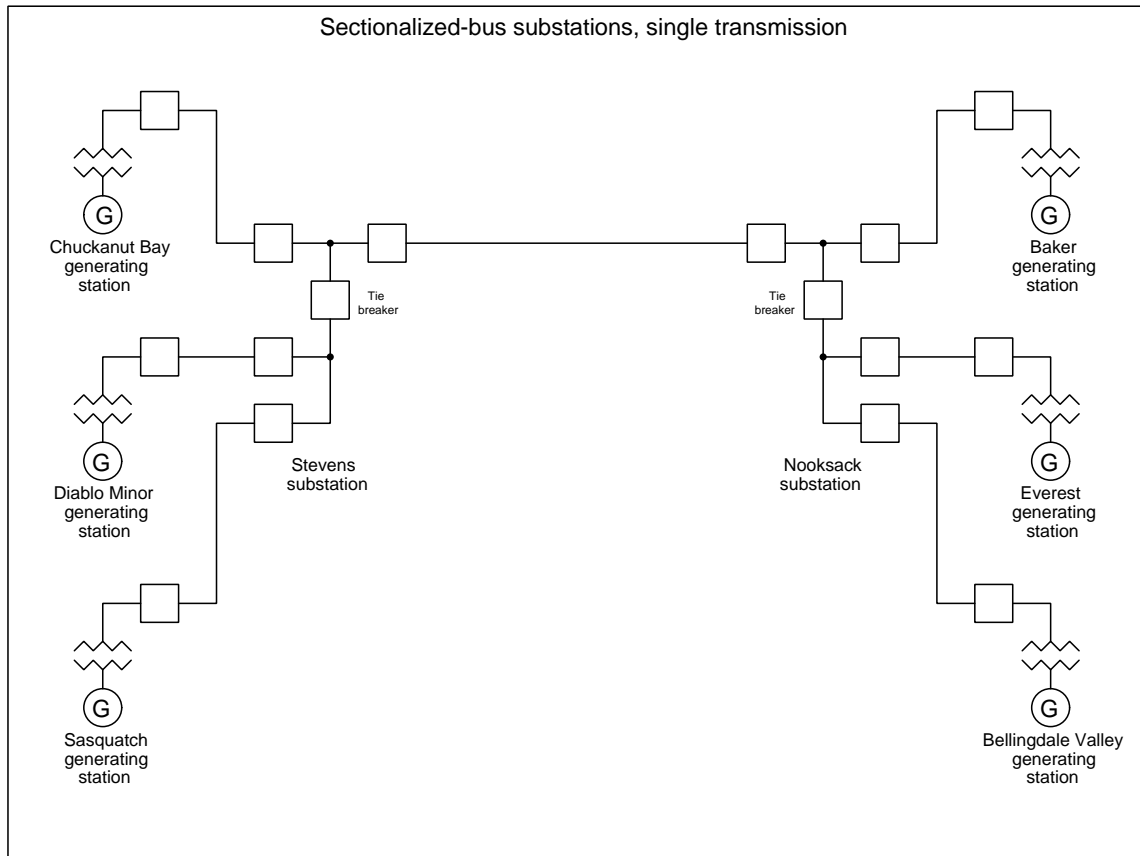


This scheme parallels all the CT secondary windings, to form a crude low-impedance version of differential current (IEEE/ANSI number code 87) protection.

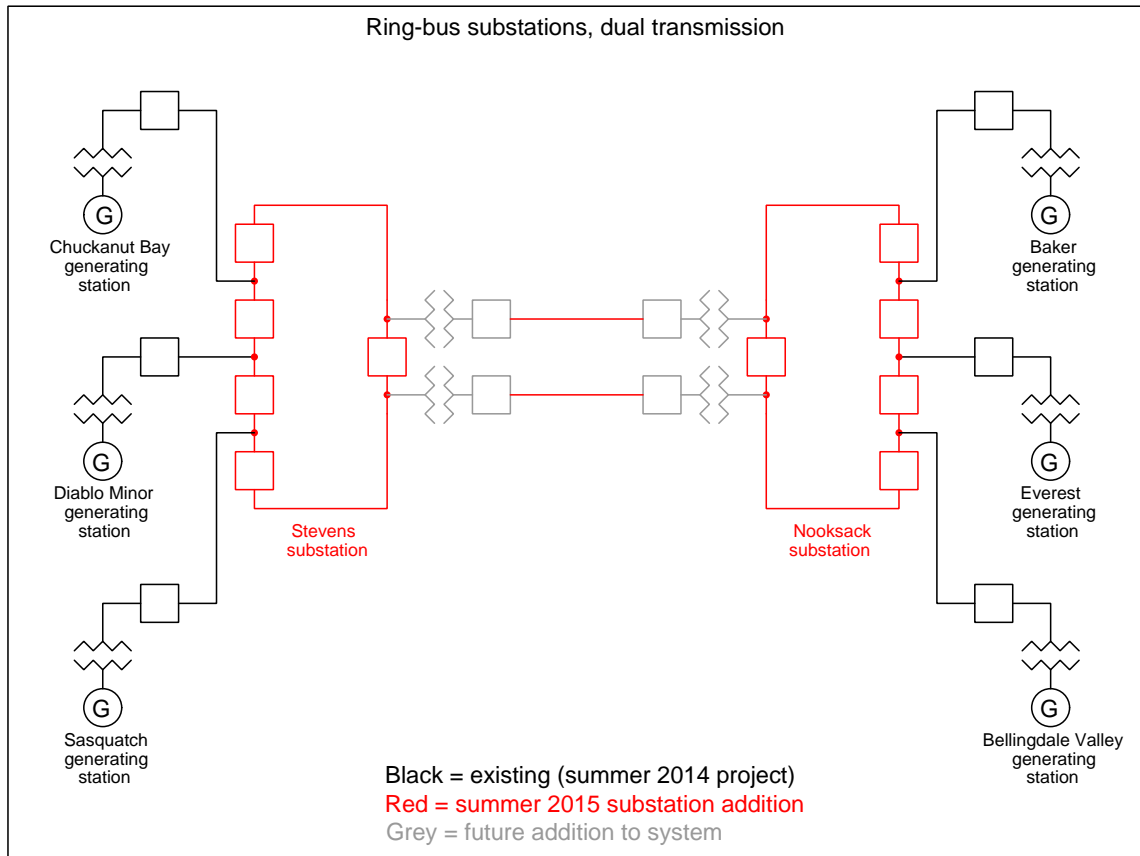
Substation configuration option: single bus



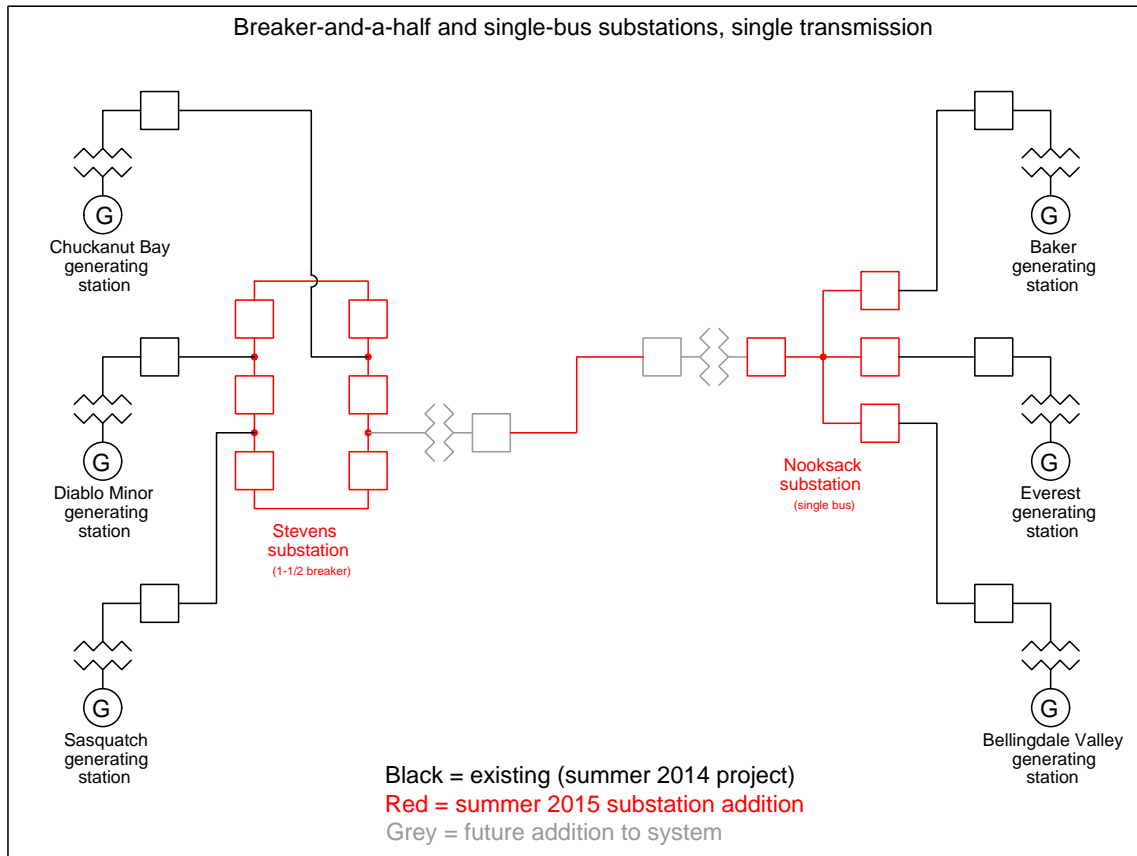
Substation configuration option: sectionalized bus



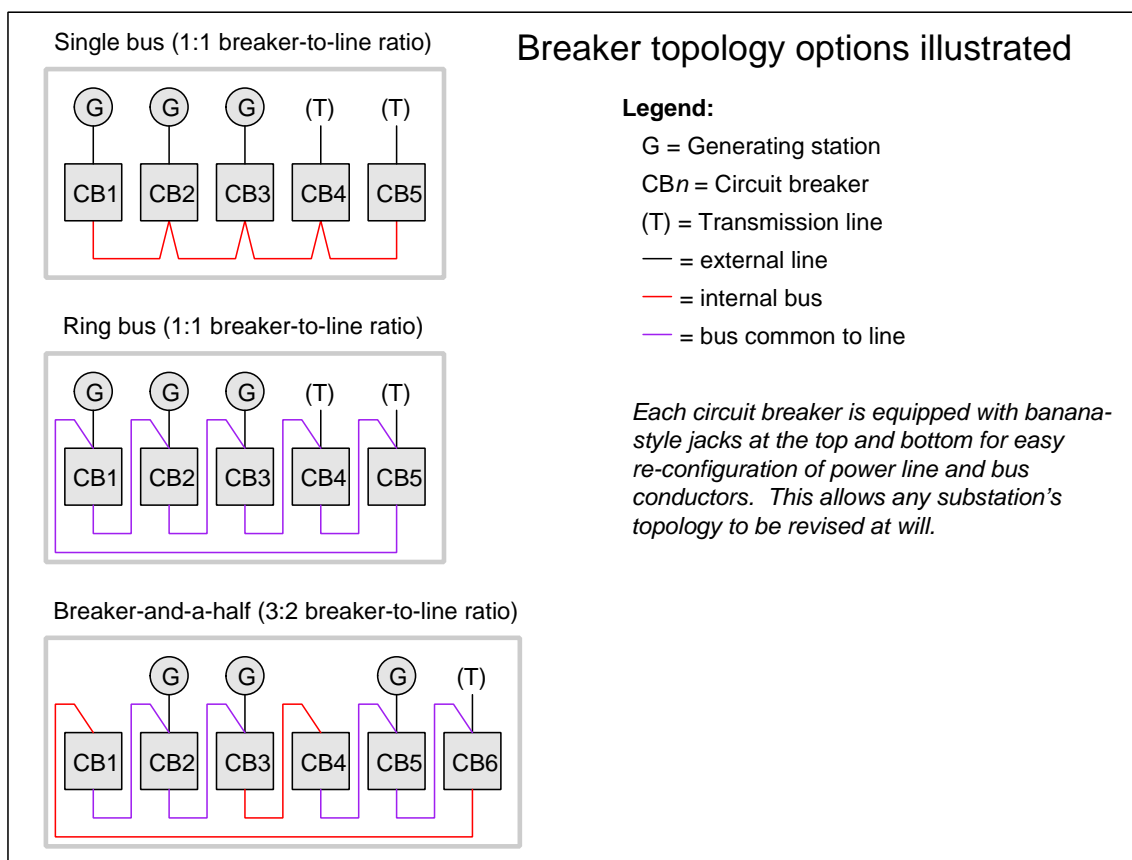
Substation configuration option: ring bus



Substation configuration option: breaker-and-a-half



Substation breaker options illustrated



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

[file i01983](#)

Answers

Answer 1

Answer 2

The output of a PT is typically somewhere at or below 120 volts AC. The output of a CT is typically at or below 5 amps AC. One of the things your procedure must address is how to accurately simulate these voltage and current levels to the wattmeter!

At the given line voltage of 4160 volts the 40:1 ratio PT should output $\frac{1}{40}$ of that (104 volts AC) to the wattmeter's voltage input terminals. At the maximum line current of 180 amps the 200:5 ratio CT should output $\frac{5}{200}$ of that (4.5 amps AC) to the wattmeter's current input terminals.

Answer 3

With 100:5 ratios at each CT, the line current to this motor is twenty times the amount of current through each ammeter:

$$(2.81) \left(\frac{100}{5} \right) = 56.2 \text{ amps}$$

At a line voltage of 480 VAC and a line current of 56.2 amps, the total electrical power in this 3-phase system may be calculated as follows:

$$P_{total} = (\sqrt{3})(I_{line})(V_{line})$$

$$P_{total} = (\sqrt{3})(56.2)(480) = 46.724 \text{ kW}$$

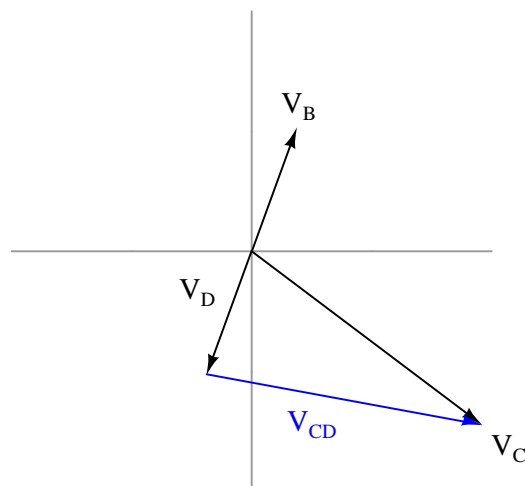
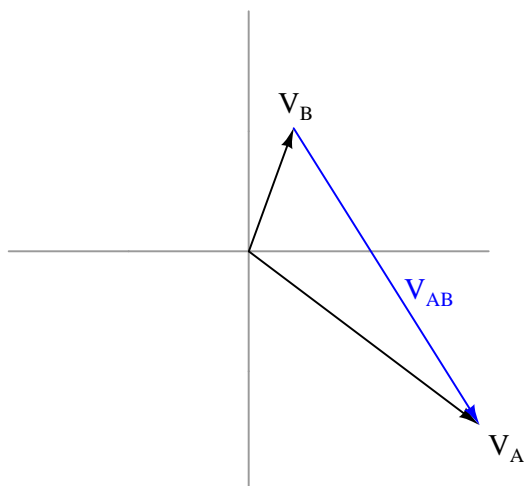
At an efficiency of 88%, only 88% of this power becomes translated into mechanical horsepower. This equates to 41.117 kW of mechanical power output at the motor shaft.

Since we know there are 746 watts to every horsepower, we may convert this kW figure into HP as follows:

$$\left(\frac{41117 \text{ W}}{1} \right) \left(\frac{1 \text{ HP}}{746 \text{ W}} \right) = 55.12 \text{ HP}$$

Answer 4

Graphical (phasor diagram) solution:

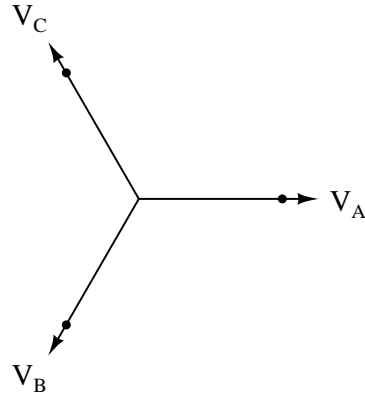


Answer 6

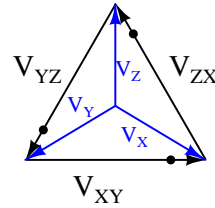
If “A” is the reference phasor and the sequence is A-B-C, it means phase B must lag 120 degrees behind phase A, and phase C must lag 120 degrees behind phase B (same as leading phase A by 120 degrees). Thus:

$$V_A = 1385.6 \text{ V} \angle 0^\circ \quad V_B = 1385.6 \text{ V} \angle -120^\circ \quad V_C = 1385.6 \text{ V} \angle 120^\circ$$

Primary side phasor diagram
(dots show transformer polarity)



Secondary side phasor diagram
(dots show transformer polarity)



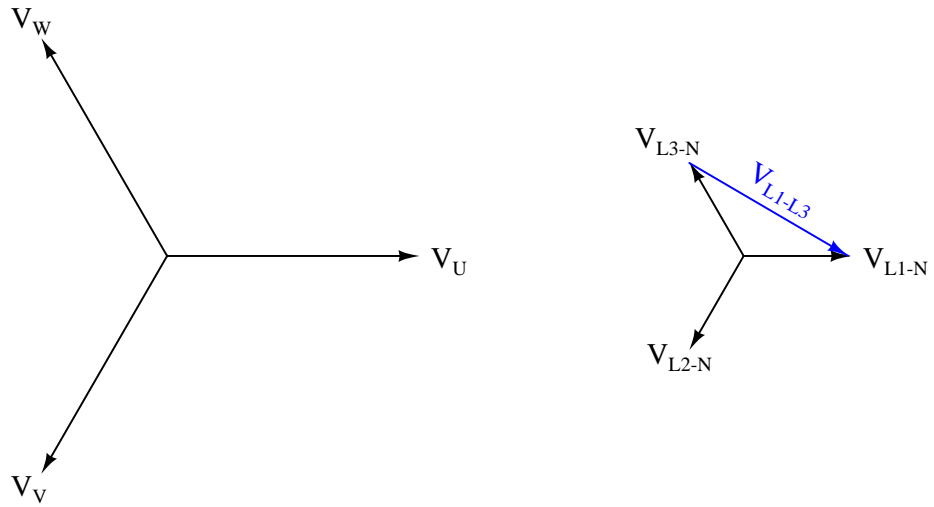
Given the 1:1 transformer turns ratios, the Delta-connected line voltage must be the same as the Wye-connected phase voltage (1385.6 VAC). Measuring V_X , V_Y , and V_Z with reference to ground means these are phase voltages to the 1385.6 volt line voltage, and therefore each of them must have a value of 800 volts ($1385.6 \text{ volts} \div \sqrt{3}$).

Judging by the secondary phasor diagram, V_Z must have a phase angle of 90° because that phasor points straight up. The other two secondary phasors are, of course, shifted 120° in either direction from each other, which leads to the following results:

$$V_X = 800 \text{ V} \angle -30^\circ \quad V_Y = 800 \text{ V} \angle -150^\circ \quad V_Z = 800 \text{ V} \angle 90^\circ$$

Answer 7

Partial answer:



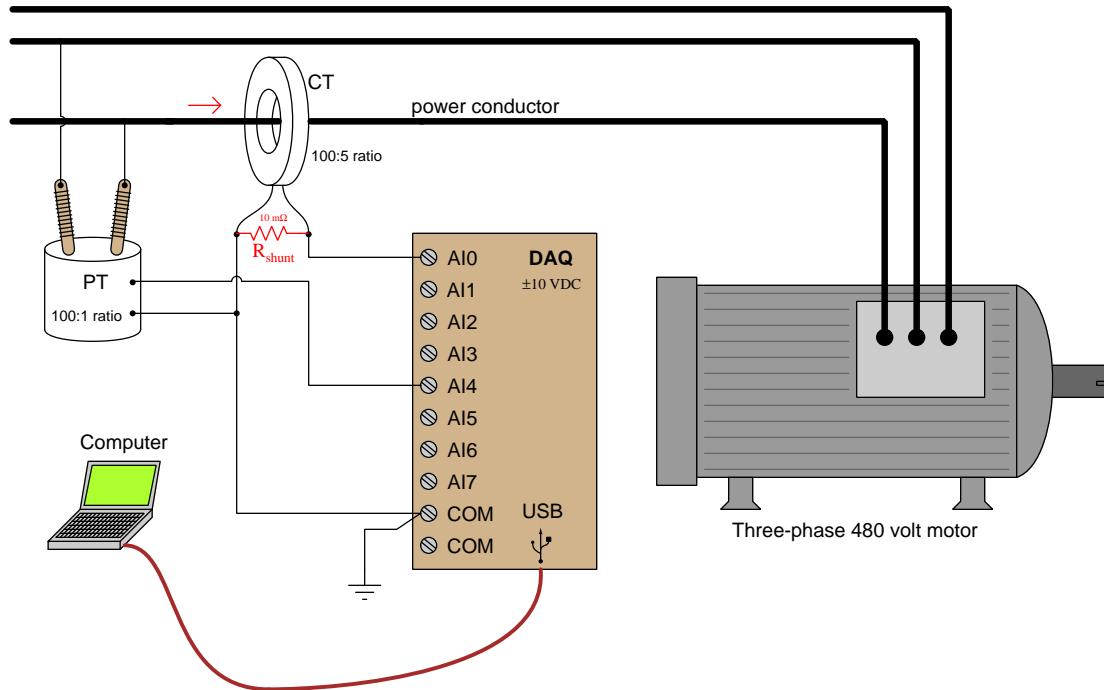
Answer 8

Answer 9

The PT ratio does not step the 480 VAC down enough. A 50:1 ratio will step 480 volts RMS down to 9.6 volts RMS, but remember that the DAQ must measure the *peak* voltage and not just the RMS value! Here, the peak output of the PT with a ratio of 50:1 and 480 volts RMS at the primary winding will be approximately 13.58 volts peak, which exceeds the DAQ's input range of ± 10 volts.

The more serious problem is in the CT circuit, where a current of approximately 1.25 amps is being forced through the DAQ's high input impedance of millions of ohms. What we need is a low-value *shunt resistor* to drop a voltage within the DAQ's measurement range. It would be advisable not to use the full ± 10 volt range, due to over-burdening the CT, so I would recommend a shunt resistor dropping mere millivolts (e.g. A precision 10 m Ω shunt resistor would work quite nicely).

Here is a proposed solution to both problems:



Answer 10

The resistor will drop more voltage.

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

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

Answer 11

- $f = 200 \text{ Hz}$; $V_L = 1.750 \text{ V}$; $V_C = 11.79 \text{ V}$; $V_{speaker} = 5.572 \text{ V}$
- $f = 550 \text{ Hz}$; $V_L = 6.472 \text{ V}$; $V_C = 5.766 \text{ V}$; $V_{speaker} = 7.492 \text{ V}$
- $f = 900 \text{ Hz}$; $V_L = 9.590 \text{ V}$; $V_C = 3.763 \text{ V}$; $V_{speaker} = 6.783 \text{ V}$

This circuit is known as a *midrange crossover* in stereo system design.

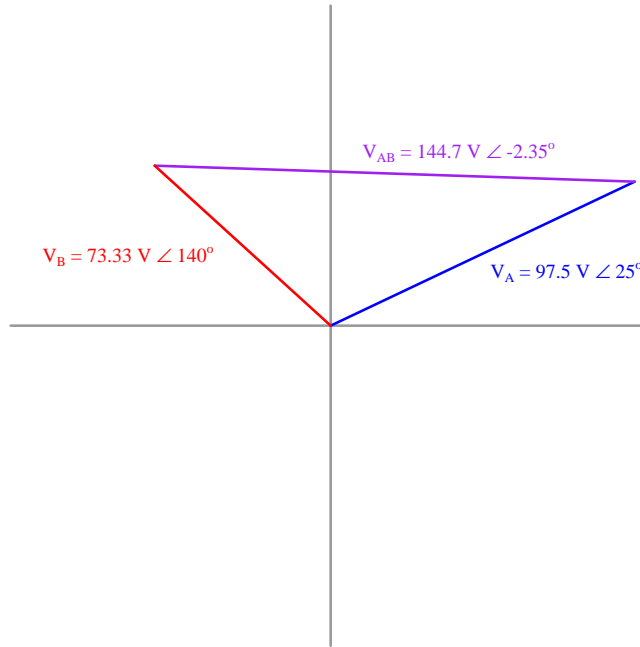
Answer 12

First, calculating the voltages between each test point and ground. V_A is nothing more than the first source's voltage divided by 2 through the resistor network. V_B is one-third of its source voltage, with an additional 180° phase shift created by the reversed polarity of the secondary winding:

$$V_A = \frac{195 \text{ V} \angle 25^\circ}{2} = 97.5 \text{ V} \angle 25^\circ$$

$$V_B = \frac{-(220 \text{ V} \angle -40^\circ)}{3} = 73.33 \text{ V} \angle 140^\circ$$

Sketching both of these quantities on a phasor diagram, we can plot the voltage V_{AB} by the distance between the V_A and V_B phasor lines:



Voltage V_{AB} is simply the difference between V_A and V_B :

$$V_{AB} = V_A - V_B$$

$$V_{AB} = (97.5 \text{ V} \angle 25^\circ) - (73.33 \text{ V} \angle 140^\circ)$$

$$V_{AB} = 144.7 \text{ V} \angle -2.35^\circ$$

Answer 13

Answer 14

Answer 15

Answer 16

Answer 17

Answer 18

Answer 19

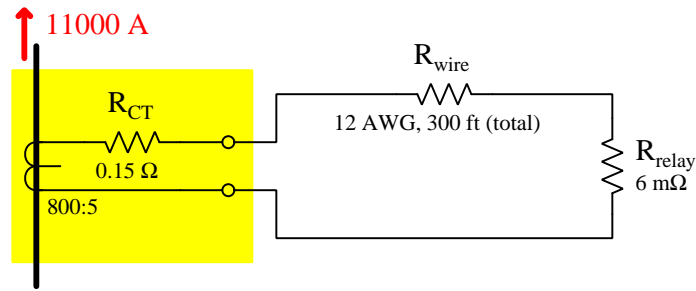
Answer 20

Answer 21

Answer 22

Answer 23

If you are having trouble knowing where to start, *begin by sketching a schematic diagram showing all components and how they connect to each other.* Represent each resistance as its own resistor symbol, and annotate the diagram with all given information. Treat the CT as a *current source* driving power to the protective relay.



We should begin by analyzing what each CT will be able to do under ideal circumstances. A “C200” class CT is supposed to be able to generate 200 volts at its terminals while experiencing $20\times$ its rated amount of current (i.e. 100 amps secondary current). In order to generate 200 volts at its terminals while overcoming the internal voltage drop of its own winding resistance (0.15 ohms carrying 100 amps), the CT’s winding must internally generate 215 volts (200 volts + [100 amps \times 0.15 ohms]). This represents the maximum amount of AC voltage the CT is capable of internally producing at full magnetic flux.

The absence of DC transients in this system means we don’t have to worry about de-rating the CT for the sake of DC bias magnetization. In other words, we may assume the full 215 volts of generating capacity will be available for this CT to drive current through its own internal resistance, the wire resistance, and the relay’s burden.

Now that we know what the CT is ideally capable of, we may apply these CT values (215 volts V_{max} , 0.15 ohms $R_{winding}$) to the scenario at hand and determine if the CT will be able to deliver its rated performance under fault conditions.

A system fault current of 11000 amps will be stepped down by the CT’s 800:5 ratio to become 68.75 amps of current in the secondary circuit. Thus, the CT must be able to produce enough voltage internally in its secondary winding to push 68.75 amps of current through its own winding resistance, the wire resistance, and the relay’s burden resistance. The next piece of information we need to do this analysis is the resistance of the wire.

150 feet of distance between the circuit breaker and the protective relay means we have 300 feet of wire connecting each CT to the relay. With a wire size of 12 AWG, its resistance per 1000 feet of length is 1.59 ohms. 300 feet of this wire will therefore give us 0.477 ohms of wire resistance in the loop.

Summing up all these resistances and using Ohm’s Law to predict the necessary voltage generated by the CT:

$$V = IR$$

$$V = I(R_{CT_winding} + R_{wire} + R_{relay})$$

$$V = (68.75 \text{ A})(0.15 \Omega + 0.477 \Omega + 0.006 \Omega)$$

$$V = (68.75 \text{ A})(0.633 \Omega)$$

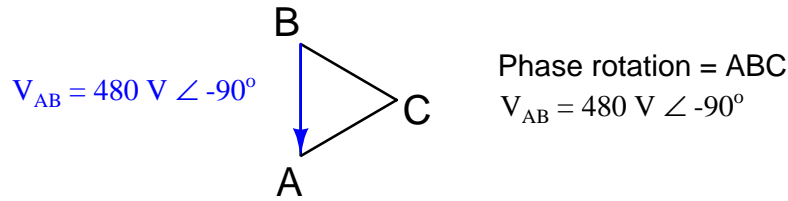
$$V = 43.53 \text{ V}$$

This necessary voltage of 43.53 volts is substantially less than the CT’s maximum of 215 volts (internal, at the secondary winding), and so this CT circuit should perform quite well under the stated conditions.

Answer 25

Answer 26

Here is a helpful hint: draw a phasor diagram of the system voltage first, showing the -90° phasor V_{AB} and the proper phase rotation (ABC, counter-clockwise):



The phasor diagram is shown as a Delta because the only voltage values we've been given are line (i.e. from one phase conductor to the other). If the given voltage was a phase quantity, it would make most sense to begin by drawing a Wye-shaped phasor diagram showing each voltage as a phasor originating from a center point (ground).

Final answers:

$$V_R = 242.56 \text{ V} \angle 148.9^\circ$$

$$P_R = 196.1 \text{ W}$$

Answer 27

Partial answer:

- Upper capacitor failing shorted: *Negative DC bus line goes to ground potential ; Positive DC bus line rises to +130 VDC above ground potential.*
- Loose connection on left side of terminal 12: *Indicator lamp refuses to energize when relay contact OUT2 asserts ; AC power circuit breaker refuses to trip when relay contact OUT1 asserts.*
- Broken wire between terminals E and 11: *Indicator lamp refuses to energize when relay contact OUT2 asserts.*

Answer 28

The *Lessons In Industrial Instrumentation* textbook shows how this is done, and provides a sample table of data from a real-life CT rat/sat test.

Answer 29

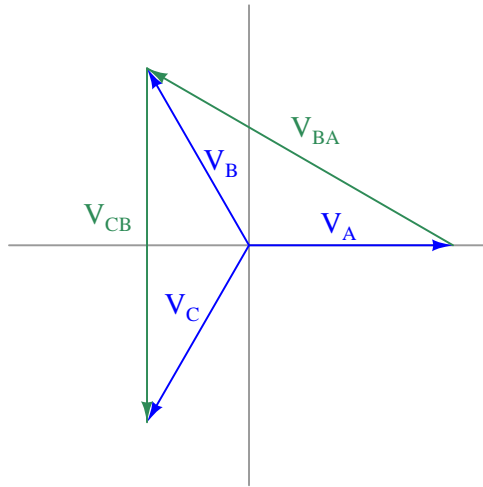
Switch left: $\theta = -45^\circ$ (V_{out} lagging behind the source voltage)

Switch right: $\theta = +45^\circ$ (V_{out} leading ahead of the source voltage)

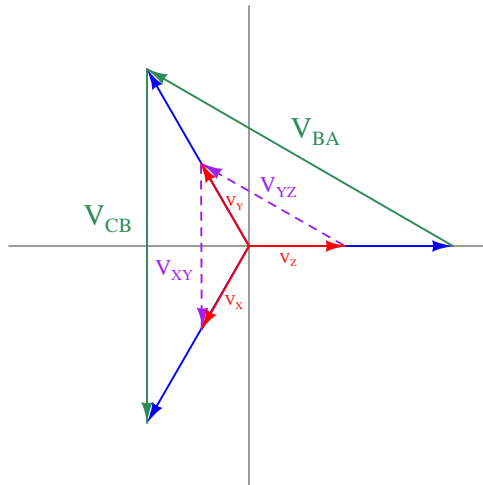
In both positions, the output voltage magnitude will be $\frac{\sqrt{2}}{2}$ that of the input voltage, or $0.707 \times V_{signal}$, because both the sine and the cosine of 45° is $\frac{\sqrt{2}}{2}$.

Answer 30

First, sketching a phasor diagram for the primary voltages. V_A , V_B , and V_C are 277 volts each, while V_{BA} and V_{CB} are both 480 volts each:



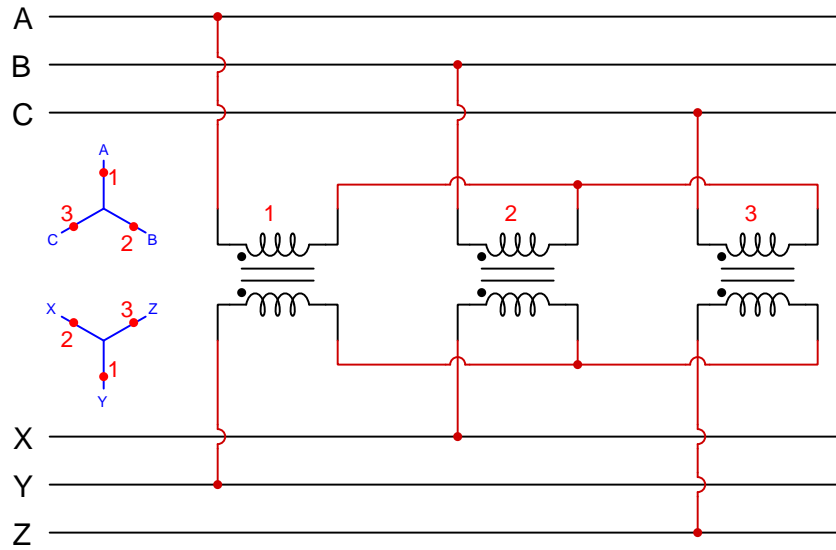
With 480 volts across each of the transformer primary windings, the secondary windings will develop 120 volts each (4:1 ratio). Given the same phase angles and the same connection pattern at the secondary windings as at the primary, the phasor diagram for the secondary voltages will look remarkably similar to the primary phasor diagram, the biggest difference being each phasor having one-quarter the length of the respective primary phasors. Phasors V_{YZ} and V_{XY} will be 120 volts apiece, while phasors V_X , V_Y , and V_Z will be 69.3 volts apiece:



The secondary phase rotation will be XYZ.

Answer 31

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:



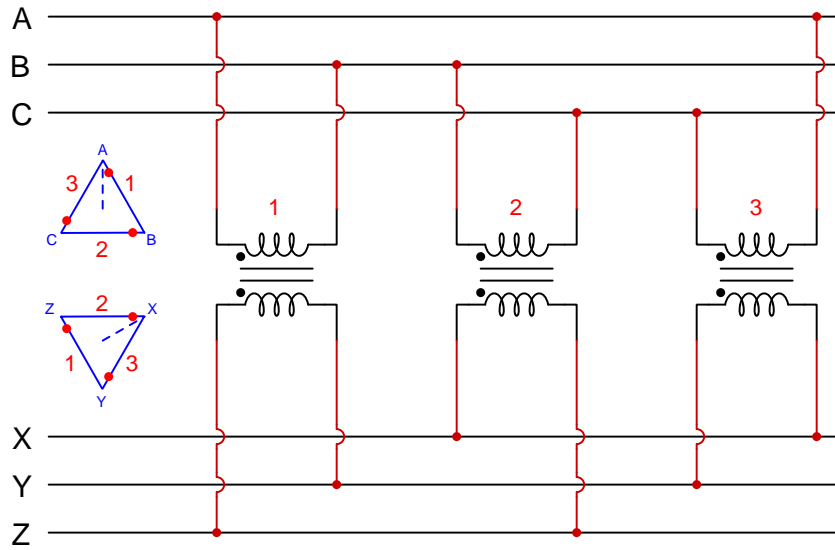
The upper bus phase rotation is ABC.

The lower bus phase rotation is XZY.

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

Answer 32

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:



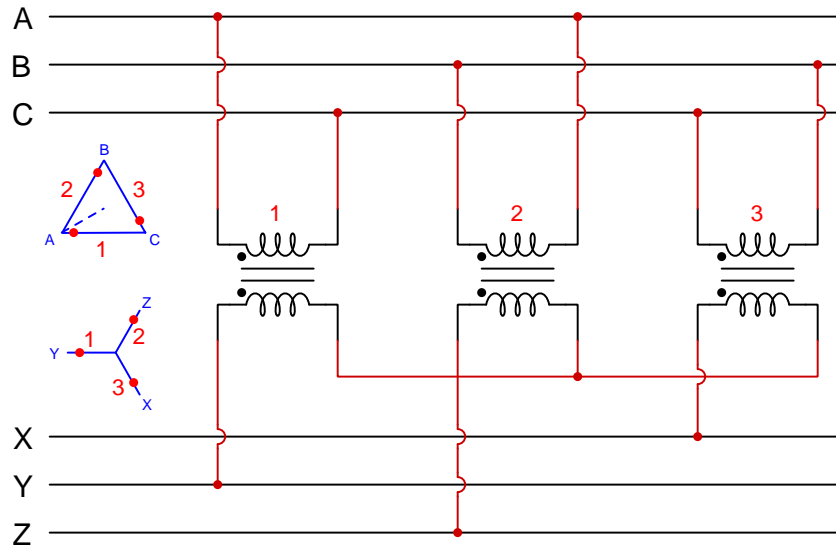
The upper bus phase rotation is ABC.

The lower bus phase rotation is XYZ.

The phase shift between the two busses (comparing V_A with V_X) is 60° , with the lower bus *lagging* behind the upper bus: $V_A = \angle 90^\circ$ and $V_X = \angle 30^\circ$

Answer 33

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 90° , with the lower bus *leading ahead* of the upper bus: $V_A = \angle -150^\circ$ and $V_X = \angle -60^\circ$

Answer 34

First, calculating line current magnitude (assuming a balanced 3-phase motor):

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

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

$$I_{line} = \frac{95000 \text{ W}}{(480 \text{ V}) \sqrt{3}}$$

$$I_{line} = 114.27 \text{ A}$$

Next, calculating CT secondary current magnitude:

$$I_{CT} = (114.27 \text{ A}) \left(\frac{5}{200} \right)$$

$$I_{CT} = 2.857 \text{ A}$$

The phase angle of each line current may be determined by the phase rotation. Given a CBA phase rotation, phase B will be 120 degrees ahead of (leading) phase A, and phase C will be another 120 degrees ahead of (leading) phase B. Therefore:

$$\text{Ammeter "A" current} = \underline{2.857 \text{ A} \angle -20^\circ}$$

$$\text{Ammeter "B" current} = \underline{2.857 \text{ A} \angle 100^\circ}$$

$$\text{Ammeter "C" current} = \underline{2.857 \text{ A} \angle 220^\circ}$$

Answer 35

--	<i>C</i>	<i>R</i>	<i>L</i>	Total
<i>V</i>	423.4 V $\angle -74.34^\circ$ 114.3 - j407.7 V	447.7 V $\angle 15.66^\circ$ 431.1 + j120.9 V	297.9 V $\angle 105.7^\circ$ -80.42 + j286.8 V	465 V $\angle 0^\circ$ 465 + j0 V
<i>I</i>	526.7 mA $\angle 15.66^\circ$ 507.2 + j142.2 mA	526.7 mA $\angle 15.66^\circ$ 507.2 + j142.2 mA	526.7 mA $\angle 15.66^\circ$ 507.2 + j142.2 mA	526.7 mA $\angle 15.66^\circ$ 507.2 + j142.2 mA
<i>Z</i>	803.8 Ω $\angle -90^\circ$ 0 - j803.8 Ω	850 Ω $\angle 0^\circ$ 850 + j0 Ω	565.5 Ω $\angle 90^\circ$ 0 + j565.5 Ω	882.8 Ω $\angle -15.66^\circ$ 850 - j238.3 Ω

Answer 36

Answer 37

Answer 38

Answer 39

Answer 40

Answer 41

Answer 42

Your instructor will have some electromechanical relays for you to inspect.

Answer 43

Partial answer:

The pickup adjustments for the 50 function and the 51 function are non-interactive: adjusting one of them does not affect the adjustment of the other.

The reason the breaker's trip coil is wired in series with the normally-open 52a auxiliary contact is to the trip circuit will not continue to (needlessly) draw current from the station battery power supply after the breaker has already been tripped. Thus, the 52a contact unlatches the 51 relay's "seal-in" circuit once the breaker reaches the tripped position.

Answer 44

Answer 45

Partial answer:

To test the "50" (instantaneous overcurrent) function, apply 11.875 amps AC to terminals 3 and 8 (or terminals 8 and 9) with an ohmmeter connected to terminals 2 and 10 to check for the IIT contact's closure. Of course, you would also need to re-test the relay at current values below 11.875 amps AC to verify that the relay does *not* pick up at any lower current value.

To test the "51" (time overcurrent) function, apply 4.70 amps AC to terminals 8 and 9 with an ohmmeter connected to terminals 1 and 10 to check for the CO contact's closure after 4.6 seconds' worth of time.

Answer 46

Answer 47

Hint: the amount of electrical power delivered to the motor at full load is 2.5432 MW.

Answer 48

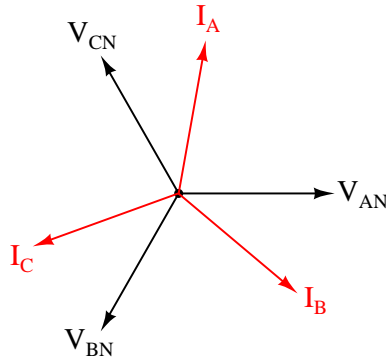
Partial answer:

In the non-interlocked 50/51 protection scheme, breaker B's overcurrent relays must have the highest pickup values and/or longest time values, not only because breaker B must typically bear a heavier load than any of the distribution line breakers (C through F), but also because in the event of a fault on one distribution line we wish that line's breaker to trip rather than tripping breaker B which would shut off the entire bus (and all distribution lines with it).

Answer 49

Partial answer:

The magnitude (length) of each current phasor is 15.45 amps AC.



Answer 50

$$I_{supply} = 12.29 \text{ A}$$

Answer 51

A fault current of 7500 amps yields a CT secondary current 120 times less than that (5:600 current reduction ratio), or 62.5 amps. This CT current is 15.625 times greater than the pickup value of 4.0 amps, so we begin our interpretation of the graph by finding 15.625 on the horizontal axis. A vertical line is already placed at $15\times$, so we can follow that line and be very close to the true value.

Seeing the point at which the $15\times$ vertical line crosses the “3” time-dial curve and then looking horizontally to the left where it reads out as time, we see a value slightly larger than 0.6 seconds.

The graph shown in the question is sampled from the SEL-551 Relay instruction manual, used with permission from Schweitzer Engineering Laboratories.

Answer 52

$$t = T \left(0.0352 + \frac{5.67}{M^2 - 1} \right) \quad \text{Extremely inverse curve}$$

Solving for the time-dial setting (T):

$$T = \frac{t}{\left(0.0352 + \frac{5.67}{M^2 - 1} \right)}$$

A fault current of 3.6 kA through a 1200:5 ratio CT gives a CT secondary current of 15 amps. Given the relay's pick-up value of 5 amps, this will be $3 \times$ the pick-up current ($M = 3$). Solving for a desired tripping time of 10 seconds (t):

$$T = \frac{10}{\left(0.0352 + \frac{5.67}{3^2 - 1} \right)}$$

$$T = 13.44$$

Therefore we must set the time dial of this relay at 13.44.

Answer 53

Answer 54

Answer 55

Answer 56

Answer 57

Answer 58

Answer 59

Answer 60

Answer 61

Answer 62

Answer 63

Partial answer:

Since it is impractical to run CT secondary wires along the entire length of the power line in order to perform differential current measurement with one relay, a *pair* of 387L relays (one at each end of the line) monitors current with their own set of CTs and compares those current measurements via a fiber-optic communications link between the two relays.

Answer 64

Partial answer:

In Figure 2.7 (page 2-10) we see the 387A relay protecting a Wye-wound step-down *autotransformer*. Both primary and secondary CTs are connected in Wye configurations, as is common for digital 87 relays.

Answer 65

You will need to use taps X1 and X3 on each CT, using 240 turns of the secondary winding. This will yield a turns ratio of 240:1, which is the same as 1200:5. The other terminals of the CT must be left floating (unconnected).

Answer 66

Answer 67

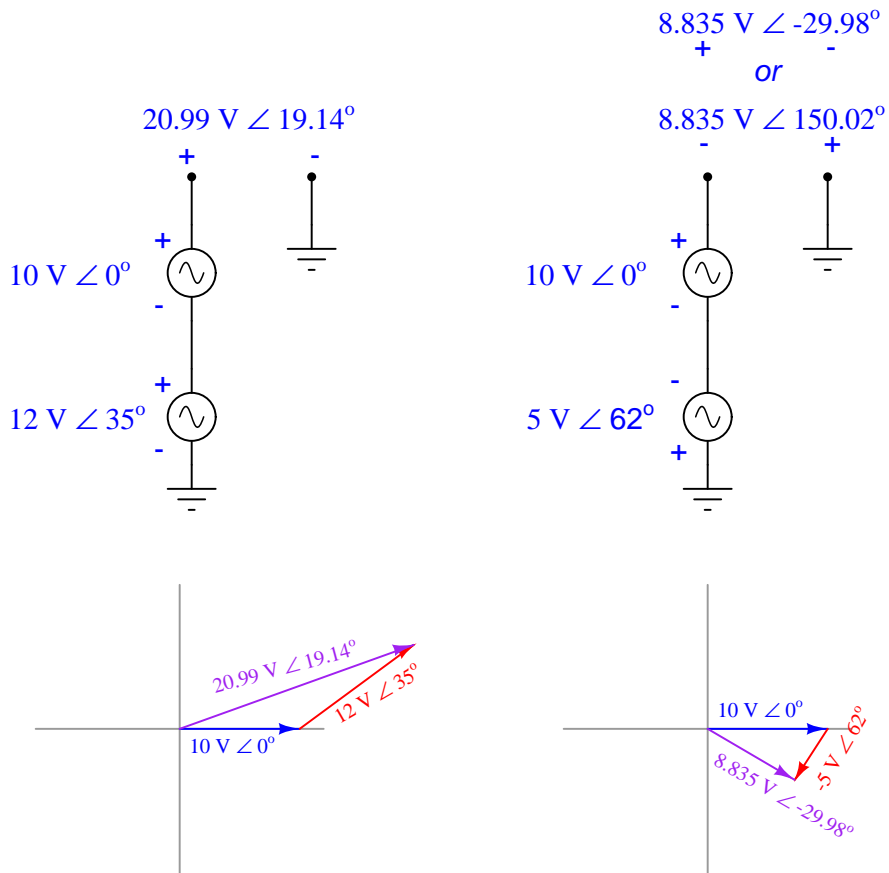
Answer 68

Partial answer:

Voltage output at each CT's terminals = 4.110 volts

Answer 69

Normally, the currents through the "hot" and "neutral" conductors are exactly equal in magnitude but opposite in direction. This means their magnetic fields exactly cancel at the CT. However, if ever there is a *ground fault* at the load where some current passes through earth ground rather than back through the CT where it came from, the CT will sense that difference in current and trip the GFCI contacts to interrupt power to the faulted load.



	R_1	L_1	C_1	Total
V	$8.92 \text{ V} \angle 145^\circ$	$8.92 \text{ V} \angle 145^\circ$	$24.8 \text{ V} \angle -11.9^\circ$	$17 \text{ V} \angle 0^\circ$
I	$40.6 \text{ mA} \angle 145^\circ$	$94.7 \text{ mA} \angle 54.9^\circ$	$103 \text{ mA} \angle 78.1^\circ$	$103 \text{ mA} \angle 78.1^\circ$
Z	$220 \Omega \angle 0^\circ$	$94.2 \Omega \angle 90^\circ$	$241 \Omega \angle -90^\circ$	$165 \Omega \angle -78.1^\circ$

	R_1	L_1	C_1	C_2	Total
V	$2.51 \text{ V} \angle 4.68^\circ$	$2.95 \text{ V} \angle -175^\circ$	$5.45 \text{ V} \angle 4.68^\circ$	$2.51 \text{ V} \angle -4.67^\circ$	$5 \text{ V} \angle 0^\circ$
I	$2.09 \text{ mA} \angle 4.68^\circ$	$12.7 \text{ mA} \angle 94.7^\circ$	$12.7 \text{ mA} \angle 94.7^\circ$	$12.8 \text{ mA} \angle 85.3$	$12.8 \text{ mA} \angle 85.3$
Z	$1.2 \text{ k}\Omega \angle 0^\circ$	$232 \Omega \angle 90^\circ$	$430 \Omega \angle -90^\circ$	$196 \Omega \angle -90^\circ$	$389 \Omega \angle -85.3^\circ$

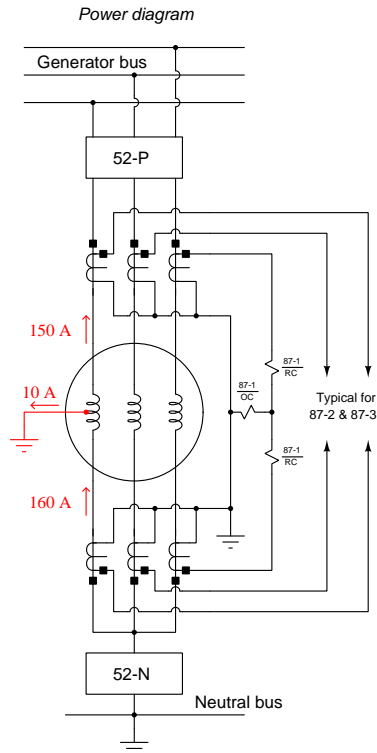
Answer 73

There is no need to express your answers in complex-number form, since an analog voltmeter does not register the phase angle of the measured voltage:

- $f = 1 \text{ Hz}$; $V_{meter} = 20 \text{ V}$
- $f = 1 \text{ kHz}$; $V_{meter} = 20 \text{ V}$
- $f = 10 \text{ kHz}$; $V_{meter} = 20.01 \text{ V}$
- $f = 100 \text{ kHz}$; $V_{meter} = 21.43 \text{ V}$
- $f = 1 \text{ MHz}$; $V_{meter} = 3.526 \text{ V}$

Answer 74

Sketching the 150 amp phase current through the breaker and the 10 amp ground fault current reveals 160 amps through the lower phase wire at the bottom of the generator:



200:5 ratios at each CT means the 150 amps through the upper CT will translate into 3.75 amps through the upper restraint coil (RC) of the 87-3 relay. 160 amps through the lower CT translates into 4.00 amps through the lower restraint coil (RC) of the 87-3 relay. The difference between these two RC currents (0.25 amps) must flow through the 87-3 relay's operate coil (OC).

Answer 75

Answer 76

Answer 77

Answer 78

Answer 79

Answer 80

Answer 81

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

Answer 82

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

Answer 83

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

Answer 84

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

Answer 85

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

Answer 86

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

Answer 87

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

Answer 88

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

Answer 89

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

Answer 90

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

Answer 91

Answer 92

Answer 93