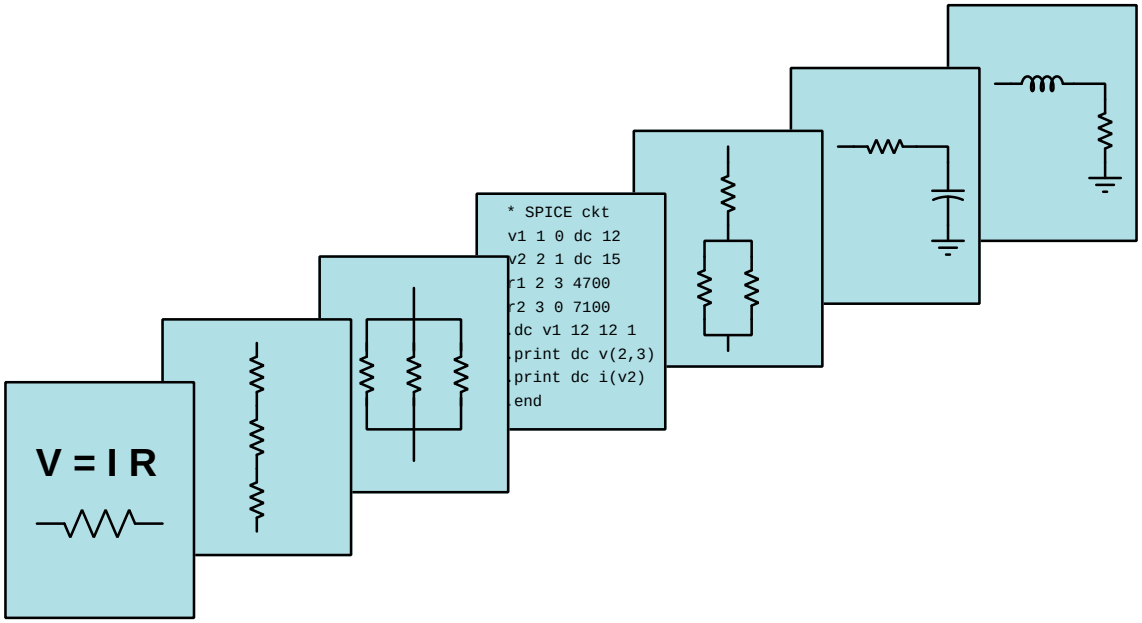
Modular Electronics Learning (ModEL) project



Electrical Power Grids

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Chapter 1

Introduction

1.1 Recommendations for students

Widespread and inexpensive electrical power service is a cornerstone of modern civilization, as it permits many necessary services (space heating, food preservation, industrial processes) to exist with a minimum of physical labor. This module focuses on the general concept of a power *grid*, which is a network of interconnected electrical sources and loads.

Important concepts related to electrical power grids include **Joule's Law**, **Ohm's Law**, **sources** versus **loads**, **Kirchhoff's Voltage Law**, **Kirchhoff's Current Law**, generator **synchronization**, **phase shift**, **frequency**, load **shedding**, and **energy storage**.

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

- How might an experiment be designed and conducted to explore the concept of generator synchronization? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- Why does alternating current (AC) dominate power grid design and not direct current (DC)?
- What is the purpose of an electrical substation?
- Which color typically represents a closed circuit breaker, and which represents an open (tripped) circuit breaker?
- How are two generators safely paralleled so as to work together in a power grid?
- How do you use a synchronization lamp to properly synchronize two generators?
- How do multiple generator units act when paralleled on a grid?
- What is the purpose of a "pumped hydroelectric" facility in a power grid?
- Why must supply and demand be constantly kept in balance for a power grid?

- Why are single-line electrical diagrams used to document large power systems, and not just schematic diagrams?

1.2 Challenging concepts related to electrical power grids

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

- **AC generator synchronization** – an AC generator produces a frequency proportional to its shaft speed at a phase angle proportional to its shaft position. Before one may safely connect two or more AC generators in parallel, their output voltages must be equal in magnitude, frequency, and phase or else one will draw power from another, and if the mismatch is severe enough this power level can be destructive. It's similar in concept to paralleling DC voltage sources, where both magnitude and polarity must match or else a dramatic short-circuit will result.

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

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Interpret power flow in single-line diagrams

  Assessment – Identify which circuit breakers must close and/or trip to route electrical power to the correct loads and avoid power going to undesired locations; e.g. pose problems in the form of the "Faults in a power system" Conceptual 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 large components and bus connections between them.

Chapter 2

Simplified Tutorial

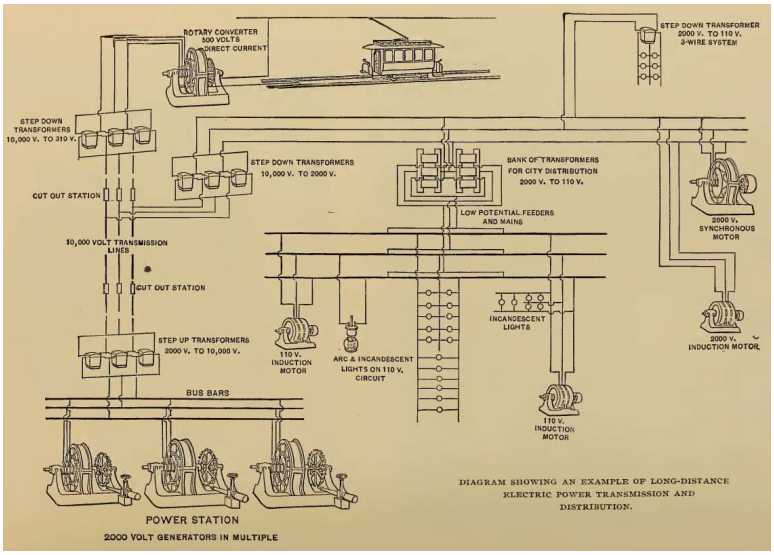
As introduced early in this modular series, electricity is tremendously useful as an energy transfer medium: energy sources and energy loads may be joined together over vast distances by relatively inexpensive conductors. When multiple energy sources are joined with multiple energy loads, the resulting electrical network is commonly referred to as a *power grid*. Prior to the advent of electrical power grids, energy-intensive loads such as industrial factories had to be located nearby convenient energy sources such as rivers (hydro power) and open fields (wind power). With a power grid, those same loads could be located anywhere convenient to their intended use rather than be shackled to their available sources.

The first electrical power grids were based on direct current (DC) which was the dominant technology of the time, and were limited in geographical range[1] owing to resistive power losses of conductors. It was not until the development of the electrical *transformer* and AC generators that long-distance electrical power transmission became practical. The reason for this is rooted in Joule's Law ($P = I^2R$): the energy losses of an electrical conductor are proportional to resistance (R) and proportional to the square of current (I). In order to transmit large quantities of electrical energy (i.e. large values of P) over long distances without suffering resistive huge losses, it must be done at low current levels which requires high voltage for any substantial amount of power ($P = IV$). Yet, high voltage levels are unsafe and impractical for end-uses such as lighting, small motors, etc. Alternating-current transformers allow voltage and current to be inversely "stepped" to levels suitable for any point within the grid: high voltage and low current for efficient transmission over long distances, low voltage and high current for end-use. Transformers also made possible the arbitrary interconnection of generators of differing voltage, as well as loads of differing voltage. The invention of the *induction motor* was another reason power grids transitioned from DC to AC, as these AC-only motors were significantly more reliable[2] than their DC counterparts.

[1] A typical city's electrical grid might extend only a few kilometers from a central generating station.

[2] An AC induction motor has just one moving component (the "rotor"), with no electrical connection necessary between the moving rotor and the stationary frame. DC motors require "brushes" and "commutators" to conduct electricity from the stationary frame to wire coils in the rotating armature, with the mechanical friction and electrical arcing between these components requiring regular maintenance and replacement.

The following illustration shows a simplified schematic diagram of a polyphase AC power system dating from the year 1895[3], showcasing an example of a Westinghouse power transmission and distribution system designed to generate power at Niagara Falls and send it some 60 miles distant:

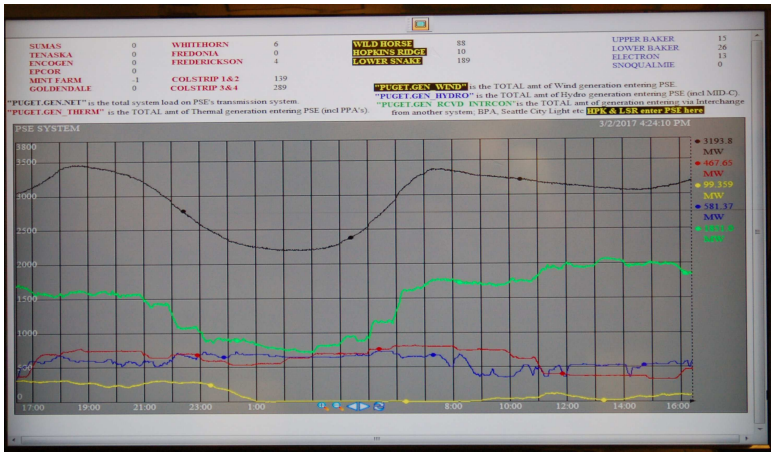


This system shows a "power station" located at Niagara Falls with multiple 2,000 Volt, three-phase generators in tandem functioning as the grid's power source. Those generators' combined output was stepped up in voltage to 10,000 Volts to facilitate long-distance transmission over economically thin wires, then stepped back down through a series of transformers to voltages appropriate for end use (e.g. 2,000 Volts for industrial use, 110 Volts for residential use). Certain applications such as traction motors for electric streetcars required DC power rather than AC power (as efficient speed control for AC motors did not exist at that time), and given the lack of modern solid-state rectifier (diode) circuits the only practical solution was to employ motor-generator machines called *rotary converters* to convert AC into DC. The "Cut Out Stations" located on the 10,000 Volt transmission lines served as points of controlled disconnection for this grid, and are simplified versions of what we would now call *substations*.

Modern electric power grids link hundreds of large electric generating stations together with thousands of cities to provide electricity across much larger geographic spans than the Westinghouse system of 1895. Modern power electronics has made rotary converters obsolete, facilitating efficient conversion between AC and DC and allowing DC to now play a role in high-voltage power transmission. Some electrical power plants located in remote regions output DC along two-conductor transmission lines, which is later converted to AC and synchronized with AC generating stations on the grid.

[3]The source for this historical illustration is *Cassier's Magazine*, which was an engineering periodical published in the late 1800's and early 1900's out of London, England. The Smithsonian Institute maintains online archives of *Cassier's* spanning many years, and it is a treasure-trove for those interested in the history of mechanical, electrical, chemical, and civil engineering.

An interesting example to ponder is the following trend graph displaying a variety of sources for the Puget Sound Energy grid in northwest Washington state:



These trend graph reveals wind power to be a relatively small percentage of the total power generated during the timespan shown, with coal and hydroelectric sources remaining fairly constant over that time and the balance made up by power purchased from other utilities.

With no means to store excess electrical energy during periods of low load and high generation, the stability of an electrical grid depends on generating stations' ability to alter their power output to meet a continuously changing demand, and/or the ability for utility operators to shed load on demand. Some types of generating stations lend themselves better to rapid changes in power output than others: single-cycle gas turbines, for example, excel at their ability to ramp power output up or down in relatively little time. Steam-based thermal generators such as coal-fired power plants are not so tolerant. Wind and solar generators operate at the whim of natural forces.

Generators sharing a power grid are essentially connected in parallel with each other. In order for AC voltage sources to be connected in parallel, they must output the same voltage, phase, and frequency. This means individual generators must be brought to equal frequency, matching phase, and compatible voltage levels with all the other generators on the grid before being "placed on the grid" (i.e. connected). The task of bringing a generator "on-line" to match its phase with that of the grid is called *synchronization*.

Chapter 3

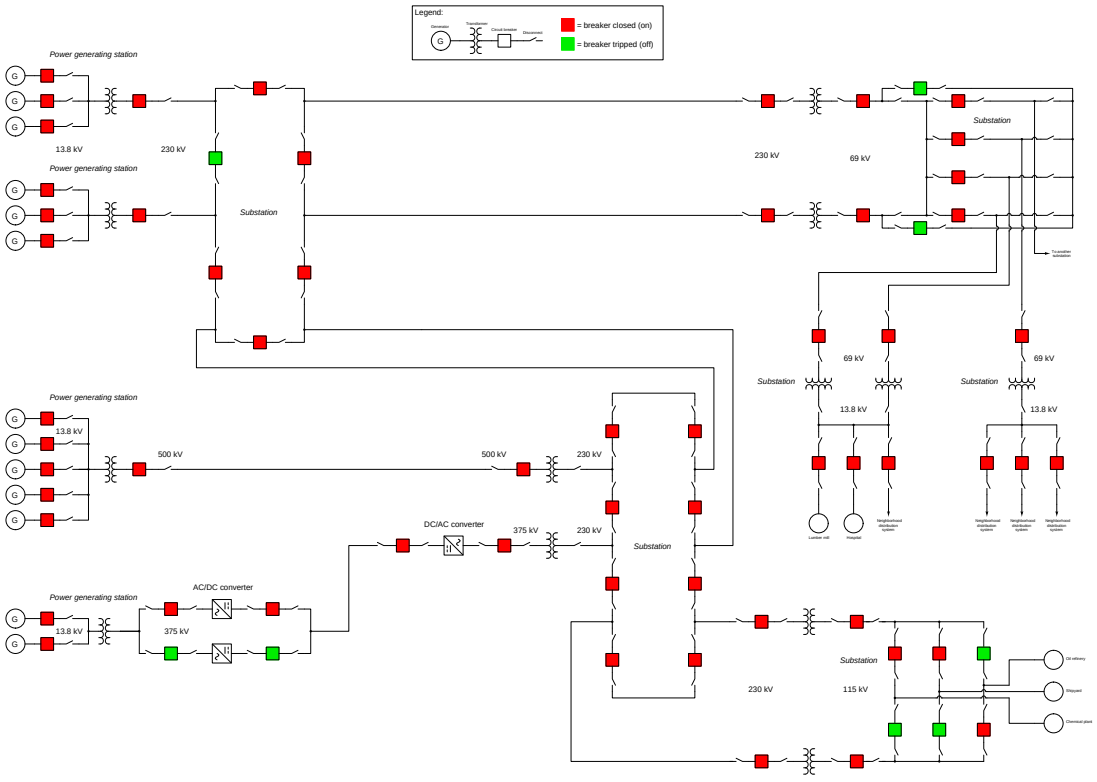
Full Tutorial

3.1 Power grid components

An electrical power *grid* is a network of generators, loads, conductors, and interconnecting components designed to convey energy from a combination of different sources to a combination of different loads, all spread out over vast distances. In its simplest form, an electrical power grid would be a collection of generators and loads all connected in parallel with each other, sharing the same voltage but distributing current proportional to power as described by Joule's Law ($P = IV$). Alternating current (AC) power grids take this model one step further by adding *transformers* to inversely step voltage and current for efficiency and safety (e.g. stepping voltage up and current down for long-distance transmission with low I^2R losses along power line conductors, and stepping voltage down and current up at generators and points of use), and using three-phase rather than single-phase for reasons of efficiency and induction motor design.

Perhaps the most noticeable features of power grids are overhead *transmission lines*, overhead *distribution lines*, and *substations*. Overhead transmission and distribution lines are nothing more than sets of metal wires tied to insulators on supporting poles or towers to keep them elevated above reach. Modern transmission lines convey electrical power at hundreds of thousands of Volts for efficient use over long distances. Modern distribution lines operate at approximately one-tenth the voltage of transmission lines, with step-down transformers located at those points to step voltage down to usable levels. Transmission and distribution lines are visually distinguished by their insulator lengths and tower heights, higher voltage levels requiring larger gaps between conductors and conductive surfaces. Substations are essentially switching networks to route power to and from these transmission and distribution lines, some of them containing *transformers* to convert between transmission and distribution voltage levels. Power generating stations are typically located far from urban centers and are therefore less visible.

An example of a modern power grid is shown in the following *single-line diagram*[1]:



Electrical *generators* appear as circles with the letter "G" inside. *Loads* also appear as circles, but labeled uniquely. *Circuit breakers* (used to interrupt the flow of power during full-load and fault conditions) appear as squares, shown here with color-coded states[2]. *Disconnect switches* (used to isolate components from power during maintenance operations) appear as standard schematic switch symbols: a line broken by a diagonal line segment. *Busses*, which are sets of rigid metal conductors suspended by insulators, appear as short line segments joining circuit breakers and disconnects with other devices in each station. *Power lines* connecting stations to each other are represented as longer line segments. *Transformers*, used to step voltage up and current down for efficient long-distance transmission, or vice-versa for distribution and end-use, appear as standard schematic winding symbols. All these devices appear on single-line diagrams with single lines showing the route for power into and/or out of the device, rather than showing all electrical conductors connecting with the actual devices. This simplification is similar to the way road maps show streets and highways as single lines but generally do not show the number of lanes within each road.

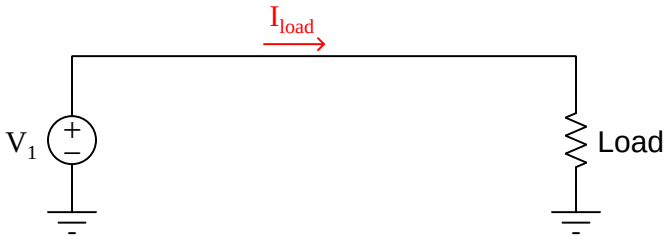
[1] This is a form of electrical diagram using single lines to represent multiple conductors comprising a circuit, which greatly simplifies the illustration. Single-line (also called *one-line*) diagrams are interpreted as though electrical power were a fluid flowing from sources to loads, analogous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

[2] In the electrical power industry, the color red universally represents an energized (closed breaker) condition while the color green represents a de-energized (open breaker) condition.

3.2 Paralleling grid generators

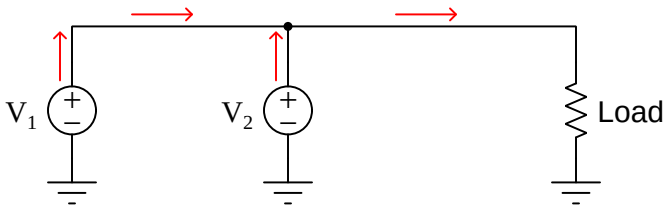
Connecting multiple generators together to equitably share load in a power grid is no trivial task. The basic concepts involved with interconnecting generators, however, are independent of the distance separating those generators. Thus, the examples given in this section are as relevant to generators located adjacent to each other as they are to generators located hundreds of miles apart.

Let's begin with a simple electromechanical DC generator application, where one generator supplies power to one load. Although not shown in this electrical schematic, there will be some form of "prime mover" such as an engine or a turbine turning the mechanical shaft of the generator:



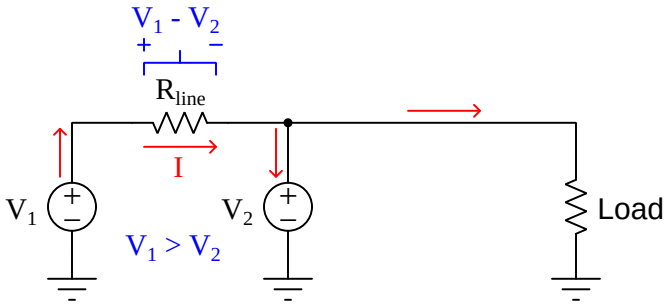
This system is almost too trivial to warrant comment: the generator outputs a constant voltage, with load current being a function of load resistance in accordance with Ohm's Law ($I = \frac{V}{R}$). If load resistance happens to decrease and generator voltage remains constant, load current will increase as a result. This additional load current has the effect of making the electromechanical generator harder to turn at the same shaft speed: demanding greater mechanical power input to the generator in order[3] to deliver greater electrical power to the load. In this way the generator naturally "senses" the power demanded by the load.

Now, let us consider a second generator added in parallel to this simple power "grid". In this configuration each of the two generators should contribute current to the grid, helping each other power the one load (resistor) shown on the right-hand side of the diagram:



[3]This phenomenon is just one more application of the *Law of Energy Conservation*, which states energy cannot be created or destroyed, but must be accounted for in all processes. Every joule of energy delivered to the load in this example circuit must be supplied by the generator, which in turn draws (at least) one joule of energy from the prime mover (e.g. engine, turbine). Since the power "grid" shown in this diagram has no means of storing energy for future use, the load's demand must be instantaneously met by the generator, and in turn by the prime mover. Thus, sudden changes in load resistance result in instantaneous changes in power drawn from the prime mover, all in accordance with the Law of Energy Conservation.

We know from basic circuit theory that parallel-connected components must share the same voltage. From this principle we may conclude that the two generators V_1 and V_2 will need to output the same amount of voltage in order to be compatible with each other in this circuit configuration. To further explore this concept, we will consider what would happen if the two generator voltages were unequal to each other, including the resistance of the line connecting the two generators together:



If the voltage of generator V_1 exceeds the voltage of generator V_2, the difference of those two generators' output voltages will be dropped along the length of the conductor R_{line} in accordance with Kirchhoff's Voltage Law. Ohm's Law allows us to predict the amount of current flowing through that line arising from the generators' differing output voltages ($I = \frac{V_1 - V_2}{R_{line}}$). If the voltage difference is substantial and the line resistance is minimal, this current will be quite large. If this amount of current exceeds the amount drawn by the load, Kirchhoff's Current Law tells us the current through generator V_2 will be going the wrong direction: *down* rather than *up*.

This situation is undesirable because it means generator V_2 will actually be functioning as a *load* rather than as the *source* it should be. Not only will generator V_2 not be contributing any power to the grid, but it will actually *draw* power away from generator V_1 that could otherwise go to the load. If generator V_2 is an electromechanical machine, it will operate as a motor as it draws power from generator V_1: "motor" V_2 increasing speed and generator V_1 slowing down from the additional loading.

To summarize: parallel-connected DC generators must output the same voltage in order to equitably share the burden of powering loads. If one generator outputs less voltage than another, it will contribute less power. if this disparity is great enough, the weaker generator will actually become a load and begin to function as an electric motor rather than the generator (source) it should be.

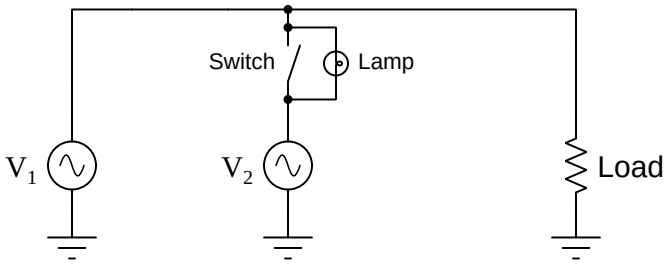
Connecting AC generators in a power grid presents the same fundamental problem: all parallel-connected generators must output the same voltage to the "grid" in order to equitably share the load. What makes AC generator interconnections more complex than DC generator interconnections is the fact that the voltage output by an AC generator is not a static quantity but rather is oscillating sinusoidally[4]. This means paralleled AC generators must closely match one another's output voltage *at every point along their sinusoidal cycles* in order for them to productively work together on the grid. The only way two or more AC generators may continuously match one another's output voltage is if their peak voltages are the same, their frequencies are the same, and they remain in-phase with each other.

[4]The standard frequency for a power grid is typically 50 Hz or 60 Hz, depending on which part of the world you are in. North American power grids typically operate at 60 Hz, while 50 Hz is more common in Europe.

AC generator frequency is a direct function of shaft speed. AC generator voltage is a direct function of shaft speed and rotor magnetization. Thus, in order to connect two or more AC generators together, these two parameters must be precisely controlled.

The process of ensuring an AC generator is ready to be connected to a live grid is called *synchronization*. This may be done manually by human operators, or automatically by synchronization relays. However it is done, the principle is the same: the voltage output by the un-synchronized generator is compared against the voltage of the grid, and the disconnecting switch or circuit breaker is not closed until the difference between those two voltages is nearly zero.

A simplified demonstration circuit serves to illustrate this process:



Imagine a condition where generator V_1 is operating and powering the load, but generator V_2 is stopped with its disconnecting switch in the open position. In this condition the lamp will glow steadily, operating on the difference of potential between the power line (full AC voltage) and the idle generator V_2 (0 Volts).

If we bring generator V_2 up to speed while keeping the disconnect switch in its open position, regulating the generator V_2's output voltage and frequency to be equal to generator V_1, the lamp will experience a voltage strictly dependent on the degree of *phase shift* between the two generators. If, at this correct voltage and frequency, the phase of generator V_2 precisely matches the phase of generator V_1 (i.e. the sinusoidal outputs of these two generators are in perfect lock-step with each other), the lamp will experience zero voltage and will remain dark. If the two generators happen to be exactly 180 degrees out of phase with each other while maintaining equal voltage and frequency, the lamp will experience a sinusoidal voltage at that same frequency having a peak value *twice* that of either generator, and will therefore glow at maximum brightness. If the amount of phase shift between these two generators is any value between 0^o and 180^o, the voltage experienced by the lamp will vary proportionately.

If the two generators output different frequencies, the phase shift angle between them will not be constant. Instead, the two generators will fall in and out of phase with each other at a frequency equal to the difference between the individual generator frequencies. For example, if V_1 outputs 240 Volts peak at 60 Hz and V_2 outputs 240 Volts peak at 59 Hz, the two generators will roll in and out of phase with each other once per second (60 Hz − 59 Hz = 1 Hz). The lamp will thus experience an AC voltage that varies from 0 Volts (when the two generators happen to be perfectly in phase) to 480 Volts peak (when the two generators happen to be 180^o out of phase). In visual terms this means the lamp will alternate from complete darkness to full brightness and back again once per second. Thus, the lamp's *oscillation* serves to indicate the difference in frequencies between the two generators.

If the two generators output different amounts of voltage *and* at different frequencies, the lamp will oscillate from bright to dim, never reaching full brightness or going completely dark. Thus, the

amount of *variance in lamp intensity* serves to indicate the difference in voltage between the two generators.

The purpose of the lamp in this circuit, of course, is to indicate when it is safe to close the disconnect switch and tie generator V_2 to the power grid. Since we know paralleled generators are electrically compatible only when their output voltages match at all times, we look for a condition of complete lamp darkness before closing the disconnect switch.

Once the generators have been synchronized and the disconnect switch closed, an interesting phenomenon occurs: the two generators now behave as if their shafts were mechanically coupled[5] together. This is similar to the phenomenon experienced with the two parallel-connected DC generators shown earlier, where an under-performing generator would begin to "motor" and draw power from the stronger generator if their voltages were sufficiently different. In the case of paralleled AC generators, a generator that begins to lag behind the other(s) in speed will act as a synchronous motor and draw power from the grid to match the speed of the other generator(s), staying in lock-step with the grid frequency so long as it is connected to the grid.

If an AC generator is synchronized and connected to the grid, and then its prime mover's power is increased in an attempt to increase the shaft speed, that generator will in effect be trying to force all the other AC generators on that grid to a faster speed. If the generator in question represents a small fraction of the grid's total power generating capacity as is typically the case, increasing or decreasing its speed becomes impossible[6] due to this coupling effect.

Generator synchronization and coupling over a power grid is just as true for transformer-coupled grids as it is for the elementary two-generator circuits shown previously. All the transformers do is permit generators of different voltage (but same frequency and same phase) to share the same grid.

[5] This "coupling" is not perfectly rigid, but does allow for some degree of phase difference between the generator and the grid. A more accurate analogy would be to say the generators act as if their shafts were linked by a *flexible* coupling.

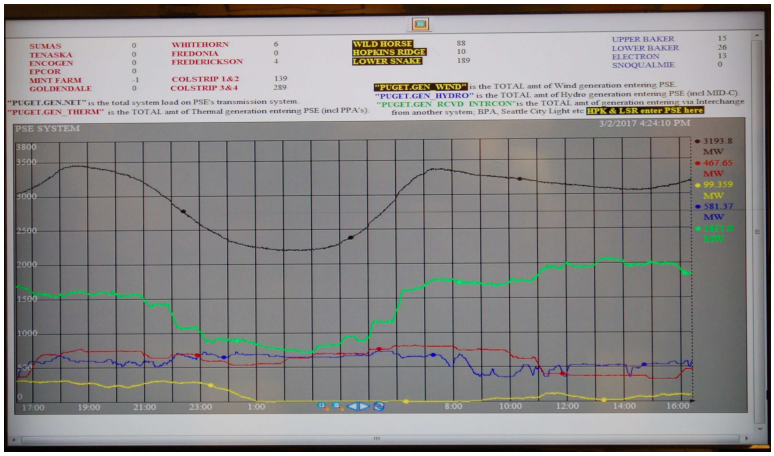
[6] It should be noted that a grid-connected AC generator can in fact be over-sped with sufficient mechanical power input, but only if it "slips a pole" and falls out of synchronization as a result. Such an event can be catastrophically to the offending generator unless it is immediately disconnected from the grid to avoid damage from overcurrent.

3.3 Grid power flow

A condition where circuit breakers in an power grid open up in such a way as to isolate a relatively small network containing both generators and loads from the rest of the grid is called *islanding*. In this condition, the generator(s) and load(s) within that isolated network function as their own small-scale grid (an "island" unto itself, if you will). Islanding is rarely sustainable, as the probability that generating capacity will match load demand within the islanded segment is very small.

Another interesting property of electrical grids is the necessity for power generation and power consumption to precisely match in order to maintain stable operating voltage and frequency. This is strictly true for any power grid lacking energy storage (e.g. chemical batteries, pumped hydroelectric facilities), but it is very nearly true for most modern power grids which lack energy storage capacity at any scale even close to matching full load. If total load in a power grid suddenly increases (i.e. an increase in total current drawn by loads, while operating at a constant line voltage), the generators in that grid must deliver that current immediately. If the power demanded by the loads exceeds the generators' combined ability to deliver, their voltages will sag and they will likely slow down from the additional mechanical burden imposed by the increased load, causing frequency to sag as well. If voltage or frequency fall below pre-set limits, protective devices will automatically act to trip circuit breakers and protect valuable power system components.

An example of generation matching loads in a power grid is seen in the following trend graph displaying a variety of sources for the Puget Sound Energy grid in northwest Washington state:



Lines of differing color reveal power flow to and from this grid. The black trend represents total *load* on the system from all consumers: industrial, commercial, and residential. Each of the other colored trends represent different sources of power to the grid. Red represents thermal-based power plants, split between natural gas and coal energy sources. Yellow represents wind turbine power generating stations, with zero output between the times of 1:00 AM and 8:00 AM on the graph (i.e. negligible wind blowing during that timespan). Blue represents hydroelectric generators. Finally, green represents power purchased from other electric utilities (e.g. Bonneville Power Administration and Seattle City Light).

These trend graph reveals wind power to be a relatively small percentage of the total power generated during the timespan shown, with coal and hydroelectric sources remaining fairly constant over that time and the balance made up by power purchased from other utilities.

With no means to store excess electrical energy during periods of low load and high generation, the stability of an electrical grid depends on generating stations' ability to alter their power output to meet a continuously changing demand. Some types of generating stations lend themselves better to rapid changes in power output than others: single-cycle gas turbines, for example, excel at their ability to ramp power output up or down in relatively little time. Steam-based thermal generators such as coal-fired power plants are not so tolerant. Wind and solar generators operate at the whim of natural forces.

Aside from being able to ramp up power generation to meet rising load, another option for some power grids is to *shed* large loads on demand. This is possible for certain industrial loads, where part of the legal agreement for purchasing electrical power at reduced rates includes the right for the electrical utility to cut or reduce power when required. An example of this might be an aluminum smelter (typically using hundreds of megawatts of electricity to reduce alumina powder to molten aluminum metal) operating as a sheddable load while the same grid employs a nuclear fission power plant as one of its sources. If the nuclear generator's reactor happens to "scram" (shut down for any reason), that reactor's power output will drop off the grid immediately, which may constitute hundreds of megawatts of lost generation. In such an event, the grid dispatch system may issue a "load shed" command to the aluminum smelter to immediately cease a substantial portion of its consumption, as it may not be practical to immediately bring that much extra power on-line from some other source.

The problem of stability in interconnected power grids is a fundamental barrier to more widespread inclusion of renewable energy sources in any grid's generation portfolio. As mentioned previously, natural energy sources such as solar and wind are essentially uncontrollable: if load suddenly increases, there is no way to command the sun to shine brighter or the wind to blow stronger to meet that need. Over-sizing renewable generating stations so that there is excess (typically unused) capacity is economically infeasible with current technology, and it still doesn't address the problem of what to do when there is no sun or wind at all. The ultimate solution to this problem is *energy storage* on very large-scale levels, such that excess energy from renewable sources may be stored up for later release when demand surges and/or supply wanes.

Pumped hydroelectric storage is a legacy technology for grid-scale energy storage, consisting of two natural water reservoirs at different elevations, with turbine/pump stations located in between. During periods of excess generation, the stations act as pumps to lift water from the lower reservoir to the upper reservoir. The mass of that water, multiplied by gravity and by the lifting height, represents potential energy which may be tapped for later use. During periods of insufficient generation, the stations act as turbines to extract energy from water falling by gravity from the upper reservoir to the lower reservoir, the elevated water releasing its potential energy to the power grid as it falls through the turbine and down to the lower reservoir.

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 Prototype electrical power transmission system

A detailed explanation of the pros and cons of transmitting power by various means is presented in an article entitled "The Transmission of Power" written by Carl Hering in Volume 1 of *Cassier's Magazine*, an engineering periodical started in 1891. Hering makes the case for efficient transmission of power over long distances by electricity versus by other means, including belts and shafts (page 449), by pressurized water (pages 449-450), by steam (page 450), by fuel gas (page 450), by compressed air (page 450), and by coal over railroad (page 450).

The bulk of the article focuses on electricity as a medium of power transfer, with several quotes shared here:

> . . . To be successful at all for long distances requires, beyond question, the use of very high potentials, as otherwise the cost of the line will make it impracticable. If continuous currents are to be used, they must be generated directly by the dynamo at that high potential, as there is no means at present known for converting a low-tension continuous current into one of high tension without the use of moving machinery ; continuous currents would therefore require that very high-tension currents be produced directly from a dynamo with a commutator. Long experience and frequent attempts have shown that it is not practicable to exceed five or fix thousand volts at the very most on continuous current dynamos, and even then there are many objections.
>
> . . . The field is therefore left tolerably clear for alternating currents, who owe it to two features, one that the alternating current dynamos require no commutator, and the other that such currents may readily be converted from a low tension to a high tension and the reverse with but a small loss of a few per cent, in each transformation. An alternating current dynamo for generating low potential currents is the simplest kind of dynamo, and a transformer requiring no moving machinery is a very simple thing to take care of, if, indeed, it required any attention at all. Simplicity alone, therefore, is very much in favor of alternating currents. `[page 451]`

Much of Hering's article is devoted to a description of a prototype electric transmission system built in Germany between the towns of Lauffen and Frankfort. Generators installed at Lauffen sent electrical power nearly 110 miles to Frankfort where it was used to power electric lamps and a large electric motor at an exhibition hall. This system was novel in its use of both step-up and step-down transformers, as well as its three-phase rather than single-phase design.

> . . . The main object of this plant was twofold, – first, to test and demonstrate to the public the feasibility of using very high-tension alternating currents on bare overhead lines; secondly, to show the practicability of a modified alternating system especially adapted for running motors. The former feature was to Mr. Brown and the latter to Mr. Dobrowolsky. It was an experiment in so far as it was at first not known whether such very high potential currents used on overhead lines would develop any new and grave difficulties, which were predicted by some mathematical electricians, involving capacity and induction effects. These fears were not realized, however, or in the terse language of Mr. Dobrowolsky, "the losses in the line all followed Ohm's law." The experiment demonstrated that with the use of carefully made and proportioned porcelain insulators containing oil, such high potentials can be used successfully on bare overhead lines.

Strange as it may seem, one of the unexpected serious difficulties experienced on a line with similar insulators, was that such large white insulators formed tempting targets for the small boys to throw stones at, because a "good shot" from one of the little rascals was awarded by the pleasure of seeing the insulator flying to pieces, ringing like a bell.

The plant consisted in general of a dynamo of exceedingly simple construction generating a large current, but of only 50 volts. This was led through the switchboard with all its accessory apparatus and was then transformed by a step-up transformer into a small current at 16,000 volts. This was led through bare overhead wires a distance of 108 miles, where is was again transformed back to a low voltage by step-down transformers. It should be noticed that the currents at the dynamo and the switchboard, where they had to be handled, were only 50 volt currents, thereby avoiding all possible danger to the attendant besides facilitating greatly the construction of the dynamo. In this feature it differed characteristically from the system used by Ferranti in London, in which the dynamo and [page 453]

switchboard were in the high potential circuit, the dynamo generating the high voltage directly. The Frankfort system was furthermore grounded in such a way that even in the case of a cross with the high-tension circuit the voltage at the dynamo or switchboard can never exceed 50 volts above the ground. The second feature of this plant is, that it enables motors to be run with the same and even greater ease than continuous current motors. It therefore solves the problem of distribution as well as of transmission of power. It should be clearly understood that it was to solve the motor problem that a certain modified alternating current system, known as the three-phase system, was used. This system involves the use of three wires throughout in place of two, but it not only overcomes the difficulty of the distribution of power and the starting of motors, but it goes farther, because such motors are very much easier to run and are simpler in construction than the best continuous current motors, a feature which counterbalances to a great extent the objection to the use of three wires.

Time will not permit a detailed discussion of this three-phase system here; it will suffice to say that it consists of three simple alternating currents, – one in each wire, – the waves or impulses in the three wires following each other in succession similarly to the relative motions of the three cranks of a three-cylinder steam engine, or the pistons of a three-plunger pump. Such a set of currents produces a *rotating* magnetic field, while the simple alternating current produces merely an *oscillating* field. The rotating field furthermore has a definite direction of rotation. It is this feature of a rotating magnetic field as distinguished from an oscillating one which renders it particularly well adapted to run motors. The ordinary simple alternating current motor may be said to be analogous to a steam-engine with one crank, having its slide-valve operated by an independent rapidly running engine ; it has a dead point from which it will not start, but after it is up to speed it will run very steadily. The rotating field motor, on the other hand, is analogous to a three-crank engine operating its own valves. There is no dead point, and it can start itself, even with full load.

As to the priority of invention of this rotary field system, I will only say here that Ferraris and Tesla seem to have invented it originally and independently of each other. Just in what respects Dobrowolsky improved it is hard to tell until we know how far Tesla

developed it. It will suffice to say here, that as modified by Dobrowolsky, the motors appear to be an undeniable success. [page 454]

. . . The dynamo is of exceedingly simple and mechanical construction, has a speed of only 150 revolutions, and is capable of generating three alternating currents of 50 volts above their common connection, and about 1400 amperes each, or a total of about 200 kilowatts. The number of alternations is 40, which is purposely made very low. This current passes through the switchboard and regulating apparatus to a three-core transformer of equal capacity. The ratio being 160, it is transformed up to about 12,500 to 15,000 volts, measured between any two of the three wires, and down to four or five amperes ; by connecting two of those with their primaries in multiple, and their secondaries in series, they will generate 25,000 to 30,000 volts.

An interesting feature about this system is that although the three currents have different phases, they need no separate return leads, because the nature of the currents is such that each acts as a return current for the other two in multiple arc. The three circuits are therefore merely connected together to [page 454]

a common terminal, after they have passed through the dynamos, transformers, and lamps. This terminal we will call the neutral point. This neutral point was grounded throughout the system, in the low-tension as well as in the high-tension circuits, and at both ends of the line. No current, however, will flow through the ground when the plant is working normally.

The line consists of three bare, hard-drawn, copper wires, 4 millimeters in diameter (slightly less than a No. 6 B. & S. wire), having a resistance of about 2 Ohms per mile. The distance being 108.6 miles, the resistance of each wire is about 217 Ohms, which, with 5 amperes, makes a loss of about 1000 volts on each of the three lines. The lines were run on poles with one cross-arm 16 feet above the ground, the wires being one meter from another. There were 3227 poles, at 200 feet spans : each pole had a skull and crossbones painted on it to indicate the sure fate of anyone who could not keep his hands off. There were 3000 large porcelain insulators, 8 inches in diameter, made in two parts and with three oil grooves, and 6500 small ones, made in one piece and with one oil groove. The only apparatus connected with the high-tension circuit was the fuse wire and a short-circuiting device to replace the switches for opening the circuit. The fuses for each of the three lines consisted of two copper wires in parallel, each .15 millimeters in diameter (between Nos. 34 and 35 B. & S. gage) and 2 meters in length. They were stretched between two poles outside of the building. They were exploded (one can hardly apply the term “blown”) several times to test their effectiveness. Even to an electrician it seems strange to think of several hundred horse-power being transmitted through a few wires about the size of a hair! The short-circuiting devices consisted of pieces of bare wire shaped like a V inverted, suspended directly over the line wires. These were placed at very frequent intervals along the line. In case of any danger or interruption, or in case the line must be handled, this wire is lowered by a string, and drops on the line wires, thereby short-cutting the line, which blows the fuse and opens the circuit. This is a very cheap and effective substitute for a switch, which would be dangerous to handle in a 30,000 volt circuit ; furthermore there is absolutely no possibility of a current being on the line when this device is down.

Both the high-tension and low-tension circuits were carefully grounded at both ends at the neutral point, that is, at the common junction of the three wires. This makes the system perfectly safe, for in no case can the voltage on the low-tension circuit be greater than the normal low voltage. In case of a ground on the line, or a cross between the high-and-low tension circuit, the fuses will blow.

Arriving at the receiving end, at the exhibition in Frankfort, the high-tension current was transformed down to about 75 volts measured between any two of the three wires. Some of it was used to illuminate one thousand 16 C.P. lamps on the exhibition grounds, consuming 58,000 watts, and some was used to run a 100 H.P. motor, which drove a centrifugal pump, the water from which formed an attractive waterfall on the exhibition grounds. The average voltage used on the line was about 16,000 volts, and the greatest amount of power, I am told, was about 180 H.P. This was now because of any failure to be able to transmit more, but merely because that was the full capacity of the bank of lamps and the motor. [page 455]

4.2 Early power system faults and protection

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

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

> There were many types developed and successfully used, but the principles and the objects accomplished were all the same; a coil carrying the main current was arranged to either attract an armature fastened to the switch blade and thus open the switch directly, or to attract an armature which in turn released a spring, thus allowing the spring to open the switch. [page 2]

Another interesting reference from the same book discusses what to do when the exact location of a fault cannot be discerned from diagnostic tests:

> When the fault, either cross, ground or partial open, is of a high resistance and it is impossible to locate is by ordinary methods, it is sometimes permissible to burn it out. This, however, must be attempted only with the greatest precautions such as having pails of sand or reliable fire extinguishers ready for immediate use should the burning-out process start a fire.
>
> To do this, connect a high potential so that it feeds current through the fault and then increase the current until something happens. This something may be a fire, a melted conduit, a ruined section of wire, additional trouble communicated to other sections of wire, or merely a carbonizing of the fault. If the fault becomes carbonized sufficiently to pass about 5 amp through from a low-voltage battery, then it is easy to locate the fault by the previously described methods.
>
> In any case burning out a fault is a method which must be resorted to only in an extreme case as practically all faults may be located in a much safer and gentler manner by a little clear thinking and sound reasoning. [page 264]

4.3 Edison DC system power cable

Thomas Edison's original DC electric power distrubution system in New York City used buried cables to convey electricity from the central generating station to various loads. Operating at relatively low voltage meant significant cable currents and therefore necessitated large-gauge copper conductors that were too heavy to be strung overhead. Edison's distribution lines, therefore, were buried in trenches dug alongside city streets.

Soon after the World Trade Center terrorist attacks of 11 September 2001 some excavation in New York City revealed a relic of this early electrical era, a photograph of a cable section shown below:

A cross-section of this cable shows the three copper conductors encased in tar within the metallic sheathing of the cable. Despite the obvious corrosion evident on the outside of the cable, it is clear that the copper conductors themselves are well-preserved.

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 Electrical safety

A subject of extreme importance to all electrical practitioners is electrical *safety*, with Ohm's and Joule's Laws being excellent starting points for a discussion on that topic. Here we examine the human body as an electrical *load*: electrical charge carriers passing through the resistance of the body from an external source relinquish some of their energy in the same way charge carriers lose energy passing through any other resistance. The rate of energy dissipation (i.e. *power*) through the body's resistance is predicted by Joule's Law, $P = I^2R$. The total amount of energy delivered to a body by an electric current is a function of that power dissipation rate multiplied by the amount of time current flowed[1].

Electrical energy poses two distinctly different threats to any living body: the first threat is forced activation of the body's nervous system by electric current passing through nerve cells, and the second threat is burning from the thermal power dissipated in flesh and bone. Both threats are direct functions of the amount of energy delivered to the body, with the first effect (called *electric shock*) beginning at lower levels of current than the second effect.

Electric shock – not to be confused with the general condition of *circulatory shock* characterized by reduced blood circulation in the body – first manifests as a tingling sensation, then as pain with greater electric current intensity. At a certain threshold value, the current will be sufficient to override voluntary muscle control. At higher levels of current, breathing will become difficult or may cease due to paralysis of the diaphragm muscles within the chest. At even higher levels of current, the heart (itself a muscle of the body) will either fall into an arrhythmic beat pattern or cease beating altogether. *All of these effects will occur at current levels significantly less than one Ampere.*

Some of the most detailed data we possess on the effects of electric shock come from the research of University of California Berkeley Professor Charles Dalziel, who in the year 1961 published a report entitled "Deleterious Effects of Electric Shock". Dalziel performed electric shock experiments on human volunteers, subjecting both males and females to varying degrees of electric current, both direct (DC) and alternating (AC), for the purpose of determining thresholds of sensation, pain, and loss of muscular control.

Table II of Dalziel's' report (shown on page 24) is partially[2] reproduced in the following table. The headings "M" and "F" refer to male and female subjects, respectively. Tests conducted using direct current[3] are labeled "DC" while tests conducted using alternating current[4] are labeled with

[1] Putting units of measurement to this concept, the amount of energy in *Joules* is equal to average power in *Joules per second* multiplied by time in *seconds*, with the unit of "seconds" canceling out. For brief exposures to electricity, such as lightning strikes, the most important measurement with regard to safety is the total energy delivered to the body. The same is true for deliberate applications of electricity to the body, for example cardiac defibrillators, where the machine's setting is calibrated in Joules of energy delivered per impulse.

[2] The original Table II contained a column of data representing thresholds for women at 10 kHz alternating current, but these were estimations and not actual data. Extrapolating from the other data points where women tended to exhibit the same effects as men at approximately $\frac{2}{3}$ the current, Dalziel writes, *"Tests on women were not made on frequencies other than 60 cycles, but if it is assumed that the response for women would be similar, values for women can be estimated at two-thirds of the corresponding value for men."* Readers should note that I have taken editorial liberties with the description of bodily effects, for no reason other than formatting.

[3] Direct current, or DC, refers to a continuous flow of electric charge carriers in one direction only.

[4] Alternating current, or AC, refers to an electric current that periodically switches direction, the period of that

frequency values expressed in the unit of Hertz (Hz) or cycles per second. All data points are expressed in *milliAmperes* (mA), one milliAmpere being $\frac{1}{1000}$ of an Ampere:

Bodily effect	**DC, M**	**DC, F**	**60 Hz, M**	**60 Hz, F**	**10 kHz, M**
Slight sensation felt on hand	1 mA	0.6 mA	0.4 mA	0.3 mA	7 mA
Median perception threshold	5.2 mA	3.5 mA	1.1 mA	0.7 mA	12 mA
Shock, with no loss of muscular control	9 mA	6 mA	1.8 mA	1.2 mA	17 mA
Pain, with 50% of subjects losing muscular control	62 mA	41 mA	9 mA	6 mA	55 mA
Pain, labored breathing, 99.5% of subjects losing muscular control	90 mA	60 mA	23 mA	15 mA	94 mA

For rather obvious reasons no human tests were conducted to the point of cardiac fibrillation. Dalziel's report does, however, provide data collected on a variety of animals (pigs, sheep, calves, dogs, cats, guinea pigs, rabbits) which were anesthetized and then administered large amounts of electric current until their hearts malfunctioned. From this admittedly limited data, Dalziel extrapolated the values to obtain 500 mA ($\frac{1}{2}$ Ampere) of direct current and 100 mA ($\frac{1}{10}$ Ampere) of alternating current as thresholds for "possible" human heart fibrillation following a three-second electric shock.

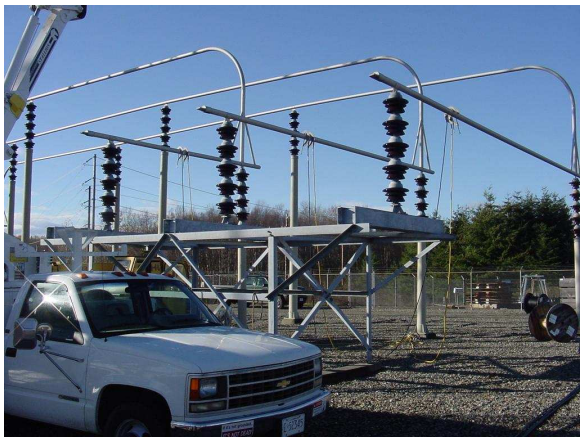
All gruesome details aside, the lesson to be learned here is very plain: *very little electric current is necessary to induce painful and even life-threatening effects on the human body!* These danger thresholds are all substantially less than the amount of current most power conductors are rated to handle, and less than the ratings of fuses and circuit breakers designed to protect conductors from overheating.

switching measured in cycles per second or Hertz. In North America, the standard AC grid power frequency is 60 cycles per second, or 60 Hz. The second AC frequency used in Dalziel's experiments is 10 kHz, which is 10 *kilo*-Hertz, or 10000 cycles per second.

The first line of defense against electrical shock is to place as much electrical resistance between your body and the circuit's conductors as is practical, as a means of impeding the flow of electric current to and through your body. Turning "off" any disconnecting switches between the circuit and its energy source is a simple means to do this, essentially inserting an air gap between the circuit and its normal source of power. This allows all points within the circuit to achieve an equipotential state, which may then be made equipotential to your body by connection to Earth ground (where you are standing). If there is no voltage present (i.e. no difference in the potential energy levels of electric charge carriers at different points), then there should be no possibility of dissipating electrical energy into your body.

Once all electrical energy sources have been disconnected from the circuit you intend to work on, an additional safety measure is to *bond* that circuit's power conductors to Earth ground. This step forces the power conductors to be *electrically common* with Earth, and therefore guarantees a condition of equipotentiality with the Earth. Line workers who install and maintain electric power line conductors do this as a standard part of their operating procedure: attaching temporary grounding cables between the power conductors and Earth after opening all disconnect switches normally connecting those lines to electrical sources. This extra step of bonding the power conductors ensures no stray sources[5] of electrical energy may pose a threat.

The following photograph shows a work site at a 230 kV (230,000 Volt!) electrical substation, where electricians are busy performing maintenance work on a high-voltage component. In addition to opening large switches (called *disconnects*) to isolate this new component from any source of voltage, they have *bonded* the high-voltage conductors to each other and to Earth ground by means of temporary wire cables. The cables on this work site happen to be yellow in color, and may be seen hanging down from C-shaped clamps attached to three horizontal metal tubes called *busbars* which serve as conductors for electricity in this substation:



[5] Examples include electrostatic or magnetic "coupling" with adjacent energized power lines, nearby lightning strikes, etc.

Obviously, such measures are quite necessary on high-voltage systems such as substation busbars – there simply is no safe way to work on energized conductors at this voltage level. However, in lower-voltage circuits it is often necessary to take electrical measurements and make certain adjustments while the circuit is in an energized state. If the circuit in question cannot be "killed" by disconnection of its power source and therefore must be worked on "live", the next best protective measure is to layer insulating material on your body where contact might otherwise be made to permit an electric current through it. This means wearing insulating gloves and shoes, at minimum. The principle behind this technique is Ohm's Law: for any given amount of voltage (V), current (I) will be inversely proportional to the total resistance (R) of the circuit pathway. Layering electrically insulating material over your body's possible points of contact (e.g. hands, feet) increases the total resistance of the circuit pathway, and therefore minimizes the amount of current that may flow in the event of physical contact between two points where a substantial voltage exists.

Lastly, in order to minimize the risk of electric current passing through one's chest (where the heart and diaphragm muscles are located), a wise habit when working on energized circuits is to place one hand in a pocket so that only one hand is in use. This will not only prevent arm-to-arm passage of electric current, but it also minimizes the number of potential points of contact with bare skin. Electrical practitioners commonly refer to this as the *One-Hand Rule*. Ideally, the best hand to place in a pocket is the left hand, because this is the side of the body where the heart is most vulnerable.

It is worth noting that the danger from electric shock is best quantified in terms of current, not voltage, since it is electric current that activates nerve cells. The amount of current passing through a victim's body from an applied voltage is a function of Ohm's Law ($I = \frac{V}{R}$), and since resistance (R) varies greatly with skin dryness and layering provided by shoes and clothing, it is difficult to predict how much voltage poses a shock hazard. A generally accepted threshold of danger is 30 Volts, but this assumes direct contact with dry skin. Moist skin, perspiration, cuts or punctures, and other factors reducing body resistance may greatly reduce the voltage threshold for shock hazard! Another factor is the general health of the victim prior to receiving the electric shock. A preexisting cardiac condition will likely predispose that individual to harm resulting from an electric shock.

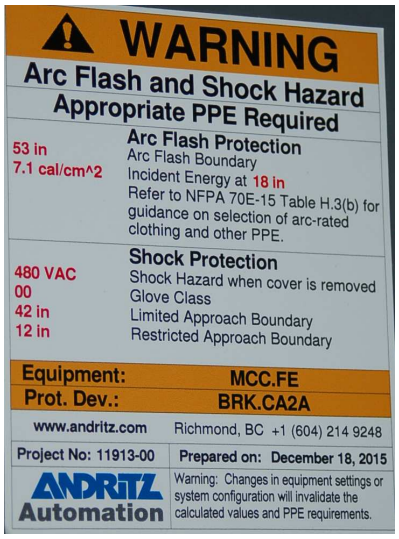
Burns produced by electricity passing through the body may manifest on the skin, at the point of contact with an electrical conductor (such as a wire), or in severe cases may extend to internal organs. Comparing internal flesh with skin, dry human skin tends to exhibit much greater levels of electrical resistance than the internal organs which are wet. This is why electricity causes skin-surface burns before causing internal organ burns: for any given amount of electric current passing through different resistances, power dissipated by that current will be greatest wherever the electrical resistance is greatest. Mathematically stated, P is maximized where R is greatest, given any value of (I), in accordance with Joule's Law (I^2R).

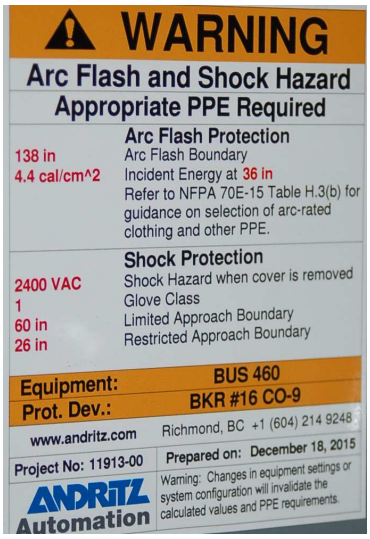
Another mechanism of electrically-caused burns is *arc flash*: the heating of air by the passage of electric current through it (rather than through the body). Under normal conditions air is an extremely good insulator of electricity, with no free charge carriers available to sustain an electric current. However, when sufficient voltage causes the electrons in air molecules to separate from their respective atoms, the negatively-charged electrons and positively-charged ions constitute charge carriers, and will form an electric current called either a *spark* or an *arc*. This current heats the air molecules by dissipating power as described by Joule's Law ($P = I^2R$), with I being the magnitude of current traveling through the ionized air and R being the resistance of the arc path.

The amount of resistance exhibited by a high-temperature arc is surprisingly low, typically less than one Ohm across the entire length of the arc. With such low resistance, Ohm's Law predicts relatively high current values for even modest voltages ($I = \frac{V}{R}$), resulting in high power levels. Even if the amount of energy released by each charge carrier moving through the arc is small, the fact that a great many charge carriers are moving through the arc each second means that the total amount of energy dissipated may be phenomenally large. This is why arcs forming in high-voltage electric power systems may reach temperatures of tens of thousands of degrees[6]!

In the United States of America, a widely respected standard document for electrical hazards and protection is the National Fire Protection Association (NFPA) standard 70E. This document rates both electric shock and arc flash hazards for electric power circuits based on voltage and current capabilities, as well as specifies best practices for protection against those hazards.

An example of NFPA 70E standards applied to an industrial installation is the following pair of photographs showing warning labels affixed to metal-clad electrical switchgear (i.e. metal cabinets housing large circuit breakers). Each label cites both arc flash and electric shock hazards, including *boundary* distances within which greater hazards exist:





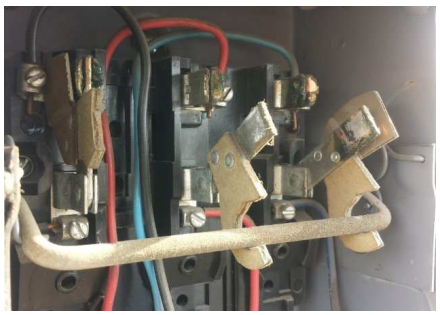
The first line of defense against arc flash is the same as for electric shock: *de-energize the circuit* so there will be no electrical energy present to harm you. The procedure for de-energizing includes placing a warning *tag* as well as a secure *lock* on any main disconnecting switches or circuit breakers to ensure power does not get accidently applied to the circuit while people are in harm's way. This is referred to in industry as *lock-out, tag-out*, or *LOTO*.

[6]The NFPA 70E electrical safety standard (Informative Annex K) cites temperatures as high as 35,000 degrees Fahrenheit in arc flash events, and states that such events are lethal at distances up to 10 feet (3.05 meters). It is worth noting that electric arc temperatures are limited only by the rate of power dissipated in the arc. Unlike chemically-driven combustion events, where temperature is limited by the rate at which the various chemical reactants are able to combine, no such limiting factor exists with electric arcs: the more power dissipated in the arc, the hotter it will become. These temperatures involved with electric power faults can be so high that they *vaporize* the metal wires!

Generally accepted lock-out, tag-out procedures for electrical equipment include (but are not limited to) the following steps:

1. Turn equipment off using regular on/off switch to interrupt load current
2. Open all disconnect switches and/or circuit breakers feeding electrical power to the equipment
3. Visually confirm (if possible) that *all* poles of the disconnecting switch(es) are open
4. Attempt to re-start equipment as your first confirmation that power is indeed shut off
5. Attach locks and tags to prevent disconnecting switches from being re-closed; if no lockable disconnect means exists, you must open and tag *two* or more redundant disconnects!
6. Confirm proper operation of voltage meter against a known source
7. Test for dangerous voltage between all relevant conductors, especially those you could bodily contact, including between pairs of phase conductors in a polyphase system as well as between each phase conductor and earth ground
8. Confirm (again) proper operation of voltage meter against a known source

Such a lengthy procedure may seem paranoid, but there is good reason for all these steps. Remember that *all safety standards and procedures are written in blood:* in other words, every one of them exists because either someone got hurt or came close to getting hurt by not taking appropriate precautions. One example of the latter is the following photograph generously shared by Jim Lyon[7] who discovered a failed three-phase disconnect switch during a routine LOTO procedure:



As you can see in this photograph, one of the linkages between the disconnecting switch pole and the actuating lever has broken, allowing one phase to remain closed while the other two opened as they should. Such a failure would neither be apparent to the operator of that switch nor by anyone's external inspection of it, but would be revealed by proper voltage testing (phase-to-ground) on that faulted phase conductor. Had Mr. Lyon simply trusted the switch handle's "off" position as proof of a zero-energy state, he could have been electrocuted touching the un-opened conductor "downstream" of the switch.

[7] Mr. Lyon granted me permission to include his safety-related photographs in my open-source writings during an exchange on the professional social-media website `LinkedIn`.

Another important note with regard to electrical safety and LOTO is the proper function of your test equipment. Multimeters and test leads are not just tools for precision measurement, but are life-saving indicators of dangerous voltage. I have personally witnessed multiple instances of failed multimeter test leads, where one or more leads failed open such that the meter could not reliably register the presence of voltage. This is why good LOTO procedure always includes verification of the meter both *before and after* checking for dangerous voltages at the system conductors.

In cases where de-energization is not possible or not practical, special "arc-flash rated" clothing may be worn to protect your skin against the high temperatures of arc flash should an arc flash occur. Arc flash suits cover all skin surfaces, and are rated according to the number of calories[8] of heat the fabric may sustain without disintegrating. The following photograph shows a pair of arc flash suits hanging on a wall ready for electricians to use while working on circuit breakers at an electric power generating station:

The blue-colored hood covers the worker's head and neck, while the grey-colored jumpsuit covers the rest of the worker's body.

[8] A *calorie* is simply another unit of energy measurement. The unit-conversion equivalence is 4.187 Joules per calorie.

The hazards of electrical arcs are not limited to bodily burns. Given sufficient arc power, the explosive expansion of hot air and the shrapnel created by disintegrating hardware represents its own unique hazard, known as *arc blast*. As an *electrically-driven* explosion[9], arc blast is limited only by the available power of the fault, and can in fact be more violent than a chemical explosion. No suit can ensure safety against arc blast, and so the only reasonable precaution is maintaining a safe distance beyond the blast radius.

[9]The concussive effects of an arc blast originate from the rapid expansion of air and vaporized metal, producing intense sound waves and blast pressures. Extremely bright light, as well as high temperatures caused by convection of super-heated air and by radiation of infrared light from the arc are capable of creating third-degree burns on unprotected skin.

Chapter 6

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

6.1 Conceptual reasoning

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

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

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

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

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

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

6.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

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

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

6.1.2 Foundational concepts

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

Energy

Conservation of Energy

Electrical source

Electrical load

Joule's Law

Ohm's Law

Switch

Transformer

Direct current

Alternating current

Frequency

Phase

Circuit breaker

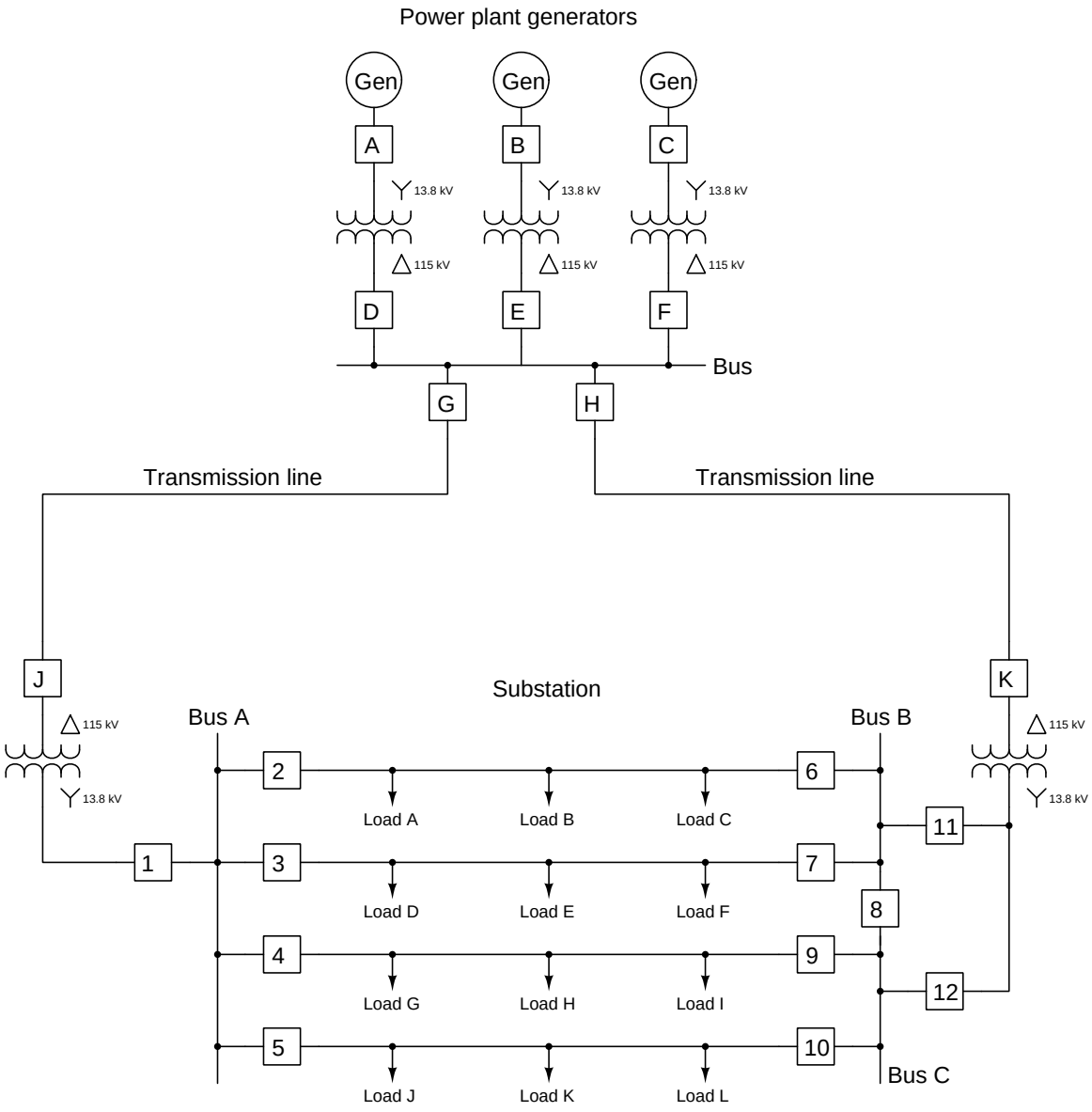
Kirchhoff's Voltage Law

Kirchhoff's Current Law

Synchronous operation

6.1.3 Faults in a power system

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



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

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

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

Challenges

- Identify the circuit breaker(s) which would have to trip in order to isolate a fault on Bus A.
- Identify the circuit breaker(s) which would have to trip in order to isolate a fault inside the right-hand substation transformer.

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 Per capita electricity consumption in 1921

The trade journal *The Electric Journal*, volume 18, number 1, published in the year 1921, contained a brief article by E.H. Sniffin stating, among other things, a simple estimate of electric power consumption in the United States at that time:

> About sixty million of our population live under electric wires. Of this great number of people, every man, woman and child requires something over one kilowatt-hour per day to take care of his or her needs and comforts. From the time we rise in the morning until we retire at night we use electric current. We light with it, we heat with it, we are transported by it and we operate our factories with it. In a myriad of ways it ministers to our necessary uses. It is one of the principal elements of our present civilization. [page 2]

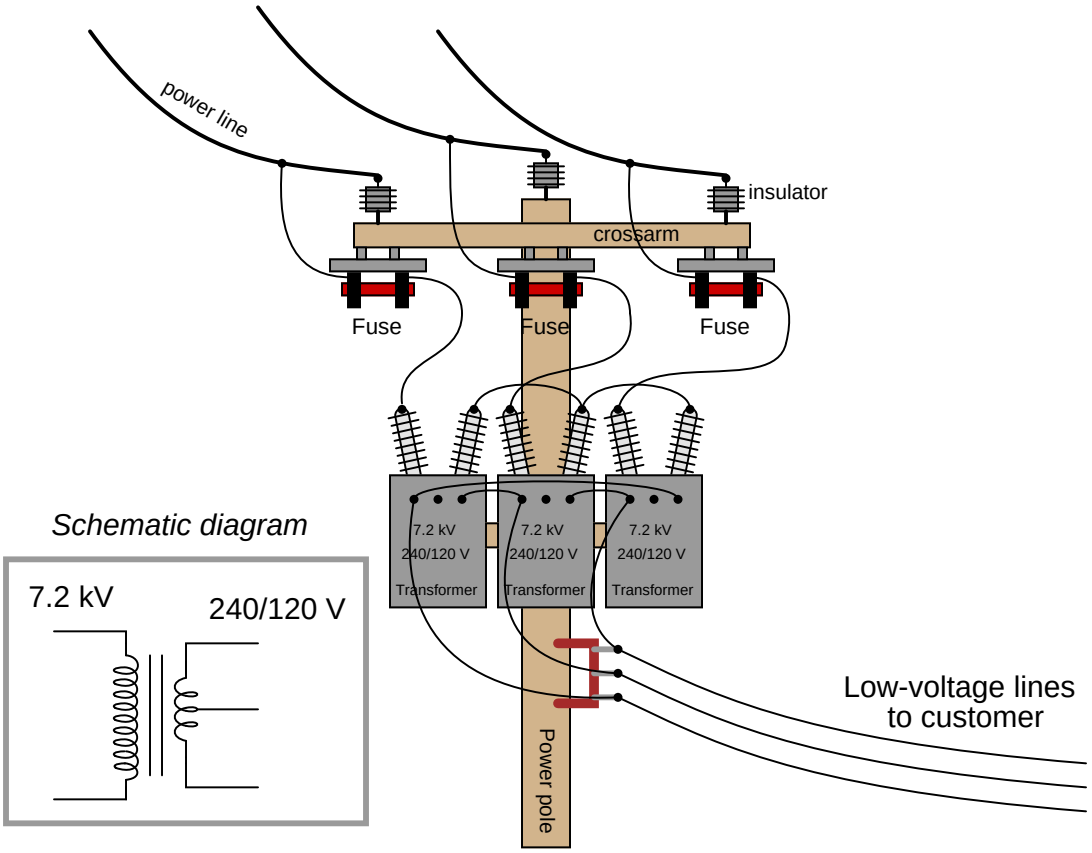
Examine one of your own electric power bills to compare your personal energy consumption versus the 1921 estimate of one kilowatt-hour per person per day. How much has electricity usage changed since then? Estimate the cost of your electric bill if your personal usage was only one kilowatt-hour per day, at present electricity rates.

Challenges

- Identify some of the ways in which you utilize electricity in your own home. How does your present-day application of electricity compare to the uses listed by Sniffin?

6.2.4 Pole-mounted transformers

Examine the primary and secondary connections on this three-phase transformer bank, and then determine the line voltage to the customer, assuming 12.5 kV line voltage on the distribution power lines. The schematic diagram shown in the grey box is typical for each of the three pole-mounted transformers:

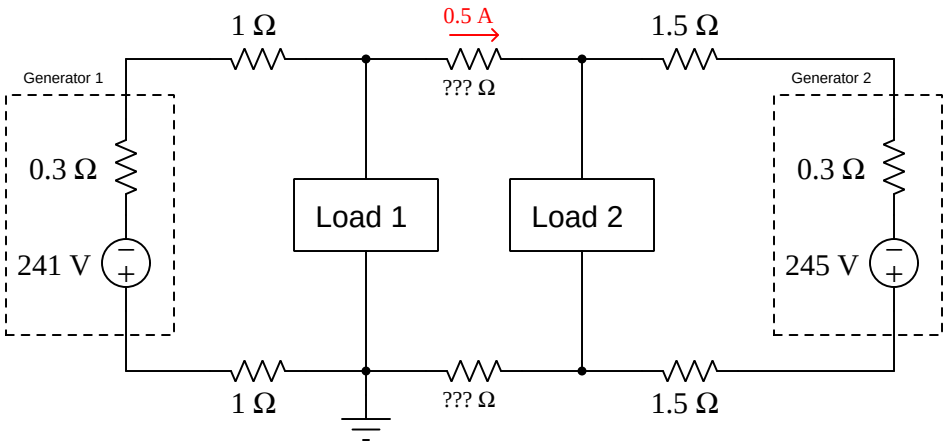


Challenges

- Identify any point(s) in this transformer circuit where it may make sense to install a connection to Earth ground.

6.2.5 Multi-generator DC power grid voltages

Calculate the voltage as measured across the terminals of each generator as well as across each load, assuming Load 1 draws 12 Amperes of current and Load 2 draws 9 Amperes of current:



- $V_{generator1}$ =
- $V_{generator2}$ =
- V_{load1} =
- V_{load2} =

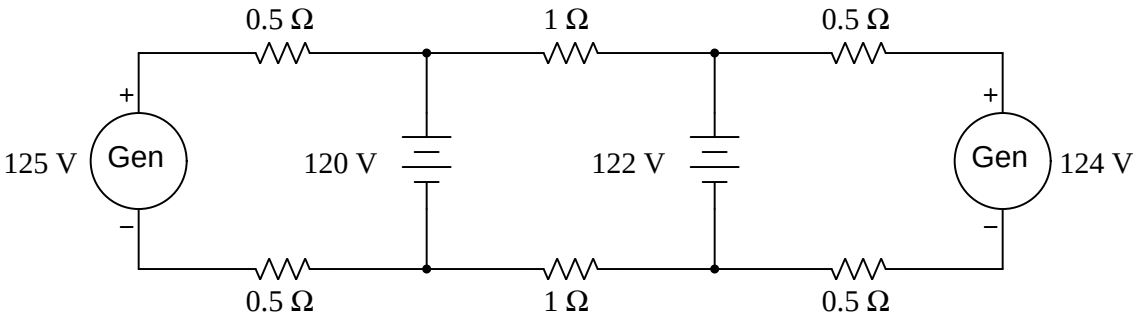
Also, calculate the voltage at generator 1's upper terminal as referenced from ground:

Challenges

- Identify realistic sources of the resistances shown in the schematic.

6.2.6 Multi-source grid simulation program

Determine all currents in this circuit:



- $I_{generator(left)} =$
- $I_{generator(right)} =$
- $I_{battery(left)} =$
- $I_{battery(right)} =$

Next, write a computer program in a text-based language (e.g. C, C++, Python) that will calculate all the same currents given fixed resistance values and user-input voltage values.

Challenges

- Determine a set of voltage conditions such that at least one of the batteries will neither be charging nor discharging.

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.

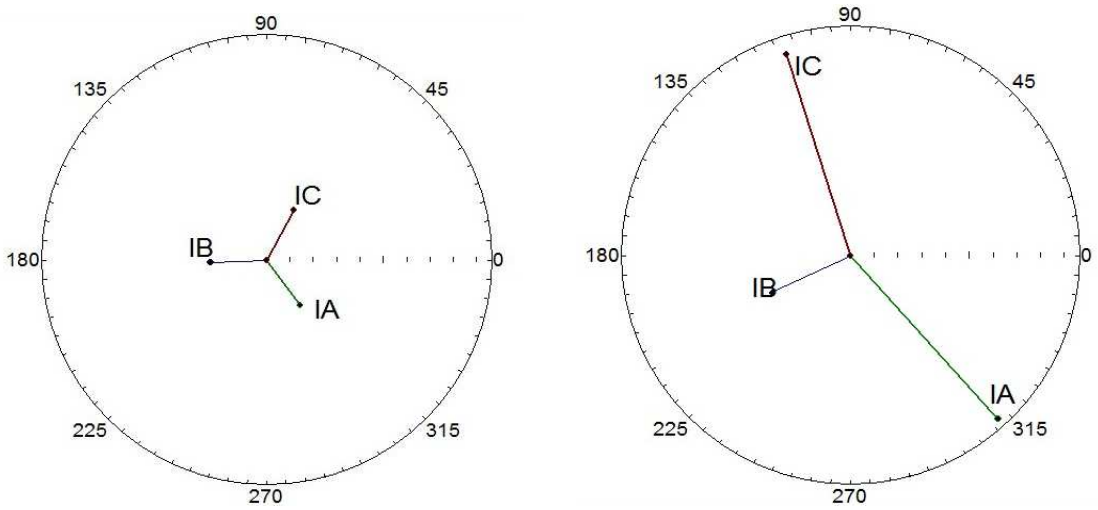
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

Modern electric power instrumentation is able to display three-phase circuit quantities as *phasor diagrams*. The following examples show screenshots from a protective relay as it senses line currents from a three-phase generator, the left-hand screenshot representing normal operation and the right-hand screenshot representing a fault in the three-phase distribution line:



First, identify the phase rotation of this power system based on the color-coding of the phasors. Is it ABC or is it CBA? How are you able to determine this fact.

Next, identify the nature of the fault in this power system, being as specific as you can.

Challenges

- What would the phasor diagram look like if one of the lines failed open?.

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.

14 March 2025 – added a new Historical References section showing a photograph of an "Edison tube" buried power cable.

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.

21-24 July 2023 – added new Quantitative Reasoning questions focused on DC power grids containing multiple sources. Also corrected coding format error in one of the instructor notes.

15 June 2023 – divided the Full Tutorial into separate sections.

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

8 May 2021 – commented out or deleted empty chapters.

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.

18 March 2021 – corrected multiple instances of "volts" that should have been capitalized "Volts".

15 March 2021 – added questions.

11 February 2021 – corrected instances where "Ohms" was uncapitalized.

9 November 2019 – added a quantitiative question based on a historial quote of electrical energy usage per capita in 1921.

1 January 2019 – added a Technical Reference section on electrical safety.

18 December 2018 – minor edits made to the order of words in the paragraph annotating the single-line grid diagram shown in the Full Tutorial, as per recommendations by Ron Felix.

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

September 2018 – renamed "Derivations and Technical References" chapter to "Historical References".

July 2018 – added more historical references, this time to Carl Hering's article in Volume I of *Cassier's Magazine* on the transmission of power by electricity.

July 2018 – minor edits made to Simplified Tutorial.

May 2018 – document first created.

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