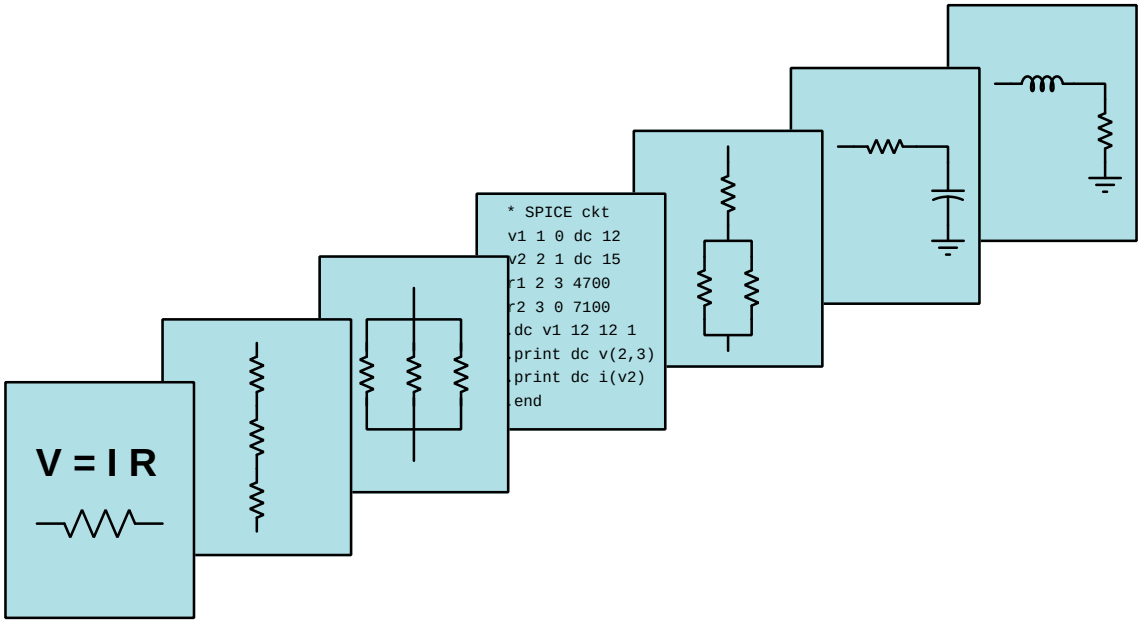
Modular Electronics Learning (ModEL) project



Circuit Breakers and Disconnects

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Chapter 1

Introduction

1.1 Recommendations for students

At root, circuit breakers and disconnects are nothing more than on/off switches. However, at high voltage and/or current ratings, these seemingly simple devices are actually quite complex. The task of closing and opening circuits at high power levels is non-trivial and is deserving of study in its own right. This module seeks to introduce the broad topic of power system switchgear.

Important concepts related to switchgear include the properties of **shorts** versus **opens**, **live-tank** versus **dead-tank** breaker designs, **lock-out, tag-out**, **racking** a breaker, **zero-energy state**, **arc extinguishment**, **actuation** mechanisms, **gas quenching**, **protective relays**, **current ratings**, **instrument transformers**, switchyard **topology**, **reclosing**, and **coordination**.

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

- How might an experiment be designed and conducted to measure the tripping time of a circuit breaker? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to test the effectiveness of different arc mitigation methods at the contacts of a switch interrupting a heavy current? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How do large circuit breakers differ in operation from the circuit breakers used in households, besides ratings and physical size?
- How does the role of a circuit breaker differ from that of a disconnect switch?
- What are some of the different techniques used to extinguish the arc of an opening circuit breaker?
- How does one render a circuit breaker safe to work on?

- What does it mean to "rack out" or "rack in" a low-voltage or medium-voltage circuit breaker?
- What is the role of a "charging motor/mechanism" inside a large circuit breaker?
- What are some of the different ways in which circuit breakers may store mechanical energy for fast-action tripping?
- What is the role of "station power" in an electrical facility?
- Which color typically represents a closed circuit breaker, and which represents an open (tripped) circuit breaker?
- Why is SF_6 gas popularly used inside large circuit breakers?
- Why do circuit breakers have multiple current ratings?
- What are some of the different configurations (topologies) of circuit breakers in a switchyard, and their relative advantages/disadvantages?
- What is the purpose of a *recloser* in a power distribution system?
- Why is automatic reclosing applied only to overhead power lines and never to underground power lines?
- What is the purpose of a *sectionalizer* in a power distribution system?
- Why don't sectionalizer switching contacts need to be constructed as ruggedly as recloser switching contacts?
- Why are some three-phase circuit breaker elements *synchronized* for tripping?

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** – Apply foundational circuit concepts of switching circuit to the analysis of power circuit breakers and protection circuits

  Assessment – Determine how a primitive overcurrent protection circuit functions based on its schematic diagram; e.g. pose problems in the form of the "Historical relay" Conceptual Reasoning question.

  Assessment – Sketch correct wire connections to form a low-pressure lockout control for a gas-quenched circuit breaker; e.g. pose problems in the form of the "Low-pressure lockout" Conceptual Reasoning question.

- **Outcome** – Interpret nameplate data for a power circuit breaker

  Assessment – Identify current, voltage, and time ratings from a circuit breaker's nameplate; e.g. pose problems in the form of the "Breaker ratings" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate a large electrical generating station, substation, or large electrical load on a satellite photograph and identify some of the circuit breakers, disconnect switches, and bus connections between them.

Chapter 2

Simplified Tutorial

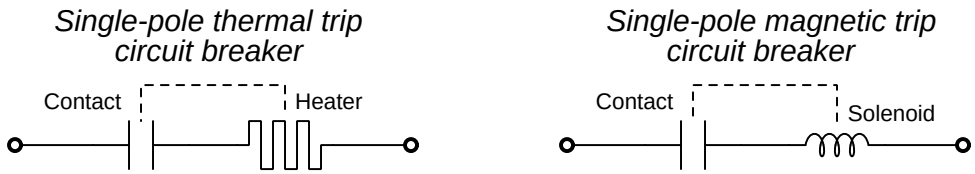
The most elementary components of an electric power system are the switches used to turn power on and off. Within this category of *switchgear* are two similar but distinct types of components: *disconnects* and *circuit breakers*. Disconnects are manually-controlled switches used to make and break (i.e. "open" and "close") unloaded circuits. Circuit breakers are heavier-duty switching devices designed to automatically open ("trip") for the purpose of interrupting electric power to a faulted circuit, and also to close (turn on) power to loads.

Basic switchgear function is very simple, but its design and construction is complex due to the rigors of operating under high voltage and/or high current conditions. With the hundreds or thousands of Volts typical in electric power systems, enough electric potential exists across open contacts to ionize air molecules lying between. Ionized gas conducts electricity, and thus switchgear *arcs* when closing or opening. Switchgear must be built to tolerate the high temperatures and physical stresses of arcing, and to do so repeatedly.

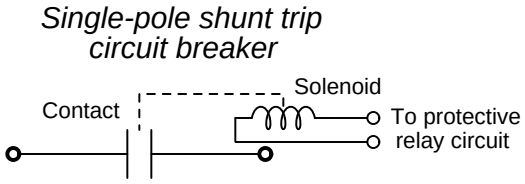
Disconnects are intended for low- or no-current switching, when series circuit breakers have already been opened, typically to secure other power system components in a de-energized state for maintenance. Disconnects may be operated by direct manual effort through some form of mechanism such as a rod or a crank, or remotely actuated using a small electric motor or other actuating device. The following photograph shows a single-pole disconnect rated for 115 kV (115,000 Volts). The disconnecting arm resembles the blade of a knife-style switch, pivoting on the left-hand side and making/breaking contact on the right-hand side. Porcelain insulators suspend the entire assembly above its grounded metal frame:

Circuit breakers are built with much more robust switching contacts, and for a different purpose. Unlike disconnect switches which are designed to open and close under low- or no-current conditions, circuit breakers must reliably open ("trip")[1] and close very rapidly in order to safely switch high-power circuits on and off while sustaining minimal wear from the inevitable arcing. Circuit breakers also differ from disconnects in the cause of their opening: unlike disconnects which are typically opened and closed by human action, circuit breakers are designed to trip *automatically* for the purpose of halting electricity to a faulted section of the power system.

Low-voltage (600 Volts and below) circuit breaker trip mechanisms are typically self-contained, and operate either by temperature or by magnetism. *Thermal* trip circuit breakers use a bimetallic element which creates a mechanical force when heated. Electric current passing through the resistance of this bimetallic strip generates heat ($P = I^2R$), and when the temperature rises high enough the force of this bimetallic strip causes the tripping mechanism to unlatch and swiftly open the circuit breaker's contact(s). *Magnetic* trip circuit breakers substitute a solenoid coil for the bimetallic strip, and use the magnetic force generated by load current passing through that coil to actuate the tripping mechanism.



Medium- and high-voltage circuit breakers rely on external devices to command them to trip. A small solenoid coil called a *shunt trip coil* causes the tripping mechanism to unlatch whenever it is energized[2]. This trip coil circuit is controlled by a device called a *protective relay* whose function it is to send power to the trip coil if abnormal power system conditions (e.g. overcurrent) are sensed. Protective relays exist to detect a wide range of faults in electric power systems, and are therefore more versatile for commanding a circuit breaker to trip than either thermal or magnetic elements.



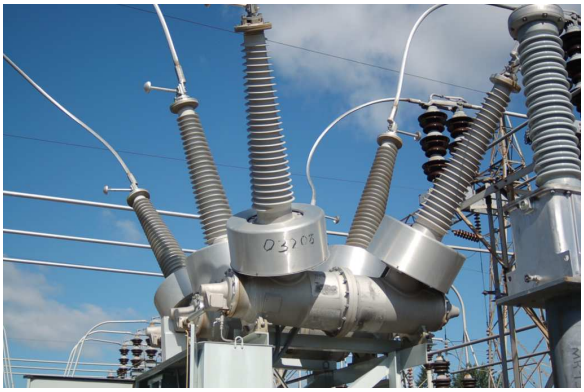
[1] There is no electrical distinction between an "open" circuit breaker and a "tripped" circuit breaker. The reason we use the word "trip" rather than "open" for circuit breakers is to reflect their design and function: circuit breaker mechanisms are pre-loaded with potential energy (often in the form of a tensed spring) which is unleashed at the command of a relatively small "trip" mechanism, not unlike the trigger mechanism on a firearm which releases a large amount of spring tension at the command of a much smaller trigger force.

[2] Note how different the trip coil's function is from the *holding coil* of a standard motor contactor. In a regular contactor, the power contacts are actuated directly by the force of the coil, and so the coil must be maintained in an energized state in order to keep the contactor's power contacts closed. In a power circuit breaker, however, the power contacts are held in a closed state by a spring-powered mechanism and not by any coil. The breaker's trip coil typically remains de-energized. Energizing the trip coil causes this spring-powered mechanism to unlatch, forcing the power contacts open.

Arcing at circuit breaker contacts, especially when the breaker trips (opens) under fault conditions when the current is abnormally high, can be quite severe. The large current and voltage values experienced at the opening contacts is able to *ionize* normally non-conductive substances such as air, and any ionized matter between the contacts will create a bridge for continued electric current. If the arc is not extinguished, the intense heat dissipated by the arc may destroy the circuit breaker. Several different design strategies exist to mitigate damage done by arcing to circuit breaker contacts, among them being:

- **Air-blast** – using a jet of compressed air aimed at the separating contacts[3] to "blow out" the ionized air plasma
- **Oil immersion** – submerging the contacts in a bath of non-conducting mineral oil
- **Vacuum** – enclosing the contacts inside of a vacuum chamber to eliminate any gas that could ionize at all
- **Gas quenching** – enclosing the contacts inside of a chamber filled with a high-dielectric gas such as sulfur hexafluoride (SF_6)

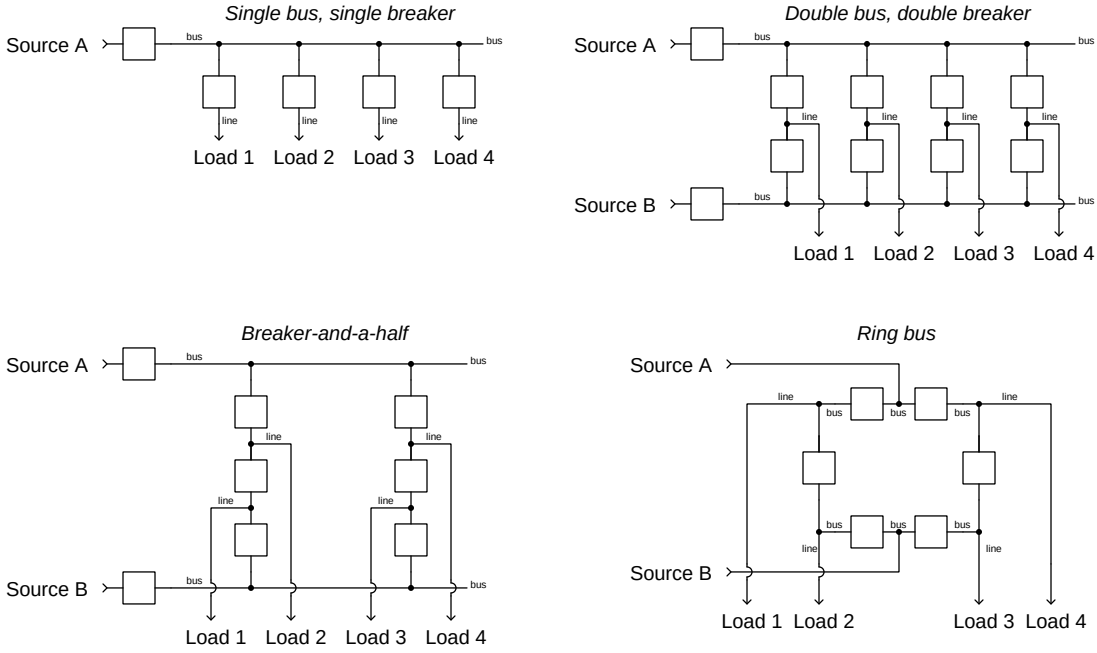
The following photographs show two different designs of high-voltage *dead tank*[4] three-phase power circuit breaker, the left-hand breaker using oil immersion and the right-hand breaker using SF_6 gas quenching to extinguish arcing. The oil circuit breaker (OCB) assembly consists of three vertical cylinders filled with mineral oil, the switching contacts submerged in that oil. The SF_6 breaker consists of three small horizontal cylinders, each one housing a pair of contacts operating within a pressurized atmosphere of SF_6 gas:



[3] Some high-voltage disconnects also use an air-blast to extinguish the arc formed at the separating contacts. Since disconnects are not designed to interrupt full load current, the arc current for an opening disconnect is usually the relatively small current resulting from capacitance in long power lines. For power lines hundreds of miles long, though, this *line charging current* may be substantial enough to warrant the use of air blast mechanisms at disconnect contacts.

[4] A "dead tank" breaker is one where the metal housing is connected to earth ground and is therefore "dead" or safe for human contact during operation. By contrast, a "live tank" breaker's housing is electrically common with the power conductor and therefore must be elevated well above ground level atop an insulating column.

Switchyards are areas within high-voltage systems housing switchgear and busses (metal cable or metal tube conductors) used to route electricity to various sources and/or loads. Different switchgear configurations exist providing varying degrees of redundancy for power routing, some of the more common shown here. For simplicity's sake, all switchgear (disconnects and circuit breakers) are generically represented as box symbols:



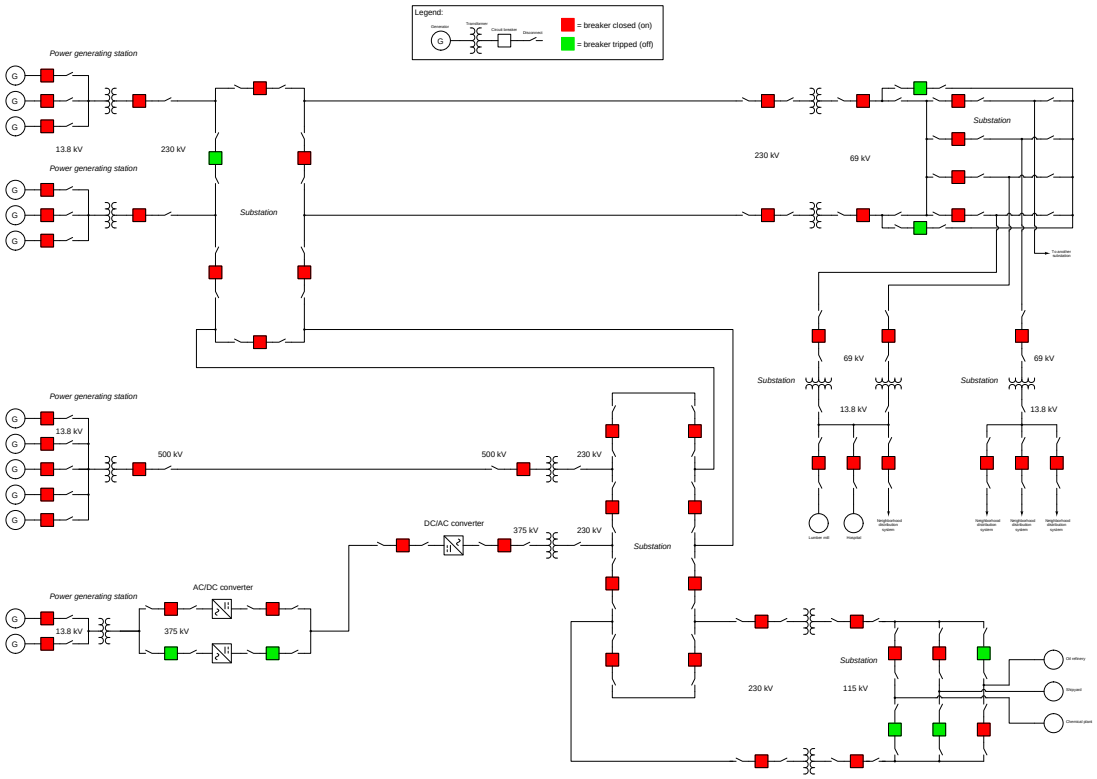
Each of these different switchyard topologies has its advantages and disadvantages in terms of physical size, cost, expandability, and reliability[5].

Another type of switchgear is the *earthing switch*, used to connect bus or line conductors to earth ground as a final step in securing those conductors in a zero-energy state. Alternatively, earthing cables may be attached to de-energized conductors to connect them to earth ground, ensuring equipotentiality with the earth by making those conductors electrically common to earth. The act of "earthing" conductors after tripping circuit breakers and opening disconnect switches positively ensures safe working conditions for maintenance personnel.

A modern trend in high-voltage switchgear resulting from the enhanced reliability of SF_6-quenched breakers is to combine the disconnect switch, circuit breaker, and earthing switch into a single unit called a *disconnecting circuit breaker* or *DCB*. The obvious advantage to this approach is reduced switchyard footprint.

[5] The ideally *reliable* switchyard permits maintenance work to be done on any single component without interrupting power to any load. The ideally *compact* and *economical* switchyard utilizes the fewest possible components. The ideally *expandable* switchyard may be easily extended to provide service to more lines without reconfiguring existing switchgear.

A *single-line diagram*[6] of a large-scale power grid shows a variety of switchgear and switchyard configurations as it would appear on the SCADA control center display. Standard color codes[7] for open/tripped (green) and closed (red) show the status of each breaker in the system:



Several *substations* appear in this diagram, serving as routing points for the electric power. Some substations contain *transformers* for conversion between different voltage and current levels while other substations contain nothing but circuit breakers and disconnects (i.e. switchyards).

[6] This is a form of electrical diagram using single lines to represent multiple conductors comprising a circuit, which greatly simplifies the illustration. Single-line (also called *one-line*) diagrams are interpreted as though electrical power were a fluid flowing from sources to loads, analogous to a piping diagram.

[7] At first the choice of green for tripped and red for closed may seem backward, since these colors are commonly intended to represent "go" and "stop", respectively. However, in the electric power industry green is intended to represent *safe* (de-energized) while red represents *dangerous* (energized).

Chapter 3

Full Tutorial

Circuit breakers are strictly on/off devices, used to make and break connections under load in power systems. Circuit breakers automatically open when dangerous circuit conditions are detected. Some low-voltage circuit breakers are strictly local-controlled devices, but larger circuit breakers (especially medium- and high-voltage units) may also be operated remotely by electrical signals.

Disconnects are switches designed to isolate sections of a power system in case of damage or to allow for routine maintenance. These may be manually-operated devices, or operated remotely by electric motor, and are typically not intended to make or break load current. *Circuit breakers*, by contrast, are designed to interrupt very high levels of electric current so they may safely cut off power in the event of a short-circuit fault.

This next photograph shows a set of three disconnect switches used on the line (input) side of a three-phase 500 kV power transformer bank in a large substation. As you can see, each disconnect is a simple "knife" switch design, bearing a striking similarity to its electrical schematic symbol. The long metal arm hinges on the left-hand side (at the top of the double insulator stands) and makes or breaks electrical contact on the right-hand side (where the arm is tipped with a sphere):

This particular high-voltage disconnect is motor-actuated, allowing all three disconnects to be operated in unison by remote control. When in the "open" state each metal arm points vertically toward the sky, clearly revealing its status to visual inspection. Lower-voltage disconnects are often built as manually-actuated devices, a crank handle or lever installed at ground level for a human lineman to actuate.

In series with these disconnect switches are a triad of 500 kV circuit breakers (with only two of them appearing in this next photograph). The circuit-breaking elements reside in the horizontal tube portion of each unit (called the "tank"), the tall ribbed structures being insulated conductors bringing the power down to the low-mounted breaker tank. Since disconnect switches are generally not rated for load current interruption, circuit breakers are necessary to "break" the current and safely extinguish the inevitable arc that forms when a live circuit is broken. In the background you can see a hinged disconnect switch in series with the furthest circuit breaker, a set of which serve to isolate power from the three circuit breakers (and every other component "downstream" of the disconnects) to permit maintenance on those components:

All three circuit breakers are remotely controlled by 125 VDC signals energizing solenoid coils within the breaker units. One solenoid coil called the "close" coil causes the breaker mechanism to move to the closed (conducting) position when momentarily energized. Another solenoid coil called the "trip" coil causes the breaker mechanism to move to the open (non-conducting) position when momentarily energized. The breakers also contain status contacts signaling the breaker's change of state. It is these solenoid coils and status contacts which permit the circuit breaker to be a part of an automatic control system rather than function merely as a manual switching device.

3.1 Low-voltage circuit breakers

This photograph shows a typical array of low-voltage[1] (480 Volt) circuit breakers in a "Motor Control Center" (MCC) panel, for 480 Volt 3-phase industrial power circuits:

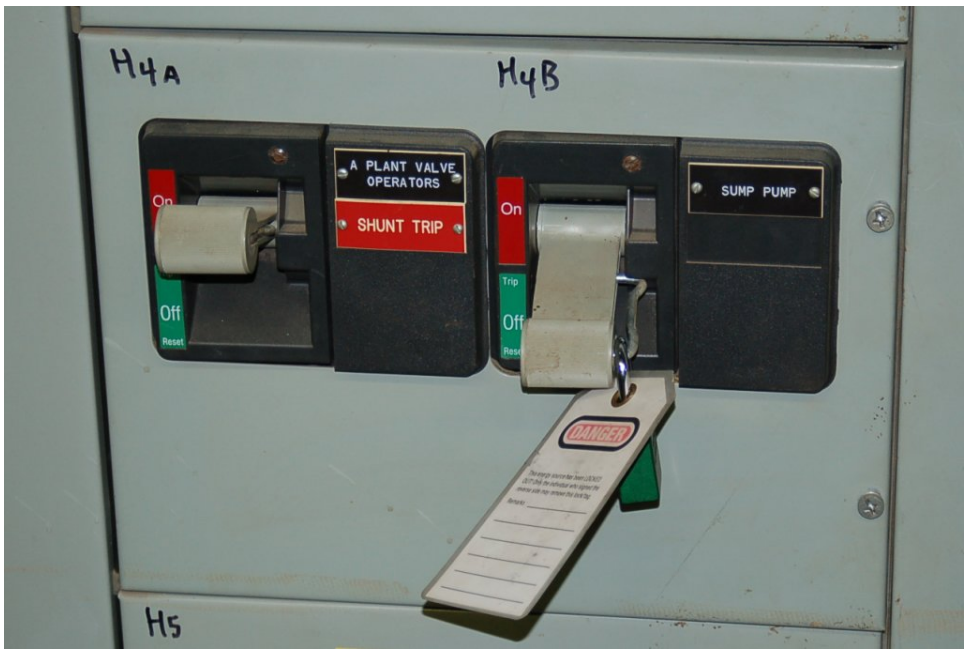
Note how each circuit breaker has its own on/off handle, for manual operation. These circuit breakers, like most low-voltage breakers, are capable of turning off ("tripping") on their own when

[1] In the United States, the term "low voltage" with reference to power circuits usually refers to circuits of 600 Volt or less potential.

high current is detected, but must be turned on ("closed") manually. That is to say, they lack "close" and "trip" solenoid coils present in larger circuit breaker units which would permit remote operation.

Some low-voltage circuit breakers utilize thermal elements to detect overcurrent conditions, much like the circuit breakers traditionally found in residential applications. When this thermal element inside the circuit breaker becomes too warm with current, it mechanically forces the mechanism to trip and open the contacts. Other low-voltage circuit breakers are magnetically operated, tripping when the magnetic field caused by conductor current becomes excessive. In either case, the trip mechanism for a low-voltage circuit breaker is typically contained within the circuit breaker itself.

A close-up photograph shows one of these breaker panels, containing two separate three-phase circuit breakers inside:



Note how the "Sump Pump" circuit breaker has been placed in the "off" position, its handle locked there by a padlock, a danger tag attached to notify any personnel of the reason for the breaker's lock-out.

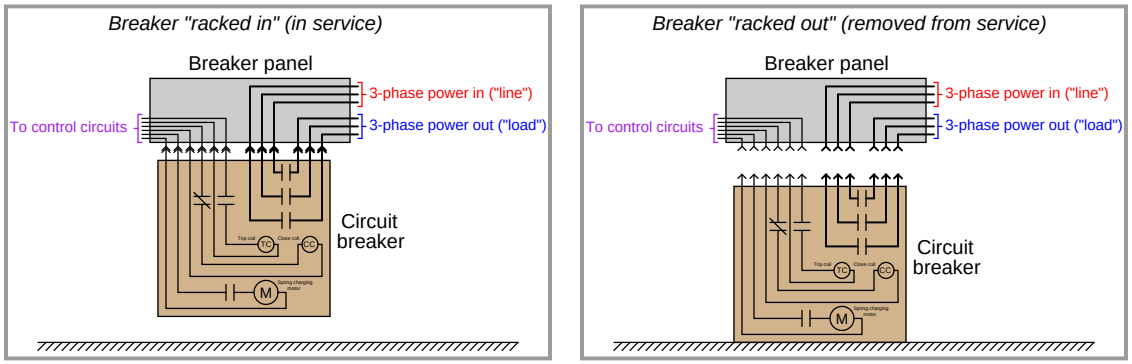
This next photograph shows a different brand of MCC (manufactured by Gould) where each unit contains not only a circuit breaker, but also an entire motor starter assembly (contactor, overload heaters, and associated switch contacts) for controlling a three-phase electric motor. One of these motor control "buckets" has been removed, revealing the line and load bus connections in the rear:

Industrial circuit breakers such as this are typically designed to be unplugged for ease of maintenance and replacement. If the "bucket" units are heavy, a lifting hoist is provided on the MCC to facilitate their removal and replacement.

3.2 Medium-voltage circuit breakers

Circuit breaker design and construction becomes more complicated at higher voltages, such as the voltage range extending from 2.4 kV to 35 kV commonly classified as "medium-voltage" in the electrical power distribution industry. Aside from being physically larger than low-voltage circuit breakers, medium-voltage circuit breakers are generally not self-tripping as low-voltage circuit breakers are. Rather, medium-voltage circuit breakers are electrically commanded to trip (and to close) by external devices called *protective relays* monitoring dangerous electrical conditions. Internally, these circuit breakers are equipped with "trip" and "close" electromagnet solenoids allowing the mechanism to be triggered by remote electrical signals.

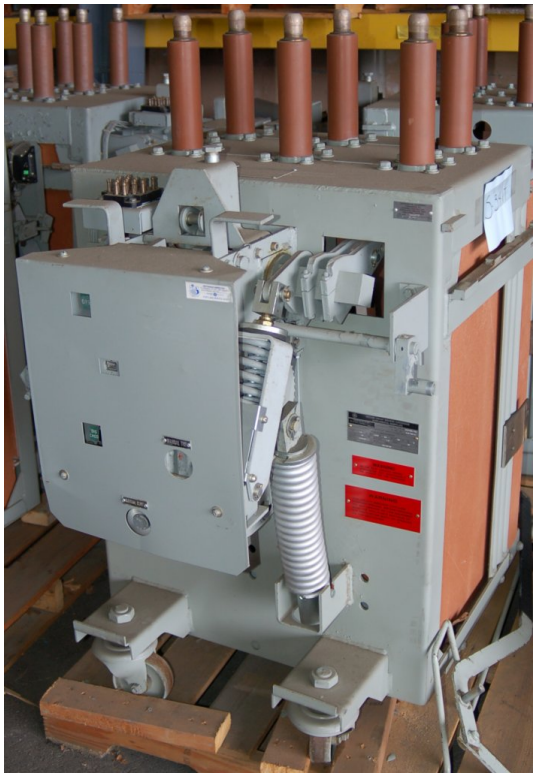
Medium-voltage circuit breakers are designed to be unplugged from the breaker panel for maintenance and replacement. This is referred to in the electrical power industry as *racking out* a circuit breaker. Some circuit breakers "rack" by moving horizontally, sliding in and out of the panel on guide rails. Other circuit breakers "rack" by moving vertically, sliding up into and down out of the stationary panel terminals, as shown in the following illustration:



The primary purpose of being able to "rack" a medium voltage breaker into and out of its place in a breaker panel is to facilitate regular maintenance on the circuit breaker mechanism. Unlike the circuit breakers you find in your home, these units may be frequently cycled and will suffer definite wear with each actuation. After a certain number of closing/tripping cycles, the breaker must be removed from service for inspection and testing.

Racking out a circuit breaker also provides another advantage, and that is an extra measure of safety when securing a power circuit in a zero-energy state. When a circuit breaker has been locked into its "racked out" position, the load conductors serviced by this breaker absolutely cannot become energized even if the circuit breaker contacts were made to close. This is analogous to unplugging an electrical appliance from a wall receptacle: it cannot be powered up even if the switch is turned on!

An example of a vertically-racking circuit breaker is the General Electric "Magneblast" unit shown below, designed for use in power systems operating up to 15 kV. The particular unit shown rests on a wooden pallet in a storage area. Normally, it would be installed in a metal-clad breaker panel, its components hidden from direct view:

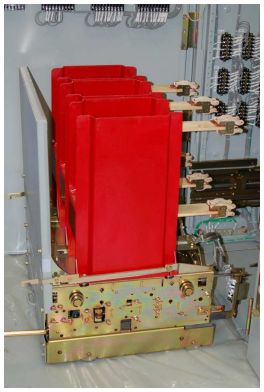


The six "stabs" seen on the top of this breaker unit engage with six sockets connected to the six bus-bar conductors inside the breaker panel (three for the three phases of the line supply, plus three more for the three phases of the load conductors). When this circuit breaker is "racked out," it is dropped down so that these six stabs disengage from the bus-bar connections, making it impossible to energize the load conductors even if the breaker contacts close.

A detail not seen in this photograph is the hoisting mechanism necessary to lift this breaker into its "racked-in" position. Medium-voltage circuit breakers such as the General Electric Magneblast are quite heavy, requiring special "lift truck" frames to hoist into and out of their engaged positions in the circuit breaker panel.

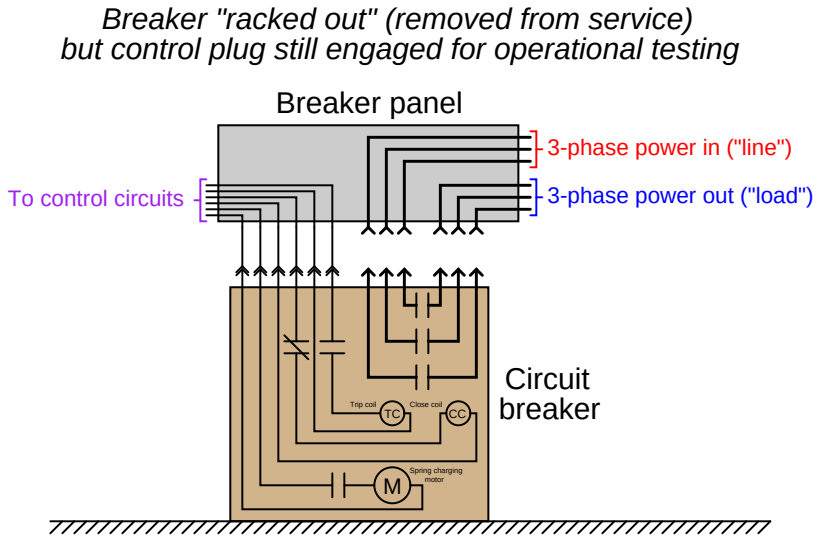
An example of a horizontal-racking medium-voltage circuit breaker is shown here. The left-hand photograph shows the breaker in its "racked-in" position inside the metal-clad switchgear housing, while the middle photograph shows the breaker being manually racked out using a hand-crank (operated with the switchgear panel door shut for added protection against arc flash), and the right-hand photograph showing the breaker partially racked out. These photographs were all taken on completely de-energized switchgear, which is why it was safe to photograph the breaker in its partially racked-out position and also which is why the person racking the breaker out did not need to wear arc flash protective clothing:

Once this breaker is completely racked out, it may be wheeled out of the switchgear panel for routine servicing. Here we see the circuit breaker entirely removed from the panel, with its six "stabs" plainly visible on the right-hand side:



An advantage of horizontal-racking circuit breakers over vertical-racking breakers such as the GE Magneblast is that the racking procedure does not require hoisting a very heavy component up or down.

Not only does "racking out" a circuit breaker add an extra measure of safety for personnel working on the load circuit, but it also allows the breaker to be tested in-place without energizing the load. The electrical connections commanding the breaker to open (trip) and close may still be connected to the control circuitry even in the racked-out state, permitting such tests. The following illustration shows how such a test may be performed in the "racked-out" condition:



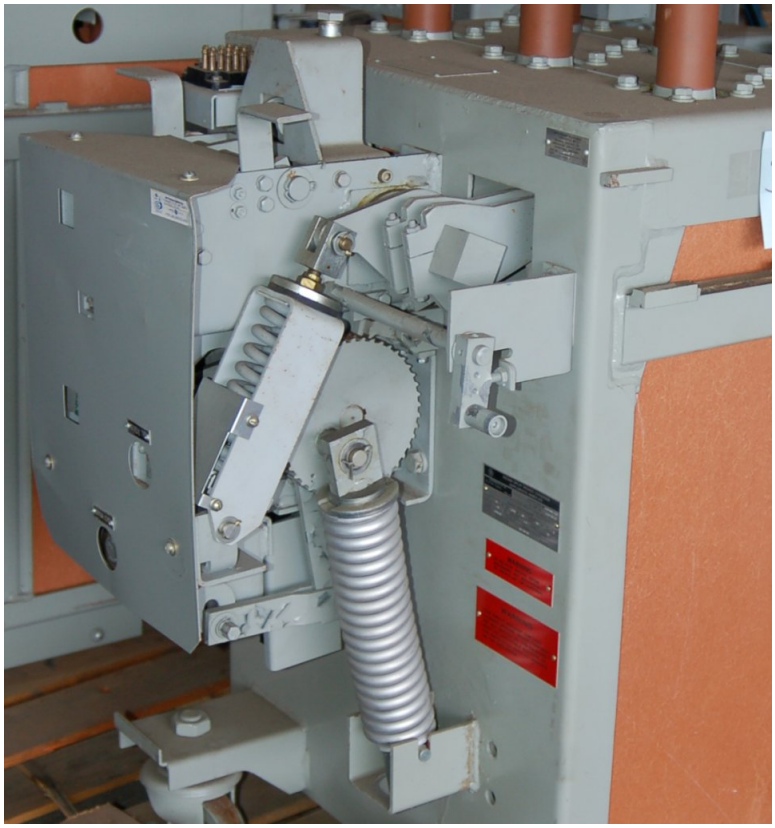
At medium-voltage and greater levels of potential, a significant design problem is how to rapidly extinguish the arc formed when contacts separate under load. Low-voltage circuit breakers simply rely on a wide and rapid enough separation of contact points to ensure the electric arc formed when the breaker trips cannot continue more than a fraction of a second. In medium-voltage circuits, both the heat output and the potential length of the electric arc formed by separating contacts is huge and therefore the arc must be extinguished as quickly as possible, both for personnel safety and for extending the operating life of the circuit breaker.

The original General Electric Magneblast circuit breaker design used a series of *arc chutes*, electromagnet coils, and pneumatic jets to direct the arc away from the separating contacts and thereby extinguish it rapidly. Other medium-voltage circuit breaker designs submerge the electrical contacts in an *oil bath* to keep them completely isolated from air so that an arc could never form. This oil has a high dielectric value (i.e. it is an excellent electrical insulator with a high breakdown rating), but needs to be tested on a regular basis to ensure good integrity.

A modern approach to the problem of extinguishing the arc drawn by opening circuit breaker contacts is to encapsulate the contacts inside of an air-tight *vacuum chamber*. This rear view of this GE Magneblast circuit breaker shows it retrofitted with vacuum contacts (the three white-colored components seen inside the breaker frame), replacing the old open-air contacts and arc chutes:

By removing all air from the vicinity of the contacts, there are no gas molecules to ionize when the contacts separate. Not only does this completely eliminate the problem of contact arcing, but it also permits the circuit breaker mechanism to perform its job with a shorter "throw" (less contact motion), since less gap distance is necessary to prevent current in a vacuum than in air. The only real challenge now is ensuring the integrity of the vacuum inside these chambers. This requires periodic testing of the contacts' dielectric rating by maintenance personnel using high-voltage testing equipment.

An interesting feature of the GE Magneblast and other medium-voltage circuit breakers is the mechanism for actuation. These circuit breaker contacts must be moved swiftly and with significant force in order to ensure quick and repeatable make/break times. In order to achieve this rapidity of motion, the breaker is designed to actuate by the stored energy of large mechanical springs. A side-view of a Magneblast circuit breaker shows a pair of large coil springs used to trip and close the circuit breaker contacts:

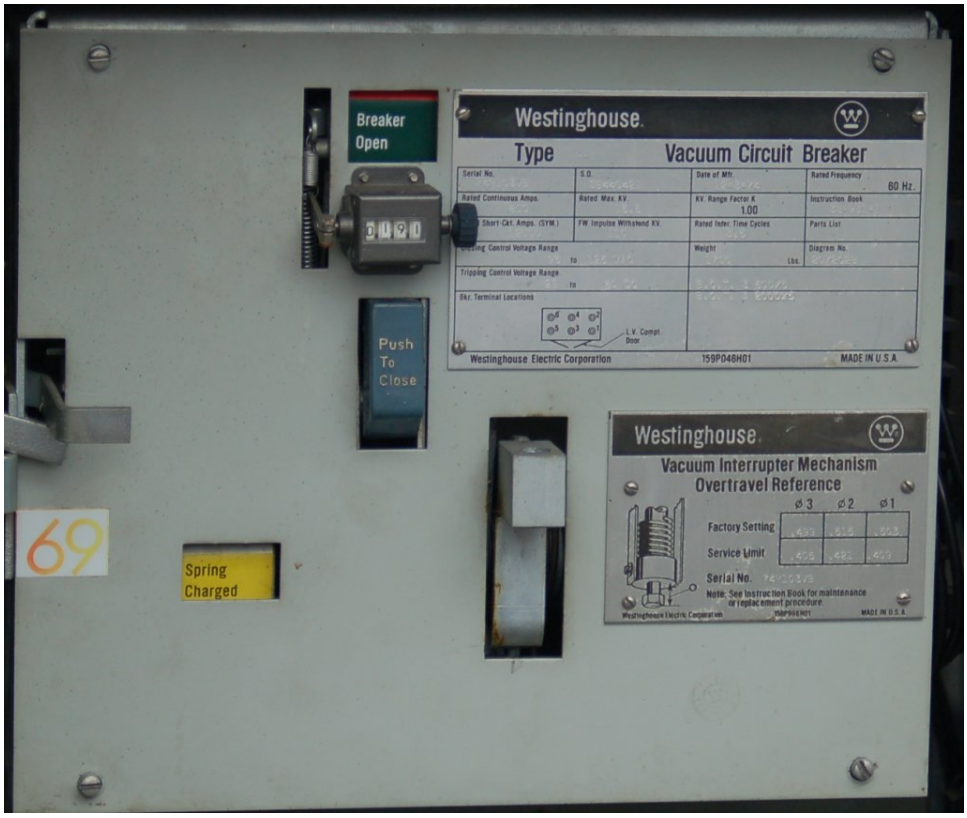


Much like the spring on the hammer of a firearm, the springs inside this Magneblast circuit breaker provide the mechanical driving force for opening and closing the breaker's three electrical power contacts. The act of opening or closing this circuit breaker is analogous to pulling the trigger of a firearm: a small mechanical movement unleashes the stored energy of these springs to do the actual work of rapidly opening and closing the contacts.

These springs are tensed ("charged") by an electric motor in the times following an actuation cycle, so they will be ready for the next actuation. Typically these charging motors are powered by 125 VDC supplied by the substation's "station power" battery bank, so they may operate even in the event of a total black-out condition where the substation loses AC line power from its incoming transmission lines. Indicator flags on the front of the circuit breaker reveal the breaker's contact status as well as its spring charge status:

Green-colored flags seen on the front panel of this breaker show the contact status as "open" and the spring status as "discharged". This circuit breaker is incapable of any action until its spring is charged. Once the spring has been charged, pushing the button labeled "Manual trip" will cause the breaker contacts to open, and pushing the button labeled "Manual close" will cause the breaker contacts to close.

A photograph of the front panel of a Westinghouse vacuum circuit breaker reveals the same basic indicators and manual controls seen on the (older) General Electric circuit breaker:



In this particular example, the actuating spring is charged, which means the breaker is in a state of readiness to switch from its present status (open, or tripped) to its opposite status (closed).

Both of these medium-voltage circuit breakers share another feature of interest: a mechanical counter tracking the number of close/trip cycles the breaker has experienced. The act of making and breaking high-power electric circuits takes a toll on the components of a circuit breaker – especially the contacts – and therefore this count value is a useful parameter for maintenance purposes. The breaker should be serviced at manufacturer-specified intervals of close/trip cycles, just like an automobile should be serviced at manufacturer-specified intervals of distance traveled.

3.3 High-voltage circuit breakers

At voltages 46 kV and above (classified as "high voltage" in the electrical power industry), the challenge of extinguishing the electric arc formed by separating breaker contacts becomes severe. Two popular strategies for mitigating contact arc in modern high voltage circuit breakers are *oil immersion* and *gas quenching*.

A set of three oil-bath circuit breakers (OCB's) rated for 230 kV service is shown here, retired from service:

Each of the three circuit breakers (one for each line of the three-phase circuit) is mechanically linked by a common shaft at the top of the breaker tanks, so they all trip and close as one unit.

The fast and reliable actuation of such a bulky mechanism requires a large amount of stored energy, and in the case of the oil circuit breaker shown above the energy storage medium is compressed air. An on-board electric air compressor powered by "station power" maintains air pressure inside a pressure vessel, and this compressed air is directed to a piston actuator through

solenoid valves to provide the actuation force necessary to move the breaker contact assemblies open and closed.

A view inside the enclosure on the far side of this oil circuit breaker reveals the air compressor (upper-right), compressed air storage tank (right) and actuation cylinder (middle):

The man shown in this photograph is pointing to a solenoid valve designed to pass compressed air to and from the piston actuator. A large-diameter black hose runs from this solenoid through the bottom of the enclosure, allowing compressed air from the cylinder to vent to atmosphere.

A more modern breaker design for 230 kV service is this gas-quenched circuit breaker unit, a mere fraction[2] of the physical size of the oil circuit breaker shown previously:

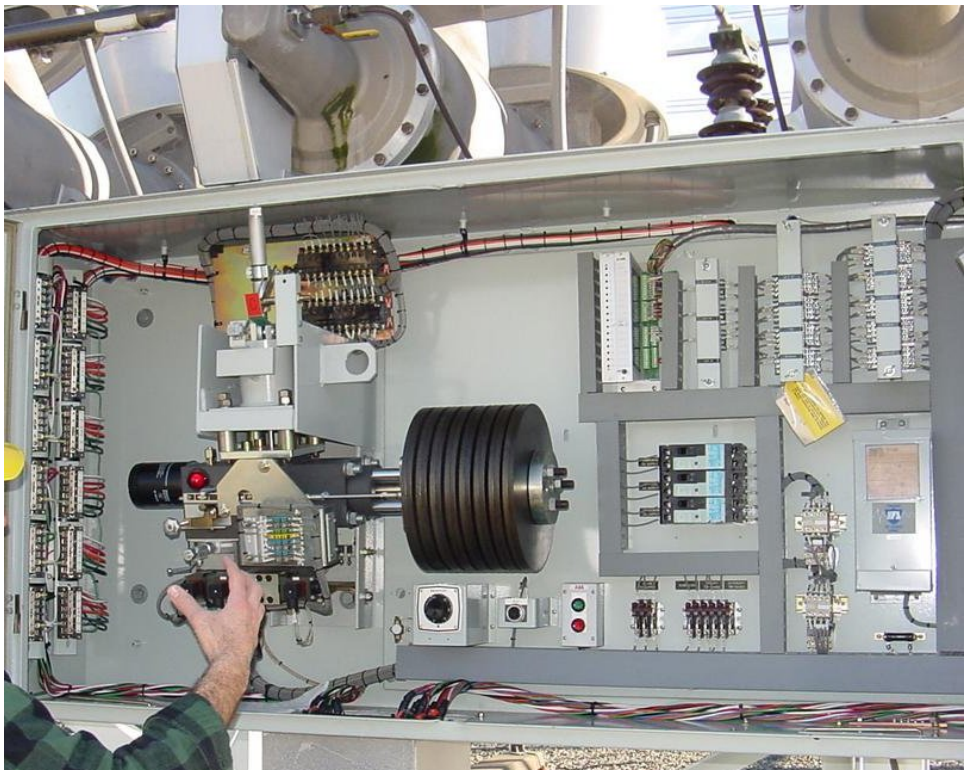
The ribbed porcelain structures are the high-voltage terminals for this circuit breaker: three for the three-phase lines coming in, and three for the three-phase load terminals exiting. The actual contact assemblies reside in the gas-filled horizontal metal tubes ("tanks"). It is striking to note that the same current interruption and isolation functions performed by the gigantic oil-filled tanks of the retired circuit breaker previously shown are performed by this relatively tiny gas-quenched breaker.

The gas inside the breaker's tanks is *sulfur hexafluoride*, a very dense gas (about 5 times denser than air) with excellent electrical insulating and arc-extinguishing properties. SF_6 gas is contained in these breaker contact chambers under pressure to maximize its dielectric breakdown strength (its ability to withstand high voltage without ionizing and passing current across the gap between the circuit breaker's open contacts). SF_6 gas is non-toxic[3] and safe to handle.

[2] For an equitable size comparison between the two different types of circuit breaker, consider the fact that the insulators on this gas-quenched circuit breaker are approximately the same physical height as the insulators on the previously-shown oil-tank circuit breaker.

[3] While pure SF_6 gas is benign, it should be noted that one of the potential chemical byproducts of arcing in an SF_6-quenched circuit breaker is hydrofluoric acid (HF) which is extremely toxic. HF is formed when SF_6 gas arcs in the presence of water vapor (H_2O), the latter being nearly impossible to completely eliminate from the interior chambers of the circuit breaker. This means any maintenance work on an SF_6-quenched circuit breaker must take this chemical hazard into consideration.

Like the large oil-filled circuit breakers seen previously, this SF_6 circuit breaker has an enclosure on one side where the actuation and control components are located. Inside this enclosure we see a large stack of Belleville spring washers (the dark-colored discs located in the center of the enclosure), which are used as the mechanical energy-storage medium instead of compressed air. This stack of spring-steel washers is compressed by an electric motor and gear mechanism, then the spring tension is released through another mechanism to close and trip the breaker's contacts on demand. As usual this charging motor receives its power from the uninterruptible "station power" supply of the substation, allowing the breaker to actuate even in the event of a total "blackout" condition:



Inside this enclosure we also see a small pair of pushbuttons (one red, one green) just below and to the right of the Belleville washer stack for manually closing and tripping the breaker, respectively. The common color coding used in the United States for electric power switchgear is *red for energized, green for de-energized*. This may seem backward to most people familiar with red and green traffic lights, where red means "stop" and green means "go," but the concept here is one of safety: red means "dangerous" (power on) while green means "safe" (power off).

It should be noted that most of the time these high-voltage circuit breakers are triggered remotely, rather than manually by someone standing near them. These command signals may come from a manual switch located in the control room, or from some automatic circuit such as a *protective relay* instructing the breaker to open due to an abnormal system condition.

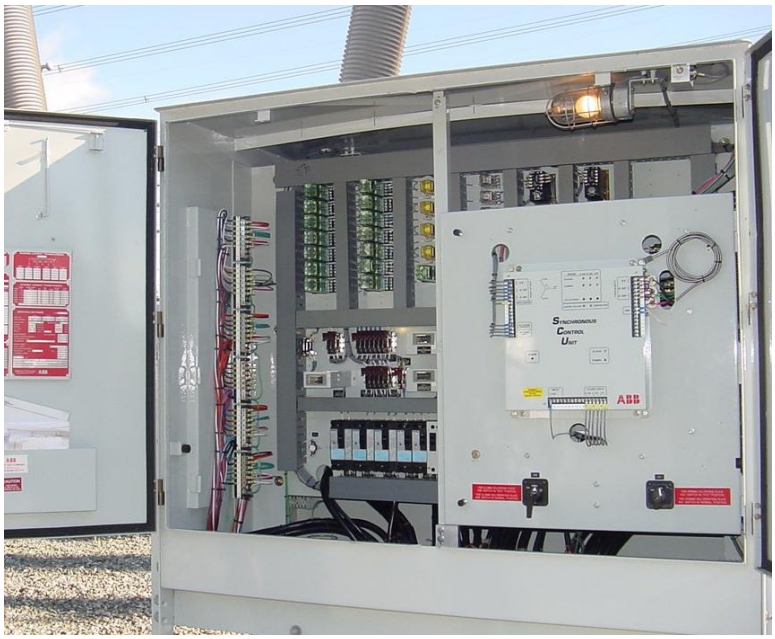
The nameplate photographed on a similar SF_6 circuit breaker reveals some interesting features:

According to this nameplate, the normal operating pressure for the SF_6 gas is 98.6 PSI. A low-pressure alarm triggers if the SF_6 gas pressure happens to fall below 85 PSI. When opening (tripping), the circuit breaker only takes *3 cycles'* worth of time at 60 Hz to completely interrupt the current. One solenoid coil closes the breaker, and that coil requires a signal of 125 Volts DC at just over 3 Amperes of current. The breaker's contacts may be tripped by energizing one or more redundant solenoid coils at 125 VDC and 1.8 Amperes (each). In either direction, the breaker's actuation is powered by a pre-charged spring, much like the 230 kV breaker seen previously. This particular breaker is rated for 123 kV at 2000 Amperes full-load.

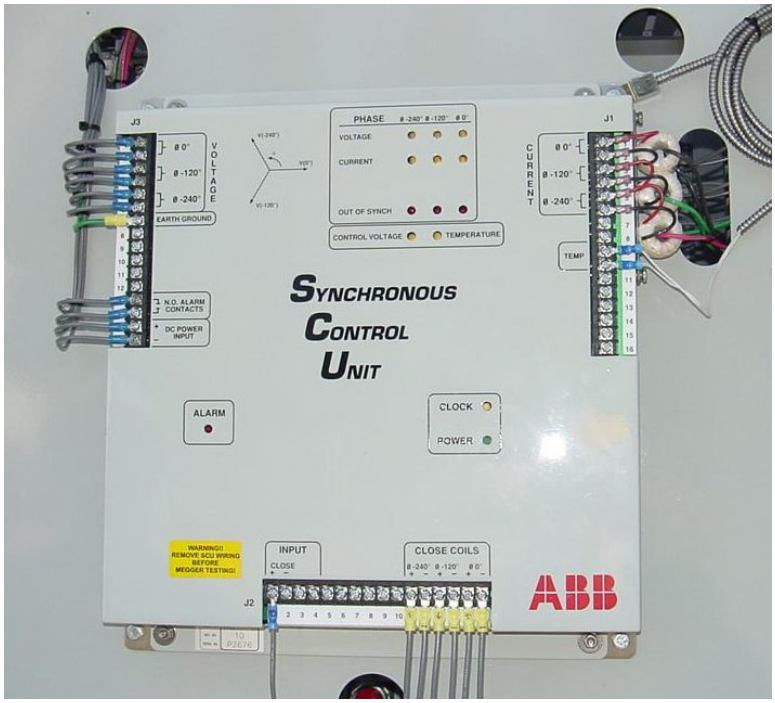
Sulfur hexafluoride gas circuit breaker technology is popular for higher voltage applications as well, such as these 500 kV circuit breakers seen here:

In this application, where three separate circuit breaker units independently interrupt current for the three-phase power lines, there is no mechanical link to synchronize the motion of the three contact sets. Instead, each single-phase circuit breaker actuates independently.

An electronic synchronizing control system is used to coordinate the closing and tripping of these three 500 kV circuit breakers, seen here in this photograph where the enclosure's door has been opened for inspection:



This synchronous control unit monitors both voltage and current for the three circuit breakers, via PT ("potential transformer") and CT ("current transformer") instrument transformers. The PT and CT signal wire connections may be seen at the top of the panel on the synchronizing unit:



In order to minimize contact arcing, each breaker contact should be closed when the voltage across its contact is such that the current will be minimized[4], and each breaker contact should be opened (tripped) when the current through the contact is near zero. The synchronizing unit not only monitors the AC voltage and current status for each breaker's contact, but it also "learns" the average actuation time for each circuit breaker mechanism by measuring the time delay between the trigger signal and the change in current signifying contact opening or closing. In this way, the synchronizer is able to anticipate when the AC voltage or current value will cross zero, and send a triggering signal to each breaker mechanism at precisely the right time so all three breaker contacts experience minimum arcing.

[4]For resistive loads, this means closing the contact at the point of voltage zero-crossing (when the voltage waveform passes through 0 Volts). For inductive loads such as shunt reactors and unloaded transformers, this means closing the contact at the point where voltage is at its peak value (i.e. where the reactive, lagging current waveform would be at zero-crossing).

So far all of the high-voltage circuit breakers shown in previous photographs are of the *dead tank* type, where the structure housing the interrupting contact(s) is maintained at ground potential (i.e. the outside surface of the circuit breaker mechanism is electrically "dead"). Some high-voltage circuit breakers are built such that their interrupting assemblies are at line potential, the entire breaker suspended above ground from insulators. This type of circuit breaker is called a *live tank*, because the "tank" containing the contact(s) operates at a high voltage with respect to earth ground. A photograph of a 500 kV, single-pole[5], SF_6-quenched, live tank breaker appears next:

The actuating mechanism for this live-tank breaker is housed in the "can" assembly seen at the base, where the vertical insulator meets the steel supporting tower.

[5]This particular circuit breaker, like most live-tank circuit breakers, interrupts just one phase (i.e. one "pole") of a three-phase bus. Portions of the second and third live-tank SF_6 breakers comprising the full three-phase breaker array for this bus may be seen near the left-hand edge of the photograph.

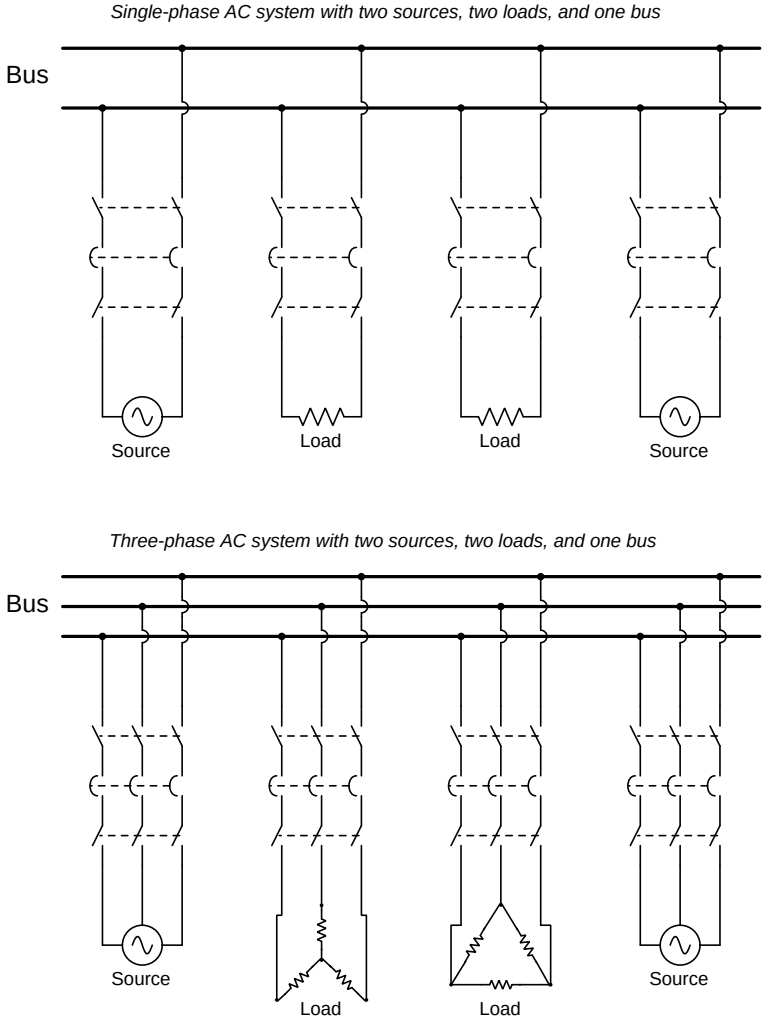
Another 500 kV, single-pole, live-tank circuit breaker assembly appears in the next photograph, this particular breaker being an older unit using *compressed air* as the interrupting medium rather than sulfur hexafluoride gas:

Air nozzles powered by hundreds of PSI of compressed air are used to "blow out" the arc formed when the circuit breaker's contacts separate. These air nozzles are not visible in the photograph, being internal to the circuit breaker's construction. An interesting feature of this style of circuit breaker is the loud report generated when it trips: the sound of the compressed air jets extinguishing the arc across the separating contact poles within the breaker is not unlike that of a firearm discharging.

Multiple series-connected contact assemblies comprise this circuit breaker, distributing the energy of the arc across multiple points in the breaker assembly rather than across a single contact. This is evident in the photograph as multiple clusters of "tanks" on the top of the left-hand assembly, as well as the second live-tank assembly connected in series to the right. Such arrangements are necessary because air is a less effective medium for extinguishing an electric arc than either oil or SF_6 gas.

3.4 Bus configurations

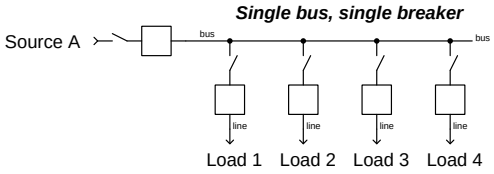
Switchyards are areas within high-voltage systems housing switchgear and busses (metal cable or metal tube conductors) used to route electricity to various sources and/or loads. At root these are just switching networks used to connect sources and loads in parallel with each other on demand, a single-phase example and a three-phase example shown below:

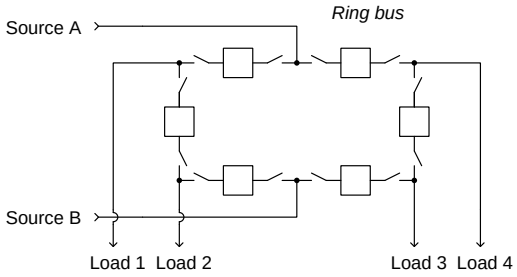


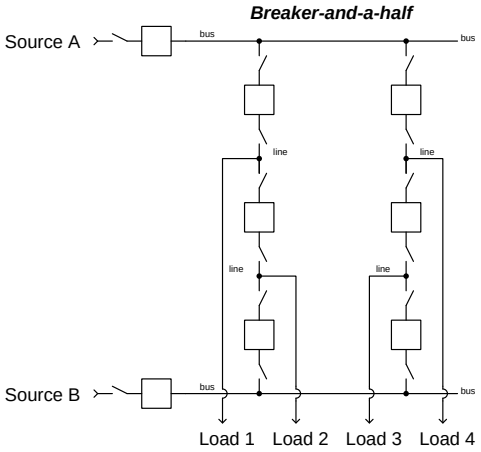
Both of these schematic diagrams represent what is known as a *single-bus, single-breaker* switching configuration, where each source and each load connects to a single bus through a single circuit breaker (and disconnect switches). As you might imagine, showing each and every conductor in typical schematic fashion tends to make that diagram cluttered, and so instead we typically use *single-line diagrams* which condense each *set* of power conductors into a single line. This means disconnect switches and circuit breakers alike have only one line in and one line out. Sources and

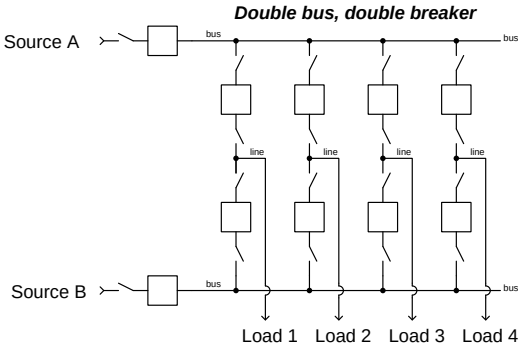
loads alike have only one line connecting them to other devices. Similarly, busses are just single lines on a single-line diagram.

The relative simplicity of the single-line diagram format allows us to easily represent complex arrangements of switchgear and busses found in modern switchyards, some of the more common configurations shown below. Note that circuit breakers are shown as box symbols, and disconnects as regular switch symbols:









Each of these different switchyard topologies has its advantages and disadvantages in terms of physical size, cost, expandability, and reliability[6]. A good *active reading* exercise you can do here is trace how power is able to flow from source(s) to each and every load in each of these switchyards, and then ask yourself if it is possible to remove any one of the circuit breakers from service for routine maintenance or repair while maintaining power to all loads. You will find that some topologies make this easy, while for others it is impossible!

[6]The ideally *reliable* switchyard permits maintenance work to be done on any single component without interrupting power to any load. The ideally *compact* and *economical* switchyard utilizes the fewest possible components. The ideally *expandable* switchyard may be easily extended to provide service to more lines without reconfiguring existing switchgear.

As you can see from these single-line diagrams, each circuit breaker must be flanked by a pair of disconnect switches to permit maintenance on any one breaker without de-energizing the rest of the bus. This can occupy a significant amount of space in high-voltage switchyards, and so a modern trend has been to integrate disconnect switches within the circuit breaker assembly itself to save space. This is called a *disconnecting circuit breaker*, or *DCB*.

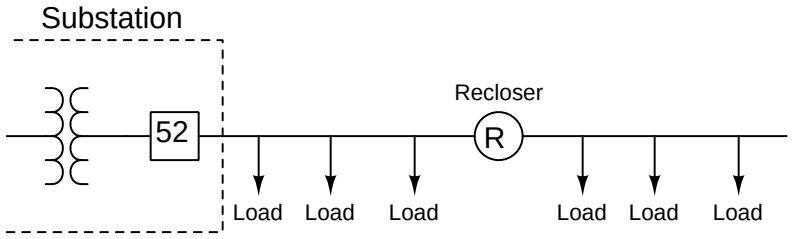
Another type of switchgear is the *earthing switch*, used to connect bus or line conductors to earth ground as a final step in securing those conductors in a zero-energy state. Alternatively, earthing cables may be attached to de-energized conductors to connect them to earth ground, ensuring equipotentiality with the earth by making those conductors electrically common to earth. The act of "earthing" conductors after tripping circuit breakers and opening disconnect switches positively ensures safe working conditions for maintenance personnel. Many disconnecting circuit breakers (DCBs) also include earthing switches.

3.5 Reclosers

A special type of medium-voltage circuit breaker used to quickly interrupt and re-establish power in distribution lines is called a *recloser*. Reclosers are designed to trip if ever a distribution line suffers a "transient" (momentary) fault due to some natural event such as a lightning strike causing an insulator to "flash over" to ground or a tree branch touching one or more line conductors, then automatically re-close moments later to test whether or not the fault still persists. If the fault clears on its own – a common occurrence with tree branches, as the branch may break off or burn away following the initial arc – then the recloser remains closed and continues providing power to customers. By some estimations transient faults account for 70% to 90% of all faults occurring on overhead power lines. If non-reclosing fault protection were applied to all distribution and transmission lines, extended interruptions of electric power service would be far more common than they are now.

If you have ever experienced momentary cessations of electrical power service to your home or business where the power "blinks" off and on in rapid succession, you have experienced a recloser at work. The recloser opens as soon as an overcurrent condition is detected, then recloses briefly to "test" for continued presence of the fault. If the fault persists, the recloser trips again and then recloses once more to "re-test" for the fault. If the fault has cleared by then, the recloser remains closed and restores normal power service to customers. Only if the fault persists after multiple "shots" does the recloser remain in the tripped (open) state and waits for line crews to repair the fault.

Reclosers are typically located some distance "downstream" of the substation, to isolate certain remote portions of the distribution network. Circuit breakers at the substation provide protection for each distribution line as a whole:



A typical recloser resembles a "circuit breaker on a stick," located near the top of a distribution power pole near the line conductors. Modern reclosers use SF_6 gas quenching to extinguish arcing resulting from the interruption of high-magnitude fault currents. Legacy reclosers typically employed oil quenching. This photograph shows a modern (SF_6-quenched) recloser, with its three phase current-interrupting contact units clearly visible:

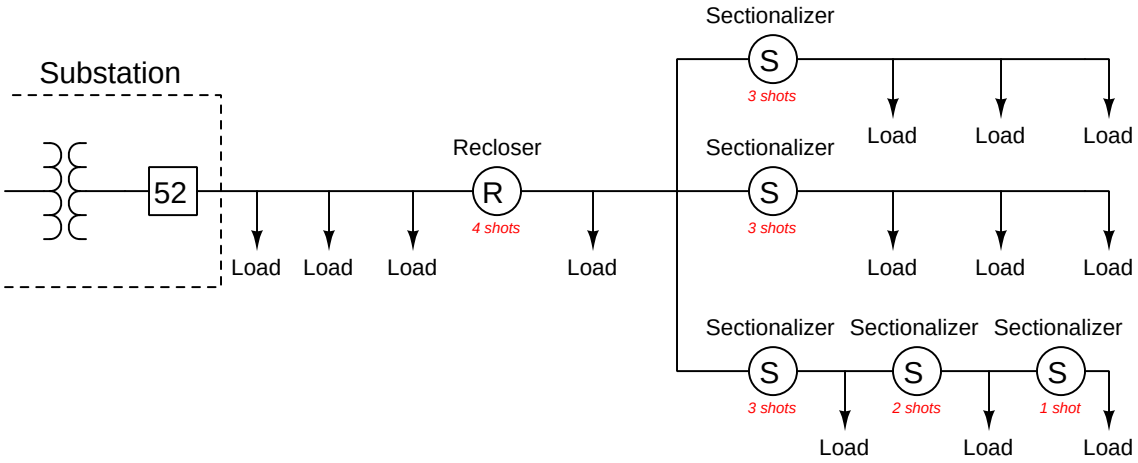
The grey enclosure located near ground level on this pole contains the *protective relay* responsible for issuing the "trip" and "close" signals to the recloser's coils. Current transformers located within the recloser provide isolated sensing of line current to the reclosing relay, necessary for detecting any overcurrent conditions that might result from a transient fault. Each attempt by the reclosing relay to re-close the breaker is called a *shot*. If the reclosing relay fails to clear the fault by a certain number of shots, it enters the *lockout* state whereby the recloser remains open and must be re-closed by human intervention.

Distribution line reclosers, unlike circuit breakers located in substations, cannot rely on an auxiliary "station power" energy source for opening and closing its line-interrupting contacts. Therefore these small units utilize AC line voltage as the actuating power for the contacts. Low-voltage "trip" and "close" circuits still exist for control purposes, but the actual energy source for rapid tripping/reclosing cycles comes from the AC line itself.

3.6 Sectionalizers

A *sectionalizer* is a special type of disconnect designed to operate "downstream" of an automatic recloser. Its contacts open after sensing a pre-determined number of re-tries ("shots") from the recloser feeding it. The concept is that each sectionalizer's zone of protection is a sub-set of the recloser's, and so if the fault exists in the sectionalizer's domain it is the job of the sectionalizer to trip (open) before the recloser gives up and remains tripped after delivering its last shot.

In order to perform this task, sectionalizers must be able to detect overcurrent conditions and also count the number of times power has been cycled off and on by the upstream recloser, and then be able to trip after a certain number of off/on cycles occur with excessive current. Consider the following single-line diagram showing a radial distribution network with one recloser (R) and multiple sectionalizers (S):



Each sectionalizer immediately downstream (i.e. to the right) of the recloser is programmed to trip after sensing overcurrent for some number of shots less than what the recloser will attempt. Each sectionalizer downstream of another sectionalizer must be programmed to trip after fewer shots, in order to "coordinate" protection along that sectionalized feeder. In the example shown, the recloser is programmed to make 4 re-closure attempts (4 shots) before declaring a permanent fault and remaining in the tripped state. Each sectionalizer immediately downstream of the recloser allows up to 3 shots with overcurrent before tripping. On the lower line, the 3-shot sectionalizer is followed by a 2-shot sectionalizer which is followed by a single-shot sectionalizer: the farther along the line you go, the fewer chances are offered for a fault to self-clear. The goal, as always, is to isolate the smallest portion of the power system necessary to isolate the fault.

Sectionalizers are less complex than reclosers, and therefore are more economical to install and maintain in a power distribution network. Their power contacts need not be as rugged as either reclosers or power circuit breakers, because the sectionalizer trips during the "off" cycle and therefore should never have to interrupt line current. Sectionalizers are also incapable of self-resetting, and must be re-set manually by line maintenance personnel following a trip.

Chapter 4

Historical References

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

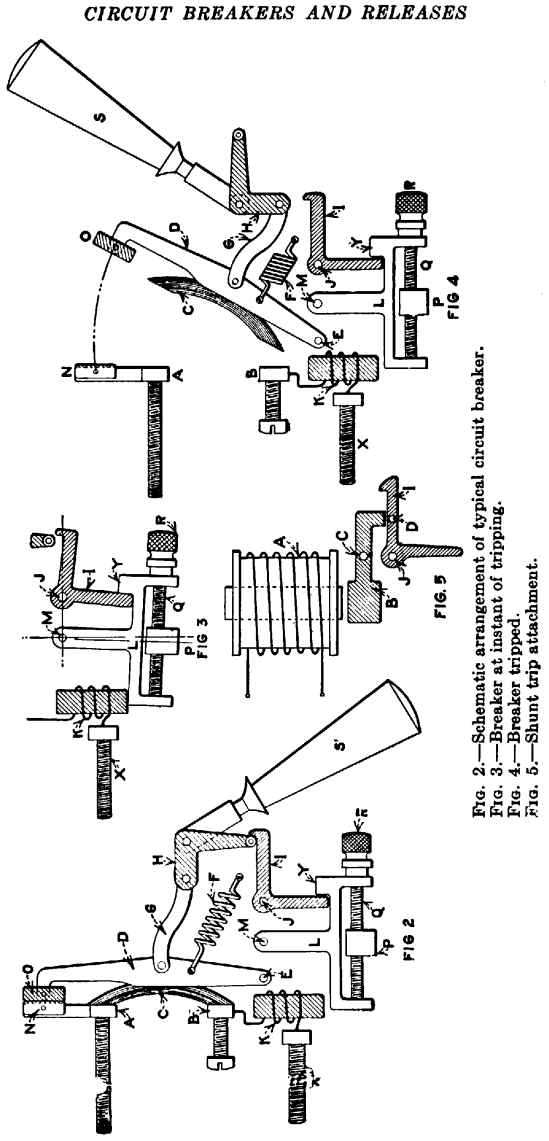
Readers may wonder why historical references might be included in any modern lesson on a subject. Why dwell on old ideas and obsolete technologies? One answer to this question is that the initial discoveries and early applications of scientific principles typically present those principles in forms that 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 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

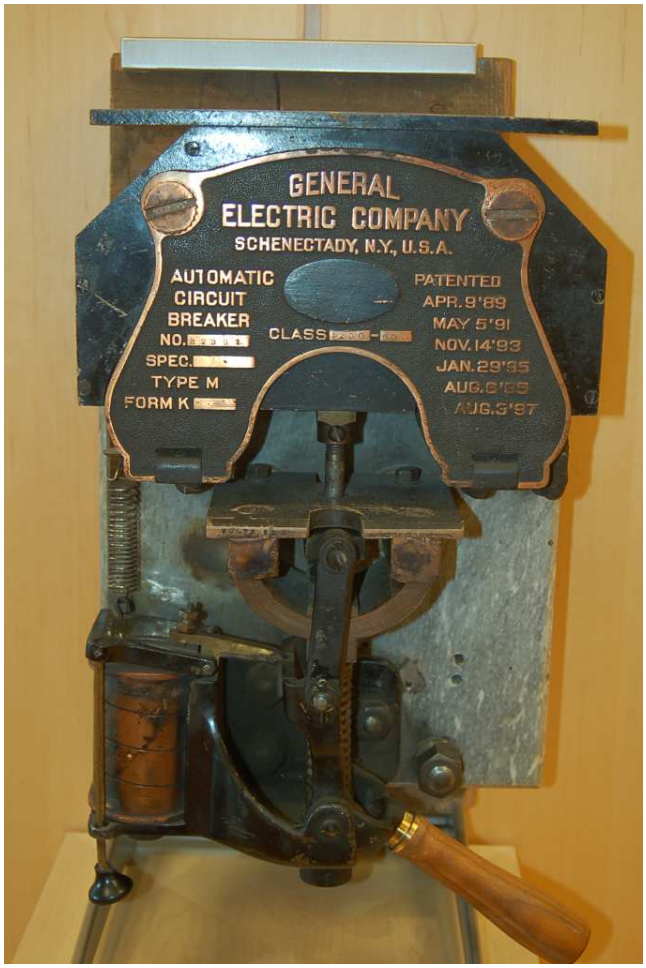
FIG. 2.—Schematic arrangement of typical circuit breaker.
FIG. 3.—Breaker at instant of tripping.
FIG. 4.—Breaker tripped.
FIG. 5.—Shunt trip attachment.

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

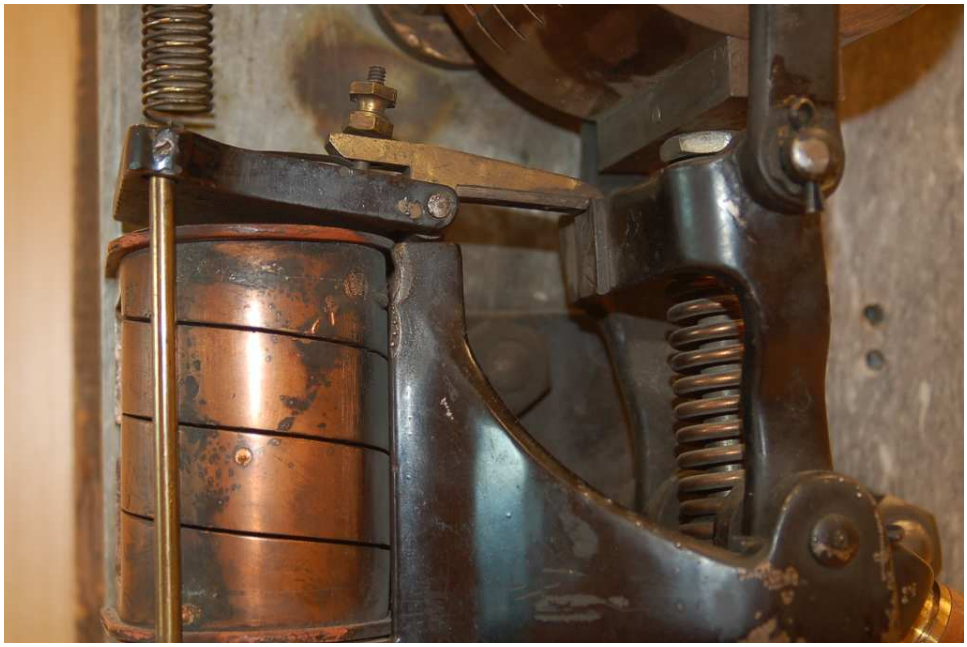
copper contact pads A and B to close the breaker. Contact pads N and O are the last to break as the circuit breaker trips, and being made of carbon rather than metal they tend to wear better under the influence of arcing.

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:

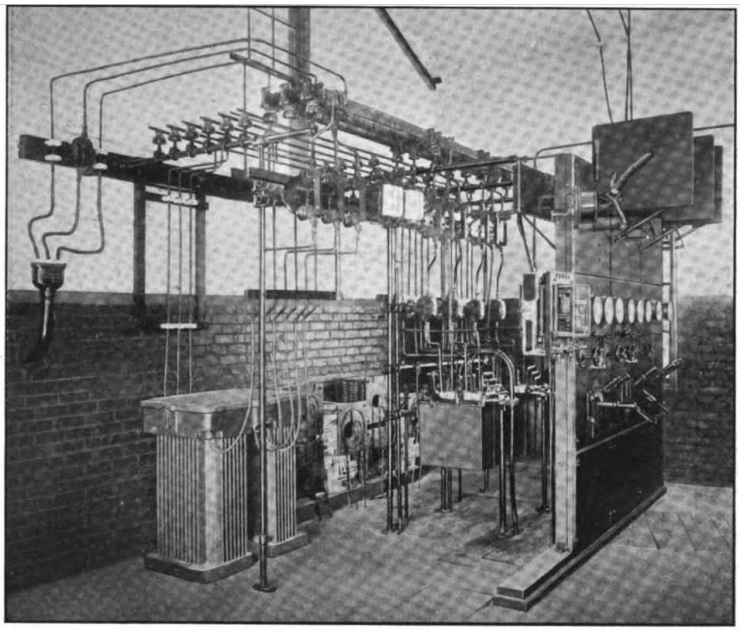


The trip coil is plainly visible in this close-up photograph:



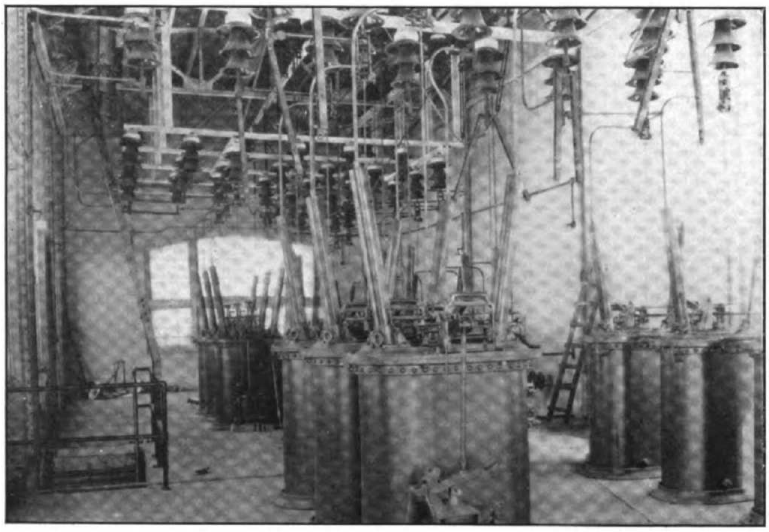
This particular trip coil uses a wide strip of copper for its *four* turns, suggesting a high current necessary to "pick up" the trip mechanism and trip the breaker. Like the breaker diagram shown on page 9 of Victor Todd's book, this breaker's trip coil was wired directly in series with the breaker 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:



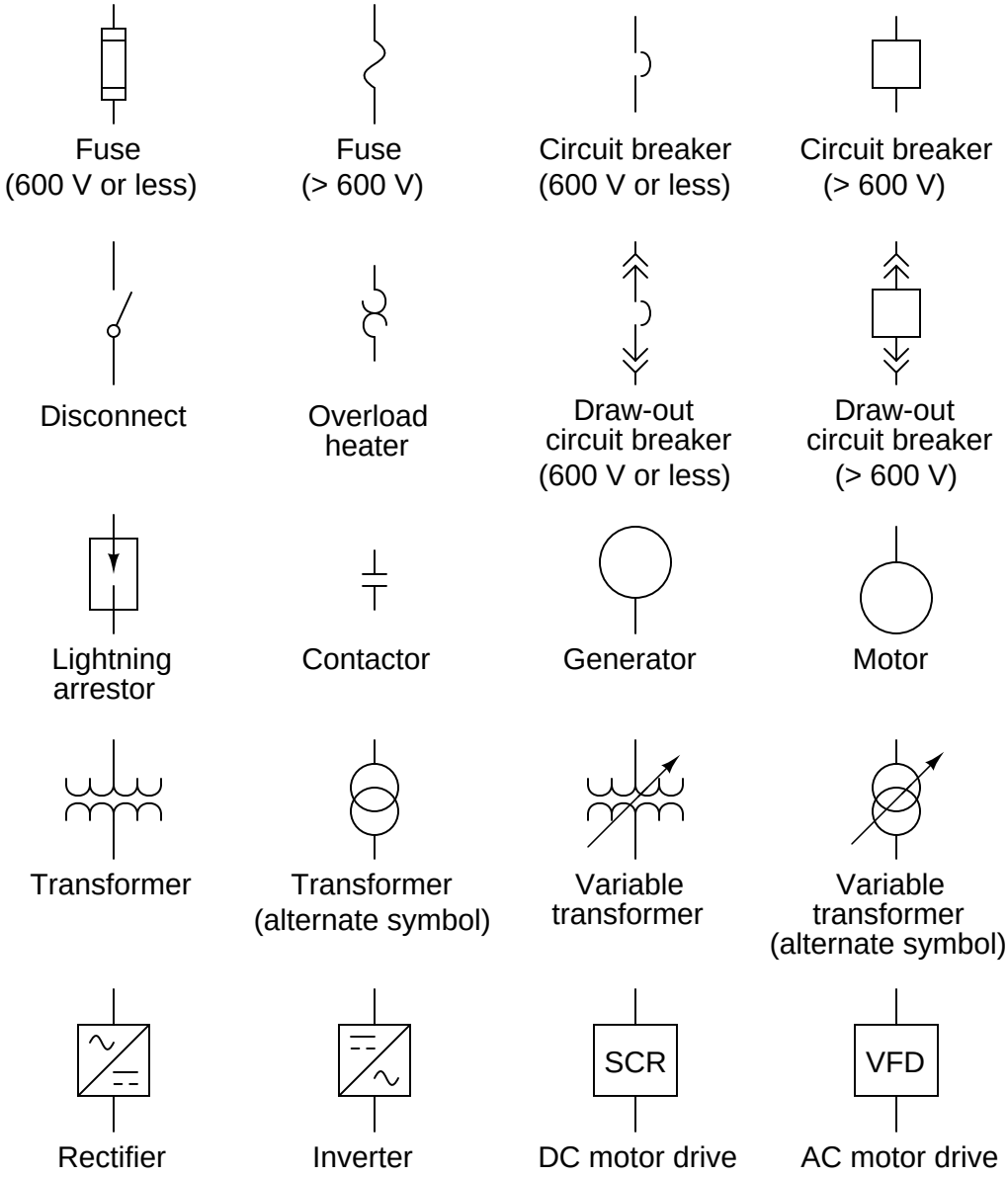
OCOEE RIVER PLANT. THE 66,000-VOLT OIL SWITCHES

Chapter 5

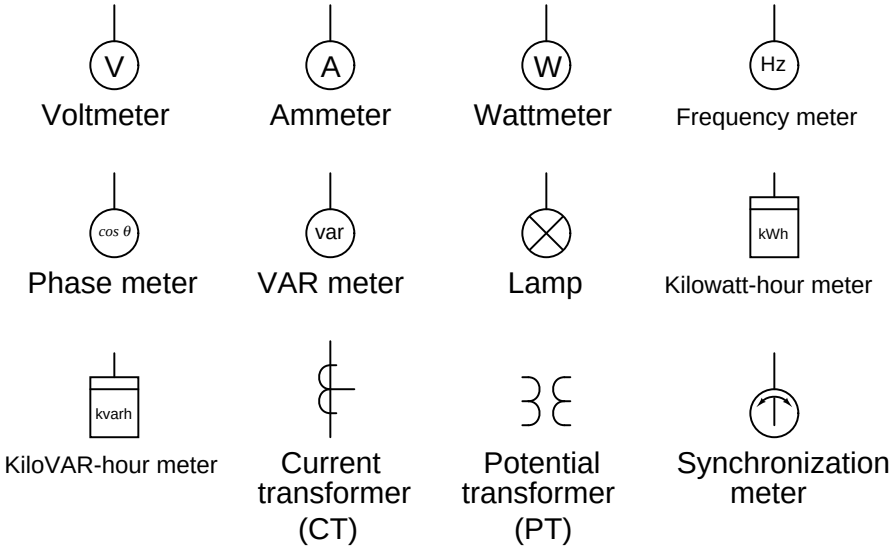
Derivations and Technical References

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 Single-line diagram power component symbols



5.2 Single-line diagram measurement component symbols



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.

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

[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.

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

Circuit breaker

Open

Short

Live-tank breaker

Dead-tank breaker

Lock-out Tag-out (LOTO)

Zero-energy state

Arc

Single-line diagram

Coordination

Reclosing

Current transformer

6.1.3 Breaker failure

Circuit breakers fulfill an important role in electric power systems, that being to interrupt current either manually-directed or automatically in the event of an electrical fault in the system. However, a possible fault within any electric power system is a failure within the circuit breaker itself, namely if it fails in such a way that it cannot interrupt current when called to do so. A robustly-designed power system will anticipate this event by providing means to detect it if it occurs, and to take protective action as a result.

Identify how a breaker failure might be detected by instruments sensing conditions at the failed circuit breaker.

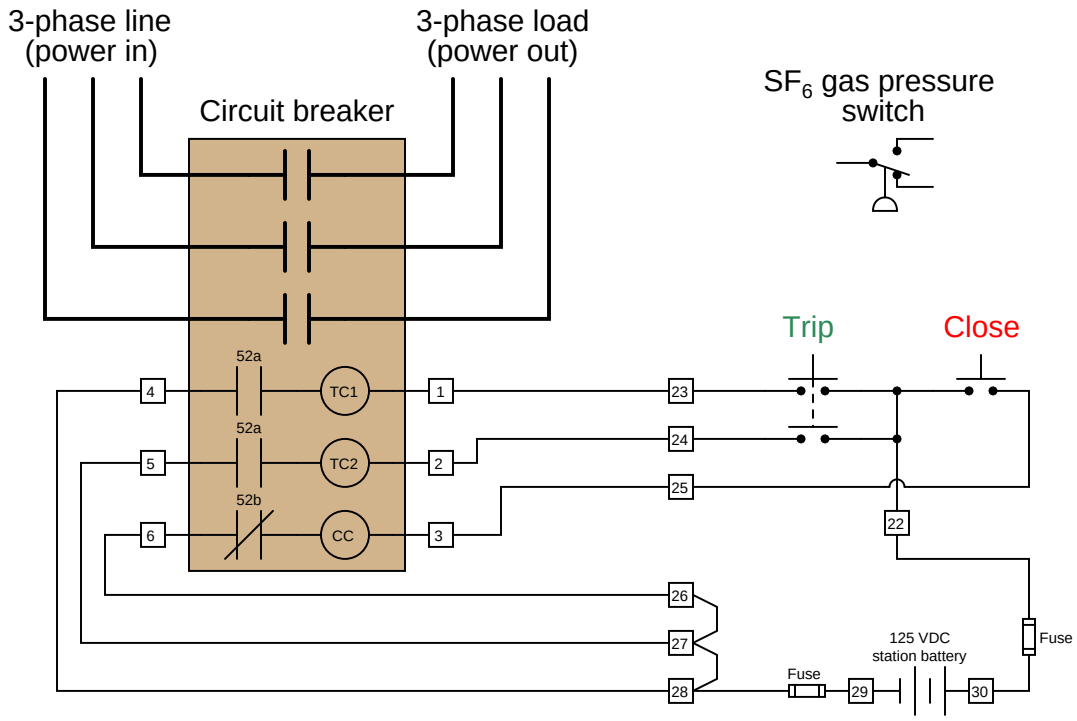
Also, identify what protective action(s) should be taken in the event of a breaker failure.

Challenges

- Identify some physical causes of a breaker failure.

6.1.4 Low-pressure lockout

A high-voltage circuit breaker is manually operated from a remote location using a pair of pushbutton switches, connected to "trip" and "close" solenoid coils within the breaker:



This particular circuit breaker is gas-quenched by sulfur hexafluoride gas (SF_6), which is normally pressurized inside the circuit breaker to approximately 45 PSI for optimum electrical performance.

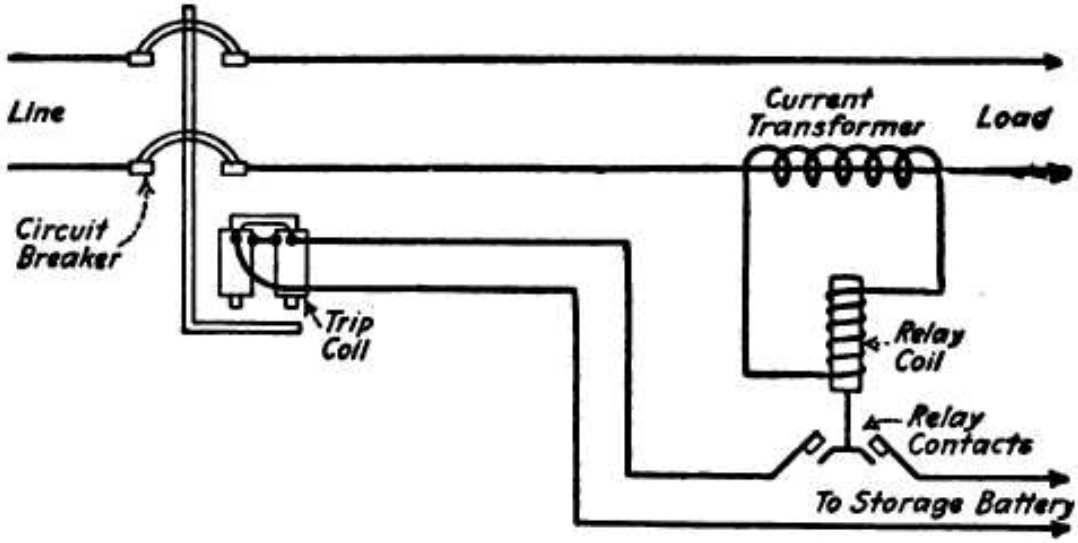
A low-pressure lockout switch is being installed on the circuit breaker to detect if the SF_6 gas pressure ever drops below 35 PSI. The purpose of this switch is to disable the breaker from either closing or tripping if the gas pressure is abnormally low. Your task is to modify the circuit shown above to include this pressure switch. The single-pole, double-throw pressure switch is shown in the upper-right corner of the diagram, not yet connected to the 125 VDC trip/close circuit.

Challenges

- Why would it be undesirable to have the breaker close or trip with low SF_6 gas pressure?

6.1.5 Historical relay

Examine this schematic diagram sampled from Victor H. Todd's 1922 book *Protective Relays* showing a very simple protection circuit comprised of a two-pole power circuit breaker with an externally energized "trip coil", a current transformer, a DC storage battery, and a "plunger-style" protective relay:



First, identify the purpose of this protective system. What abnormal condition is it designed to sense, and how does it protect the system against damage from this abnormal condition?

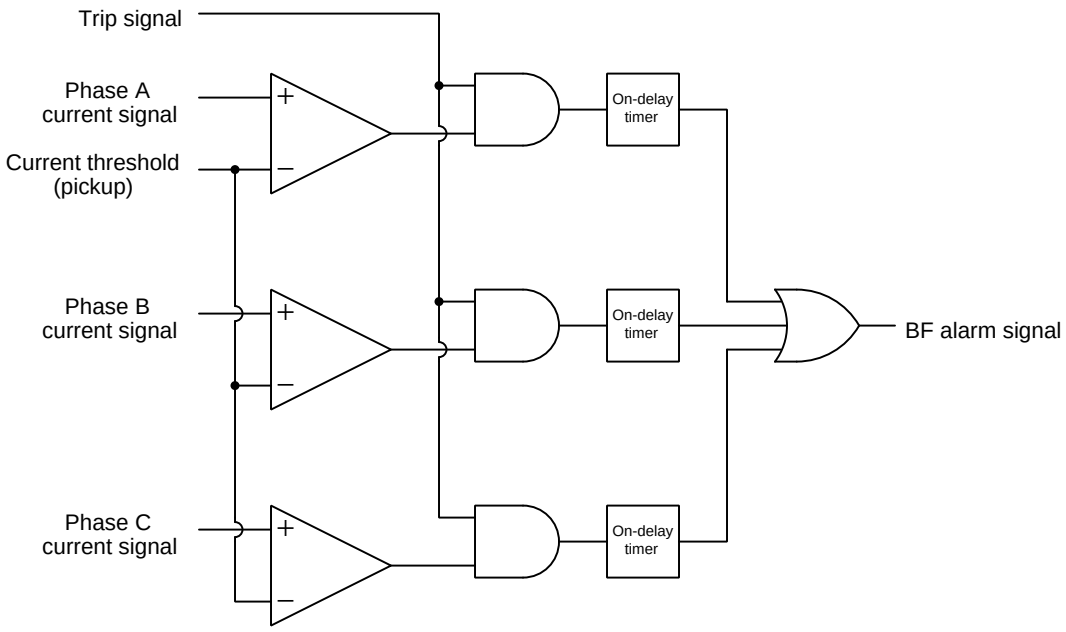
Second, identify how the "pickup" value (i.e. the trip threshold) for this protective relay might be adjusted by a technician.

Challenges

- Which ANSI number code best corresponds to this particular protective relay function? How can you tell?
- Suppose the storage battery became discharged so that it measured only about 90 Volts rather than 120 Volts. How would this affect the operation of this protective system, if at all?
- Two important concepts are used in the electric power industry to express the reliability of the system: *dependability* and *security*. Dependability is the likelihood that a protective device or system will shut off power as designed in the event of an fault. Security is the likelihood that a protective device will allow power to remain on when there is no fault (i.e. the likelihood it will not needlessly trip). Identify a specific fault in this protective system that could compromise its dependability, and another specific fault that could compromise its security.

6.1.6 BF logic diagram

The following diagram shows the logic programmed within a protective relay to detect a *breaker failure* (BF) event:



Explain how this logic network functions, and its purpose.

Challenges

- What would happen if the current threshold value were set too high?
- What would happen if the on-delay time value for any timer were set too short?

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	

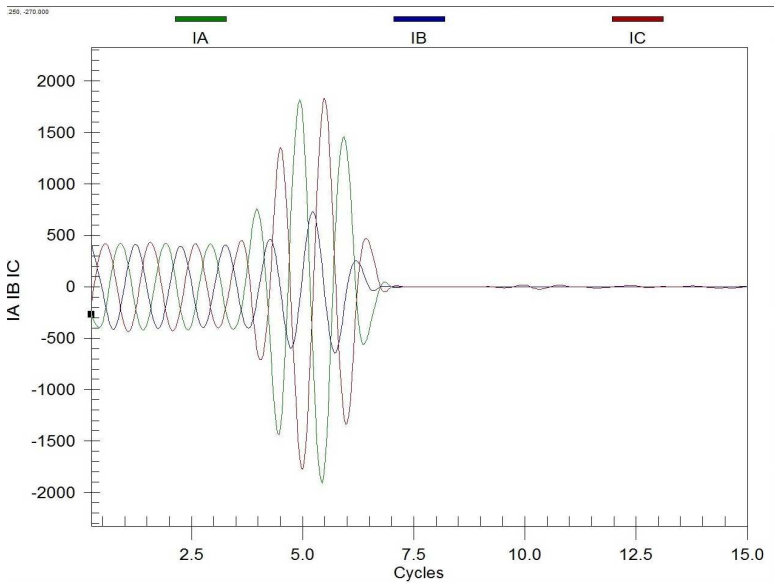
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

The following computer screenshot is a *fault oscillograph* recording an overcurrent "fault" event in a three-phase power system (wye source and delta load), each of the sinusoidal plots representing line current:



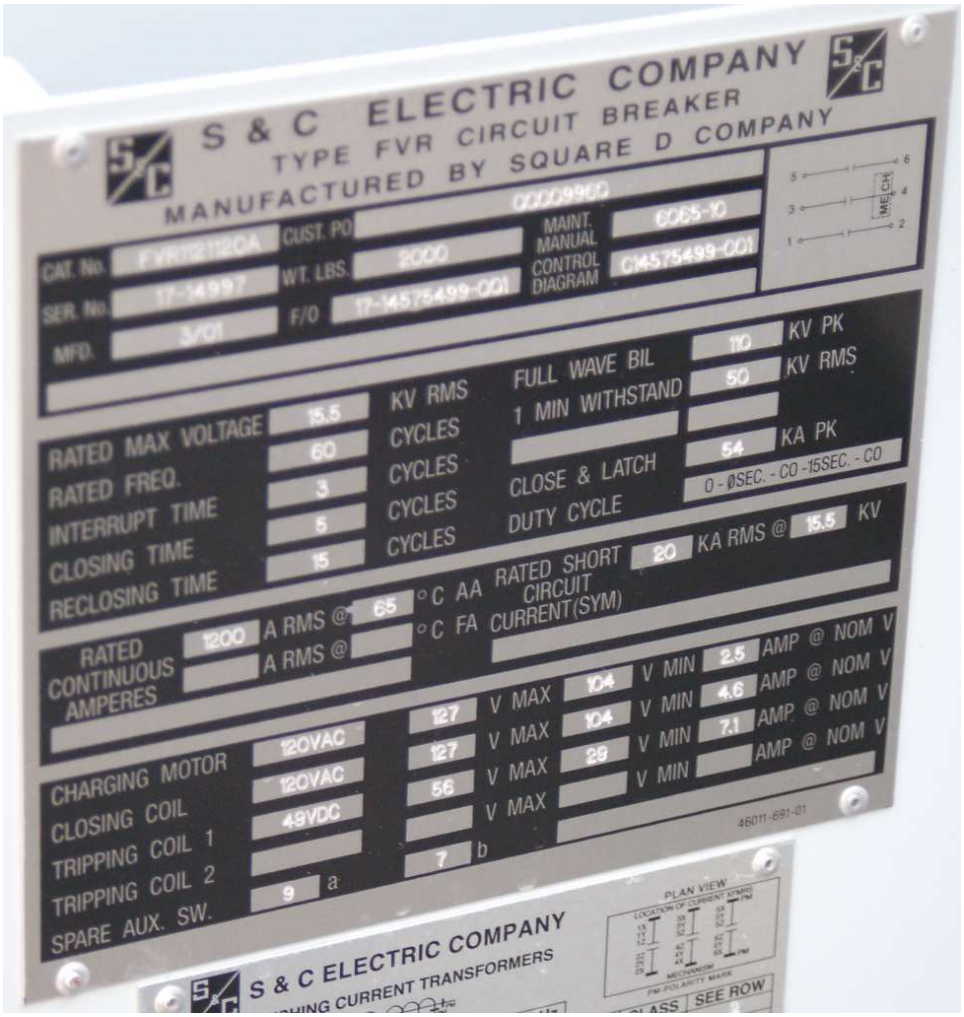
From this oscillograph, calculate the *tripping time* of the circuit breaker, both in *milliseconds* and in *cycles*, assuming a line voltage of 4160 Volts and a frequency of 60 Hz.

Challenges

- How high is the highest peak current recorded for this fault?
- What design factors might influence the tripping time of a power circuit breaker?

6.2.4 Breaker ratings

Examine this nameplate for a medium-voltage circuit breaker and then answer the following questions:



Why do you suppose the BIL (Basic Impulse Level) and one-minute withstand voltage ratings are so much greater than the "rated maximum voltage" rating?

How long (in milliseconds) should it take this circuit breaker to clear a fault once tripped?

How long (in milliseconds) should it take this circuit breaker to close after receiving a close signal?

How much electrical power is this circuit breaker designed to convey to a load, assuming operation

at maximum (line) voltage and line current?

Challenges

- Why do you suppose the close and trip coils have different voltage ratings?

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.

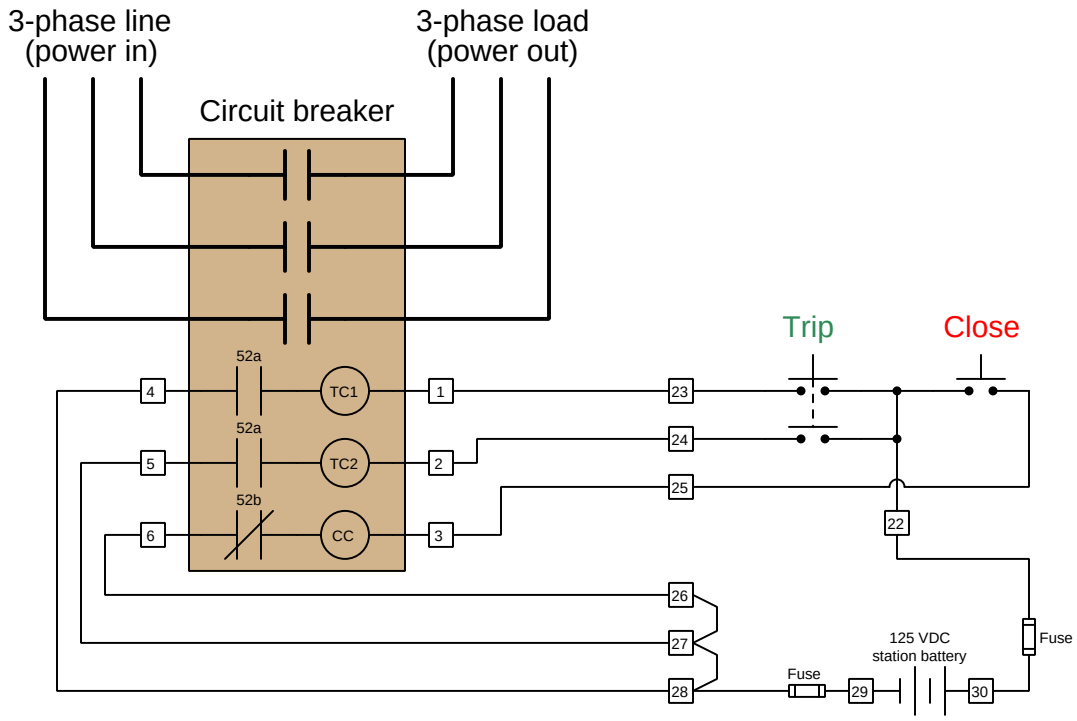
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

Suppose the following circuit breaker refuses to close after successfully tripping when the "Trip" pushbutton was pressed:



Propose a first diagnostic test to perform on this failed system, and then another test following the results of the first.

Challenges

- What is the purpose of having two trip coils and two trip pushbutton contacts?

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.

9 March 2025 – edited the "Bus configurations" section of the Full Tutorial to better explain single-line diagrams, showing full schematic diagrams for all power conductors as a contrast.

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.

4 December 2023 – fixed a typographical error in the "Low-voltage circuit breakers" section of the Full Tutorial chapter, and also added some Introduction chapter questions.

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.

2 September 2021 – placed "Early circuit breakers" into its own separate file, to be included in other modules.

8 May 2021 – commented out or deleted empty chapters.

17 April 2021 – added questions.

15 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.

13 April 2021 – added questions.

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".

August 2018 – added comments about horizontal-racking MV circuit breakers.

July 2018 – added a Full Tutorial chapter.

June 2018 – elaborated on function of trip coil in a power circuit breaker, in order to help dispel a common misconception that the trip coil functions like the holding coil of a three-phase contactor.

May 2018 – document first created.

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