

MODULAR ELECTRONICS LEARNING (MODEL) PROJECT



DIFFERENTIAL GENERATOR, LINE, AND BUS PROTECTION RELAYS

© 2018-2025 BY TONY R. KUPHALDT – UNDER THE TERMS AND CONDITIONS OF THE
CREATIVE COMMONS ATTRIBUTION 4.0 INTERNATIONAL PUBLIC LICENSE

LAST UPDATE = 1 MAY 2025

This is a copyrighted work, but licensed under the Creative Commons Attribution 4.0 International Public License. A copy of this license is found in the last Appendix of this document. Alternatively, you may visit <http://creativecommons.org/licenses/by/4.0/> or send a letter to Creative Commons: 171 Second Street, Suite 300, San Francisco, California, 94105, USA. The terms and conditions of this license allow for free copying, distribution, and/or modification of all licensed works by the general public.

Contents

1	Introduction	3
1.1	Recommendations for students	3
1.2	Challenging concepts related to differential current protection	5
1.3	Recommendations for instructors	6
2	Tutorial	7
2.1	Differential current protection	7
2.2	Differential current relays	10
2.3	Differential current protection zones	14
2.4	Differential current bus protection	17
2.5	Protection zone overlap	19
3	Questions	21
3.1	Conceptual reasoning	25
3.1.1	Reading outline and reflections	26
3.1.2	Foundational concepts	27
3.1.3	87 line protection	29
3.2	Quantitative reasoning	30
3.2.1	Miscellaneous physical constants	31
3.2.2	Introduction to spreadsheets	32
3.2.3	Generator differential current	35
3.2.4	Faulted generator	36
3.3	Diagnostic reasoning	37
3.3.1	Faulted 87 system	38
A	Problem-Solving Strategies	41
B	Instructional philosophy	43
C	Tools used	49
D	Creative Commons License	53
E	References	61

<i>CONTENTS</i>	1
F Version history	63
Index	64

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 *pipng* 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

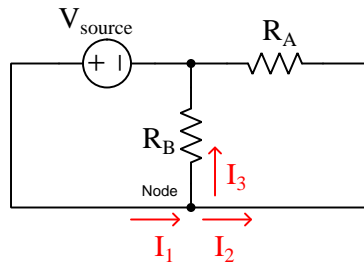
Assessment – Locate differential current protective relay datasheets and properly interpret some of the information contained in those documents including operate and restraint settings, current ratings, ANSI/IEEE protective functions, etc.

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:



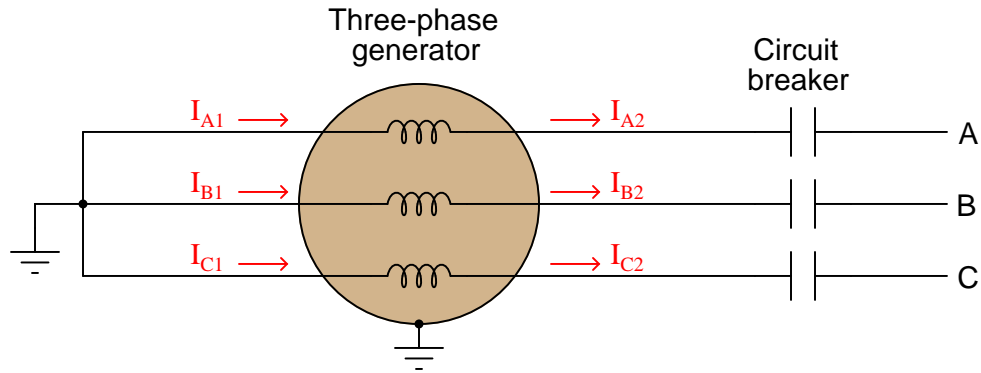
$$I_1 = I_2 + I_3$$

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:

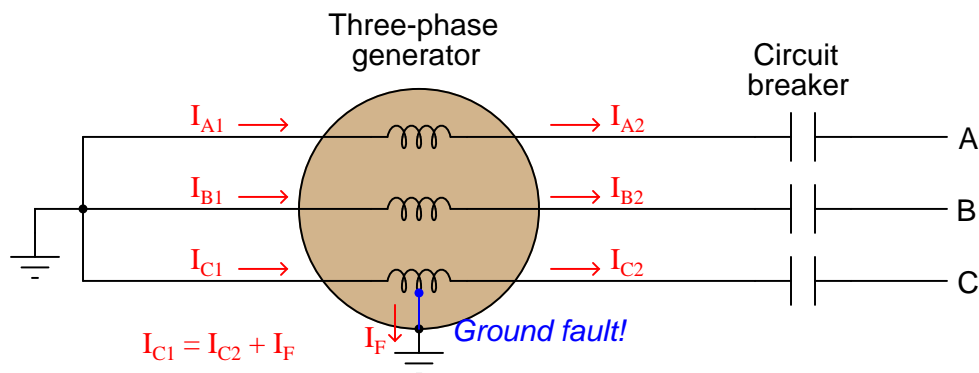


Like most large power generators, this unit brings both terminals of each phase winding to external points so that they may be connected in either a Wye or a Delta configuration as desired. In this particular case, the generator's windings are Wye-connected. So long as we measure current going in and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

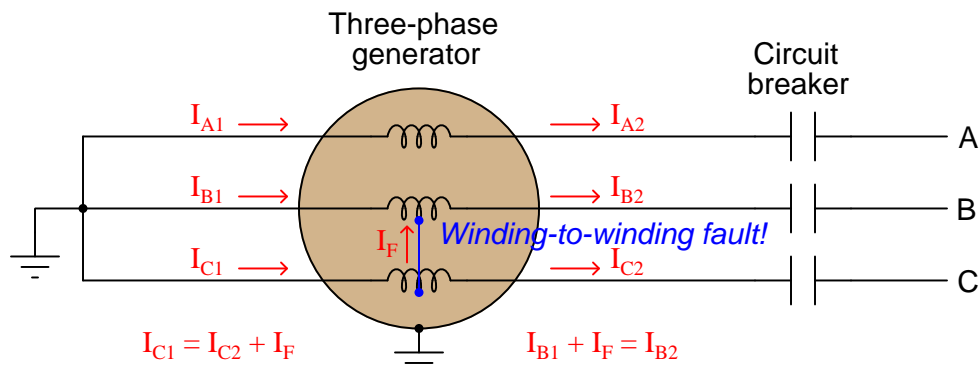
If the circuit is exactly as drawn above, the amount of current entering and exiting each phase winding must be the same in accordance with Kirchhoff's Current Law. That is to say:

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

Suppose now that one of the turns within the “C” phase winding were to accidentally 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:

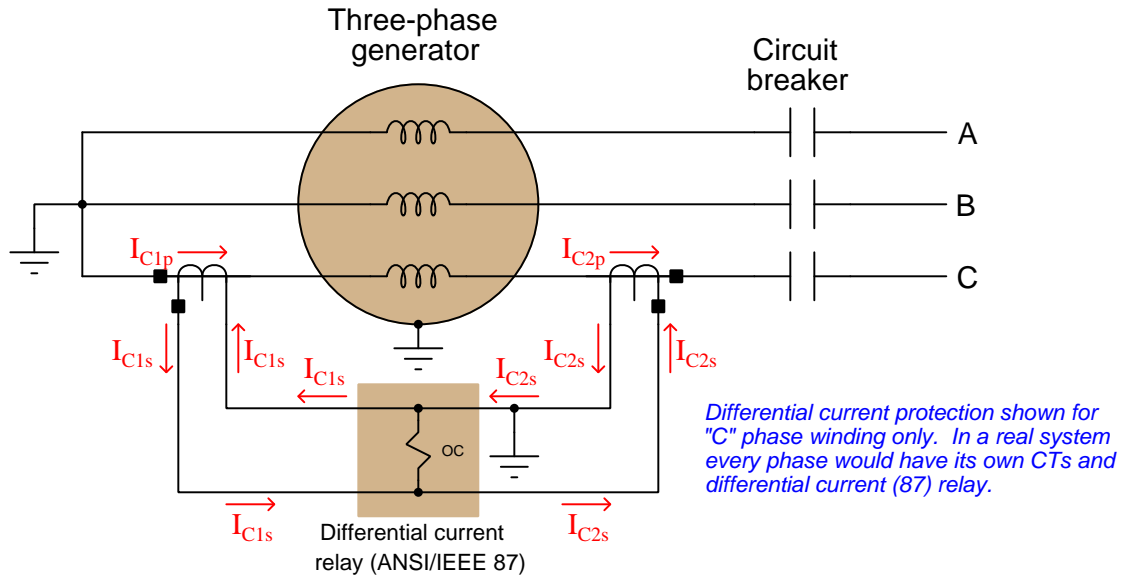


It should be noted that the magnitude of a ground fault or a winding-to-winding fault current might not be large enough to pose an overcurrent threat to the generator, yet the very existence of a current imbalance in any phase proves the winding is damaged. In other words, this is a type of system fault 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:

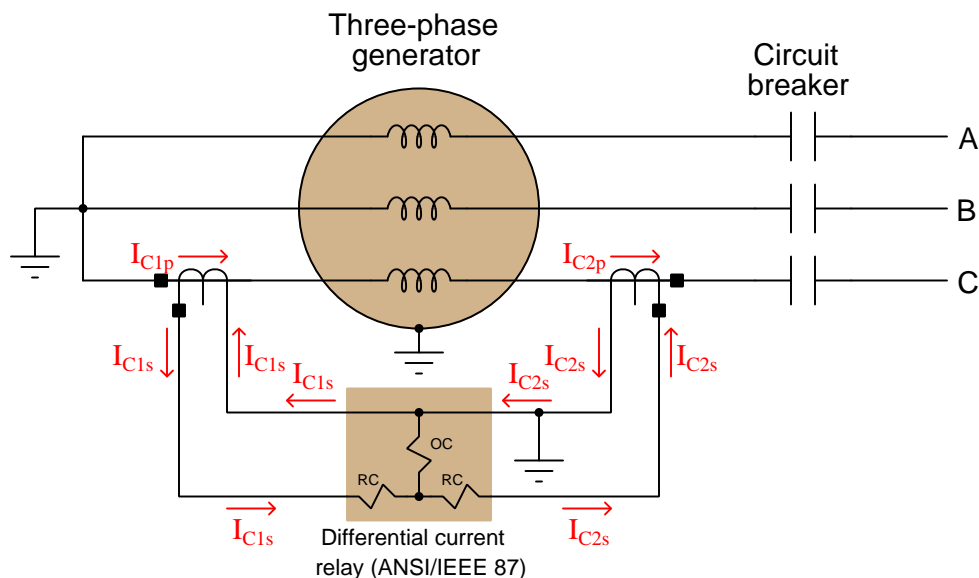


If the CT primary currents I_{C1p} and I_{C2p} are equal and the CT ratios are equal, the CT secondary currents I_{C1s} and I_{C2s} will be equal as well. The result should be zero current through the operating coil (OC) of the differential relay. In practice, perfect cancellation of currents is nearly 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 coils² (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.

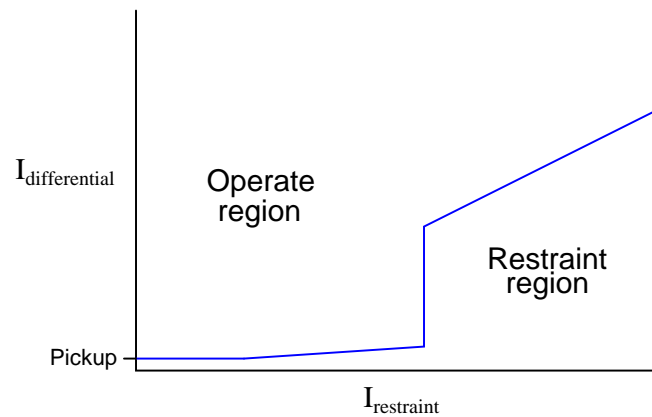
¹Transformers exhibit inrush current for reasons different than capacitors (reactance) or motors (counter-EMF). Residual magnetism in a transformer core from the last time it was energized biases that core toward saturation in one direction. If the applied power happens to match that direction, and have 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.

²Restraint 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:

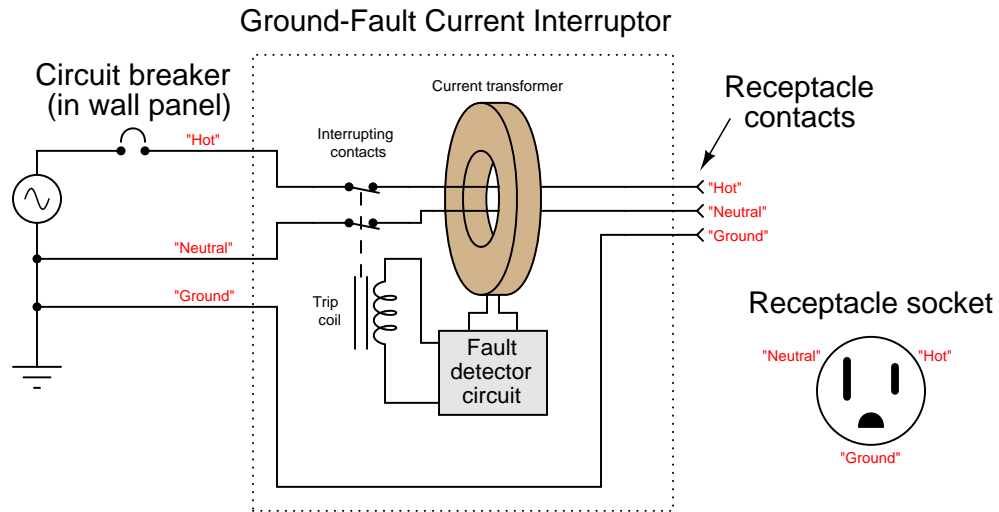


Modern digital differential relays typically sense CT signals from all three phases, allowing protection in a single panel-mount unit. Digital protective relays offer much more sophisticated approaches to the problem of false tripping based on mismatches between current transformer pairs and/or harmonic 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:

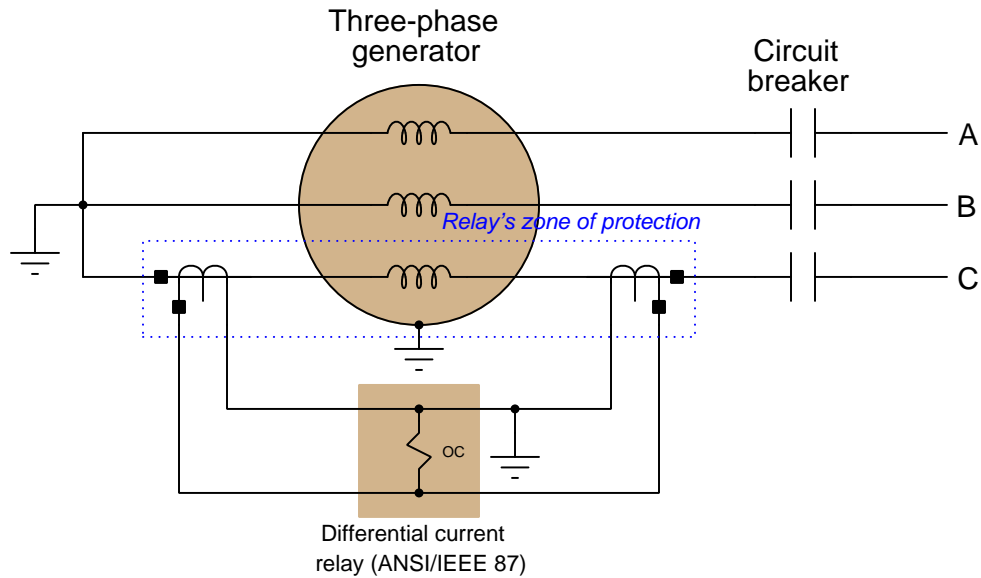


A single current transformer (CT) within the GFCI unit senses any differential current by sensing the *net* magnetic field around both current-carrying conductors. If the “hot” and “neutral” currents are equal, their opposite directions will produce opposing magnetic fields, with zero net magnetic field 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*:

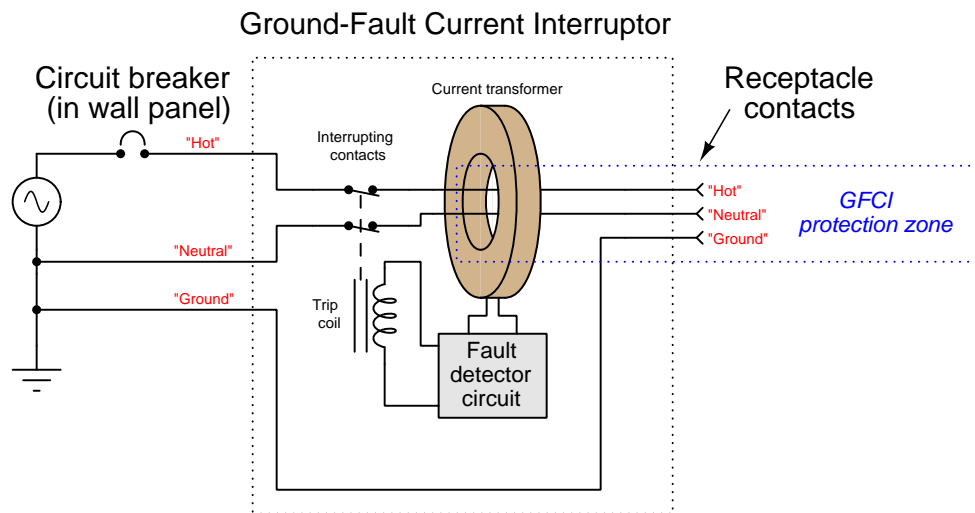


Only a fault within the relay’s protection zone (i.e. an “internal” fault) is capable of forcing the two CTs currents to become unequal. Thanks to Kirchhoff’s Current Law, no fault outside the protection zone (i.e. an “external” fault), no matter how severe, can make the CT primary currents become unequal³.

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.

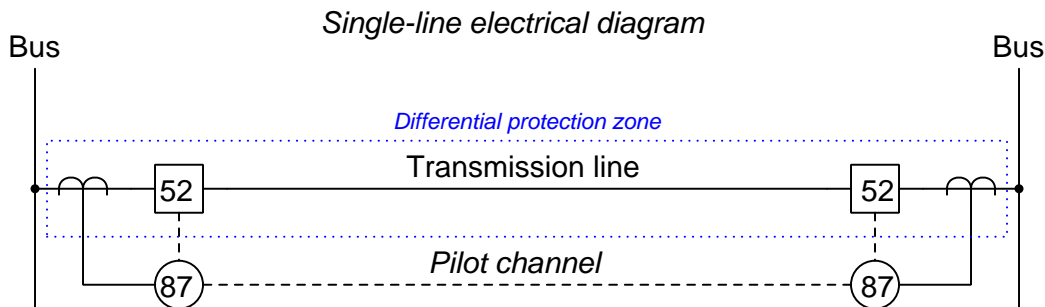
³It should be mentioned that an external fault generating currents high enough to saturate one or more of the CTs used in the differential protection system may cause the differential current system to falsely trip, due to saturation causing the affected CT(s) to no longer faithfully represent line current 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 accidentally 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 cable⁵ 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.

⁴Power-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.

⁵Schweitzer 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.

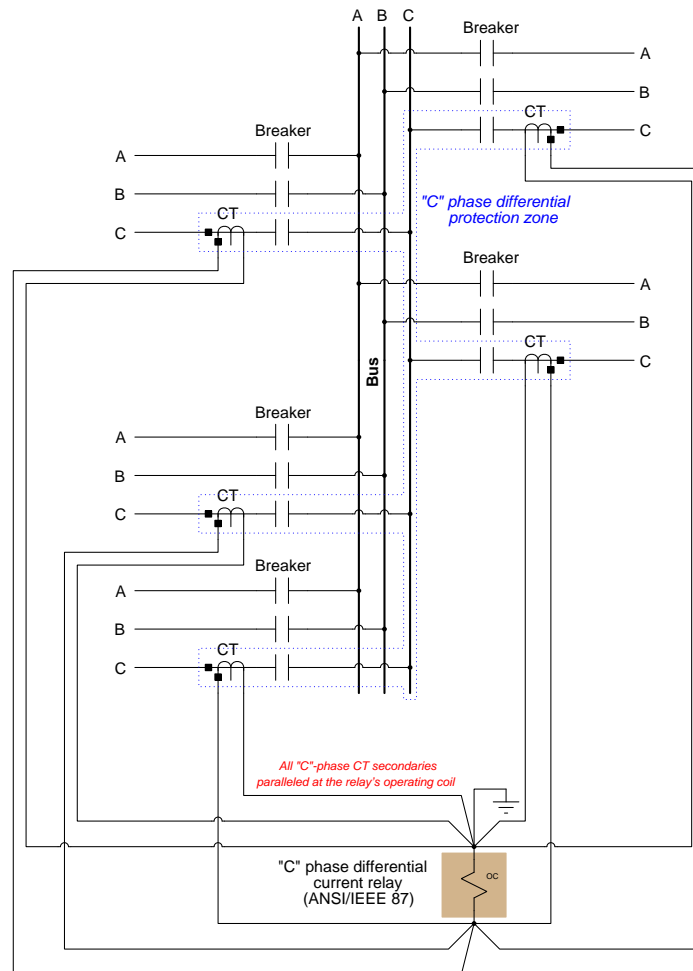
2.4 Differential current bus protection

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.

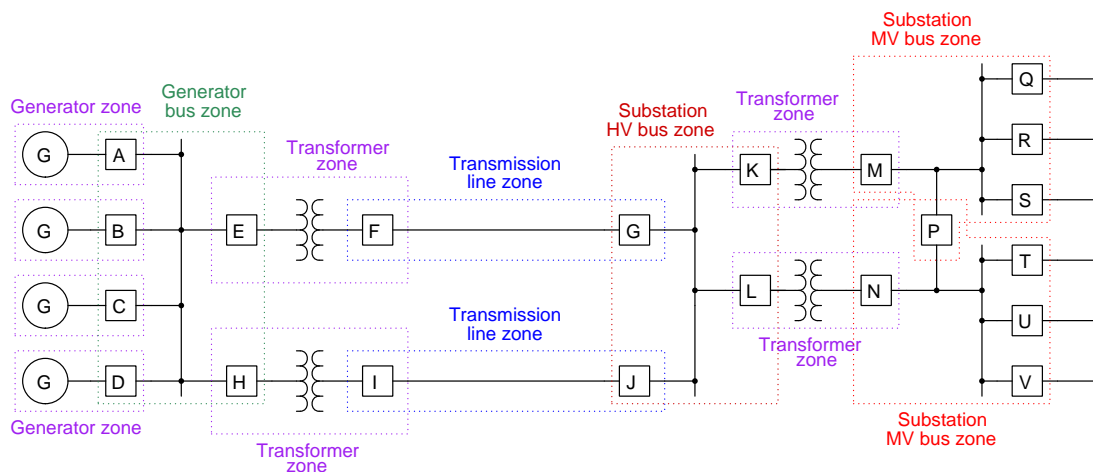
A schematic diagram showing one bus with five different feeds reveals how differential current protection may be used to protect a bus with any number of lines. For simplicity's sake the CT and 87 relay wiring is shown only for one phase on this three-phase bus. In any realistic bus differential protection 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.

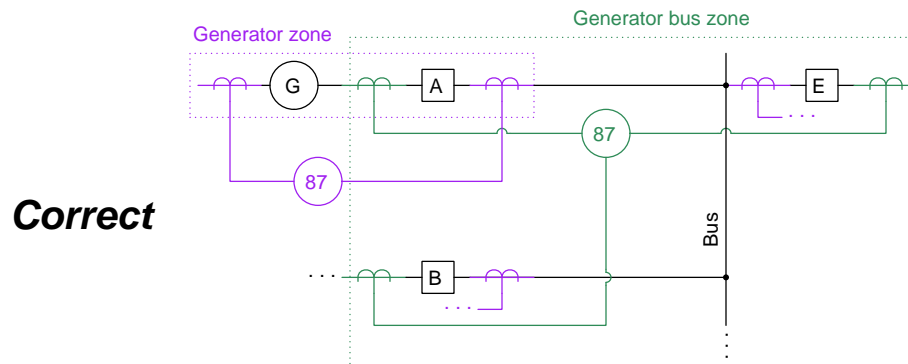
2.5 Protection zone overlap

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:

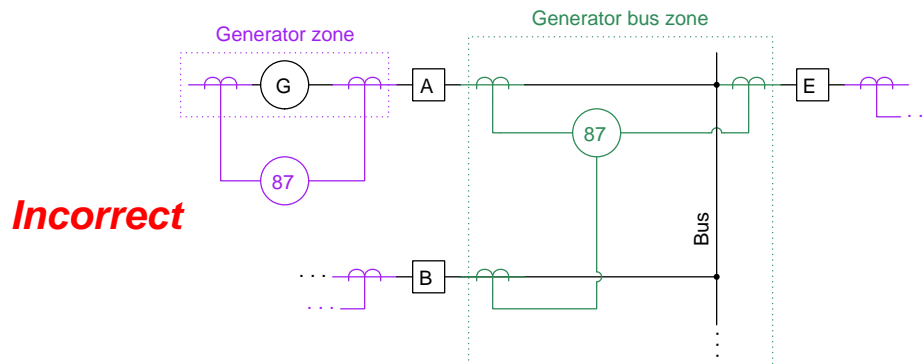


For example, a fault in the upper transmission line belongs to that protection zone only, and will therefore only trip circuit breakers F and G, leaving the other transmission line and associated components to carry power from the generating station to the substation. Note how each circuit breaker in 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 read¹ the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture², 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.

¹Technical 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 *Reading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms* by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

²Lecture 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 thinking³. 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

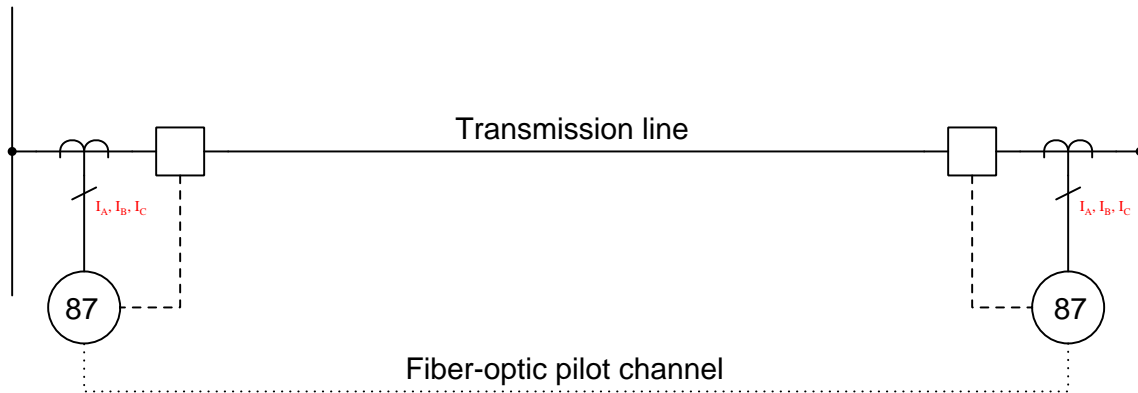
Capacitance

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 cases⁴” for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely⁵ on an answer key!

⁴In 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.

⁵This 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 (m³/kg-s²)

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-Kelvin⁴** (W/m²·K⁴)

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.

⁶Spreadsheets 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.

Common⁷ 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 ensure⁸ 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 roots⁹ 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.

⁷Modern 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.

⁸Spreadsheet 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.

⁹Reviewing 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:

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

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

	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	

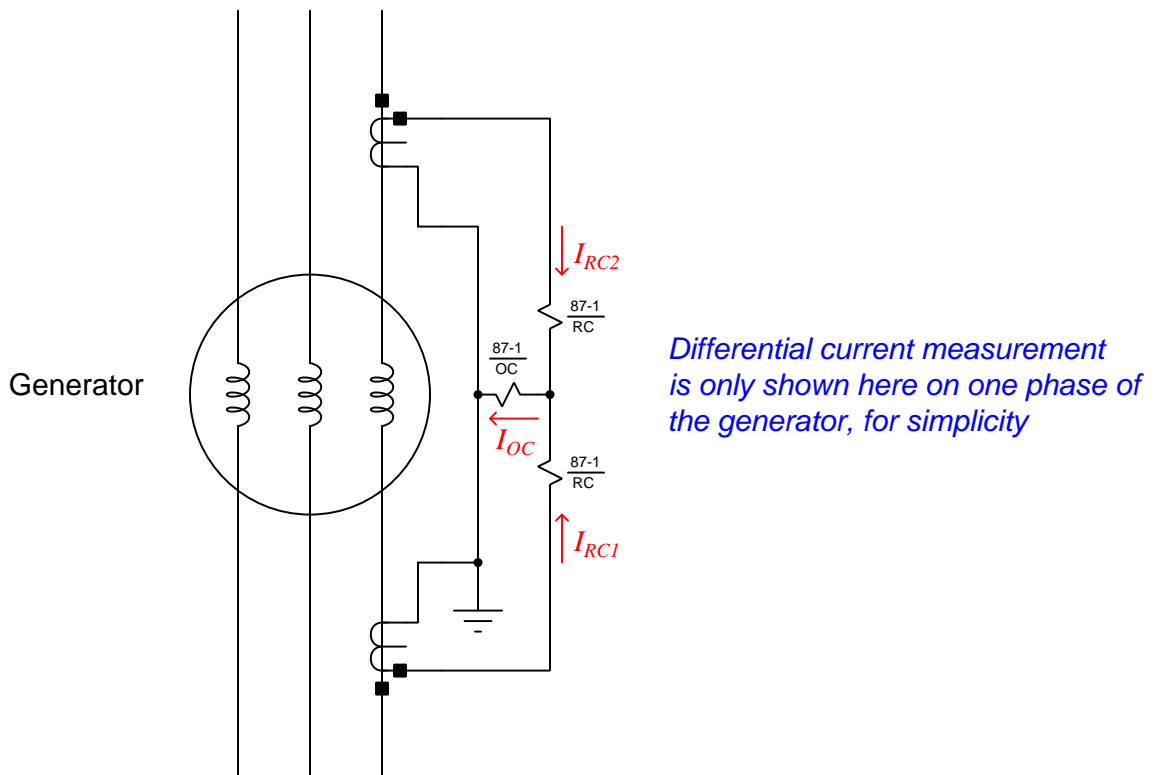
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary¹⁰ – all that matters is that they properly reference 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.

¹⁰My 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):



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

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

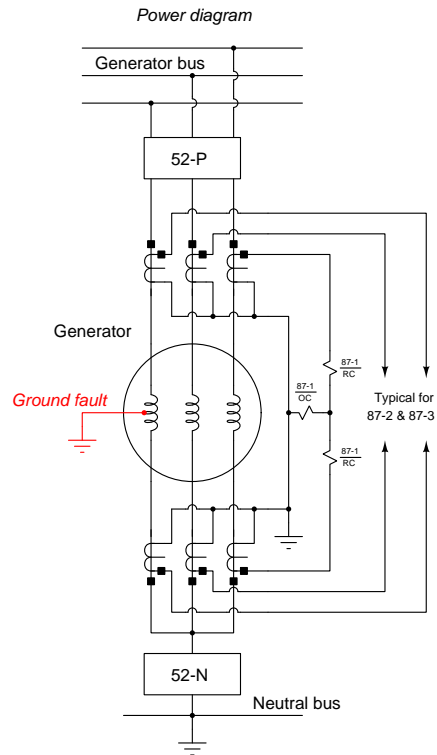
In addition to calculating a symbolic answer for I_{OC} , sketch a phasor diagram showing how the three currents (I_{RC1} , I_{RC2} , and I_{OC}) relate to one another.

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.

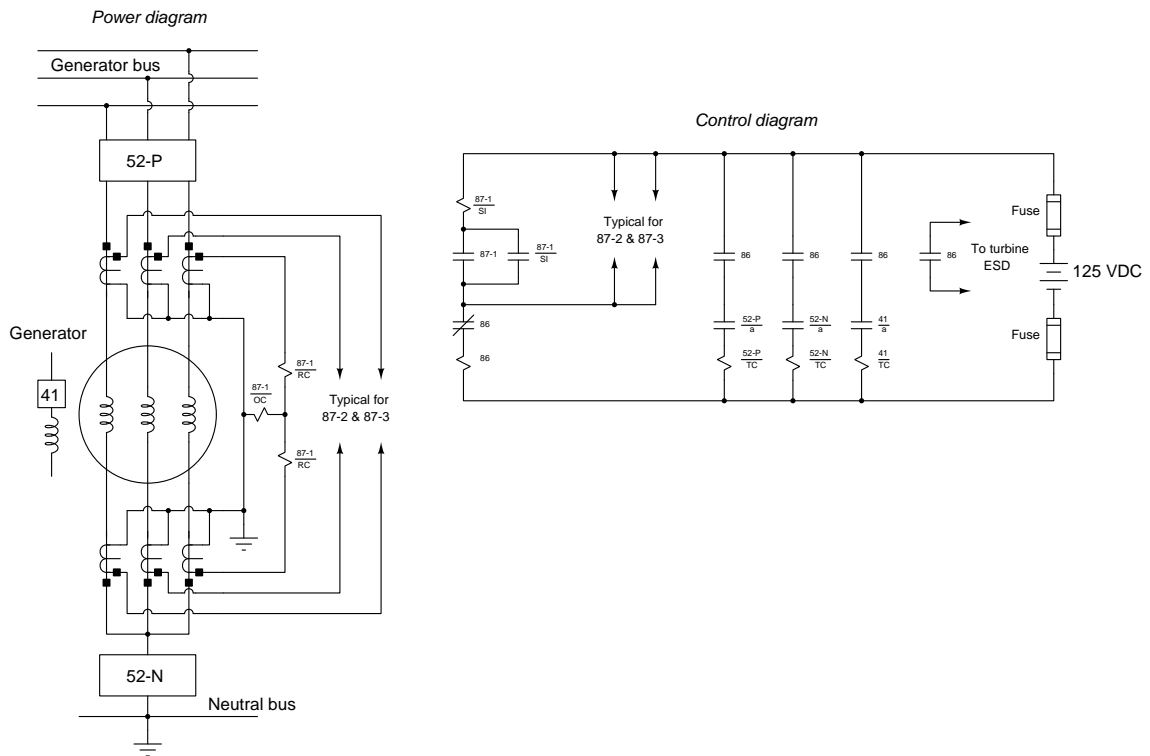
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of 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

“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.

The following principles inform the instructional and assessment philosophies embodied in these learning modules:

- 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 environment¹ 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 Socratic² 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 absurdity³ 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

¹In 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.

²Socrates 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.

³This 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 characteristic of these learning modules is a lack of step-by-step instructions in the Project and Experiment chapters. Unlike many modern workbooks and laboratory guides where step-by-step instructions are prescribed for each experiment, these modules take the approach that students must learn to closely read the tutorials and apply their own reasoning to identify the appropriate experimental steps. Sometimes these steps are plainly declared in the text, just not as a set of enumerated points. At other times certain steps are implied, an example being assumed competence in test equipment use where the student should not need to be told *again* how to use their multimeter because that was thoroughly explained in previous lessons. In some circumstances no steps are given at all, leaving the entire procedure up to the student.

This lack of prescription is not a flaw, but rather a feature. Close reading and clear thinking are foundational principles of this learning series, and in keeping with this philosophy all activities are designed to *require* those behaviors. Some students may find the lack of prescription frustrating, because it demands more from them than what their previous educational experiences required. This frustration should be interpreted as an unfamiliarity with autonomous thinking, a problem which must be corrected if the student is ever to become a self-directed learner and effective problem-solver. Ultimately, the need for students to read closely and think clearly is more important both in the near-term and far-term than any specific facet of the subject matter at hand. If a student takes longer than expected to complete a module because they are forced to outline, digest, and reason on their own, so be it. The future gains enjoyed by developing this mental discipline will be well worth the additional effort and delay.

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.

This methodology of assigning text-based modules to students for digestion and then using Socratic dialogue to assess progress and hone students’ thinking was developed over a period of several years by the author with his Electronics and Instrumentation students at the two-year college level. While decidedly unconventional and sometimes even unsettling for students accustomed to a more passive lecture environment, this instructional philosophy has proven its ability to convey conceptual mastery, foster careful analysis, and enhance employability so much better than lecture that the author refuses to ever teach by lecture again.

Problems which often go undiagnosed in a lecture environment are laid bare in this “inverted” format where students must articulate and logically defend their reasoning. This, too, may be unsettling for students accustomed to lecture sessions where the instructor cannot tell for sure who comprehends and who does not, and this vulnerability necessitates sensitivity on the part of the “inverted” session instructor in order that students never feel discouraged by having their errors exposed. *Everyone* makes mistakes from time to time, and learning is a lifelong process! Part of the instructor’s job is to build a culture of learning among the students where errors are not seen as shameful, but rather as opportunities for progress.

To this end, instructors managing courses based on these modules should adhere to the following principles:

- Student questions are always welcome and demand thorough, honest answers. The only type of question an instructor should refuse to answer is one the student should be able to easily answer on their own. Remember, *the fundamental goal of education is for each student to learn to think clearly and independently*. This requires hard work on the part of the student, which no instructor should ever circumvent. Anything done to bypass the student's responsibility to do that hard work ultimately limits that student's potential and thereby does real harm.
- It is not only permissible, but encouraged, to answer a student's question by asking questions in return, these follow-up questions designed to guide the student to reach a correct answer through their own reasoning.
- All student answers demand to be challenged by the instructor and/or by other students. This includes both correct and incorrect answers – the goal is to practice the articulation and defense of one's own reasoning.
- No reading assignment is deemed complete unless and until the student demonstrates their ability to accurately summarize the major points in their own terms. Recitation of the original text is unacceptable. This is why every module contains an "Outline and reflections" question as well as a "Foundational concepts" question in the Conceptual reasoning section, to prompt reflective reading.
- No assigned question is deemed answered unless and until the student demonstrates their ability to consistently and correctly apply the concepts to *variations* of that question. This is why module questions typically contain multiple "Challenges" suggesting different applications of the concept(s) as well as variations on the same theme(s). Instructors are encouraged to devise as many of their own "Challenges" as they are able, in order to have a multitude of ways ready to probe students' understanding.
- No assigned experiment or project is deemed complete unless and until the student demonstrates the task in action. If this cannot be done "live" before the instructor, video-recordings showing the demonstration are acceptable. All relevant safety precautions must be followed, all test equipment must be used correctly, and the student must be able to properly explain all results. The student must also successfully answer all Challenges presented by the instructor for that experiment or project.

Students learning from these modules would do well to abide by the following principles:

- No text should be considered fully and adequately read unless and until you can express every idea *in your own words, using your own examples*.
- You should always articulate your thoughts as you read the text, noting points of agreement, confusion, and epiphanies. Feel free to print the text on paper and then write your notes in the margins. Alternatively, keep a journal for your own reflections as you read. This is truly a helpful tool when digesting complicated concepts.
- Never take the easy path of highlighting or underlining important text. Instead, *summarize* and/or *comment* on the text using your own words. This actively engages your mind, allowing you to more clearly perceive points of confusion or misunderstanding on your own.
- A very helpful strategy when learning new concepts is to place yourself in the role of a teacher, if only as a mental exercise. Either explain what you have recently learned to someone else, or at least *imagine* yourself explaining what you have learned to someone else. The simple act of having to articulate new knowledge and skill forces you to take on a different perspective, and will help reveal weaknesses in your understanding.
- Perform each and every mathematical calculation and thought experiment shown in the text on your own, referring back to the text to see that your results agree. This may seem trivial and unnecessary, but it is critically important to ensuring you actually understand what is presented, especially when the concepts at hand are complicated and easy to misunderstand. Apply this same strategy to become proficient in the use of *circuit simulation software*, checking to see if your simulated results agree with the results shown in the text.
- 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 varied⁴ effort, and never give up!

Students interested in using these modules for self-study will also find them beneficial, although the onus of responsibility for thoroughly reading and answering questions will of course lie with that individual alone. If a qualified instructor is not available to challenge students, a workable alternative is for students to form study groups where they challenge⁵ one another.

To high standards of education,

Tony R. Kuphaldt

⁴As 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.

⁵Avoid the temptation to simply share answers with study partners, as this is really counter-productive to learning. Always bear in mind that the answer to any question is far less important in the long run than the method(s) used to obtain that answer. The goal of education is to empower one’s life through the improvement of clear and independent thought, literacy, expression, and various practical skills.

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 **T_EX** 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

Creative Commons License

Creative Commons Attribution 4.0 International Public License

By exercising the Licensed Rights (defined below), You accept and agree to be bound by the terms and conditions of this Creative Commons Attribution 4.0 International Public License (“Public License”). To the extent this Public License may be interpreted as a contract, You are granted the Licensed Rights in consideration of Your acceptance of these terms and conditions, and the Licensor grants You such rights in consideration of benefits the Licensor receives from making the Licensed Material available under these terms and conditions.

Section 1 – Definitions.

a. **Adapted Material** means material subject to Copyright and Similar Rights that is derived from or based upon the Licensed Material and in which the Licensed Material is translated, altered, arranged, transformed, or otherwise modified in a manner requiring permission under the Copyright and Similar Rights held by the Licensor. For purposes of this Public License, where the Licensed Material is a musical work, performance, or sound recording, Adapted Material is always produced where the Licensed Material is synched in timed relation with a moving image.

b. **Adapter’s License** means the license You apply to Your Copyright and Similar Rights in Your contributions to Adapted Material in accordance with the terms and conditions of this Public License.

c. **Copyright and Similar Rights** means copyright and/or similar rights closely related to copyright including, without limitation, performance, broadcast, sound recording, and Sui Generis Database Rights, without regard to how the rights are labeled or categorized. For purposes of this Public License, the rights specified in Section 2(b)(1)-(2) are not Copyright and Similar Rights.

d. **Effective Technological Measures** means those measures that, in the absence of proper authority, may not be circumvented under laws fulfilling obligations under Article 11 of the WIPO Copyright Treaty adopted on December 20, 1996, and/or similar international agreements.

e. **Exceptions and Limitations** means fair use, fair dealing, and/or any other exception or

limitation to Copyright and Similar Rights that applies to Your use of the Licensed Material.

f. **Licensed Material** means the artistic or literary work, database, or other material to which the Licensor applied this Public License.

g. **Licensed Rights** means the rights granted to You subject to the terms and conditions of this Public License, which are limited to all Copyright and Similar Rights that apply to Your use of the Licensed Material and that the Licensor has authority to license.

h. **Licensor** means the individual(s) or entity(ies) granting rights under this Public License.

i. **Share** means to provide material to the public by any means or process that requires permission under the Licensed Rights, such as reproduction, public display, public performance, distribution, dissemination, communication, or importation, and to make material available to the public including in ways that members of the public may access the material from a place and at a time individually chosen by them.

j. **Sui Generis Database Rights** means rights other than copyright resulting from Directive 96/9/EC of the European Parliament and of the Council of 11 March 1996 on the legal protection of databases, as amended and/or succeeded, as well as other essentially equivalent rights anywhere in the world.

k. **You** means the individual or entity exercising the Licensed Rights under this Public License. **Your** has a corresponding meaning.

Section 2 – Scope.

a. License grant.

1. Subject to the terms and conditions of this Public License, the Licensor hereby grants You a worldwide, royalty-free, non-sublicensable, non-exclusive, irrevocable license to exercise the Licensed Rights in the Licensed Material to:

A. reproduce and Share the Licensed Material, in whole or in part; and

B. produce, reproduce, and Share Adapted Material.

2. Exceptions and Limitations. For the avoidance of doubt, where Exceptions and Limitations apply to Your use, this Public License does not apply, and You do not need to comply with its terms and conditions.

3. Term. The term of this Public License is specified in Section 6(a).

4. Media and formats; technical modifications allowed. The Licensor authorizes You to exercise the Licensed Rights in all media and formats whether now known or hereafter created, and to make technical modifications necessary to do so. The Licensor waives and/or agrees not to assert any right or authority to forbid You from making technical modifications necessary to exercise the Licensed Rights, including technical modifications necessary to circumvent Effective Technological Measures.

For purposes of this Public License, simply making modifications authorized by this Section 2(a)(4) never produces Adapted Material.

5. Downstream recipients.

A. Offer from the Licensor – Licensed Material. Every recipient of the Licensed Material automatically receives an offer from the Licensor to exercise the Licensed Rights under the terms and conditions of this Public License.

B. No downstream restrictions. You may not offer or impose any additional or different terms or conditions on, or apply any Effective Technological Measures to, the Licensed Material if doing so restricts exercise of the Licensed Rights by any recipient of the Licensed Material.

6. No endorsement. Nothing in this Public License constitutes or may be construed as permission to assert or imply that You are, or that Your use of the Licensed Material is, connected with, or sponsored, endorsed, or granted official status by, the Licensor or others designated to receive attribution as provided in Section 3(a)(1)(A)(i).

b. Other rights.

1. Moral rights, such as the right of integrity, are not licensed under this Public License, nor are publicity, privacy, and/or other similar personality rights; however, to the extent possible, the Licensor waives and/or agrees not to assert any such rights held by the Licensor to the limited extent necessary to allow You to exercise the Licensed Rights, but not otherwise.

2. Patent and trademark rights are not licensed under this Public License.

3. To the extent possible, the Licensor waives any right to collect royalties from You for the exercise of the Licensed Rights, whether directly or through a collecting society under any voluntary or waivable statutory or compulsory licensing scheme. In all other cases the Licensor expressly reserves any right to collect such royalties.

Section 3 – License Conditions.

Your exercise of the Licensed Rights is expressly made subject to the following conditions.

a. Attribution.

1. If You Share the Licensed Material (including in modified form), You must:

A. retain the following if it is supplied by the Licensor with the Licensed Material:

i. identification of the creator(s) of the Licensed Material and any others designated to receive attribution, in any reasonable manner requested by the Licensor (including by pseudonym if designated);

ii. a copyright notice;

- iii. a notice that refers to this Public License;
- iv. a notice that refers to the disclaimer of warranties;
- v. a URI or hyperlink to the Licensed Material to the extent reasonably practicable;

B. indicate if You modified the Licensed Material and retain an indication of any previous modifications; and

C. indicate the Licensed Material is licensed under this Public License, and include the text of, or the URI or hyperlink to, this Public License.

2. You may satisfy the conditions in Section 3(a)(1) in any reasonable manner based on the medium, means, and context in which You Share the Licensed Material. For example, it may be reasonable to satisfy the conditions by providing a URI or hyperlink to a resource that includes the required information.

3. If requested by the Licensor, You must remove any of the information required by Section 3(a)(1)(A) to the extent reasonably practicable.

4. If You Share Adapted Material You produce, the Adapter's License You apply must not prevent recipients of the Adapted Material from complying with this Public License.

Section 4 – Sui Generis Database Rights.

Where the Licensed Rights include Sui Generis Database Rights that apply to Your use of the Licensed Material:

- a. for the avoidance of doubt, Section 2(a)(1) grants You the right to extract, reuse, reproduce, and Share all or a substantial portion of the contents of the database;
- b. if You include all or a substantial portion of the database contents in a database in which You have Sui Generis Database Rights, then the database in which You have Sui Generis Database Rights (but not its individual contents) is Adapted Material; and
- c. You must comply with the conditions in Section 3(a) if You Share all or a substantial portion of the contents of the database.

For the avoidance of doubt, this Section 4 supplements and does not replace Your obligations under this Public License where the Licensed Rights include other Copyright and Similar Rights.

Section 5 – Disclaimer of Warranties and Limitation of Liability.

a. Unless otherwise separately undertaken by the Licensor, to the extent possible, the Licensor offers the Licensed Material as-is and as-available, and makes no representations or warranties of any kind concerning the Licensed Material, whether express, implied, statutory, or other. This includes, without limitation, warranties of title, merchantability, fitness for a particular purpose, non-infringement, absence of latent or other defects, accuracy, or the presence or absence of errors,

whether or not known or discoverable. Where disclaimers of warranties are not allowed in full or in part, this disclaimer may not apply to You.

b. To the extent possible, in no event will the Licensor be liable to You on any legal theory (including, without limitation, negligence) or otherwise for any direct, special, indirect, incidental, consequential, punitive, exemplary, or other losses, costs, expenses, or damages arising out of this Public License or use of the Licensed Material, even if the Licensor has been advised of the possibility of such losses, costs, expenses, or damages. Where a limitation of liability is not allowed in full or in part, this limitation may not apply to You.

c. The disclaimer of warranties and limitation of liability provided above shall be interpreted in a manner that, to the extent possible, most closely approximates an absolute disclaimer and waiver of all liability.

Section 6 – Term and Termination.

a. This Public License applies for the term of the Copyright and Similar Rights licensed here. However, if You fail to comply with this Public License, then Your rights under this Public License terminate automatically.

b. Where Your right to use the Licensed Material has terminated under Section 6(a), it reinstates:

1. automatically as of the date the violation is cured, provided it is cured within 30 days of Your discovery of the violation; or

2. upon express reinstatement by the Licensor.

For the avoidance of doubt, this Section 6(b) does not affect any right the Licensor may have to seek remedies for Your violations of this Public License.

c. For the avoidance of doubt, the Licensor may also offer the Licensed Material under separate terms or conditions or stop distributing the Licensed Material at any time; however, doing so will not terminate this Public License.

d. Sections 1, 5, 6, 7, and 8 survive termination of this Public License.

Section 7 – Other Terms and Conditions.

a. The Licensor shall not be bound by any additional or different terms or conditions communicated by You unless expressly agreed.

b. Any arrangements, understandings, or agreements regarding the Licensed Material not stated herein are separate from and independent of the terms and conditions of this Public License.

Section 8 – Interpretation.

a. For the avoidance of doubt, this Public License does not, and shall not be interpreted to, reduce, limit, restrict, or impose conditions on any use of the Licensed Material that could lawfully

be made without permission under this Public License.

b. To the extent possible, if any provision of this Public License is deemed unenforceable, it shall be automatically reformed to the minimum extent necessary to make it enforceable. If the provision cannot be reformed, it shall be severed from this Public License without affecting the enforceability of the remaining terms and conditions.

c. No term or condition of this Public License will be waived and no failure to comply consented to unless expressly agreed to by the Licensor.

d. Nothing in this Public License constitutes or may be interpreted as a limitation upon, or waiver of, any privileges and immunities that apply to the Licensor or You, including from the legal processes of any jurisdiction or authority.

Creative Commons is not a party to its public licenses. Notwithstanding, Creative Commons may elect to apply one of its public licenses to material it publishes and in those instances will be considered the “Licensor.” Except for the limited purpose of indicating that material is shared under a Creative Commons public license or as otherwise permitted by the Creative Commons policies published at creativecommons.org/policies, Creative Commons does not authorize the use of the trademark “Creative Commons” or any other trademark or logo of Creative Commons without its prior written consent including, without limitation, in connection with any unauthorized modifications to any of its public licenses or any other arrangements, understandings, or agreements concerning use of licensed material. For the avoidance of doubt, this paragraph does not form part of the public licenses.

Creative Commons may be contacted at creativecommons.org.

Appendix E

References

Blackburn, J. Lewis and Domin, Thomas J., *Protective Relaying Principles and Applications*, Third Edition, CRC Press, Taylor & Francis Group, Boca Raton, FL, 2007.

Mason, C. Russell, *The Art and Science of Protective Relaying*, First Edition, John Wiley & Sons, 1956.

Todd, Victor H., *Protective Relays – their theory, design, and practical operation*, First Edition, Fourth Impression, McGraw-Hill Book Company, Inc., New York, 1922.

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.

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.

Index

- 87 relay, differential protection, 9
- Adding quantities to a qualitative problem, 42
- Annotating diagrams, 41
- Bus, electrical power, 16, 17
- Charging current, power line, 16
- Checking for exceptions, 42
- Checking your work, 42
- Code, computer, 49
- Conservation of Electric Charge, 3, 7
- Differential current protection, 9
- Differential voltage protection, 9
- Dimensional analysis, 41
- Edwards, Tim, 50
- External fault, power system protection zone, 14
- GE Multilin model 745 protective relay, 12
- Graph values to solve a problem, 42
- Greenleaf, Cynthia, 21
- Ground fault, 9
- How to teach with these modules, 44
- Hwang, Andrew D., 51
- Identify given data, 41
- Identify relevant principles, 41
- Instructions for projects and experiments, 45
- Intermediate results, 41
- Internal fault, power system protection zone, 14
- Inverted instruction, 44
- KCL, 3, 7
- Kirchhoff's Current Law, 3, 7
- Knuth, Donald, 50
- Lamport, Leslie, 50
- Limiting cases, 42
- Metacognition, 26
- Moolenaar, Bram, 49
- Murphy, Lynn, 21
- Open-source, 49
- Operating coil, protective relay, 10
- Pick-up, 8, 10
- Pilot, protective relay, 16
- Power line charging current, 16
- Problem-solving: annotate diagrams, 41
- Problem-solving: check for exceptions, 42
- Problem-solving: checking work, 42
- Problem-solving: dimensional analysis, 41
- Problem-solving: graph values, 42
- Problem-solving: identify given data, 41
- Problem-solving: identify relevant principles, 41
- Problem-solving: interpret intermediate results, 41
- Problem-solving: limiting cases, 42
- Problem-solving: qualitative to quantitative, 42
- Problem-solving: quantitative to qualitative, 42
- Problem-solving: reductio ad absurdum, 42
- Problem-solving: simplify the system, 41
- Problem-solving: thought experiment, 41
- Problem-solving: track units of measurement, 41
- Problem-solving: visually represent the system, 41
- Problem-solving: work in reverse, 42
- Protection zone, power system, 14
- Qualitatively approaching a quantitative problem, 42
- Reading Apprenticeship, 21

- Reductio ad absurdum, [42–44](#)
- Restrained differential relay, [11](#)
- Restraint coil, protective relay, [11](#)

- Schoenbach, Ruth, [21](#)
- Schweitzer Engineering Laboratories model SEL-387L differential current relay, [16](#)
- Scientific method, [26](#)
- Selectivity, protective relay, [14](#)
- Sensitivity, [8](#)
- Simplifying a system, [41](#)
- Socrates, [43](#)
- Socratic dialogue, [44](#)
- Speed, [8](#)
- SPICE, [21](#)
- Stallman, Richard, [49](#)

- Thought experiment, [41](#)
- Torvalds, Linus, [49](#)

- Units of measurement, [41](#)
- Unrestrained differential relay, [11](#)

- Visualizing a system, [41](#)

- Work in reverse to solve a problem, [42](#)
- WYSIWYG, [49](#), [50](#)

- Zone of protection, power system, [14](#)