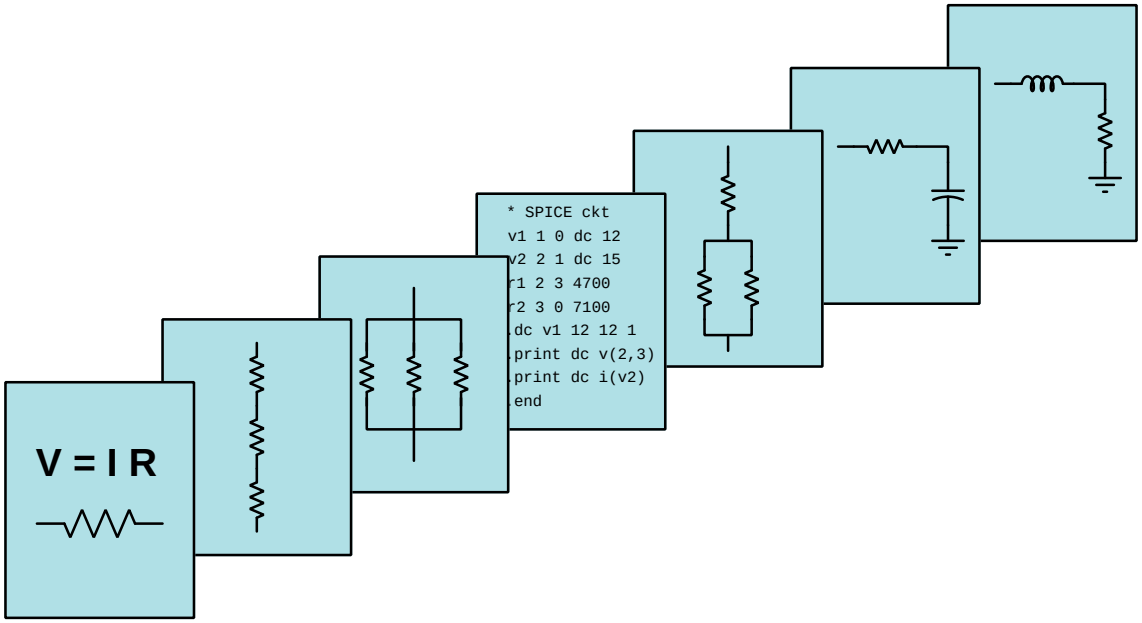
Modular Electronics Learning (ModEL) project



Principles of Protective Relaying

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Chapter 1

Introduction

1.1 Recommendations for students

When an electric power system component fails, the effect of that failure may cause more damage and/or threat to life and limb than the initial fault, and it is the purpose of protection devices to de-energize that failed component as soon as possible. Special devices called *protective relays* are made to equip circuit breakers with "intelligence" for discriminating faults in electric power systems. A protective relay senses power circuit conditions by monitoring the output signals of sensors and instrument transformers connected to the power circuit, and then sends a discrete (on/off) signal commanding a circuit breaker to trip when those conditions pass safe thresholds. Protective relays may be made as complex as necessary to detect specific types of fault conditions, connected together to form comprehensive *protection schemes*, and maintained independent of the sensors and breakers they connect to.

This module is intended to give the reader a broad overview of protective relays and some of the important general concepts associated with electric power system protection.

Important concepts related to protective relays include **reliability**, **dependability**, **security**, **fuses**, **circuit breakers**, **instrument transformers**, **station power**, **trip** and **close** coils, **coordination**, **protection zones**, **feeders**, **busses**, **pick-up**, , and **ANSI/IEEE codes**.

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

- How might an experiment be designed and conducted to explore the concept of overcurrent coordination in an electric circuit? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What are some of the ways in which medium- and high-voltage circuit breakers differ from residential circuit breakers?
- What are the advantages and disadvantages of fuses, in contrast with circuit breakers?
- How does a protective relay sense dangerous conditions in a power circuit?
- What action does a protective relay take when it senses a dangerous condition?

- How do induction-disk relays differ in operation from simple solenoid-type protective relays?
- What does it mean for a protection system to "trip minimally and trip quickly"?
- What is a protection zone?
- How are the boundaries of a protection zone established in a real power system?
- What does it mean to coordinate overcurrent protection devices?
- Does coordination apply to fuses as well as overcurrent relays?
- What are some of the different types of protective relays?

1.2 Challenging concepts related to circuit breakers and disconnects

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

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

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 present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Interpret protective actions for power systems in single-line diagrams

  Assessment – Identify which circuit breakers must trip in order to clear a fault in an electrical power system; e.g. pose problems in the form of the "Proper breakers to trip" Conceptual Reasoning question.

  Assessment – Identify which protective relays will detect a fault in an electrical power system; e.g. pose problems in the form of the "Identifying which relays will pick up" Conceptual Reasoning question.

- **Outcome** – Interpret an overcurrent protection curve

  Assessment – Explain how to interpret/apply a fuse curve; e.g. pose problems in the form of the "Fuse curve" Quantitative Reasoning question.

  Assessment – Explain how to interpret/apply an overcurrent relay curve; e.g. pose problems in the form of the "Overcurrent relay curve" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate protective relay datasheets and properly interpret some of the information contained in those documents including principle of operation, ANSI/IEEE protective functions offered, instrument transformer connections, etc.

Chapter 2

Simplified Tutorial

All machines eventually fail. Some fail more spectacularly than others.

When electric power systems fail, they tend to fail spectacularly because the *normal* amount of energy they convey is staggering in scope. A typical nuclear power plant or major hydroelectric dam outputs over a *billion* Watts of electric power to customers, more than enough to cause major damage if mis-directed. In order to prevent relatively minor faults in an electric power system from causing major damage, dedicated protection devices exist to automatically de-energize the faulted component(s).

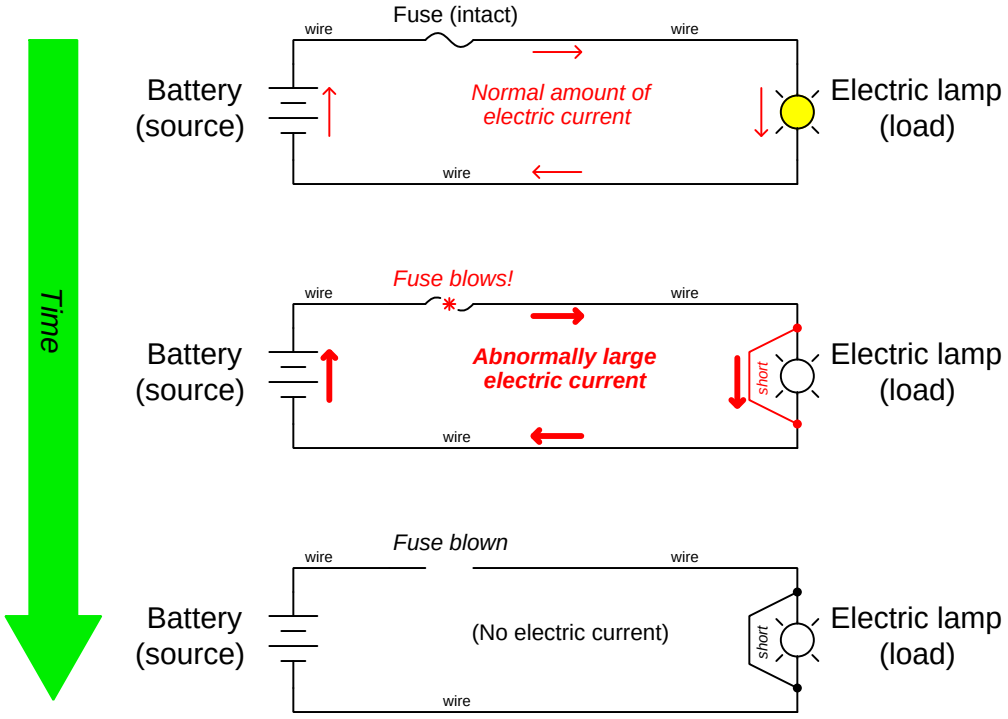
It is the purpose of any electric power system to convey energy from *sources* to *loads*. Sources include hydroelectric dams, wind turbines, solar arrays, coal-fired power plants, nuclear power plants, gas turbine power plants, etc. Loads include everything from electric lamps and electronic appliances in your home to huge electric motors and arc furnaces in industrial facilities. Those thin wires you see stretched for kilometers, suspended on power poles, are the conduits for all this energy. The purpose for all the power lines, substations, and other electrical "grid" apparatus visible in our modern world is to direct the energy where it should go, and prevent the energy from going places it should not.

What happens when electrical energy goes places it should not? Energy is *that which sets matter into motion*, and so mis-directed electrical energy makes things move that should not move. Specifically, this motion usually takes the form of *heat* which is the result of molecular vibration (atomic-level motion), which means mis-directed electricity poses a fire hazard. In some cases the hazard is even more severe than a fire, because an electric arc (i.e. electricity passing through ionized air) is capable of temperatures of at least 19,000 degrees Celsius – over three times hotter than the surface of the Sun! This intense heat is capable of vaporizing metal and causing air to explosively expand, a phenomenon called *arc blast*.

Not only is mis-directed electricity hazardous to life and limb, but it also takes a toll on the very expensive equipment comprising an electric power system. Expensive electrical machinery such as generators and transformers are susceptible to damage from electrical faults, and must be protected from damage in order to ensure rapid and reliable restoration of electric power service.

Fuses were the first protective devices historically used for electric power systems, and are still used today. Their operation is simple: a relatively fragile strip of metal conducts the electric current, and will disintegrate if ever that current exceeds safe operating levels for that circuit. A "blown" fuse opens the circuit and halts current through anything connected in-line with it, effectively "clearing" the fault to prevent further damage. A blown fuse is akin to a blockage inside a water pipe, preventing flow through that pipe.

The following series of schematic diagrams show how a fuse protects a simple electric circuit from the damaging effects of a "short" (a type of electrical fault[1]). Under normal conditions electricity travels in a loop, conducted by metal wires to and from the load, conveying energy from source to load in a manner not unlike a hydraulic system using pressurized liquid to convey energy from a pump (hydraulic source) a piston actuator or hydraulic motor (load)[2]. In a circuit the fuse conducts electricity like any wire, but when a short occurs at the lamp causing a greater flow of electric current the fuse quickly burns open and interrupts that flow:



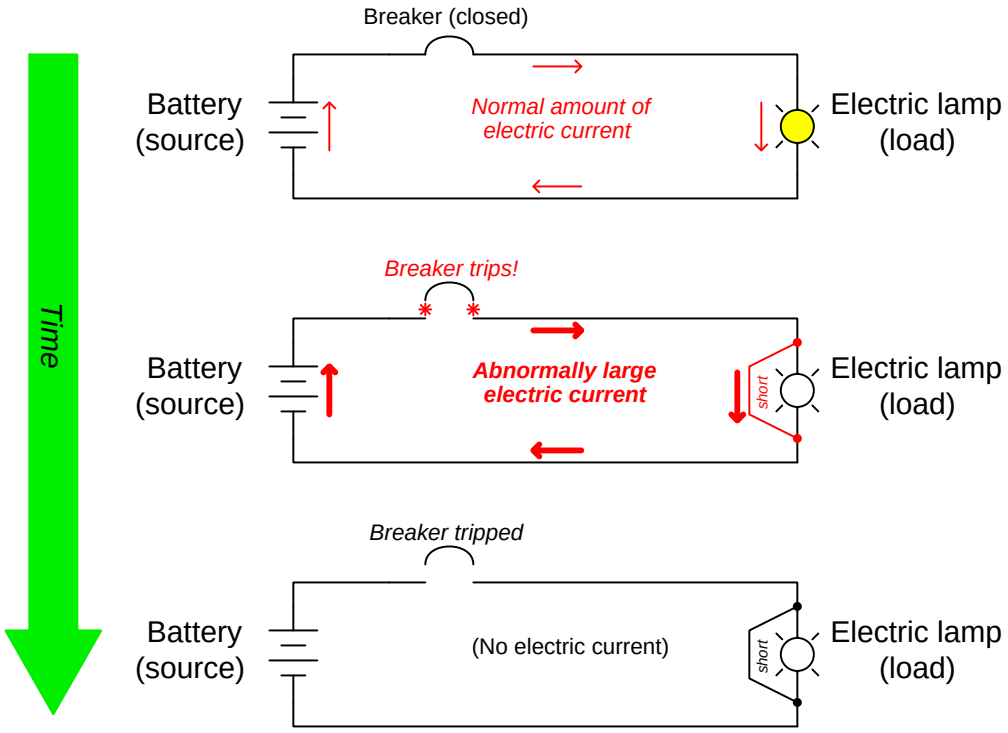
A well-selected fuse is the "weakest link" in the chain comprising any circuit, intended to rupture before any harm comes to something more expensive or more difficult to replace than the fuse itself.

[1] Realistic examples of "shorts" in electric power systems include detached wires that touch other wires they're not supposed to (or coming into contact with the Earth), tree limbs falling across power lines, animals finding their way between power line conductors and bridging the gap, etc.

[2] Although the sub-atomic electric charges move in a circuitous path through the conductive wires, *energy* always moves from source to load. A mechanical analogy is the chain on a bicycle which "circulates" around both driving and driven sprockets, yet the mechanical energy travels unidirectionally from the pedals to the wheel.

Next in the evolution of power system protection was the advent of the self-tripping *circuit breaker*: a switch designed to turn itself off (i.e. *trip*) if ever current exceeds a pre-set limit. Like fuses, these mechanisms are relatively simple and reliable, and enjoy the advantage of being easily reset (i.e. turned back on) to restore electric power service. Fuses are one-time-use devices and must be replaced after "blowing" open. A tripped circuit breaker is akin to a shut-off valve in a water pipe, preventing flow but allowing flow to resume once more when reset (i.e. opened up).

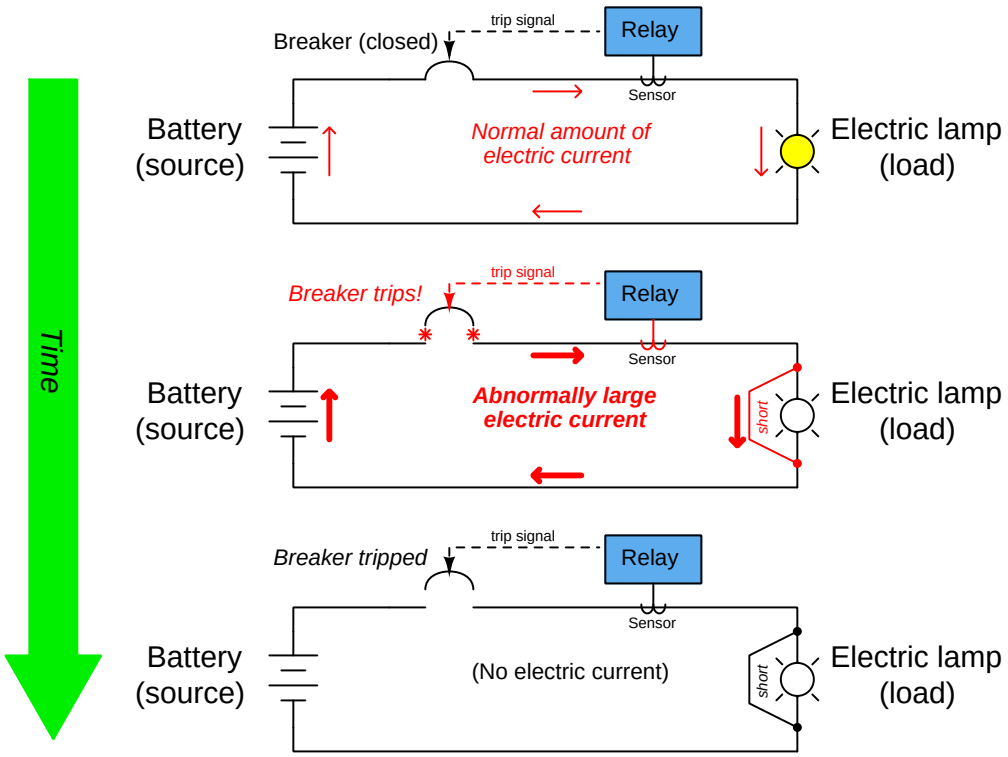
Like a fuse, a circuit breaker permits normal amounts of electric current to pass through, but automatically trips if ever current exceeds a pre-set limit:



However, both fuses and self-tripping circuit breakers lack discrimination between different types of fault conditions, and as a result may de-energize sections of a power system unnecessarily. In modern power systems supplying critical services with electricity (e.g. traffic signal systems, water treatment plants, hospitals), unnecessary power outages are more than just inconveniences. In order to maximize electric power *reliability* – consisting both of *dependability* in automatic fault-clearing as well as *security* in maintaining power whenever possible – more "intelligence" is necessary than what is possible with fuses and self-tripping circuit breakers alone.

This is the role played by *protective relays*: special-purpose devices designed to detect abnormal conditions in an electric power system and send command signals causing circuit breakers to trip (and/or close). Being separate from the circuit breaker itself, a protective relay may be made as complex as necessary in order to fulfill its function, and multiple relays may be interconnected to provide forms of protection unattainable by any one device alone.

A protective relay serves as an "intelligent control" instructing a circuit breaker when to trip (and for some relays, when to re-close). Being a sensitive and precise instrument, a protective relay is capable of repeatable action far superior to a self-actuated circuit breaker or a fuse:

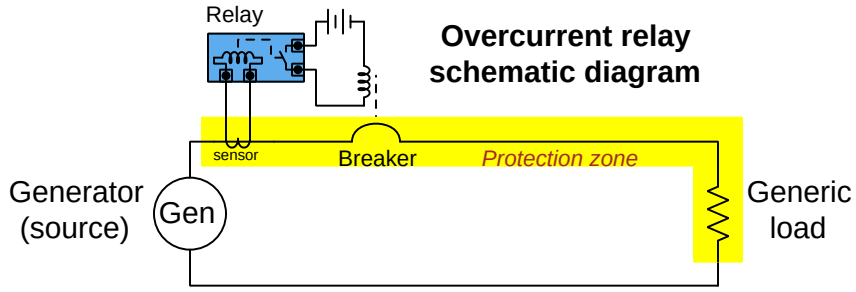


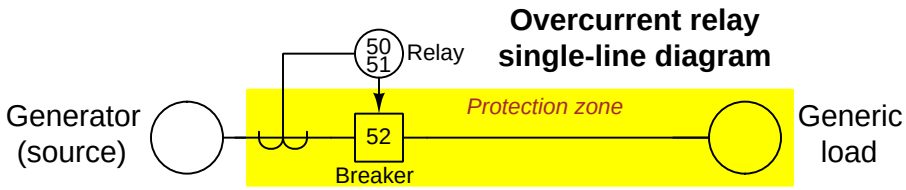
With modern electronic technology, protective relays may be located many kilometers away from the circuit breakers they control – for example at the far end of a long-distance power line – detecting dangerous conditions that would be otherwise unknown at the location of the circuit breaker. Thus, protective relays not only make fault detection and corrective action more accurate, but they may act upon fault conditions that were previously inactionable!

Microprocessor-based digital protective relays can also take high-speed measurements of the electric circuit's condition during a fault event, and store that recorded data for later analysis. This data has forensic value, like flight recorder data recovered after an airplane crash, to help power system professionals isolate the root-cause of the fault and restore electric power service as quickly and safely as possible.

Different types of protective relays exist for different purposes, and we will explore just a few of them here. The first and most elementary type of protective relay mimics the behavior of a fuse, and is called an *overcurrent relay*. It senses electric current through the power line and commands a circuit breaker to trip if that current exceeds a pre-set value. The "protection zone" for an overcurrent relay is anything "downstream" (i.e. away from the source and toward the load) of its current-sensing element, delineating those areas of the system where a short-circuit fault could be detected by the relay.

Two types of circuit diagrams will be used to show an overcurrent relay in context: *schematic diagram* revealing every wire in the circuit, and a *single-line diagram* representing the circuit as one line on the page instead of multiple wires. Single-line diagrams represent the power system's function analogous to water distributed through a piping system: the reader is asked to think of electricity as a unidirectional flow of *energy* moving from the source to the load rather than as a *circuitous* motion of electric charge carriers through sets of wires:

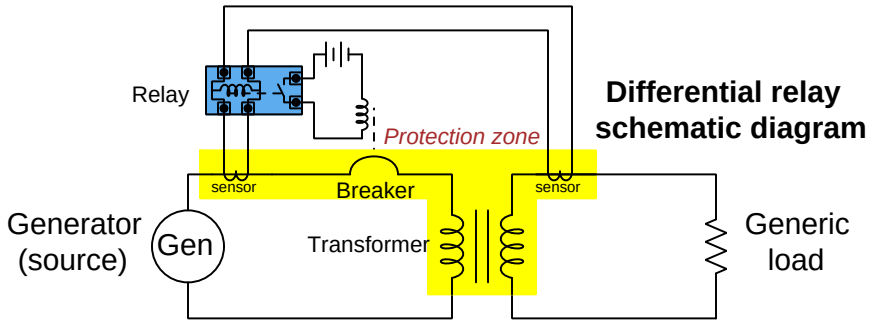


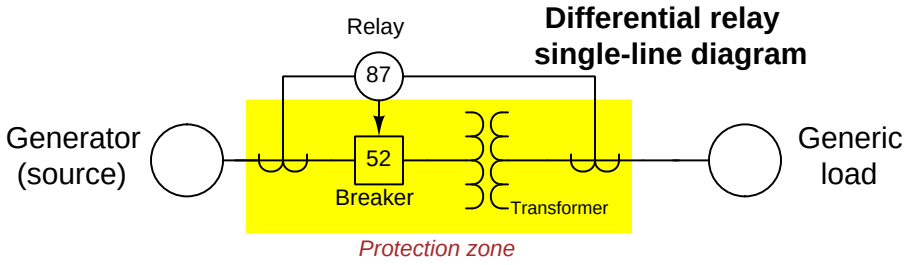


A convention in single-line diagrams is to label relays and other specific pieces of electrical equipment by industry-standardized numerical codes. *52* is the ANSI/IEEE device code for a power circuit breaker. *50* and *51* are ANSI/IEEE functional codes for instantaneous overcurrent and time-overcurrent protection, respectively. The yellow-shaded protection zones shown in these two diagrams are usually omitted from industry-standard diagrams, the reader being expected to discern those zones based on their knowledge of relay functions and the placement of the sensors.

Another type of protective relay is the *differential current* relay, designated by the ANSI/IEEE function code *87*. It works by sensing the amount of electric current entering and exiting a portion of the circuit, checking to see if those currents match each other. If not, the relay concludes that current must be "leaking" somewhere else and it responds by tripping the circuit breaker.

A popular application of differential current protection is for devices called *transformers* which are extensively used in electric power transmission and distribution systems to boost efficiency. Schematic and single-line examples are shown below:

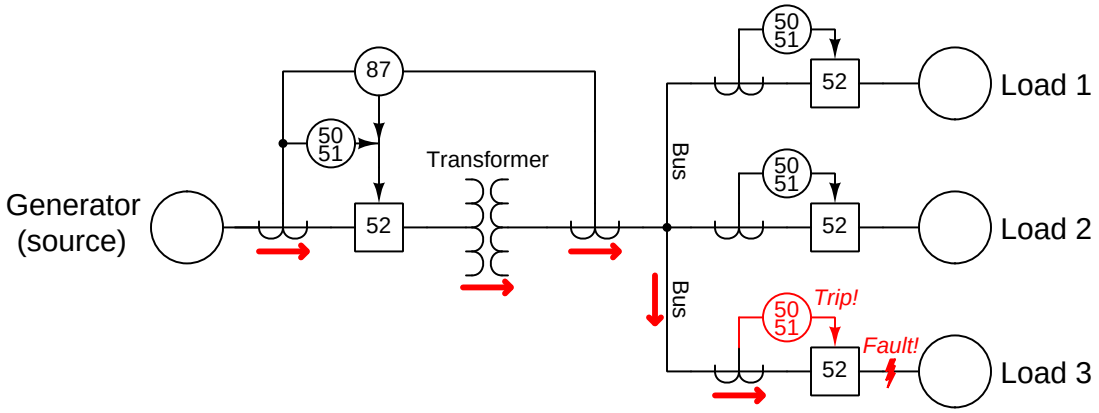




Differential protection requires sensing on both sides of the protected zone. Interestingly, differential protection provides far greater sensitivity in detecting faults than simple overcurrent protection because *any amount of discrepancy* between the in-going and out-going currents represents a mis-direction of the electricity. Overcurrent relays, by contrast, cannot identify the presence of a fault unless and until the magnitude of that fault current becomes larger than the maximum allowable current for that circuit. The more sensitive a protective relay is, the faster it will react to the onset of any fault, and the less damage will occur.

With differential current protection we see another characteristic of well-designed power system protection: *discrimination*. This means the ability to recognize faults within the protection zone but ignore faults outside of the protection zone. The differential relay (87) should trip the breaker for any fault occurring inside the transformer, but it should *ignore* any fault occurring at the load. The rationale for having a protective relay discriminate between in-zone faults and out-of-zone faults is that this specificity of protection allows us to design protection *systems* whereby any conceivable fault is detected and "cleared" as fast as possible with a minimum amount of disruption as possible.

In order to explore this principle, we will need to consider a more complicated electrical power system. The following single-line diagram shows one such system, with a generator, transformer, "bus" conductors, and three separate loads, and is currently shown with a fault at load 3:

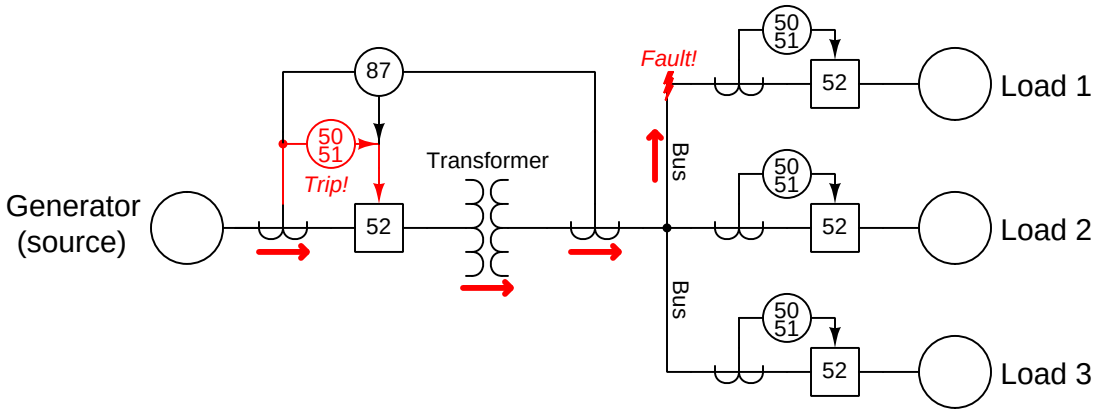


The 50/51 (overcurrent) relay near load 3 should be the only one to trip, even though this same fault current is sensed by the transformer's 87 (differential) relay and the main 50/51 relay near the generator. The differential relay should not trip on this fault because it's out of the relay's protection zone (i.e. the differential relay senses no *discrepancy* between incoming versus outgoing currents). The main overcurrent relay near the generator should not trip on this fault either because it's programmed to expect the combined load currents rather than just one, and so its trip setting will be higher[3] than load 3's overcurrent relay. If either the 87 or the main 50/51 relay tripped on this fault, it would shut power off to all three loads rather than selectively clearing the fault on load 3.

An important principle in electric power system protection is for protective relays to *trip minimally and trip quickly*. To "trip minimally" means to trip only those circuit breakers absolutely necessary to interrupt fault current and no more, in order to avoid interrupting electric power service to non-faulted loads. To "trip quickly" means to trip the necessary circuit breaker(s) as rapidly as possible once the fault is detected because the longer a fault is energized, the greater the damage. The goal is always to minimize hazard while maximizing availability of the electric power service.

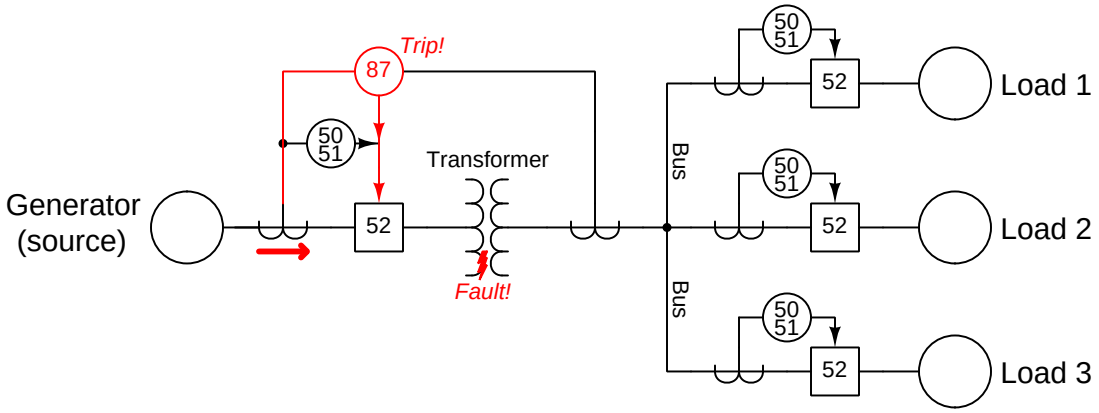
[3] This is a good example of *coordination* between overcurrent relays, ensuring "upstream" relays trip later/slower than "downstream" relays

Next we will see how this system responds to a fault on the distribution bus[4]:



None of the load overcurrent relays "see" this fault's current, leaving it to the main 50/51 overcurrent relay near the generator to clear the fault. Once again the 87 differential relay ignores this fault because it lies outside of its protection zone. Tripping the main circuit breaker (near the generator) of course cuts power to all loads, but in this case there is nothing else to do.

Lastly, we will consider how this system responds to a fault within the transformer:



This fault will be cleared very quickly, owing to the extreme sensitivity of the differential (87) relay. None of the overcurrent relays in this system will trip, not even the main 50/51 relay near the generator because the 87 relay will detect and act upon the sensed fault well before the fault current reaches a level that would be deemed excessive by the main overcurrent relay.

[4] A "bus" is nothing more than a collection of conductors connecting multiple power system components together, usually found in a *substation* or other secure electrical power facility. The conductors are either metal cables or metal tubes suspended from wooden or metal structures by porcelain insulators.

Overcurrent and differential current relays are just two types applied in modern power system protection. Many others exist, including the following:

- **Reclosing** (ANSI/IEEE number 79) – This is a variant of overcurrent protection, where the relay has the ability to both trip and close the circuit breaker. A reclosing relay waits for a short period of time following an overcurrent event before re-closing the breaker to "test" for the continued presence of a fault. This is useful in distribution systems using overhead power lines, where tree limbs and small animals comprise the majority of faults, and often "self-clear" during the fault. Reclosing relays make multiple attempts to restore power, and if the fault persists after the maximum number of "shots" it *locks out* and leaves the breaker in a tripped condition for a human line crew to investigate and remove the fault.

- **Distance** (ANSI/IEEE number 21) – When a fault occurs on a long-distance transmission line, it is helpful to know approximately where that fault is to expedite repairs. Distance relays do this by sensing voltage and current, mathematically estimating the distance between the relay and the fault based on known electrical characteristics of the transmission line. If that estimated distance falls within the programmed "reach" of the distance relay, it trips the breaker.

- **Directional** or **Reverse** power (ANSI/IEEE number **32**) detects when energy flows in the wrong direction. This function is intended to prevent *sources* (generators) from behaving as loads (motors).

Chapter 3

Full Tutorial

3.1 Overcurrent protection

All machines eventually fail. Some fail more spectacularly than others.

The above statements, as obvious as they may be, apply very strongly to electric power systems. In an industrialized nation's electric power grid where a large nuclear power plant or major hydroelectric dam outputs over a *billion* Watts of electric power to loads under normal operating conditions, the effect of certain power system components failing is spectacular indeed. In order to prevent relatively minor faults in an electric power system from causing major damage, dedicated protection devices exist to automatically de-energize the faulted component(s).

Fuses were the first protective devices historically used for electric power systems, and still find wide use today. Their operation is simple: a relatively fragile strip of metal conducts the electric current, and will disintegrate if ever that current exceeds safe operating levels for that circuit. A "blown" fuse opens the circuit and halts current through anything connected in-line with it, effectively "clearing" the fault to prevent further damage.

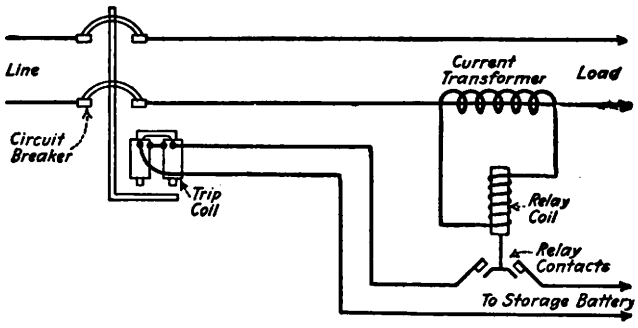
A technological advance over fuses are self-tripping *circuit breakers*: mechanical switches designed to turn themselves off (i.e. *trip*) if ever current through them exceeds a pre-set limit. Like fuses, these mechanisms are relatively simple and reliable, and enjoy the advantage of being easily reset (i.e. turned back on) to restore electric power service. Fuses are one-time-use devices and must be replaced after "blowing" open.

However, both fuses and self-tripping circuit breakers are simply too crude to discriminate between different types of fault conditions, and therefore may de-energize sections of a power system unnecessarily. In modern power systems where many critical services depend on electricity to function (e.g. traffic signal systems, water treatment plants, hospitals), unnecessary power outages are more than just inconveniences. In order to maximize electric power *reliability* – consisting both of *dependability* in automatic fault-clearing as well as *security* in maintaining power whenever possible – more "intelligence" is necessary than what is possible with fuses and self-tripping circuit breakers alone.

This is the role played by *protective relays*: special-purpose devices designed to detect abnormal conditions in an electric power system and send command signals causing circuit breakers to trip (and/or close). Being separate from the circuit breaker itself, a protective relay may be made as complex as necessary in order to fulfill its function, and multiple relays may be interconnected to provide forms of protection unattainable by any one device alone.

3.2 Historical relay designs

The technical discipline of protective relaying is over 100 years old. A primitive protective relay and circuit breaker may be seen in this schematic diagram, taken from page 17 of Victor Todd's book *Protective Relays – their theory, design, and practical operation* published in 1922:



Here, we see a two-pole circuit breaker used to interrupt power to a single-phase (two-wire) load. The breaker mechanism will be "tripped" to its open (off) state if ever its trip solenoid coil is energized by an external source. That external source in this protection system is a chemical battery ("storage battery"), and the trip circuit is made complete by a normally-open relay whose coil is energized by current from a CT (current transformer). If ever the line current exceeds a pre-set limit, the protective relay "picks up" and closes its trip contact, sending DC electricity to the circuit breaker's trip coil to initiate the trip. Thus, this protective relay system is intended to detect a condition of *overcurrent*, immediately tripping the breaker if line current exceeds a pre-set threshold.

This particular protective relay example is perhaps the simplest possible design, intended to detect a condition of dangerous overcurrent and take swift action to trip the breaker feeding that current. Many other types and designs of protective relay exist, which are all more complex than this simple example. As complex and intricate as some protective relays are, though, they all trip circuit breakers in the same general manner: by closing[1] a switch contact to pass DC electricity to a trip coil inside the breaker.

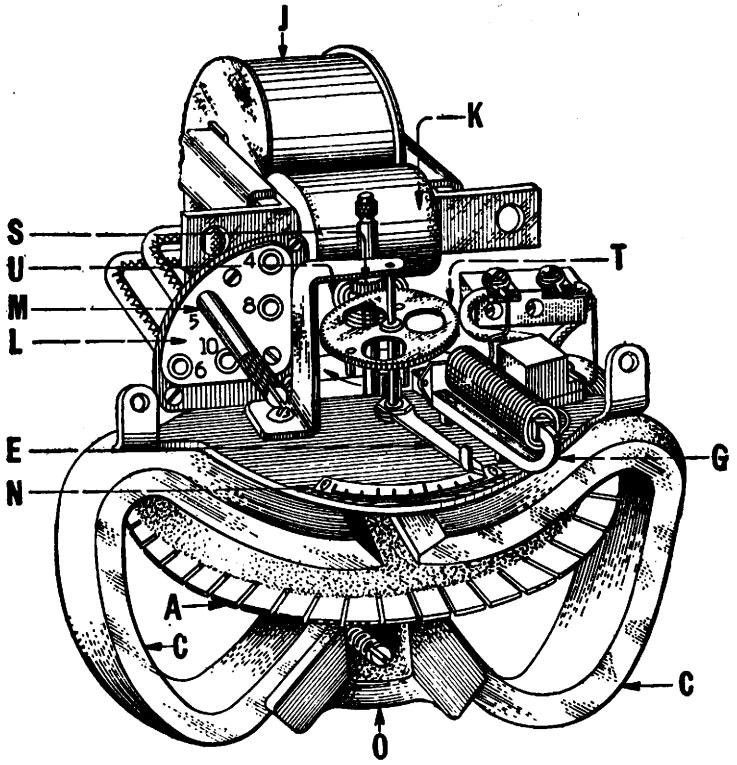
[1] Interestingly, much of modern protective relay terminology reflects legacy technologies. For example, the act of a protective relay closing its trip contact is still called *picking up*, and the threshold trip value still called the *pick-up* value, based on the operation of legacy gravity-reset relays. A relay such as the one shown on page 17 of Todd's book uses gravity to pull the relay armature down to open its contacts, and sufficient CT current acts to literally *pick up* the armature against gravity to close the contacts.

In a modern electrical power facility the "storage battery" for all the protective relay trip circuits typically takes the form of a series-connected network of lead-acid batteries providing 125 Volts DC, generally called *station power*. A photograph showing one of these battery banks at a gas-fired power generation plant appears here:

An AC-to-DC power converter circuit takes AC power during normal operations and converts it to DC for the purposes of trickle-charging the station power battery bank, so that it is always in a full state of charge and ready for service if the AC power is ever lost. This is important, as circuit breakers may still need to be closed and/or tripped in a "black-out" condition where AC grid power is no longer available.

Not only does station power provide energization of circuit breaker trip and close coils, but also energization of electronic protective relays, as well as emergency lights and sometimes even critical electric motors (e.g. cooling water pumps). It is a simple and effective *uninterruptible power supply system* critical to the reliable operation of all protection and control systems in an electrical power facility.

An illustration of an electromagnetic overcurrent relay manufactured by General Electric, circa 1922, appears below:

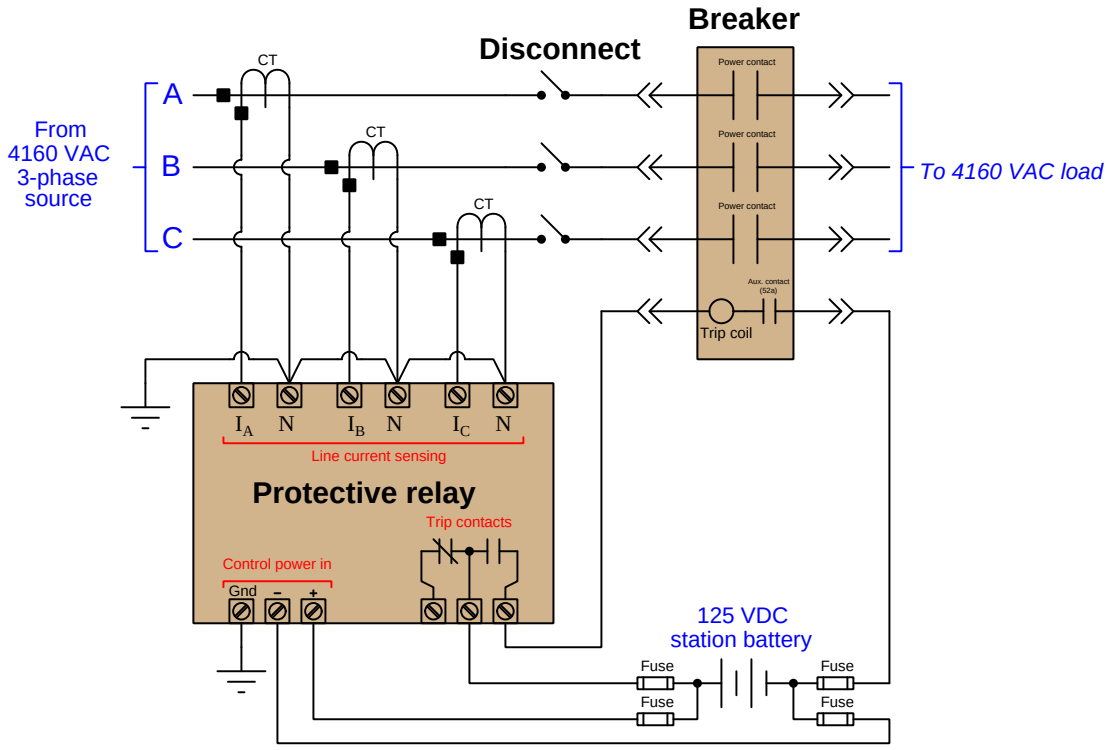


Instead of the CT's current producing a magnetic field that instantly attracts a set of switch contacts beyond the pick-up value, this relay uses an *induction disk* (component A in the diagram) forced to rotate by a magnetic field. That field still originates from the CT's current passing through a set of electromagnet coils, but the effect is that the switch contact's closure is *delayed* rather than instant because the disk must rotate a certain amount before forcing the contacts closed. The disk's rotation is restrained by a spiral spring and cannot rotate at all until the CT current exceeds a minimum (pick-up) value, and the time to trip is a function of how high the CT current is above that pick-up value. Thus, the induction-disk overcurrent relay mimics the operation of a thermal fuse: tripping almost immediately for heavy overload conditions but taking longer to trip for milder overloads.

Interestingly, overcurrent relays using the exact same principle of operation are still manufactured and used today (2020)!

3.3 Modern protective relays

Modern electronic overcurrent relays have multiple input terminals for receiving current signals from multiple current transformers (CTs), one for each line of the three-phase power circuit. If current through *any* line becomes excessive, the relay mathematically concludes that an overcurrent condition exists and responds by closing a small relay contact. This trip contact sends DC "station power" to the trip coil of the power circuit breaker, commanding it to open. The same "station battery" provides electric power to the relay itself to energize its microprocessor and other circuitry:



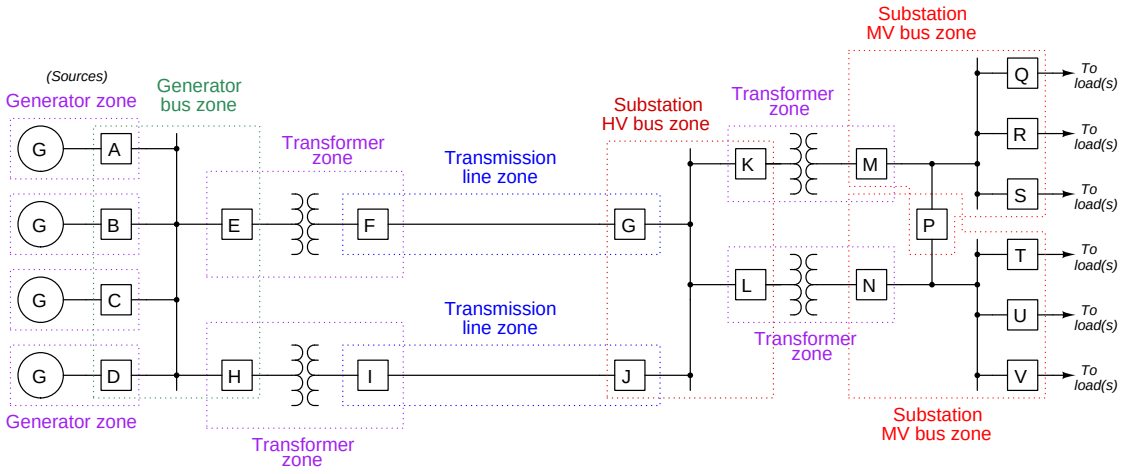
The circuit breaker's *trip coil* acts like the trigger on a firearm, unleashing some form of stored mechanical energy (e.g. compressed spring, compressed air) to quickly pull the contacts apart and safely interrupt the line current.

An important principle in electric power system protection is for protective relays to *trip minimally and trip quickly*. To "trip minimally" means to trip only those circuit breakers absolutely necessary to interrupt fault current and no more, in order to avoid interrupting electric power service to non-faulted loads. To "trip quickly" means to trip the necessary circuit breaker(s) as rapidly as possible once the fault is detected because the longer a fault is energized, the greater the damage. The goal is always to minimize hazard while maximizing availability of the electric power service.

3.4 Protection zones and coordination

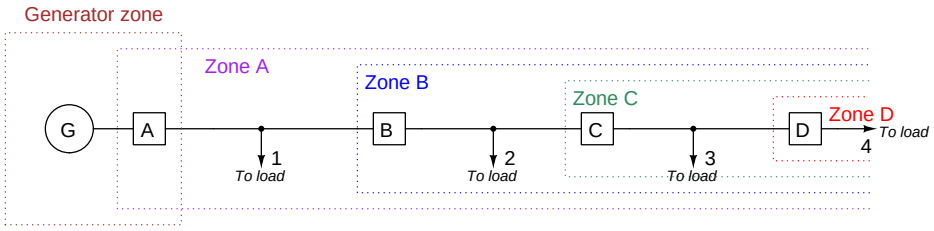
Two concepts related to the mantra of "trip minimally and trip quickly" are *protection zones* and *coordination*. Protection zones refer to limited areas within a power system that a particular protective relay is responsible for protecting. When each protective relay is responsible for a prescribed portion of the power system and for no others, there will be less chance of that relay interrupting power to non-faulted zones. Coordination is a similar principle related specifically to overcurrent protection, where multiple overcurrent protection devices (fuses, self-tripping breakers, overcurrent relays) are rated and/or configured such that the smallest necessary portion of the power system will be interrupted in the event of a short-circuit anywhere.

Consider the following single-line diagram showing four generators supplying power over high-voltage transmission lines to a substation where high voltage is stepped down to medium voltage for distribution to various loads. Each of the *zones* outlined in this diagram is protected by one or more relays, the purpose of each is to de-energized all equipment within that zone (and *only* that zone) in the event of a fault within that zone. For example, if the upper substation transformer were to fail internally, circuit breakers K and M would be automatically tripped by the relay(s) protecting that transformer zone. If "tie" breaker P were closed, the both medium-voltage busses in the substation would still be energized and all loads will still receive power while the faulted transformer was successfully cleared:



As a counter-example, consider the same fault (upper substation transformer) but this time "picking up" not only that transformer zone's protective relay but also the relay for the HV bus zone. The cause of this poor discrimination for the HV bus relay could be improper relay settings, incorrect wiring to the instrument transformers, or any number of other problems within that HV bus zone's protection scheme. While the transformer relay trips breakers K and M, the HV bus relay would trip breakers G, J, L, and (redundantly) K. This would still clear the faulted transformer, but it would also needlessly de-energize the entire substation and all of its loads. Proper zone discrimination, therefore, is essential to the *security* of an electric power system.

Now consider a feeder line carrying power from a single generator to multiple (numbered) loads along its length, with several circuit breakers along the way. Each circuit breaker, of course, has the ability to interrupt power to *everything* "downstream" of it, and so the load-protection zone for each breaker extends from that location all the way to the end of the line:



If we assume the use of overcurrent relays at each breaker, and the only source of power being the single generator at the far left of the line, the only way to achieve discrimination between these protection zones is to *coordinate* the trip settings of the relays such that relay C "picks up" at a higher current value than relay D, relay B picks up at a higher value than C, and so on. This way a fault at load 3, for example, will only trip breaker C and not breakers B or A, avoiding needless loss of service to loads 1 and 2.

A benefit of overcurrent protection coordination is that zones closer to the source may serve as *back-up*[2] protection in the event of a protection system failure. Consider again a fault at load 3, but this time the overcurrent relay for breaker C fails to pick up for some reason. As the fault current grows in magnitude over time, it will eventually reach a level sufficient to pick up the next zone's relay, tripping breaker B. This back-up action, of course, results in greater loss of service, but this additional loss was necessary in light of zone C's protection failure.

[2]Back-up protection works by having a less-sensitive relay pick up in the event the proper relay fails to operate within its intended time. For greater reliability it is possible to incorporate *redundant* relays within any one zone, the concept being that one of these should still function if the other fails during a fault condition. Redundancy provides superior protection to back-ups because there is no need for the fault to grow worse over time or last longer than it should. Redundant protection schemes, of course, cost more to install and maintain than simplex (i.e. single-relay) protection.

3.5 Protection device and function codes

Protection devices and functions are commonly associated with standard number codes by the ANSI and IEEE organizations. Some of these codes refer to specific pieces of equipment (e.g. *52* refers to an AC power circuit breaker) while other codes refer to abstract functions (e.g. *50* refers to instantaneous over-current, *51* refers to time-overcurrent). Tables of ANSI device codes may be found on pages 38 through 40. The remainder of this Tutorial will explore some of the more common protective relay functions.

An **overcurrent** relay detects a condition of excessive line current and trips the circuit breaker feeding that line in such an event. *Instantaneous* overcurrent (ANSI/IEEE code **50**) trips the breaker as soon as the relay senses current in excess of a pre-determined pick-up value, and is intended to protect against major short-circuit faults. *Time* overcurrent (ANSI/IEEE code **51**) trips the breaker based on a combination of percentage overcurrent and time delay: the more severe the overcurrent event, the sooner the relay trips the breaker. This time-delayed function is intended to protect against thermal damage created by relatively mild overcurrent conditions, based on the assumption that the protected components are able to withstand overcurrent conditions for some amount of time before sustaining damage. Letter codes sometimes follow the ANSI/IEEE number code to designate which line current is being sensed (e.g. 50N = instantaneous overcurrent on the Neutral line, 51P = time overcurrent on a Phase line).

A **reclosing** relay (ANSI/IEEE code **79**) commands a circuit breaker to automatically re-close following an automatic trip event, the purpose of this being to test whether the fault still remains on the line. Reclosing relays are used in conjunction with special circuits breakers called *reclosers* designed to trip and close in rapid succession. The concept of reclosing is used for overhead distribution line protection where common faults include accidental tree branch and wild animal contact where the short-circuit path is likely a foreign object. Successful reclosing restores electric power service to loads much faster than waiting for a line maintenance personnel to arrive and manually re-close the breaker.

A **differential** current relay (ANSI/IEEE code **87**) detects a condition where current flowing in to a component or zone does not match current exiting that same component or zone, implying that some current is flowing along an unintended (fault) path. This protection principle is based on Kirchhoff's Current Law, which states that the sum of all currents entering a node must be equal to the sum of all currents exiting that node. Differential current protection is better able to detect faults than overcurrent, since *any* amount of current imbalance is theoretically improper and therefore an 87 relay need only detect any non-zero current imbalance quantity while a 50 or 51 relay must detect current above and beyond normal load current.

A **distance** relay (ANSI/IEEE code **21**) detects short-circuits along a transmission line by sensing the electrical *impedance* of that shorted line. A normally-loaded line will appear as a high impedance to the source, total impedance being the sum of Z_{line} and Z_{load}. A shorted line appears as a fraction of the normal Z_{line} value, with fault proximity to the source determining that fractional value. Distance protection trips the breaker if ever the measured impedance falls below a pre-determined "reach" limit based on line characteristics and line distance between the relay's location and the fault location.

A **directional** or **reverse** power relay (ANSI/IEEE code **32**) detects when power flows in a direction that is opposite from normal. This function is intended to prevent *sources* (generators) from behaving as loads (motors).

An **overfluxing** or **V/Hz** relay (ANSI/IEEE code **24**) detects whenever the ratio between voltage and frequency becomes excessive. This protection is intended for iron-core electromagnetic devices such as generators and transformers which will *magnetically saturate* if subjected to excessive V/Hz ratios. Such an event may occur if one or more generators become "islanded" from the rest of the power system by a tripped breaker, the unloaded generators' voltages typically rising with the sudden absence of load.

A **lockout** relay (ANSI/IEEE code **86**) is an auxiliary device used in conjunction with other protective relays, serving as a latch requiring manual reset following a trip event. This forces personnel to visit the location of the lockout relay to reset its latch before power may be restored, which encourages visual inspection for damage and/or the cause of the fault.

Detailed exploration of different protective relays and protection systems will be treated in separate modules within this series, as each type is sufficiently complex to warrant its own tutorial.

Chapter 4

Historical References

This chapter is where you will find references to historical texts and technologies related to the module's topic.

Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that are unusually easy to grasp. Anyone who first discovers a new principle must necessarily do so from a perspective of ignorance (i.e. if you truly *discover* something yourself, it means you must have come to that discovery with no prior knowledge of it and no hints from others knowledgeable in it), and in so doing the discoverer lacks any hindsight or advantage that might have otherwise come from a more advanced perspective. Thus, discoverers are forced to think and express themselves in less-advanced terms, and this often makes their explanations more readily accessible to others who, like the discoverer, comes to this idea with no prior knowledge. Furthermore, early discoverers often faced the daunting challenge of explaining their new and complex ideas to a naturally skeptical scientific community, and this pressure incentivized clear and compelling communication. As James Clerk Maxwell eloquently stated in the Preface to his book *A Treatise on Electricity and Magnetism* written in 1873,

> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

Furthermore, grasping the historical context of technological discoveries is important for understanding how science intersects with culture and civilization, which is ever important because new discoveries and new applications of existing discoveries will always continue to impact our lives. One will often find themselves impressed by the ingenuity of previous generations, and by the high degree of refinement to which now-obsolete technologies were once raised. There is much to learn and much inspiration to be drawn from the technological past, and to the inquisitive mind these historical references are treasures waiting to be (re)-discovered.

4.1 Early power system faults and protection

A fascinating historical reference on protective relay systems is Victor Todd's *Protective Relays – their theory, design, and practical operation* published in 1922. A few pages from the introductory chapter ("What Are Protective Relays") are reproduced here:

> When the first electric generators were built and installed, no provision was made for disconnecting them automatically from the lines in case of trouble such as overload or short-circuits. This was overlooked for two reasons: (1) It was not considered detrimental to have service interrupted, as the electric system was more or less a novelty and in the experimental stage, and (2) the design of generators and prime movers was such that in case of heavy overload either the prime mover would stop, or the belt fly off, or the voltage drop so low that no electrical damage could be done.
>
> However, as the mechanical and electrical design of generators and prime movers was gradually improved, it was noticed that in the event of a heavy overload, the increased current would burn out the weakest spot in the system; sometimes this was in the armature, sometimes in the wiring and sometimes in the switches. Naturally the result was to insert intentionally a weak spot at some convenient point in the system, by connecting a piece of wire much smaller than the main wires, s that when the overload occurred, this wire would burn out and then the operator knew just where to go and look for trouble when the power went off. This was the first fuse.
>
> Installing the fine wiring near inflammable material led to another trouble; i.e., fire risk, as during a heavy short-circuit, the wire was melted, and the red-hot metal thrown violently in all directions.
>
> The remedy was to enclose the fuse in an insulating non-inflammable tube to prevent fires, and also to provide fuse blocks and clips so that the fuses could be replaced easily in case of an overload blowing them out. `[page 1]`
>
> Even today, there is no other piece of equipment which can excel a properly designed fuse for reliability, and no matter what other protective apparatus is installed, as will be described later, there is hardly an installation which does not have fuses as an absolute guarantee of protection against heavy overloads, should the other protective devices fail.
>
> **Objections.** – The greatest objection to fuses was the maintenance cost, or cost of replacement, as every time a fuse blew out, it meant a new fuse, and as the current capacity of the system went up, every new fuse meant considerably money. Not only that, but it took some time to locate and replace a fuse and besides, if a new fuse were not immediately at hand, there was a severe temptation to use a convenient piece of copper or solder-wire to complete the circuit, thus again introducing a hazard. This improper replacement of fuses is one of the deepest-rooted evils in the electrical industry and is alone responsible for thousands upon thousands of dollars' worth of damage by fire every year, in addition to burning out of many motors, generators and other apparatus.
>
> In order to eliminate this replacement expense, as well as to restore service in a minimum of time, it was found necessary to develop an automatic switch which would open the circuit in the event of trouble. This was the forerunner of the present circuit breaker.

There were many types developed and successfully used, but the principles and the objects accomplished were all the same; a coil carrying the main current was arranged to either attract an armature fastened to the switch blade and thus open the switch directly, or to attract an armature which in turn released a spring, thus allowing the spring to open the switch.

From the foregoing it would appear that the problem of protection was solved. But protection was not the only desirable feature; customers demanded continuous service and many times an interruption was caused only by a transient short-circuit; for instance, a wire or tool dropped across a switch, immediately falling off or burning out. It was not necessary for the breaker to open as the overload disappeared almost immediately and if the breaker had not opened, service would have continued uninterrupted. In other words, the circuit [page 2]

breaker had no discriminating, "reasoning" or "thinking" power. This led to the development of the protective relay.

Protective Relays. – The protective relay is an electrical instrument, generally accurate, sensitive, rugged and reliable in construction, interposed between the main circuit and the circuit breaker in such a manner that any abnormality in the circuit acts on the relay, which in turn, after proper discrimination of the magnitude and characteristic of the abnormality, causes other apparatus such as a circuit breaker to function and relieve or protect the circuit and apparatus.

The great need of adequate protection and continuous service under all conditions has gradually caused the crude types of relays of a few years ago, which sometimes gave protection under special conditions but often failed at the critical moment, to be developed into present-day types, which are built with the accuracy of a watt-hour meter and can be depended upon in practically all conceivable cases of electrical distress.

In alternating-current systems, the need of continuity of service is so great that the lines must be kept alive until there is no chance of the disturbance clearing itself. In some states the public utility boards require an explanation of each and every interruption that occurs in an operating company's service as well as a report of the steps taken to prevent its recurrence.

Many power plants and factory managements have required in the past duplicate supply lines, so that their power supply would not be interrupted in case of trouble on other parts of the system. Others have maintained stand-by plants ready to assume the load in case of electrical trouble.

As a typical example of how protective relays have eliminated this necessity, one operating company has as many as 25 interruptions a year, but after making an intelligent survey of the system, a few changes were made in the sectionalizing apparatus and accurate relays installed which reduced the interruptions to about one annually, although the system suffered not less than 100 short-circuits per year from various causes.

The relays instantly sectionalize and isolate a defective line or piece of apparatus without disturbing the rest of the system. This allows spare lines to be used continually, and the [page 3]

great saving and economy of copper will often finance the installation of relays.

Like a silent sentinel, the protective relay stands on guard on the lines, day and night, summer and winter, ready to detect trouble instantly, to determine if it is serious enough to open the circuit, and, if so, to disconnect faulty apparatus or sectionalize defective lines with almost human intelligence and more than human accuracy.

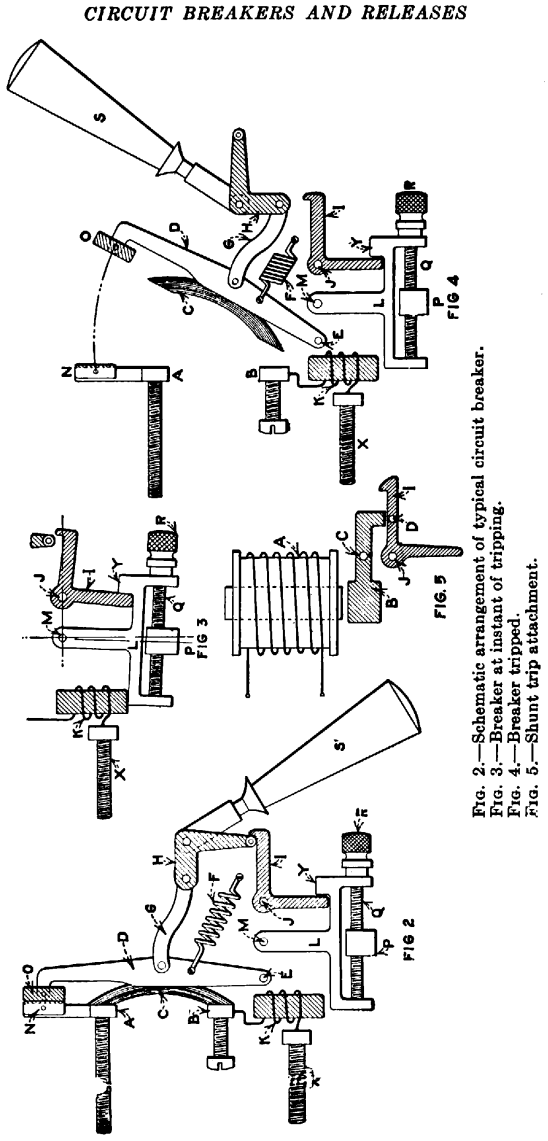
At present, protective relays are so specialized and highly developed that there is practically no electrical defect or abnormal condition on a line that cannot be detected by a relay and the circuit protected against it. Excess current (generally called "overload"), under current, over-voltage, under-voltage, over and under-wattage, reverse current or power, high or low frequency, high or low temperature, reverse phases, and numerous other conditions which may occur, all can be detected by a suitable relay.

Principles of Operation. – As electricity is an intangible something which cannot be measured like water or gas, we must detect its presence and characteristics by the effect it produces. The effects are four in number: chemical changes, heat, magnetism and static attraction. Although electrical-indicating instruments have been made to operate on all these various effects, yet practically all protective relays depend on the magnetic effect of an electric current for their operation.

The three main principles used are (1) the D'Arsonval principle, utilizing a moving coil reacting on a permanent magnet, (2) the solenoid and plunger type, utilizing the sucking effect of an energized solenoid on an iron plunger, and (3) the induction type, utilizing the same principle as employed in induction motors and watt-hour meters. Various relays operating on these principles will be considered in detail on following pages. [page 4]

4.2 Early circuit breakers

An early model of hand-reset circuit breaker is shown in this set of illustrations from page 9 of Victor Todd's book *Protective Relays – their theory, design, and practical operation* published in 1922:



CIRCUIT BREAKERS AND RELEASES 9

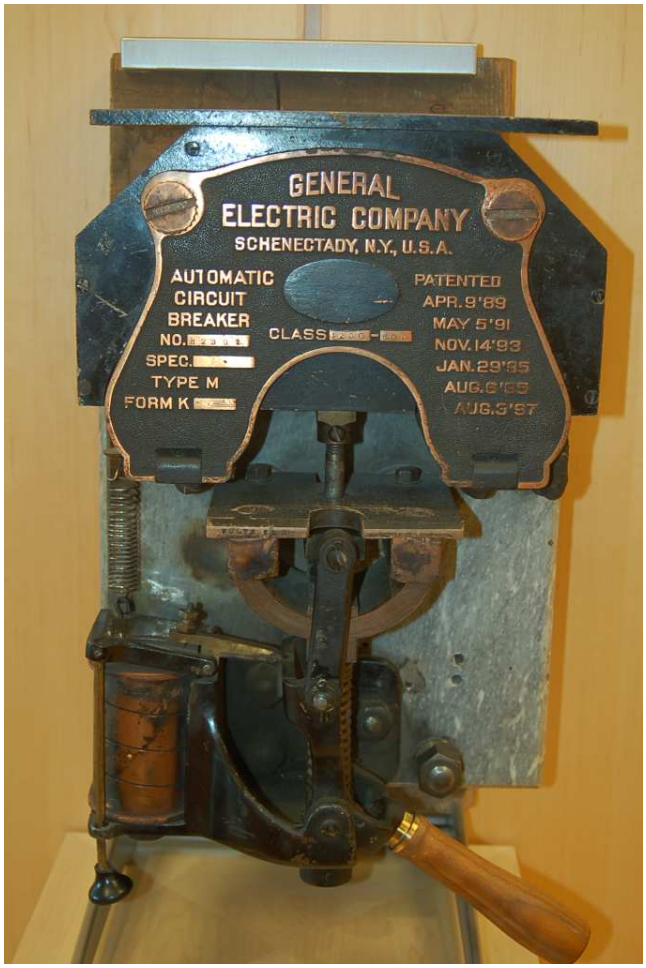
FIG. 2.—Schematic arrangement of typical circuit breaker.
FIG. 3.—Breaker at instant of tripping.
FIG. 4.—Breaker tripped.
FIG. 5.—Shunt trip attachment.

Figures 2 and 4 show a series-connected trip coil directly energized by the line current, in order to make the circuit breaker self-tripping. A shunt trip coil shown in Figure 5 replaced the series trip coil and permitted remote tripping via operator switch and/or protective relay(s). The breaker's line and load terminals are A and B, with C being a section of copper bridging the gap between

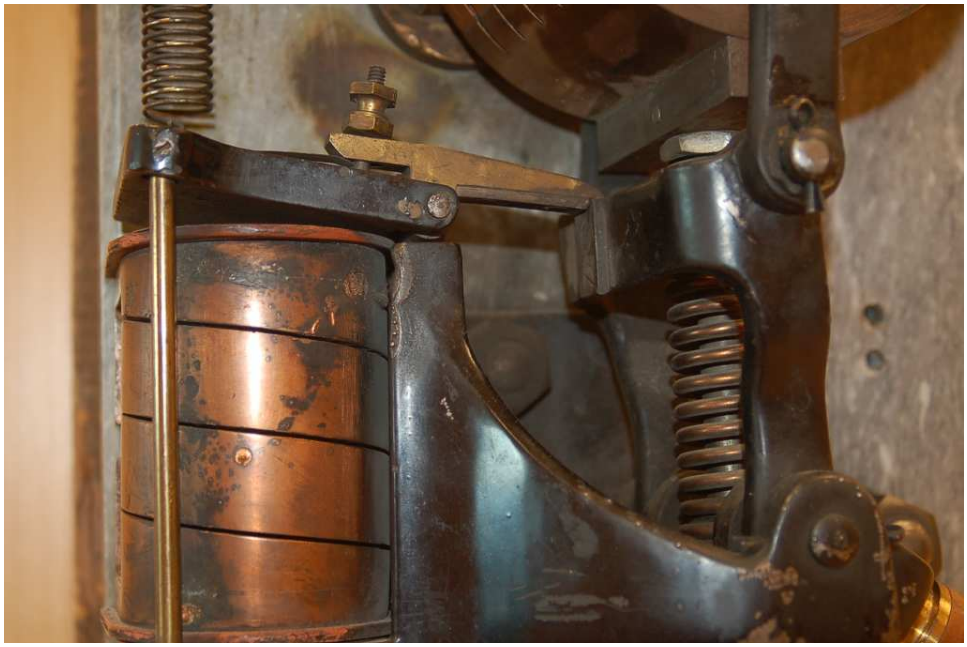
copper contact pads A and B to close the breaker. Contact pads N and O are the last to break as the circuit breaker trips, and being made of carbon rather than metal they tend to wear better under the influence of arcing.

It is interesting to note that these circuit breakers were quite slow to trip compared to modern AC power breakers. A typical tripping time (cited on page 71 of Todd's book) for a circuit breaker was 0.2 seconds. At a power system frequency of 60 Hz, 0.2 seconds equates to 12 cycles. Modern power breakers typically interrupt the arc in 2 to 3 cycles' worth of time following a trip command.

A photograph of a circuit breaker made by General Electric in the 1890's appears here:

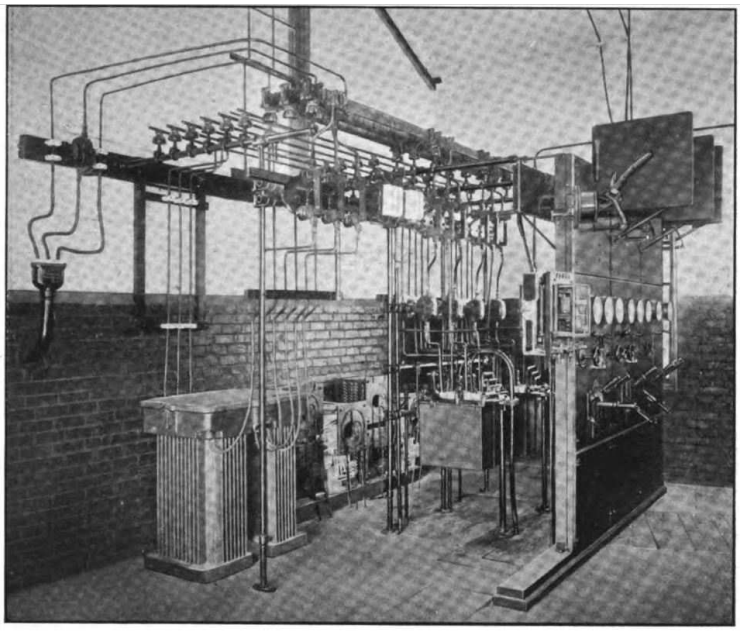


The trip coil is plainly visible in this close-up photograph:



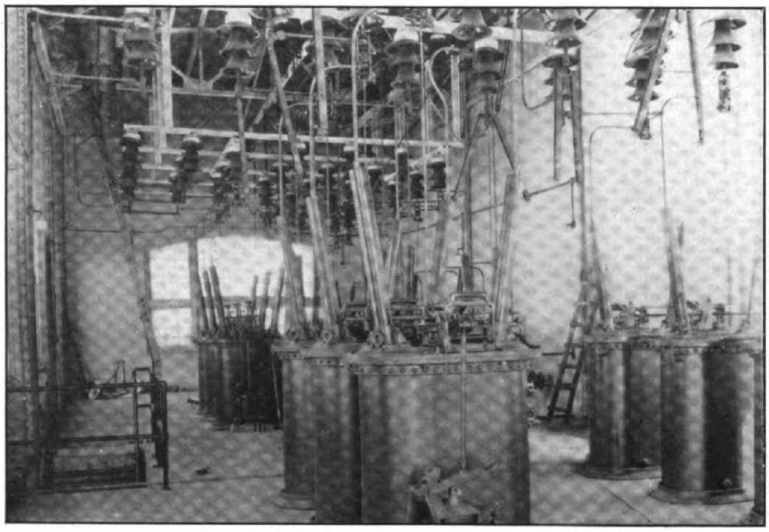
This particular trip coil uses a wide strip of copper for its *four* turns, suggesting a high current necessary to "pick up" the trip mechanism and trip the breaker. Like the breaker diagram shown on page 9 of Victor Todd's book, this breaker's trip coil was wired directly in series with the breaker contacts which meant it carried full load current. Only a current of sufficient magnitude (i.e. a fault) could generate enough magnetic attraction to operate the trip mechanism. You may also see the dark-colored armature in this photograph, which when pulled downward toward the coil releases the spring-loaded breaker mechanism which consequently pulls the contacts apart to form an open circuit.

The following photograph, taken from a 1912 edition of *Cassier's Magazine*, shows a 1500 Volt substation constructed with remote linkages connecting hand levers to the switch blades, in order to improve the safety for any personnel operating these switches:



1,500-VOLT SWITCHBOARD EQUIPMENT SUB-STATIONS, PIEDMONT TRACTION COMPANY, ARRANGED FOR REMOTE HAND CONTROL, ELIMINATING DANGER OF ACCIDENTS. WESTINGHOUSE ELECTRIC & MANUFACTURING COMPANY

The next photograph, from page 571 of Volume 41 of *Cassier's Magazine* (1912), shows sets of oil-quenched circuit breakers operating in an indoor switchyard at 66 kiloVolts:



OCOEE RIVER PLANT. THE 66,000-VOLT OIL SWITCHES

Chapter 5

Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

5.1 ANSI/IEEE Function Codes

Protective function	**ANSI/IEEE code**
Over-speed	12
Under-speed	14
Reduced voltage start	19
Distance	21
Temperature control	23
Voltage/Hz (over-fluxing)	24
Synchronism check	25
Under-voltage	27
Flame safety detection	28
Annunciator	30
Directional (reverse) power	32
Under-current / under-power	37
Bearing overtemperature	38
Loss of excitation	40
Manual transfer/selector	43
Current unbalance	46
Broken conductor	46R
Phase reversal	47
Motor stall	48
Thermal overload	49
Over-current (instantaneous)	50
Arc fault	50ARC
Over-current (time)	51
Power factor	55
Rectifier failure	58
Over-voltage	59

(continued)

Protective function	**ANSI/IEEE code**
Ground fault	64
Speed governing	65
Starts per hour / time between starts	66
Directional over-current	67
Blocking	68
Alarm	74
Phase angle / out-of-step	78
Automatic reclose	79
Over-frequency / under-frequency	81
Lockout or auxiliary	86
Differential	87

5.2 ANSI/IEEE Device Codes

Device	**ANSI/IEEE code**
Position switch	33
Field winding circuit breaker	41
AC power circuit breaker	52
Shorting/grounding switch	57
Pressure switch	63
Rheostat	70
Liquid level switch	71
DC power circuit breaker	72
Fluid flow switch	80
Operating mechanism (generic)	84
Auxiliary motor or motor/generator	88
Line switch (power disconnect)	89

Chapter 6

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

6.1 Conceptual reasoning

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

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

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

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

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

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

6.1.1 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.

6.1.2 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 Energy

Electrical source

Electrical load

Arc blast

Fuse

Circuit breaker

Reliability

Dependability

Security

Schematic diagram

Single-line diagram

Overcurrent protection

Differential current protection

Discrimination

Trip minimally, trip quickly

Protection zone

Coordination

Relay pick-up

Reclosing

Distance protection

Impedance

Saturation

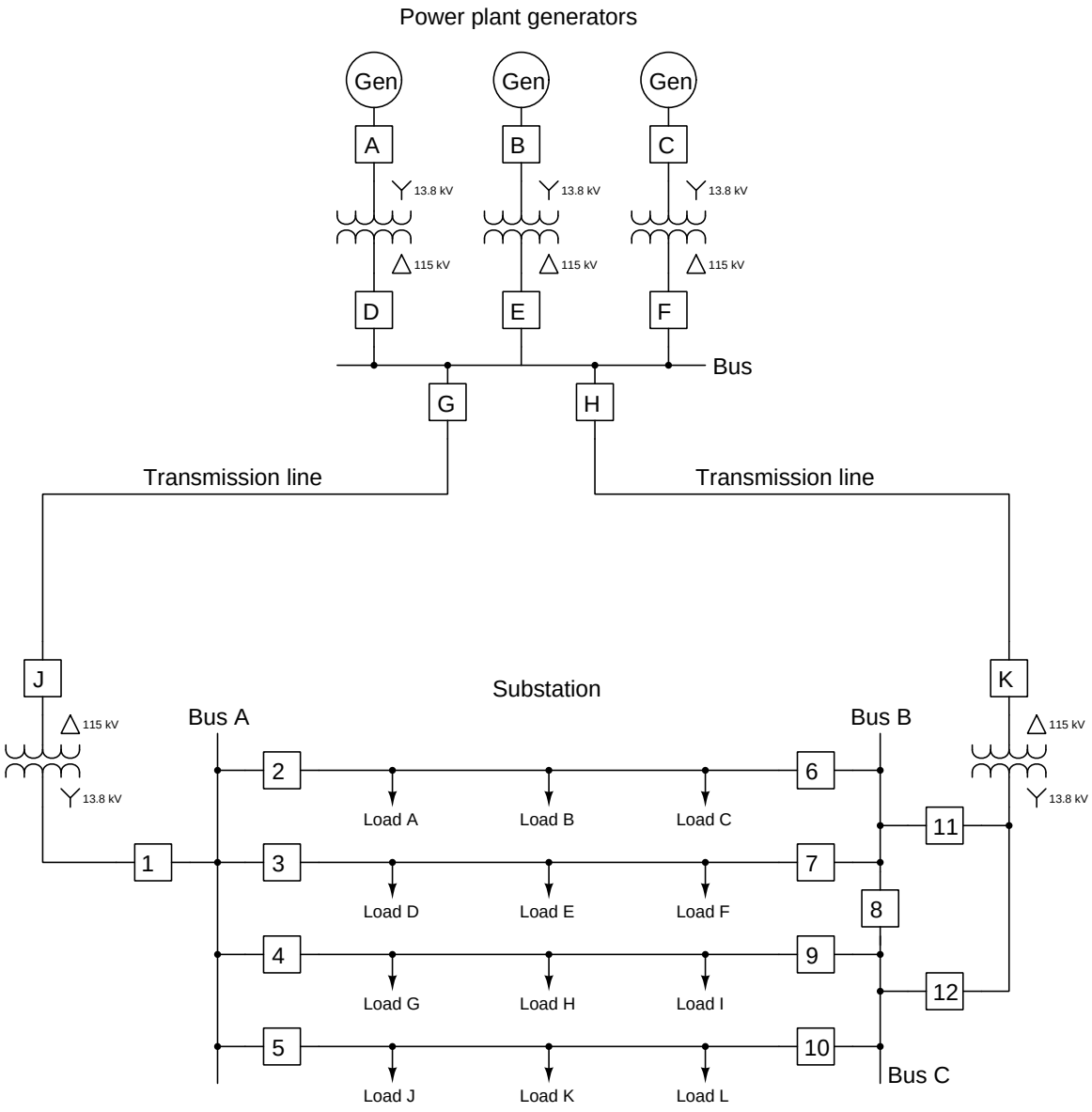
Kirchhoff's Current Law

Backup protection

Bus

6.1.3 Proper breakers to trip

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



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

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

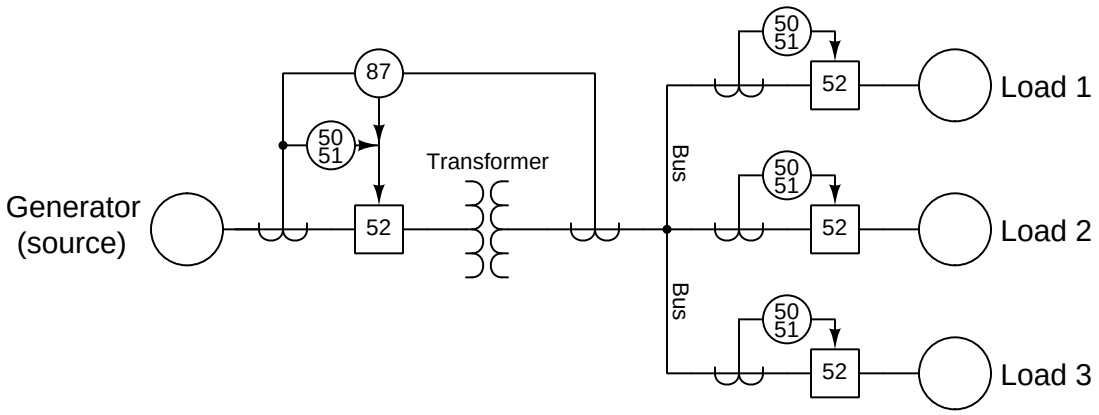
Suppose one of the high-voltage insulators on Bus C fails, causing a high amount of current to flow into that bus. Identify which circuit breakers must trip in order to de-energize that bus while maintaining power to as many loads as possible.

Challenges

- Suppose load K was prone to faults for some reason, and the other customers were weary of having their power interrupted whenever K failed. Re-organize the power system to avoid this problem.

6.1.4 Identifying protection zones

Sketch the protection zones associated with each of the protective relays in this power system

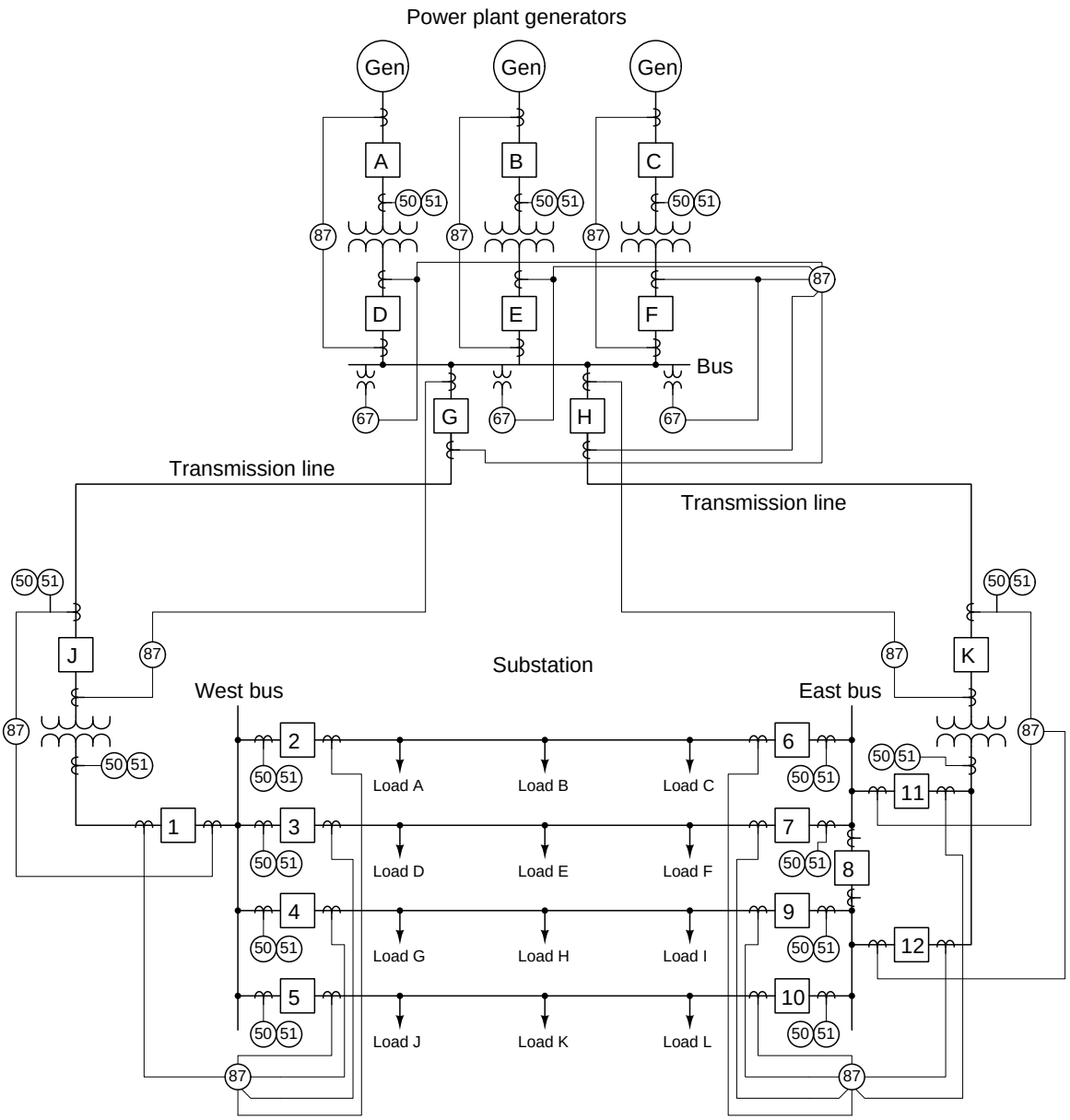


Challenges

- Is there any area of this power system that is unprotected (i.e. outside of all protection zones)?
- Which of these protection zones has the greatest sensitivity to a fault.
- Identify the location of a fault that would be within one of these zones but not within another.

6.1.5 Identifying which relays will pick up

Identify which protective relays in this system will "pick up" (i.e. detect a fault and trip breakers) in the event of the following faults:



- Phase-to-phase fault on the West substation bus

- Internal winding fault within the right-hand (East) substation transformer
- A tree branch touching one of the power line conductors feeding Load B
- An internal phase-to-phase fault inside circuit breaker 4

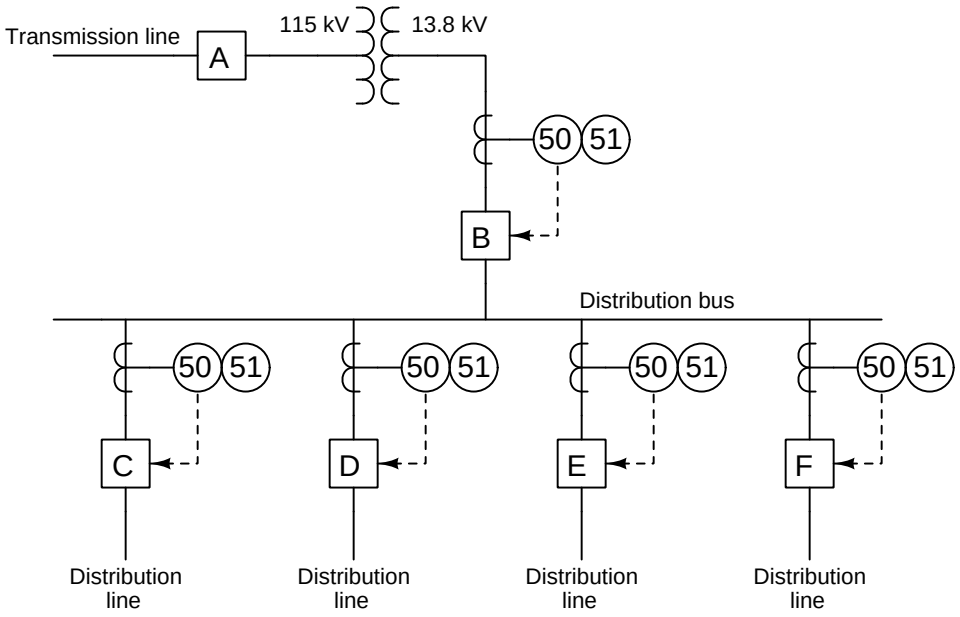
Challenges

- Why does the 87 relay toward the top of the diagram have so many inputs?

6.1.6 Fast bus trip scheme

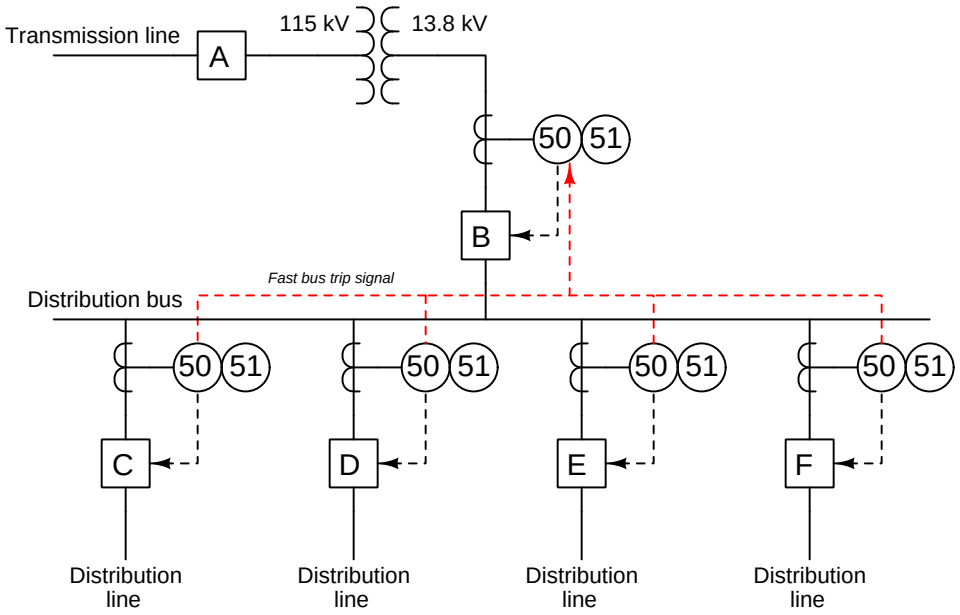
A very important concept in overcurrent protection is something called *coordination*. This is where overcurrent-protection devices (e.g. fuses, circuit breakers, reclosers, protective relays) closer to the power source have trip thresholds greater than protection devices farther away from the source.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

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



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

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



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

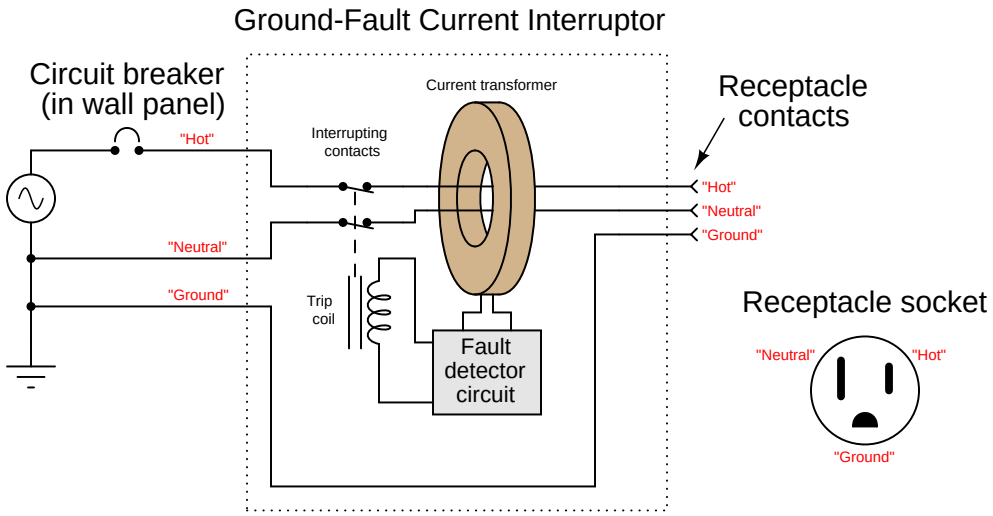
Challenges

- Identify a completely different protection scheme that would serve the same end.

6.1.7 GFCI

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

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



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

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

Challenges

- Ground fault current interruption is required by code in residential and commercial installations where the possibility of a wet surface exists. Explain why ground/floor moisture is a factor for consideration here.

6.2 Quantitative reasoning

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

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

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

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

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

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

6.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.2.3 Fuse curve

The following graph comes from page 20 of Victor Todd's 1922 book *Protective Relays*, showing the characteristic time-load curve for a typical 6-Ampere fuse:

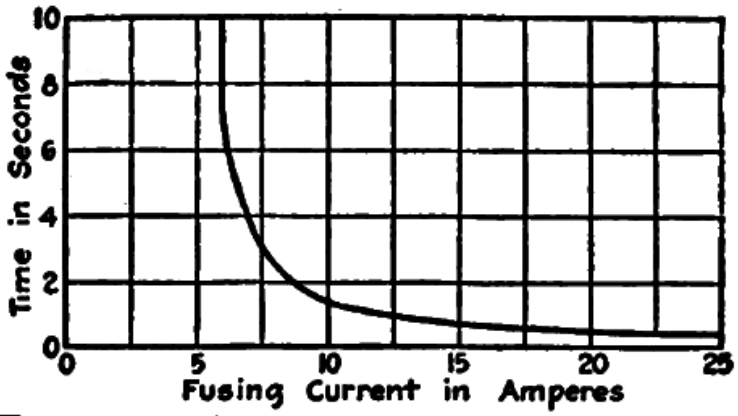


Fig. 18.—Characteristic time-load curve of a 6-ampere fuse.

Explain how to interpret this graph, and why you think it has the shape it does.

Challenges

- Overlay the time curves for a fast-acting 6-Ampere fuse and a slow-blow 6-Ampere fuse.

6.2.4 Overcurrent relay curve

The following graph comes from page 179 of Victor Todd's 1922 book *Protective Relays*, showing the characteristic time-load curve for a Westinghouse time-overcurrent relay (ANSI/IEEE code 51):

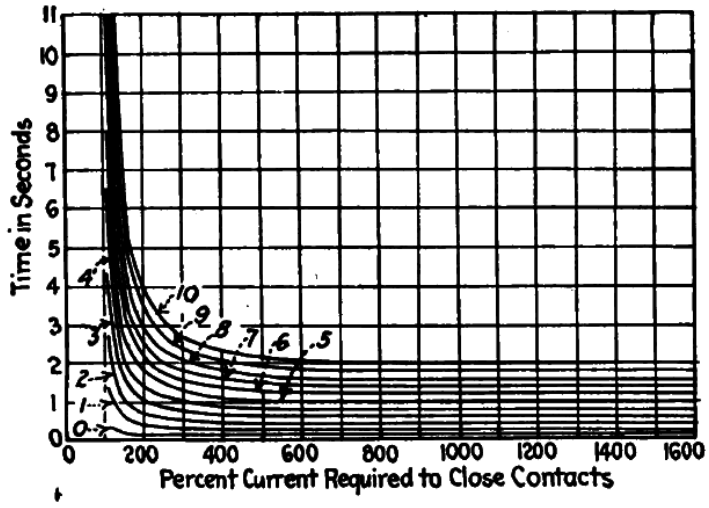


Fig. 171.—Time load curves of a Westinghouse induction type overload relay.

Each of the curves has a number label, corresponding to a setting inside the relay mechanism called a "time dial".

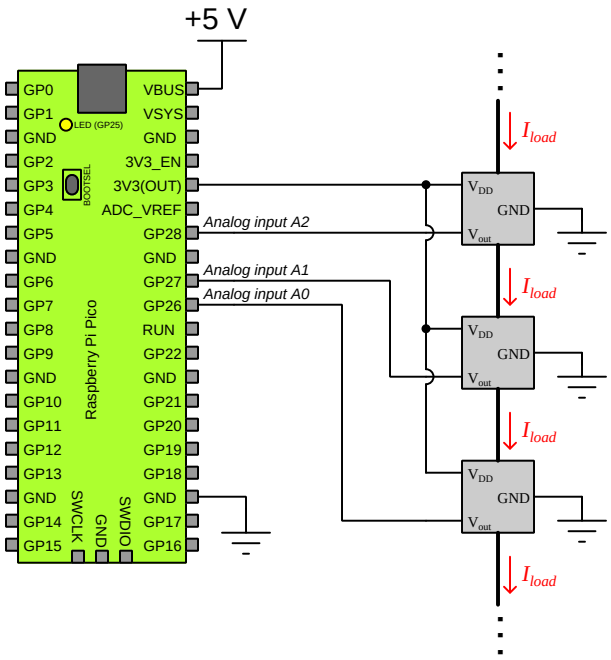
Explain why a single overcurrent relay would have upwards of ten different "time dial" setting options. Also, comment on the relationship between these ten time-dial settings and the relay's "pickup" value (i.e. the maximum amount of line current it will indefinitely permit without tripping the breaker).

Challenges

- Explain how this relay's behavior differs from that of a fuse.

6.2.5 Median-select microcontroller program

The following microcontroller circuit and program (written in the Sketch language, similar to C) takes analog voltage signals from three Hall-effect current sensors and performs a *median-select* function on them. Each Hall-effect current sensor outputs an analog voltage ranging between 0 Volts (no sensed current) and 3.3 Volts (10 Amperes DC sensed current), and each of the Raspberry Pi Pico microcontroller's analog inputs digitizes those voltage signals into integer "count" values from 0 (0 Volts) to 1023 (3.3 Volts):



Median-select functions are useful for high-reliability sensor applications because since the value chosen is the *middle* of the sampled measurements, any measurement that happens to be erroneously high or erroneously low will be ignored by the system and it will continue to operate on good data.

For example, if the three load current measurements from the three sensors happens to be 5.5 Amperes (count = 563), 5.6 Amperes (count = 573), and 5.2 Amperes (count = 532), the microcontroller's program should select the middle of these which happens to be a count value of 563 corresponding to 5.5 Amperes of load current.

Analyze the source code listing shown on the following page and answer these questions:

- Where is a custom *function* being used in this program?
- By what means does this program select the middle (median) of the three measured values?
- What practical action might the microcontroller take on this median-selected current measurement?

```
int x, y, z, hixy, hixz, hiyz, med;

void setup() { } // Nothing to do here

void loop()
{
  x = analogRead(A0);
  y = analogRead(A1);
  z = analogRead(A2);
  med = 1023;

  hixy = hiselect(x, y);
  hixz = hiselect(x, z);
  hiyz = hiselect(y, z);

  // Three-input low-select function
  if (hixy < med)
    med = hixy;

  if (hixz < med)
    med = hixz;

  if (hiyz < med)
    med = hiyz;

  // (OTHER CODE GOES HERE)
}

// Two-input high-select function
int hiselect(int a, int b)
{
  int hi = 0;

  if (a > hi)
    hi = a;

  if (b > hi)
    hi = b;

  return hi;
}
```

Challenges

- An alternative median-select algorithm works by using a low-select function in place of this program's high-select function, and a high-select function in place of this program's low-select function.

6.3 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.

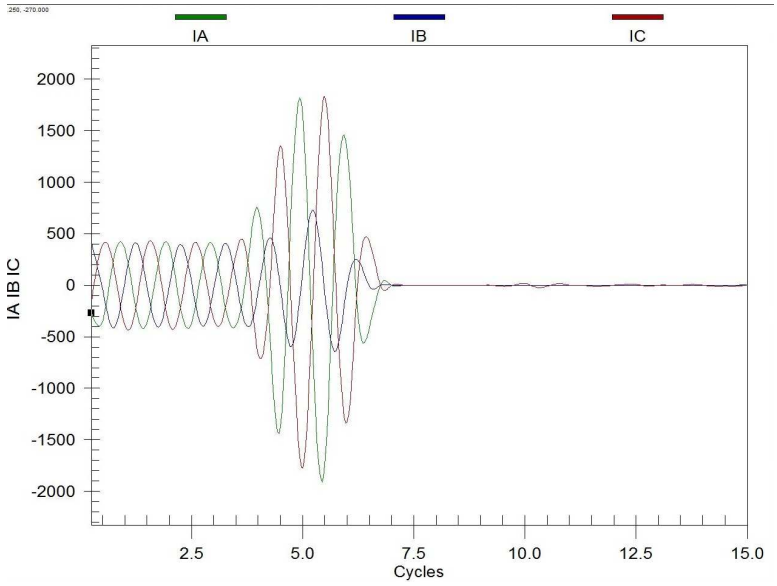
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

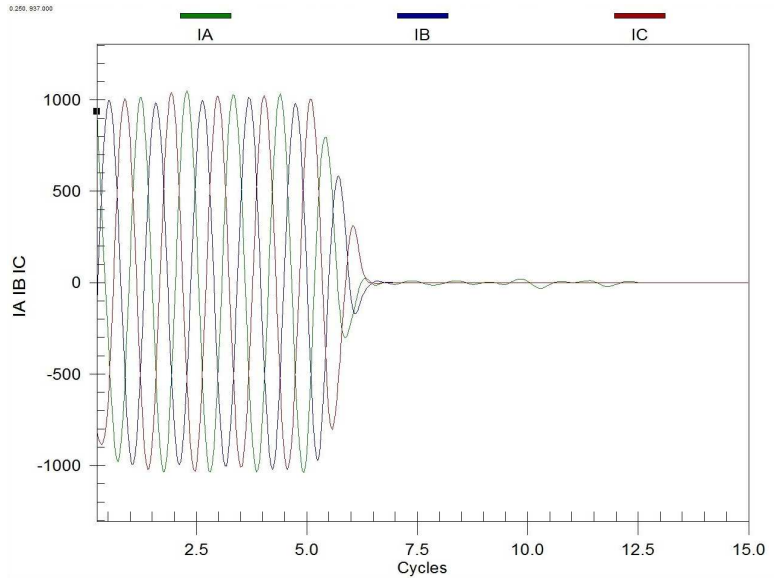
You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far 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.

6.3.1 Fault oscillographs

An *oscillograph* is a time-domain recording of voltages or currents, typically archived by a digital protective relay following a fault event in a an electrical power system. Two examples of oscillographs are shown here, each one representing line currents in a three-phase AC (alternating current) power line connected to a power station generator:





Identify which of these two oscillographs represents a *sustained overload* condition that finally

trips a time-delayed protective relay, versus a *sudden short-circuit fault*.

Challenges

- Note the different vertical-axis scales in these two examples, and explain why this is significant.

Appendix A

Problem-Solving Strategies

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

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

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

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

Appendix B

Instructional philosophy

B.1 First principles of learning

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

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

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

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

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

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

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

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

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

B.2 Proven strategies for instructors

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

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

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

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

B.3 Proven strategies for students

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

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

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

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

B.4 Design of these learning modules

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

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

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

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

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

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

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

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

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

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

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

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

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

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

The `GNU/Linux` computer operating system

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

Bram Moolenaar's `Vim` text editor

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

Donald Knuth's TEX typesetting system

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

Leslie Lamport's LATEX extensions to TEX

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

Tim Edwards' `Xcircuit` drafting program

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

`Gimp` graphic image manipulation program

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

`SPICE` circuit simulation program

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

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

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

`gnuplot` mathematical visualization software

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

`Python` programming language

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

Appendix D

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Appendix E

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Appendix F

Version history

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

3 December 2024 – minor edits to the Sketch source code in the "Median-select microcontroller program" Quantitative Reasoning question, as well as corrected a coding error where the variable `hi` was declared as floating-point rather than integer as it should have been. Also corrected a typographical error in this same question courtesy of Galen Bennett.

16 November 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

29 April 2024 – corrected a formatting error in one of the instructor notes. Also edited image_0667 to show a generator protection zone. Also corrected multiple spelling errors.

5 December 2023 – divided the Full Tutorial chapter into sections.

20 June 2023 – added a microcontroller-programming question related to high-reliability current measurement.

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.

9 July 2021 – replaced some TeX-style italicizing markup with LaTeX-style.

8 May 2021 – commented out or deleted empty chapters.

26-27 April 2021 – minor additions to the Full Tutorial chapter (including a photograph of station power battery bank) and to instructor notes for certain questions. Also added some Foundational Concepts.

16 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.

7 June 2020 – two typographical errors corrected in the Simplified Tutorial, courtesy Paul Garfield.

20 May 2020 – added schematic diagram to the Full Tutorial showing how a modern three-phase overcurrent relay connects to CTs and a power circuit breaker.

13-15 May 2020 – re-wrote "Simplified Tutorial" chapter and moved previous contents to the "Full Tutorial" chapter.

5 November 2018 – retitled Historical References section(s) so as to not be redundant to the "Historical References" chapter.

September 2018 – separated "Derivations and Technical References" chapter into two chapters, one for technical references and the other for "Historical References".

July 2018 – minor edits made to Simplified Tutorial.

May 2018 – document first created.

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