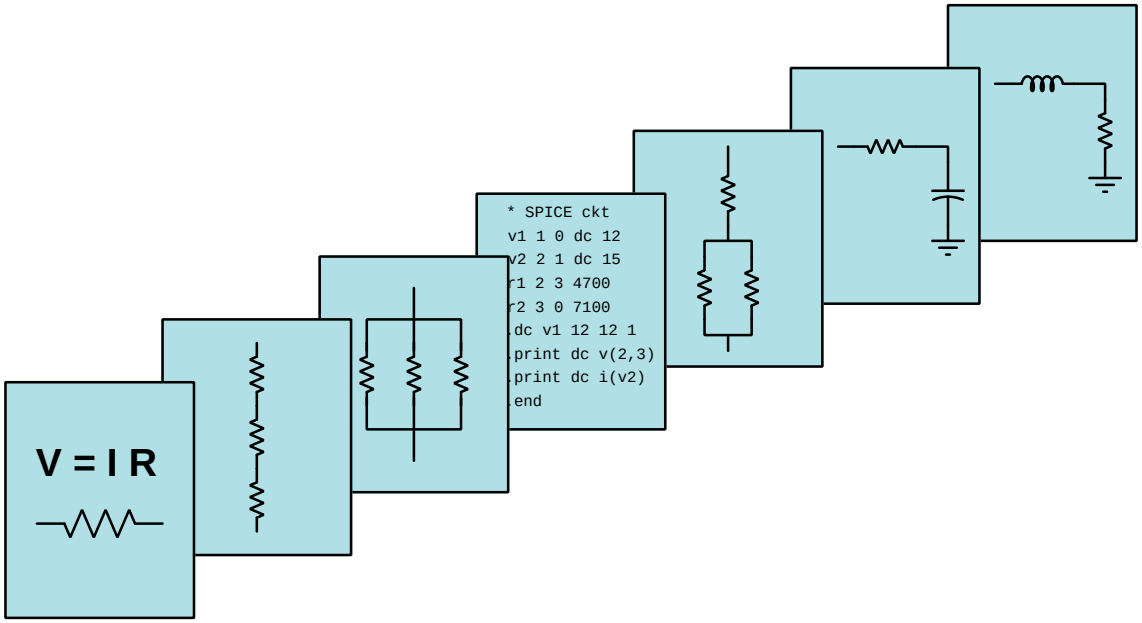
Modular Electronics Learning (ModEL) project



Differential Generator, Line, and Bus Protection Relays

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Chapter 1

Introduction

1.1 Recommendations for students

Kirchhoff's Current Law states that the algebraic sum of all currents entering and exiting a node must be zero. This law is based on the Law of Electric Charge Conservation, and it is a fundamental principle of circuit analysis. It also happens to be the basis for an entire class of protective relays designed to detect a fault within a power system component or a span of power conductors, by monitoring current in versus current out at all times. If any fault develops that diverts current from its regular path, the currents measured at the in and out points will no longer precisely match, thereby signaling a fault. This is known as *differential current* protection.

Important concepts related to differential current protection include **Kirchhoff's Current Law**, **pick up**, **current transformers**, **Wye** versus **Delta** networks, **ground fault**, **operate** versus **restraint**, **hot** versus **neutral** conductors, **protection zone**, **selectivity**, **sensitivity**, and **pilot channels**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to test the effectiveness of a ground fault current interruptor (GFCI)? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- Why is differential current protection much more sensitive to faults than overcurrent protection?
- How does Kirchhoff's Current Law relate to power system protection?
- Are there electric power components or subsystems that cannot be protected by differential current measurement?
- How are ground faults detected by the differential current method?
- How are phase-to-phase faults detected by the differential current method?

- Why do transformers sometimes (but not always) exhibit high "inrush" currents when initially energized?
- How far does the protection zone of a GFCI extend?
- What defines the boundaries of the protection zone for a generator, line, or bus differential current relay?
- Why are pilot channels required for differential line protection?
- What are some realistic causes of power-system faults that might trip a differential current relay?
- Why is it important that protection zones overlap each other in a power system?

1.2 Challenging concepts related to differential current protection

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Interpreting single-line diagrams** – a common form of technical documentation in the electrical power industry is the *single-line* or *one-line* diagram, which shows interconnected power system components with lines representing flow-paths of electrical power rather than lines representing individual conductors defining the flow-paths of electric current. To anyone familiar with schematic diagrams, single-line diagrams can seem confusing because one tries to look for current return paths where none are documented. Single-line diagrams should be viewed as though they were *piping* diagrams showing the flow of some fluid from sources to drains, the fluid in question being electrical energy.

- **Operation versus Restraint** – certain protective relay functions must balance the intent to trip the circuit breaker against other factors necessitating restraint, hence the concepts of "operate" (trip) versus "restrating" (do not trip). For differential current (ANSI/IEEE-87) relays, the operate function is based on differences in phase current as detected by CTs while the restraint function is based on normal line current. We don't want an 87 relay to trip simply because line current is at relatively high values, so line current is used to restrain the tripping action such that any current imbalance must exceed a certain *percentage* of line current in order to trip the breaker. Modern digital 87 relays can exhibit very non-linear operate/restraint ratios unlike electromechanical 87 relays which are mostly ratio-based.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students show how quantitative results were obtained by the author in the Tutorial chapter's examples.

- **Outcome** – Calculate currents in a differential protection scheme

  Assessment – Calculate operate coil current given CT secondary currents (all in phasor form) for one phase of a differential current protective relay; e.g. pose problems in the form of the "Generator differential current" and "Faulted generator" Quantitative Reasoning questions.

- **Outcome** – Diagnose a faulted differential current protection system

  Assessment – Determine the probability of various component faults in a generator differential protection system given symptoms and measured values; e.g. pose problems in the form of the "Faulted 87 system" Diagnostic Reasoning question.

- **Outcome** – Independent research

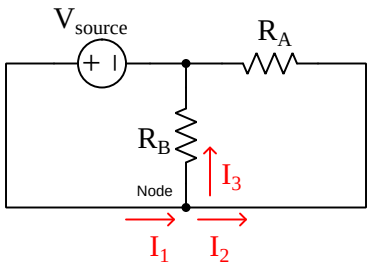
  Assessment – Locate differential current protective relay datasheets and properly interpret some of the information contained in those documents including operate and restaint settings, current ratings, ANSI/IEEE protective functions, etc.

Chapter 2

Tutorial

2.1 Differential current protection

One of the fundamental laws of electric circuits is *Kirchhoff's Current Law*, which states the algebraic sum of all currents at a circuit node (junction) must be zero. This law is based on an even more fundamental law of physics: the *Conservation of Electric Charge* which states electric charges are eternal and thus cannot be created nor destroyed. That being the case, Kirchhoff's Current Law may be thought of in the simple terms of "what goes in must come out," as illustrated in the following schematic diagram showing three currents at a node:



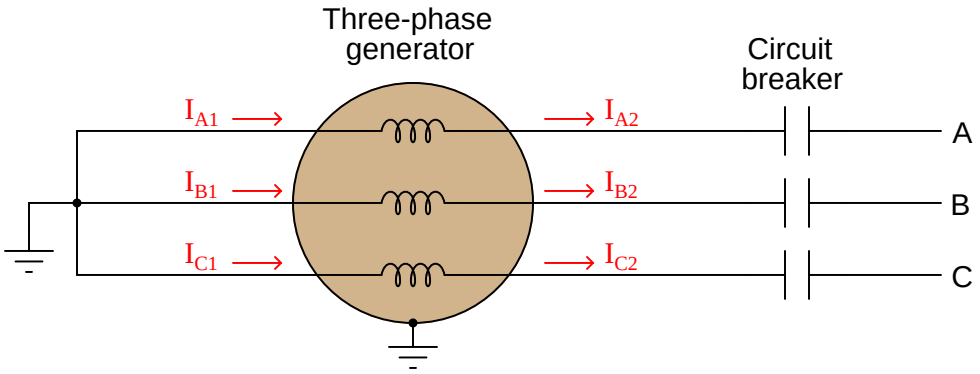
$$I_1 = I_2 + I_3$$

We may exploit this principle to provide another form of protection against certain faults in electric circuits by measuring the amount of current entering and exiting a circuit component and then tripping a circuit breaker if those two currents ever fail to match. The concept here is that current in *must* equal current out so long as there is no "fault path" for current to go somewhere it should not.

An advantage of detecting faults by an imbalance of in versus out current compared to overcurrent (50/51) protection is sensitivity and speed. Since a non-faulted power system line or component should exhibit the same amount of current in as current out, even relatively small imbalances signify a fault. Thus, a protective relay comparing currents in and out of a component or line is able to "pick up" at far lower levels of current because Kirchhoff's Current Law predicts that *any* amount of

current imbalance, for *any* length of time, is abnormal. Lower pick-up thresholds along with no time delay means that differential protection is able to take action sooner than any form of overcurrent protection can, thereby limiting equipment damage by clearing the fault in a shorter amount of time.

Suppose we were to measure the amount of current at both ends of every phase winding in a three-phase generator, shown in the following diagram:

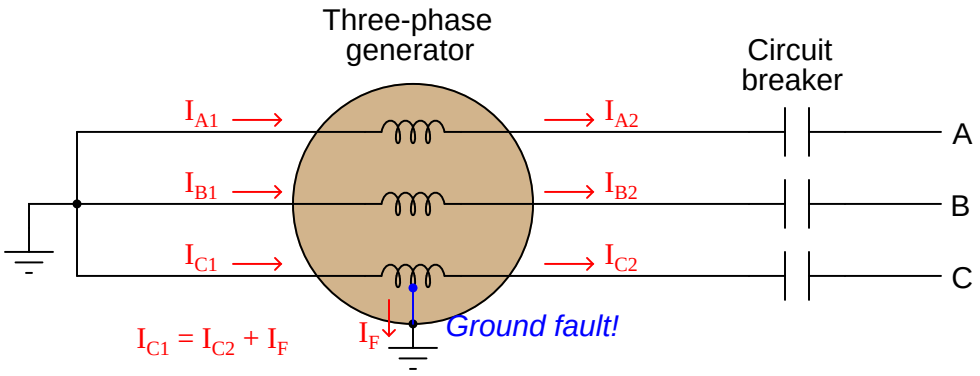


Like most large power generators, this unit brings both terminals of each phase winding to external points so that they may be connected in either a Wye or a Delta configuration as desired. In this particular case, the generator's windings are Wye-connected. So long as we measure current going in and out of each winding individually, it matters little whether those generator windings are Wye- or Delta-connected.

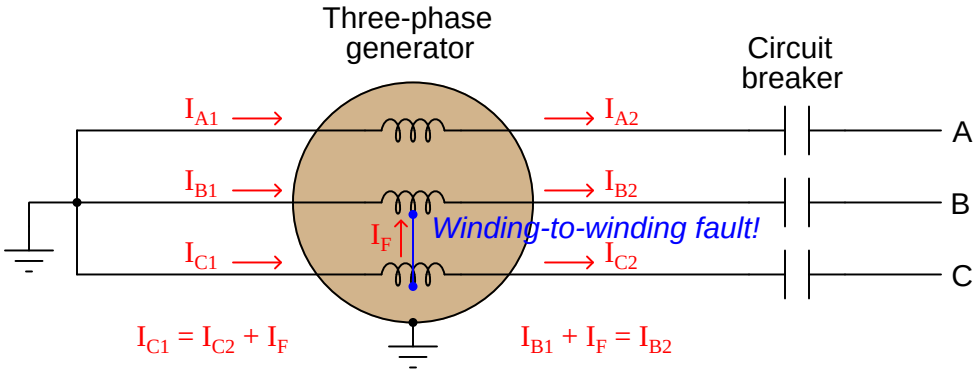
If the circuit is exactly as drawn above, the amount of current entering and exiting each phase winding must be the same in accordance with Kirchhoff's Current Law. That is to say:

$$I_{A1} = I_{A2} \qquad I_{B1} = I_{B2} \qquad I_{C1} = I_{C2}$$

Suppose now that one of the turns within the "C" phase winding were to accidently contact the generator's metal frame, such as what might happen as a result of insulation damage. This *ground fault* will cause a third path for current in the faulted winding. I_{C1} and I_{C2} will now be imbalanced by an amount equal to the fault current I_F:



Another fault detectable by Kirchhoff's Current Law is a phase-to-phase winding fault, where current flows from one winding to another. In this example, a fault between B and C phases in the generator upsets the balance of incoming and outgoing currents for both phases:

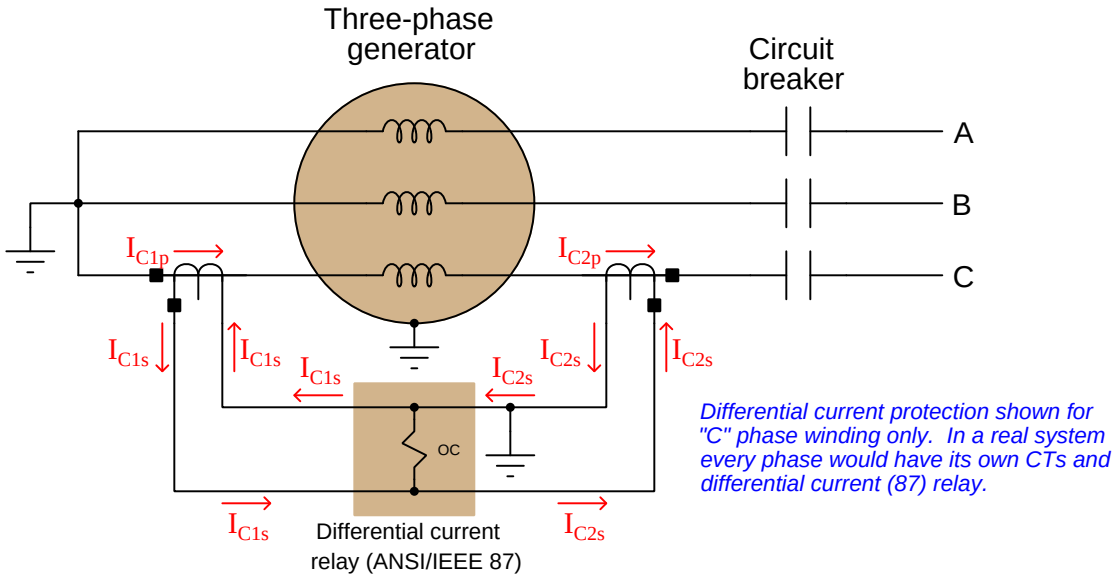


It should be noted that the magnitude of a ground fault or a winding-to-winding fault current might not be large enough to pose an overcurrent threat to the generator, yet the very existence of a current imbalance in any phase proves the winding is damaged. In other words, this is a type of system fault that would not necessarily be detected by an overcurrent (50/51) relay, and so must be detected by some other means.

The relay type designated for this task is called a *differential current* relay. The ANSI/IEEE number code for differential protection is *87*. Differential voltage relays also exist, with the same "87" ANSI/IEEE designation, making it necessary to specify whether the differential quantity in question is voltage or current whenever mentioning an "87" relay.

2.2 Differential current relays

A simple form of differential current protection for this generator may be implemented by connecting CTs on either side of each winding to operating coils of an electromechanical relay like this. For the sake of simplicity, protection for only one phase winding (C) of the generator will be shown. A practical differential current protective relay system would monitor current through all six stator wires on the generator, comparing currents in and out of every phase:

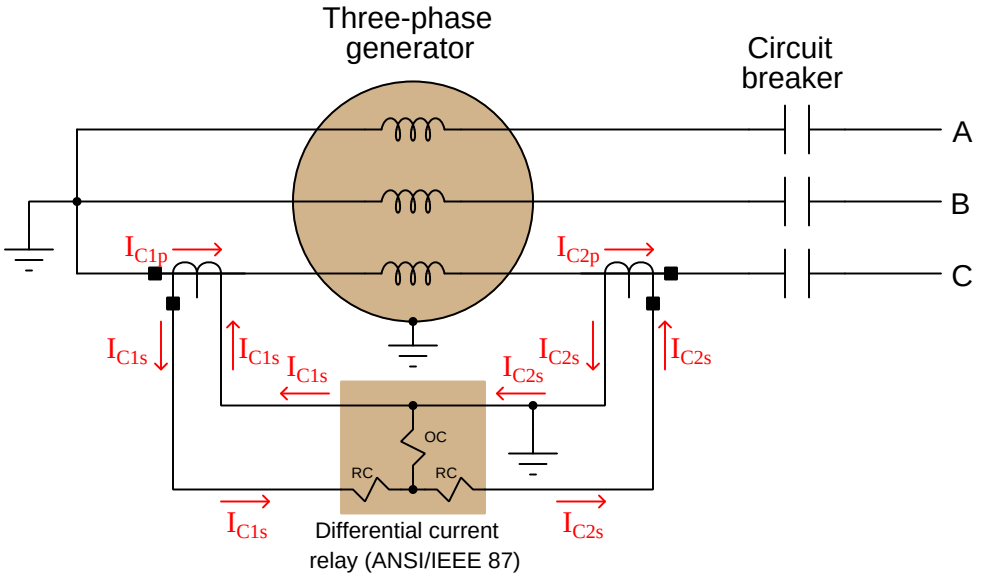


If the CT primary currents I_{C1p} and I_{C2p} are equal and the CT ratios are equal, the CT secondary currents I_{C1s} and I_{C2s} will be equal as well. The result should be zero current through the operating coil (OC) of the differential relay. In practice, perfect cancellation of currents is nearly impossible due to mismatched CTs and other imperfections, and so a small amount of current typically passes through the differential relay's operating coil even under normal circumstances. The pickup value of this relay must be set such that this small amount of current does not unnecessarily trip the relay.

If, however, a fault to ground or to an adjacent winding were to develop anywhere within the generator's "C" stator winding, the primary currents of the two CTs will become unequal, causing unequal secondary currents, thereby causing a substantial amount of current to flow through the differential relay's operate coil (OC). If this current is sufficient to cause the differential relay to "pick up", the relay will send a signal commanding the generator's circuit breaker to trip.

Even with the relay's pickup value biased to avoid unnecessary tripping, it is still possible that a heavy phase current demanded from the generator may cause the differential relay to trip, due to the impossibility of a perfect match between the two "C" phase current transformers. Any mismatch between these two CTs will result in an inequality of secondary currents that will become larger as phase current grows in magnitude. Large, harmonic-rich *inrush currents*[1] occasionally experienced when a large power transformer is initially energized may also cause false trips in this simple form of differential protection. We do not wish this differential relay to trip for any condition but an internal generator fault in its phase winding, and so a modification is necessary to provide a different operating characteristic.

If we modify the relay to have three coils, one to move its mechanism in the trip direction, and two to help "restrain" its mechanism (working to hold the mechanism in its normal operating position), we may connect these coils in such a way that the two restraint coils[2] (RC) are energized by the two CT secondary currents, while the operating coil only sees the difference between the two CT secondary currents. We refer to this scheme as a *restrained differential relay*, and the former (simpler) design as an *unrestrained differential relay*:



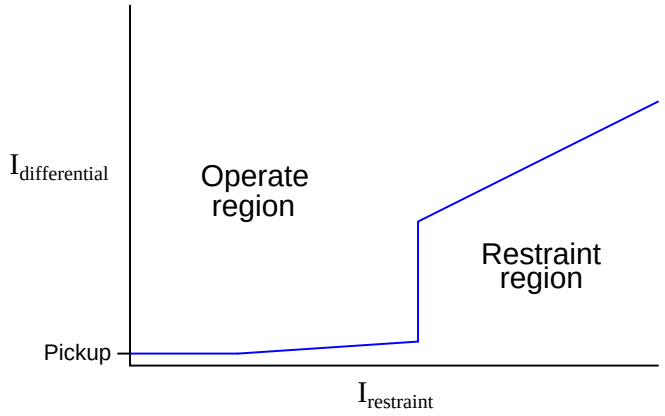
The general characteristic of a restrained differential relay is to trip on the basis of the differential current exceeding a set *percentage* of phase current.

[1] Transformers exhibit inrush current for reasons different than capacitors (reactance) or motors (counter-EMF). Residual magnetism in a transformer core from the last time it was energized biases that core toward saturation in one direction. If the applied power happens to match that direction, and have sufficient magnitude, the transformer core will saturate on power-up which results in abnormally high current for multiple cycles until the core's magnetic domains normalize.

[2] Restraint coils are sometimes labeled as "RC" and other times labeled as "R". It should be noted that the principle of a "restraining element" within a protective relay is not unique to differential (87) relays. Other relay types, notably distance (21) relays, also employ restraint coils or other mechanisms to prevent the relay from tripping under specific circumstances.

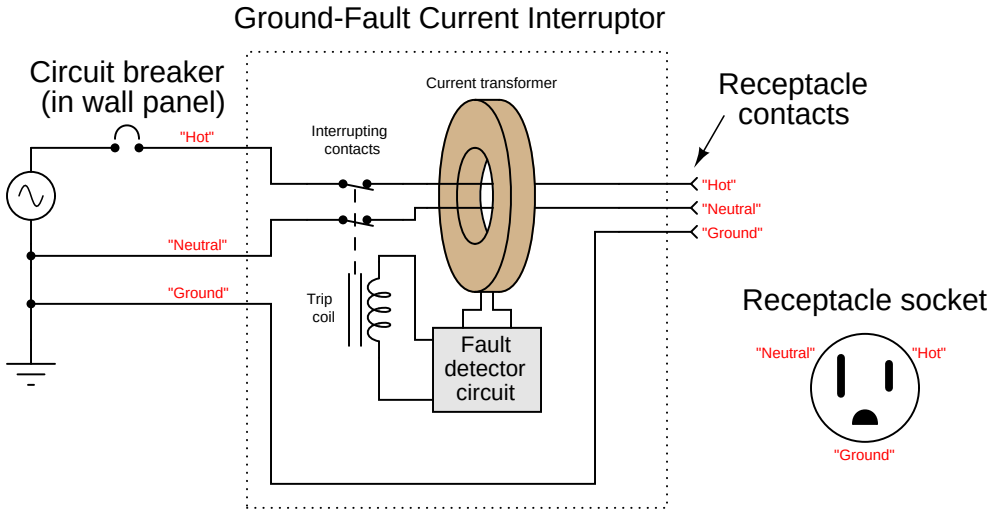
This photograph shows three differential relays used to protect the windings of a three-phase generator at a gas turbine power plant. Note how one differential current relay is required to protect each of the generator's three phases:

Modern digital differential relays typically sense CT signals from all three phases, allowing protection in a single panel-mount unit. Digital protective relays offer much more sophisticated approaches to the problem of false tripping based on mismatches between current transformer pairs and/or harmonic currents. The following graph shows the characteristic for a General Electric model 745 transformer protective relay providing differential current protection:



Not only may the pickup value be adjusted by the user, but also the slope of each line segment on the graph, the height of the "kneepoint" step, etc. Note how the term "restraint" is still used in digital relay configuration, even though it originated in electromechanical relay designs.

It is noteworthy that a form of differential current protection also finds application in American households, where electrical codes require the installation of *Ground Fault Current Interruptor* (GFCI) protected circuits in areas where contact between electrical appliances and water is likely (e.g. bathrooms, kitchens). GFCI receptacles function by sensing any difference in current between the "hot" and "neutral" conductors carrying current to and from any load plugged into the receptacle:

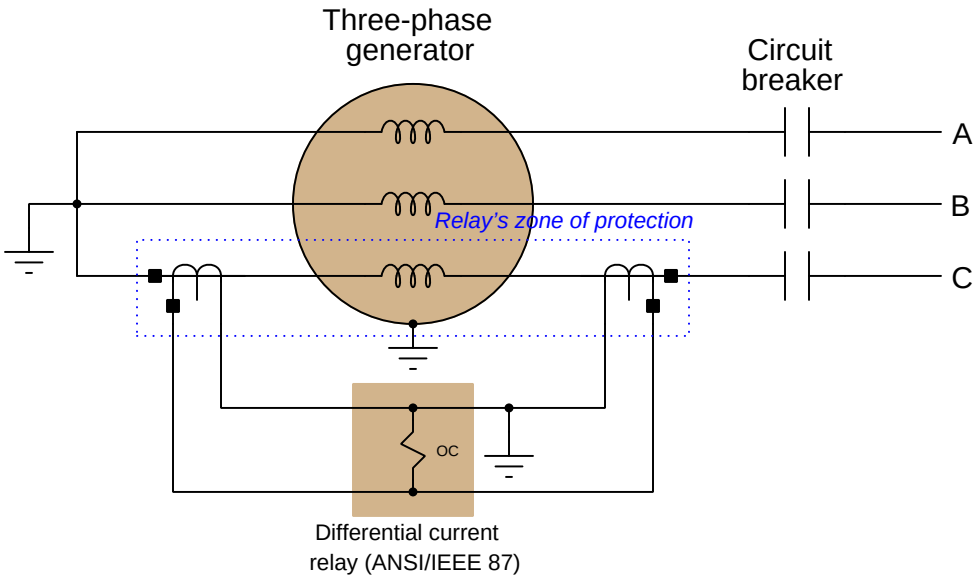


A single current transformer (CT) within the GFCI unit senses any differential current by sensing the *net* magnetic field around both current-carrying conductors. If the "hot" and "neutral" currents are equal, their opposite directions will produce opposing magnetic fields, with zero net magnetic field sensed by the CT. If, however, a ground fault exists at the load plugged into this receptacle, these two currents will be unequal and the CT will detect a net magnetic field. These protective devices are extraordinarily sensitive, tripping the contacts with differential current values in the *milliAmpere* range. This is important, as a ground fault existing in an electrical appliance may very well pass through the body of a person or an animal, in which case mere milliAmperes may prove harmful or even fatal.

If a GFCI receptacle trips, it may be reset by pressing a "reset" button on its face. GFCI units may also be manually tested by pressing a "test" button also mounted on the front face.

2.3 Differential current protection zones

A very important concept in the field of protective relaying is that of *protection zones*, which is easily explained in the context of differential current relays. Simply defined, a relay's "protection zone" is the physical range wherein the specified electrical fault may be detected, and thereby any components and connections within the zone may be protected through proper relay action. Overcurrent (50/51) relays discussed in an earlier section of this book do not exhibit well-defined zones of protection, since overcurrent relays pick up on a certain minimum fault current *value*, not necessarily on any certain fault *location*. Differential current relays, however, exhibit very clear and unambiguous zones of protection: *the area lying between the current-sensing CT pair*:

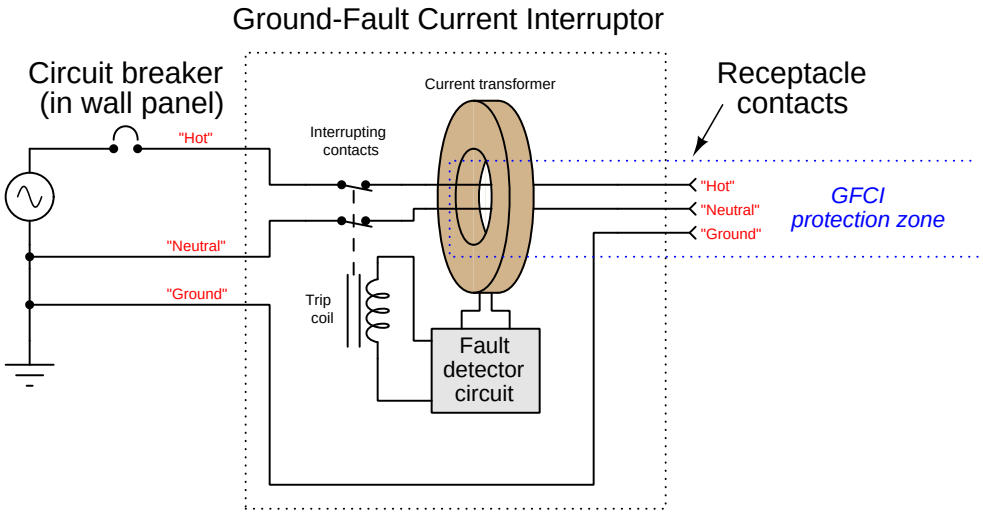


Only a fault within the relay's protection zone (i.e. an "internal" fault) is capable of forcing the two CTs currents to become unequal. Thanks to Kirchhoff's Current Law, no fault outside the protection zone (i.e. an "external" fault), no matter how severe, can make the CT primary currents become unequal[3].

The concept of protection zones is a very important one in protective relaying, and finds application well beyond differential current (87) systems. It is closely related to the concept of *selectivity*, which means the ability of a protective relay to discriminate between a fault within its own protection zone and one lying outside of its zone. A relay with high selectivity is one capable of ignoring external faults, while a relay with poor selectivity may falsely trip when faced with external faults.

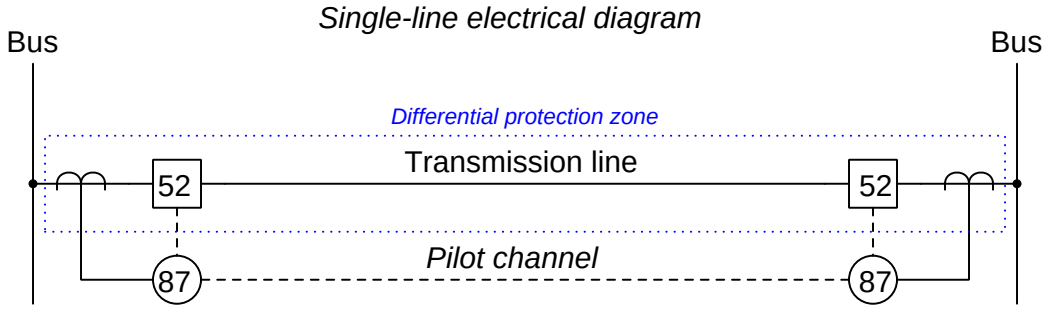
[3]It should be mentioned that an external fault generating currents high enough to saturate one or more of the CTs used in the differential protection system may cause the differential current system to falsely trip, due to saturation causing the affected CT(s) to no longer faithfully represent line current to the relay.

Ground Fault Current-Interrupting (GFCI) household power receptacles also exhibit well-defined zones of protection. In the case of a GFCI the zone of protection extends to anything plugged into the receptacle (i.e. to the right of the CT in the diagram):



A common residential wiring practice in the United States is to "daisy-chain" regular receptacles to a GFCI receptacle where water hazards exist, such that all receptacles powered through the GFCI become part of the GFCI's protection zone. A bathroom wired this way, for example, provides the exact same degree of ground fault protection at all receptacles in the room. If someone were to plug an electric hair dryer into one of those "daisy-chained" receptacles and then accidently drop that appliance into a bathtub full of water, the GFCI would trip and cut power to all of the receptacles just as surely as it would trip if the hair dryer had been plugged directly into the GFCI receptacle itself.

Differential current protection is most practical to implement over short physical distances, such as over the phase windings in a generator or some other power system component, but the fundamental concept is applicable over longer distances as well because Kirchhoff's Current Law knows no bounds. Consider for example a transmission line spanning miles of distance between two busses, shown in this single-line diagram:



Here, two differential relays control the tripping of circuit breakers (ANSI/IEEE function 52) at each end of the transmission line. The current at each end of the line is monitored by current transformers connected to local 87 relays, which makes the differential current protection zone cover the entire length of the transmission line. In order for this protection scheme to work, the two local 87 relays must somehow communicate with one another to continuously compare measured current values at both ends of the line. This is accomplished via a communication route between the two relays called a *pilot channel*. The term "pilot" is a general term in the field of protective relaying, referring to any form of data communication. If a significant difference in line current is detected (i.e. resulting from a fault anywhere along the length of the transmission line), both relays trip their respective circuit breakers and thereby de-energize the transmission line.

Pilot systems may take the form of an analog current or voltage "loop" circuit, a microwave radio link, a power-line carrier (PLC)[4] link, a fiber-optic cable[5] data link, or any other form of point-to-point data link allowing the relays to communicate data with each other. The details of pilot systems in protection schemes is complex and will not be treated in any detail here.

An interesting caveat when applying differential current protection to long lines is that the lines' capacitive *charging current* may in some cases be substantial enough to trip an 87 relay that is configured too sensitively. One can visualize line-to-ground capacitance as a form of AC "ground fault" because any current taking that path to earth ground is current passing through one CT but not the other.

[4] Power-line carrier, or PLC as it is known in the electric power industry, consists of data communications conveyed over the power line conductors themselves. This usually takes the form of a high-frequency AC signal (in the hundreds of kilohertz range) which is then modulated with the data of interest, similar to radio communication except that the RF signals travel along power lines rather than through empty space as electromagnetic waves. Power-line carrier systems are generally less reliable than fiber optic networks, because the presence of faults on the protected line may compromise the pilot communication.

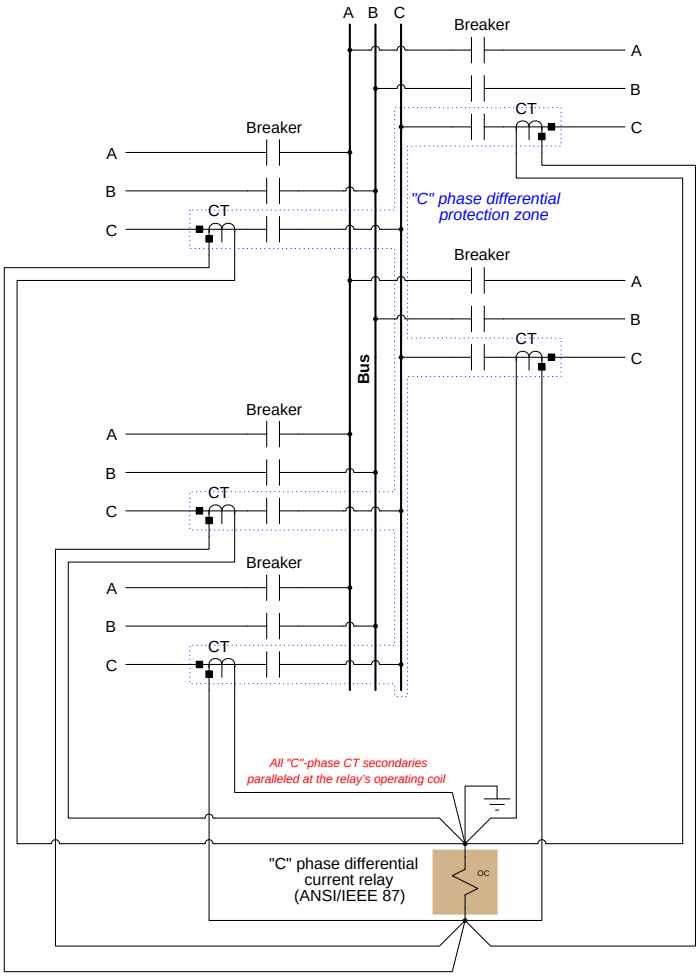
[5] Schweitzer Engineering Laboratories manufactures a differential current relay specifically designed for line protection called the model 387L. It is billed as a "zero settings" relay because there are no parameters to configure. Simply set up a pair of 387L's (one at each end of the line), each one connected to matched CTs monitoring current through all three line conductors, and then link the relays together via a pair of fiber optic cables, and it's ready to work.

2.4 Differential current bus protection

Not only is Kirchhoff's Current Law unbounded with regard to distance, it is also unlimited with regard to the number of lines entering or exiting a node. This fact permits us to apply differential current protection to *busses* where multiple power lines and/or devices interconnect. An example of a high-voltage bus photographed at Grand Coulee Dam in Washington state appears here, connecting multiple three-phase transformer banks (each one fed by a hydroelectric generator):

Busses are typically constructed from flexible cable or rigid tube, suspended from ground by insulators. Faults may arise in a bus if an insulator "flashes over" (i.e. develops an electric arc from a bus conductor to ground), or if anything conductive happens to bridge between bus lines. As such, busses may be protected by the differential current principle just like any other electrical component or power line. The algebraic sum of all currents entering and exiting each phase of a bus should equal zero, and if it doesn't it means the bus must be faulted.

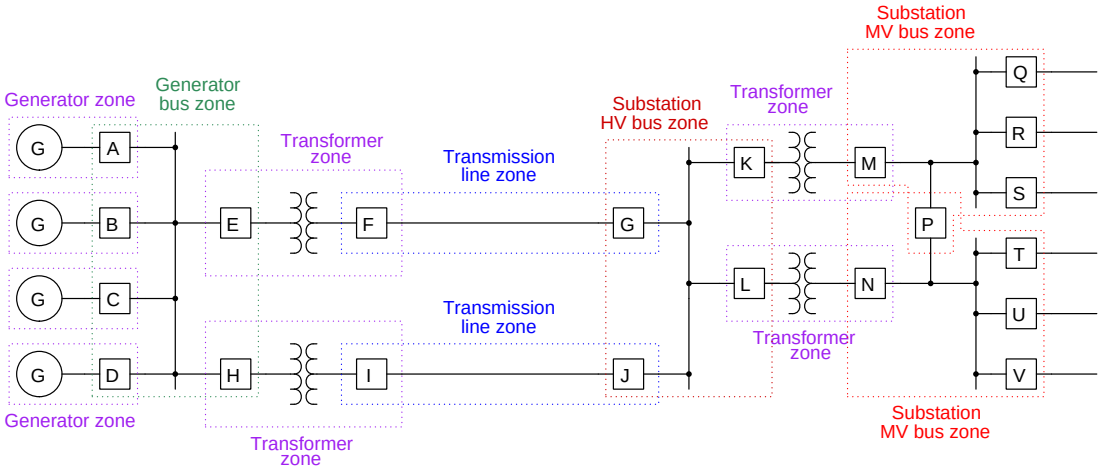
A schematic diagram showing one bus with five different feeds reveals how differential current protection may be used to protect a bus with any number of lines. For simplicity's sake the CT and 87 relay wiring is shown only for one phase on this three-phase bus. In any realistic bus differential protection circuit all three phases would be equipped with CTs and there would be three separate 87 "operating coil" elements, one for each phase:



Kirchhoff's Current Law informs us that the algebraic sum of all currents at a node must equal zero. In this case the node in question is the sum of all conductors shown enclosed within the dotted blue protection zone outline. With all CTs possessing the same turns ratio and connected in parallel as shown, their combined secondary currents should all sum to a net value of zero Amperes through the 87 relay's operate coil during normal operation. However, if a ground fault or a phase-to-phase fault happens to develop anywhere within the protection zone, the CT secondary currents will *not* sum to zero, causing the differential relay to pick up.

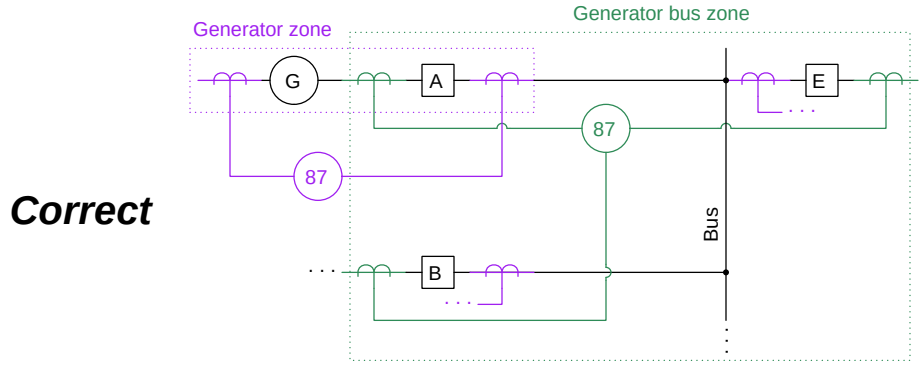
2.5 Protection zone overlap

Another important concept in protective relaying is *protection zone overlap*. The philosophy here is that each protection zone's size should be limited in order to avoid unnecessarily tripping any more sections of the power system than are necessary to isolate any fault, while leaving no component or conductor unprotected. The following single-line diagram shows how protection zones are configured to overlap each other at each circuit breaker where they connect:

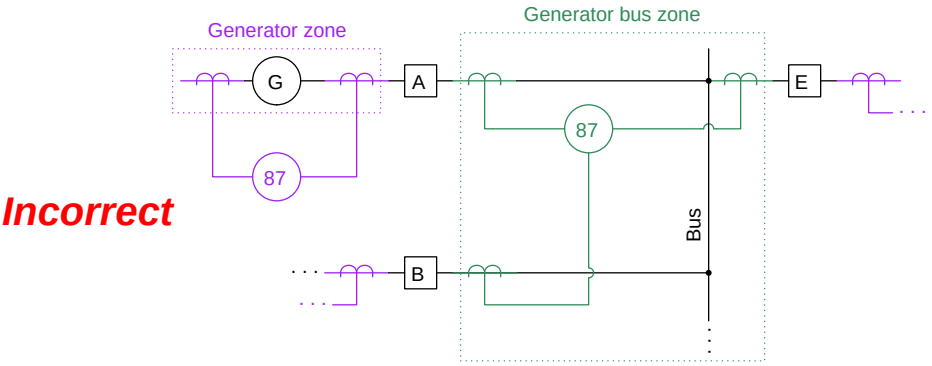


For example, a fault in the upper transmission line belongs to that protection zone only, and will therefore only trip circuit breakers F and G, leaving the other transmission line and associated components to carry power from the generating station to the substation. Note how each circuit breaker in the above system falls within *two* protection zones. If fault happened to develop within breaker F, it would trip the breaker E in the upper generating station transformer zone as well as breaker G in the upper transmission line zone, isolating the failed breaker.

Differential protection zone overlap is accomplished by judicious placement of CTs on either side of a circuit breaker. Recall that the boundary of any differential current protection scheme is defined by the location of the CTs sensing current in and out of the node. Which CT a differential current relay connects to, therefore, defines how far the boundary of that relay's protection zone will reach. We will take a closer look at the single-line diagram in order to explore this concept further, focusing in on the upper-left corner of the generating station and omitting all transformers and all but one generator as well as breakers C, D, and F for simplicity:



Here we see how zone overlap is achieved by connecting each differential relay to the *far* CT on each circuit breaker. If we instead chose to connect each 87 relay to the *near* CT, the two protection zones would not overlap, leaving every circuit breaker unprotected:



Chapter 3

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- 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.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

3.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

3.1.1 Reading outline and reflections

"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, journal their own 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 SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did 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.

3.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Energy

Conservation of Electric Charge

Kirchhoff's Current Law

Circuit breaker

Schematic diagram

Single-line diagram

Overcurrent protection

Relay pick-up

Polyphase

Phase versus line

Inrush current

Operate

Restraint

Ground fault

Selectivity

Sensitivity

Pilot channel

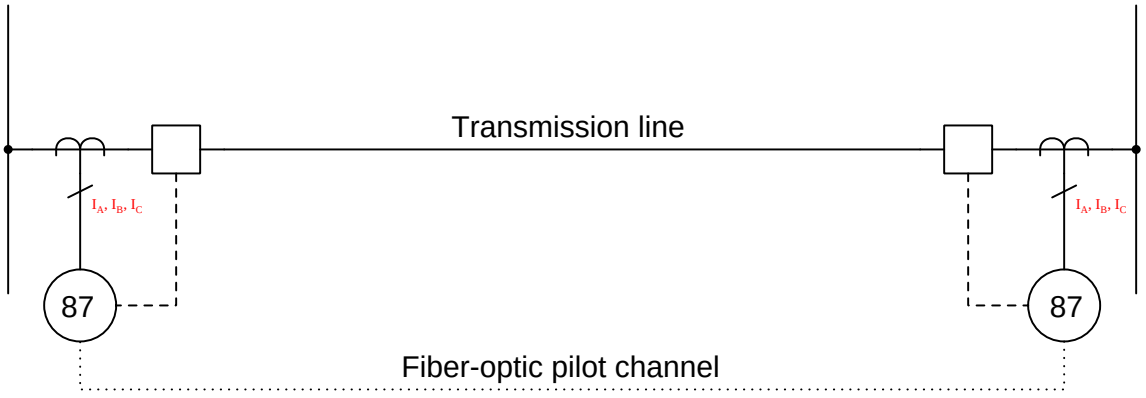
Capacitance

Bus

Protection zone

3.1.3 87 line protection

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.

Challenges

- Explain why a pilot channel of some form is absolutely essential to the operation of this system

3.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

3.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = $1.25663706212(19) \times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = $8.8541878128(13) \times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = $6.67430(15) \times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

3.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

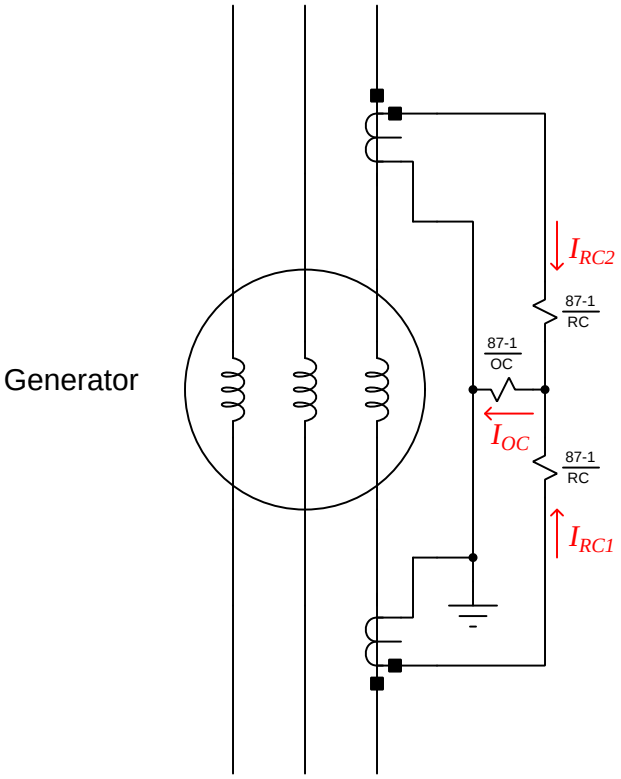
Note how the square-root term (y) is calculated in cell `C1`, and the denominator term (z) in cell `C2`. This makes the two final formulae (in cells `B1` and `B2`) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

3.2.3 Generator differential current

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

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

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

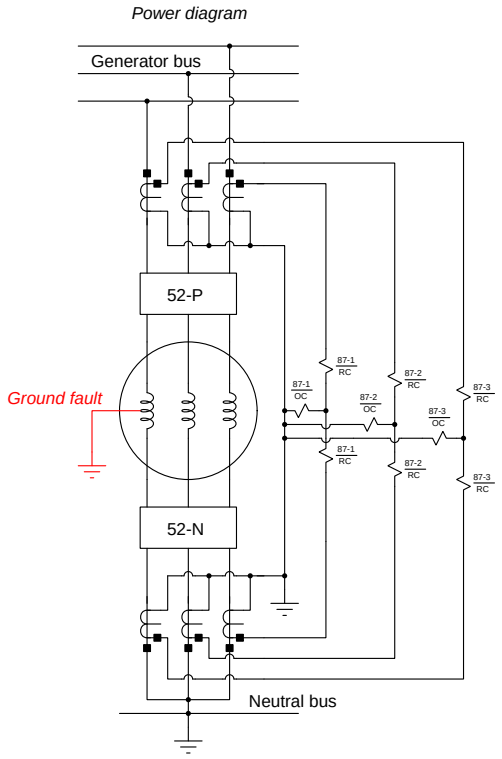
In addition to calculating a symbolic answer for I_{OC}, sketch a phasor diagram showing how the three currents (I_{RC1}, I_{RC2}, and I_{OC}) relate to one another.

Challenges

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

3.2.4 Faulted generator

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



Challenges

- What might physically occur inside of a generator to create such a ground fault?

3.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

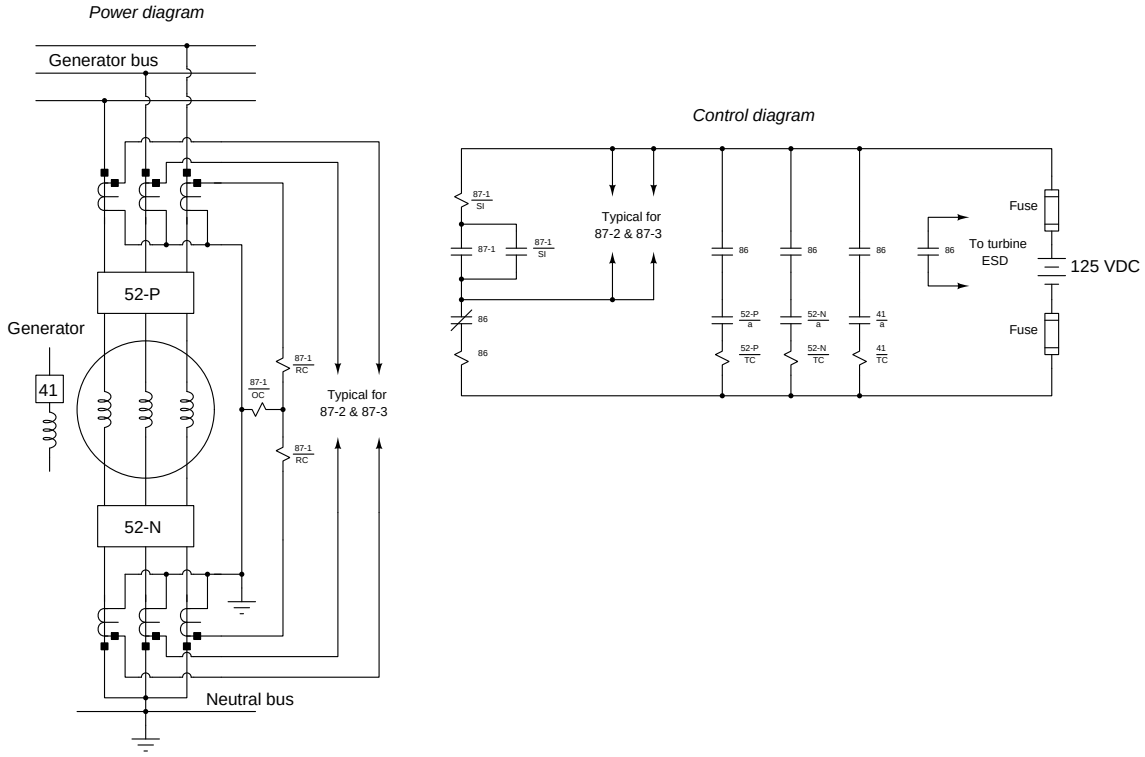
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

3.3.1 Faulted 87 system

The following diagrams document the differential current protection system for a three-phase generator driven by a steam turbine (the mechanical "prime mover" in this system):



One day the auxiliary relay (86) trips for no apparent reason, which in turn trips the 52-P power breaker, the 52-N neutral breaker, the 41 field breaker, and activates the steam turbine's Emergency ShutDown system (ESD). 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.

- Dead DC station power supply
- 52-N/TC coil failed open
- 87-2/SI coil failed shorted
- 87-3/SI coil failed open
- 87-1 contact failed open
- 87-2 contact failed shorted

- 52-P/a contact failed open
- 52-N/a contact failed shorted
- 86 normally-closed contact failed open
- Any 86 normally-open contact failed shorted
- 86 coil failed open
- 86 coil failed shorted
- 87-3/SI contact failed shorted
- CT secondary failed shorted

Challenges

- Would any of the "possible" faults listed here cause one or more relay target flags to be raised?
- Identify any faults not listed which could also account for the trip.

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- 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.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

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Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

6-8 December 2025 – edited some instructor notes, and also edited power diagrams on two of the questions to show CTs in their proper locations (*outside* the circuit breakers). These were the "Faulted 87 system" and "Faulted generator" questions.

30 April 2025 to 1 May 2025 – deleted one of the former symptoms of the fault in the "Faulted 87 system" Diagnostic Reasoning question. It used to say that none of the brightly-colored "target" flags on the electromechanical were visible after the breaker trip, but this would have made *none* of the listed faults possible because any that would have tripped the breaker would have also raised a target flag.

9 December 2024 – edited some instructor comments, and added a bit more explanatory text to the beginning of the Tutorial chapter.

6 May 2024 – added more questions to "Faulted 87 system" Diagnostic Reasoning question.

11 December 2023 – divided Tutorial chapter into sections.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

8 May 2021 – commented out or deleted empty chapters.

29 April 2021 – minor edits to image_0816, and also to the Tutorial text and also to one of the Diagnostic Reasoning questions.

27 April 2021 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions. Also

added some Foundational Concepts.

25 April 2021 – minor edits to the "Faulted 87 system" question.

18 April 2021 – added questions.

July 2018 – document first created.

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