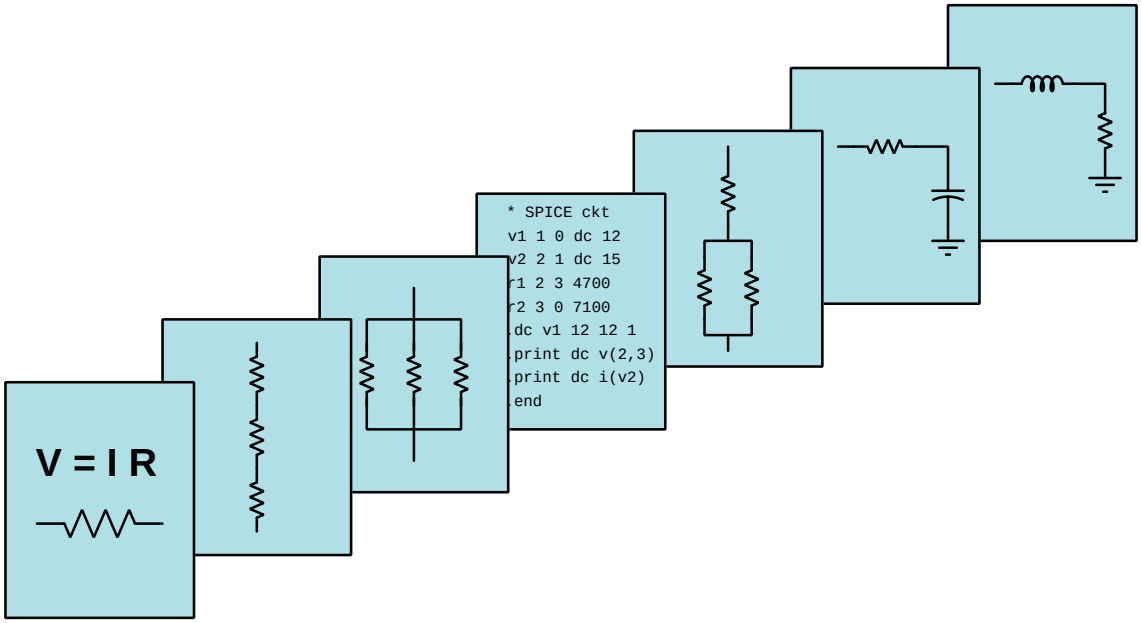
Modular Electronics Learning (ModEL) project



AC Generators

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Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to AC generators . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Case Tutorial **7**
- 2.1 Example: Delco-Remy 10SI with regulator . . . 8

3 Tutorial **9**
- 3.1 Basic alternator construction . . . 11
- 3.2 Basic operating characteristics . . . 13
- 3.3 Delco-Remy 10DN alternator disassembly . . . 15
- 3.4 Large hydroelectric generators . . . 24
- 3.5 Lenz's Law in generators . . . 26

4 Historical References **29**
- 4.1 Generators at Niagara Falls . . . 30
- 4.2 Solenoid-driven turbine control . . . 33

5 Questions **35**
- 5.1 Conceptual reasoning . . . 39
  - 5.1.1 Reading outline and reflections . . . 40
  - 5.1.2 Foundational concepts . . . 41
  - 5.1.3 Induced voltage in stator winding . . . 42
  - 5.1.4 Moving wire and magnet . . . 43
  - 5.1.5 Moving versus stationary coil . . . 44
- 5.2 Quantitative reasoning . . . 45
  - 5.2.1 Miscellaneous physical constants . . . 46
  - 5.2.2 Introduction to spreadsheets . . . 47
  - 5.2.3 Generator frequency . . . 50
  - 5.2.4 Poles and speed and frequency . . . 50
  - 5.2.5 Two-phase generator . . . 51
  - 5.2.6 Three-phase generator . . . 53
- 5.3 Diagnostic reasoning . . . 55

5.3.1 Effects of faults in manually-regulated generator 56

A Problem-Solving Strategies **57**

B Instructional philosophy **59**
B.1 First principles of learning 60
B.2 Proven strategies for instructors 61
B.3 Proven strategies for students 63
B.4 Design of these learning modules 64

C Tools used **67**

D Creative Commons License **71**

E References **79**

F Version history **81**

Index **82**

Chapter 1

Introduction

1.1 Recommendations for students

An electromechanical *generator* is a machine designed to convert mechanical energy into electrical energy, using the principle of electromagnetic induction where a time-varying magnetic field induces a voltage in one or more conductors. Most electromechanical generators utilize a rotating magnet (the "rotor") surrounded by stationary coils of wire (the "stator"), with the output of those stationary coils naturally being alternating current (AC). This module explores the basic operating principles of AC generators and goes into some detail of a small generator's construction.

Important concepts related to AC generators include **frequency**, **phase**, **prime mover**, **electromagnetic induction**, **Faraday's Law**, **Conservation of Energy**, **transformers**, generator **poles**, **polyphase** AC networks, phase **sequence** or phase **rotation**, generator **synchronization**, **brushes** and **slip rings**, **electromagnetism**, and **rectifier** circuits.

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

- How might an experiment be designed and conducted to demonstrate the phenomenon of electromagnetism? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How might an experiment be designed and conducted to demonstrate the phenomenon of electromagnetic induction? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What factors influence the amount of voltage induced in a coil of wire by a magnetic field?
- What is a "prime mover" for a generator?
- What are some common types of prime movers for electrical generators?
- How may we extract DC from a generator that is inherently AC?
- Why are electromagnetic rotors used more so than permanently-magnetized rotors?

- How do single-phase generators differ in construction from three-phase generators?
- What determines the output frequency of an AC generator?
- Why is the paralleling of multiple AC generators more complicated than the paralleling of DC voltage sources?
- Why do generators require cooling?

1.2 Challenging concepts related to AC generators

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

- **Lenz's Law** – only after the curled version of the Right-Hand Rule has been understood, may it be used as an effective tool to predict the induced current vector direction predicted by Lenz's Law. Usually students who struggle to apply Lenz's Law have not yet mastered the Right-Hand Rule!

1.3 Recommendations for instructors

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

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

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

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

- **Outcome** – Apply Lenz's Law to determine induced voltage polarity in a generator

  Assessment – Given magnetic field direction and relative motion, determine induced voltage polarity in a generator; e.g. pose problems in the form of the "Moving wire and magnet" Conceptual Reasoning question.

- **Outcome** – Relate generator shaft speed to output frequency

  Assessment – Calculate shaft speed given number of poles and output frequency; e.g. pose problems in the form of the "Poles and speed and frequency" Quantitative Reasoning question.

  Assessment – Calculate number of poles given shaft speed and output frequency; e.g. pose problems in the form of the "Poles and speed and frequency" Quantitative Reasoning question.

  Assessment – Calculate output frequency given number of poles and shaft speed; e.g. pose problems in the form of the "Poles and speed and frequency" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Locate AC generator datasheets and properly interpret some of the information contained in those documents including number of poles, winding configuration, output voltage, maximum power, etc.

Chapter 2

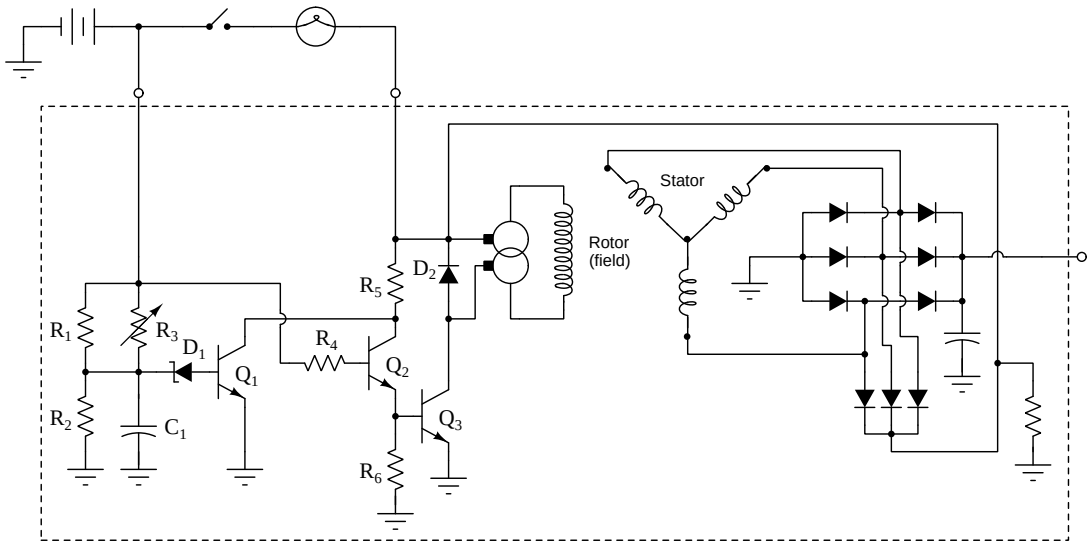
Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: Delco-Remy 10SI with regulator

Most Delco-Remy model 10SI alternators come equipped with internal solid-state regulator circuits, connected to the windings as shown here:



Chapter 3

Tutorial

Electricity, as a medium for conveying energy, must always originate from some source in accordance with the *Law of Energy Conservation*. Like all forms of energy, electricity cannot spontaneously appear from nothing, nor can it disappear – in all cases its source and destination must be accounted. Most of the electricity generated in the world does so by means of electro-mechanical *generators* which are machines designed to convert mechanical energy into electrical energy. The vast majority of these generators are *rotating machines*, which means they possess a shaft which must be turned by some *prime mover* such as a hydroelectric turbine, steam turbine, wind turbine, internal-combustion engine, or other mechanism. These "prime movers" in turn receive their energy from various sources including falling water, heat from combustion or nuclear processes, moving wind, and chemical fuels, respectively.

The fundamental principle upon which all electro-mechanical generators function is *Faraday's Law of Electromagnetic Induction*, where the amount of voltage induced in a coil of wire is equal to the number of turns in that coil multiplied by the rate at which the magnetic flux is changing strength:

$$V = N\frac{d\Phi}{dt}$$

Where,

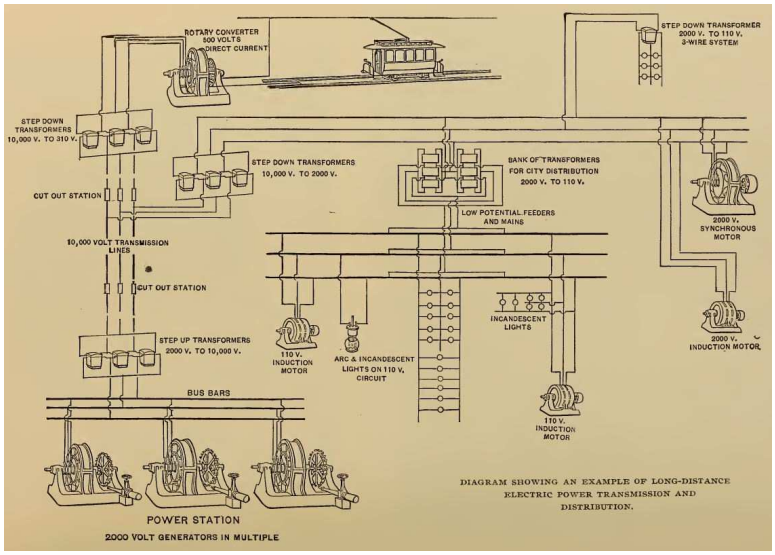
V = Induced voltage across the coil, in Volts

N = Number of "turns" or "wraps" in the coil

$\frac{d\Phi}{dt}$ = Rate-of-change of magnetic flux[1], in Webers per second

[1] Magnetic flux is related to magnetic field strength by cross-sectional area, with $B = \frac{\Phi}{A}$. Thus, it is valid to think of magnetic field strength as the degree to which magnetic flux is *concentrated* into an area. This holds true for the units of measurement used to express each: the unit of the *Tesla* used for magnetic field strength (B) is equivalent to *Webers of flux per square meter*.

The following illustration shows a simplified schematic diagram of a polyphase AC power system dating from the year 1895[2], 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:

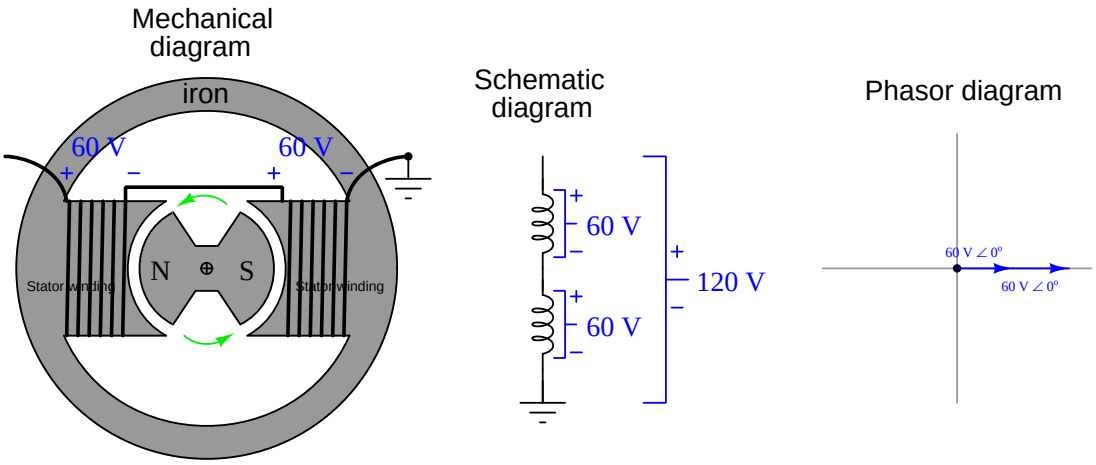


This system shows a "power station" located at Niagara Falls with multiple 2,000 Volt, three-phase generators in tandem functioning as the grid's power source. Those generators were of course using falling water as the energy source, with hydraulic turbines being the prime mover machines turning the generator shafts. Alternating-current (AC) electrical power from these generators 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). 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*.

[2]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.

3.1 Basic alternator construction

A simple *alternator* or *AC generator* is nothing more than a magnetized rotor spinning between a pair of electromagnetic poles, the stationary wire coils ("stator windings") developing AC voltage as the spinning rotor's magnet passes by:

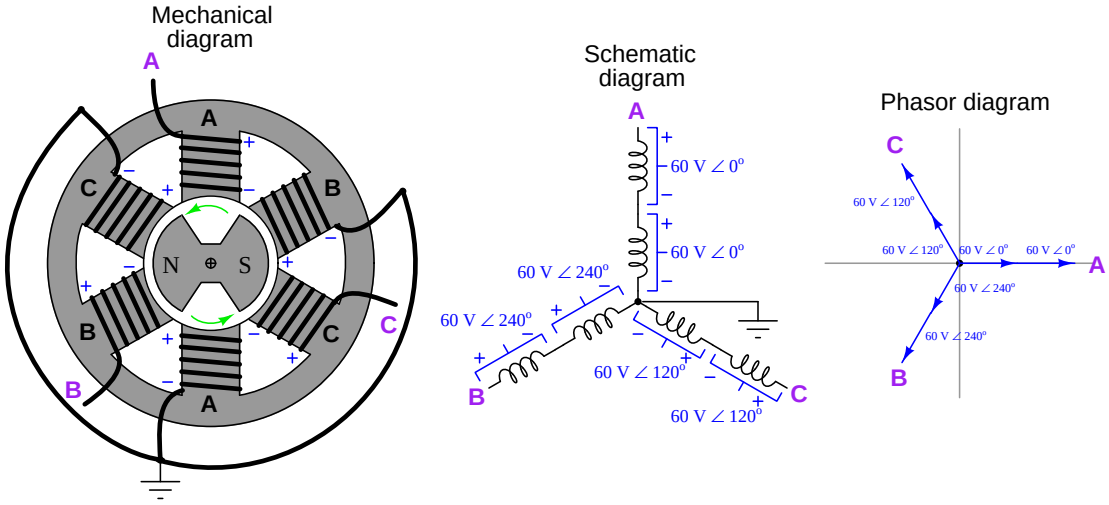


In this particular example each stator winding outputs 60 Volts AC, and since they're connected in series-aiding fashion the total output voltage will be 120 Volts. This machine is properly called a *single-phase* generator, because all its stator winding voltages are in-phase with each other. Recall that AC polarity symbols (+ and −) indicate the actual polarity of each voltage during the positive half-cycle of the alternating waveform.

A permanently-magnetized rotor is what is shown in this simplified illustration, and will serve well for some generator applications, but most generators utilize an *electromagnetic* rotor requiring an external source of direct-current (DC) electrical power to "excite[3]". Although an electromagnetic rotor may seem inefficient compared to a permanently-magnetized rotor because additional electrical power is needed to energize it, the practical advantage of using an electromagnetic rotor is that by varying the amount of current sent through the rotor's winding the generator's output voltage may be controlled independent of shaft speed.

[3]Some large AC generators have as auxiliary equipment a small DC generator coupled to the same shaft with the prime mover called the *exciter*. The sole purpose of the exciter is to provide DC excitation for the main generator's field coil so that the latter will be able to generate electricity. Alternatively, one would have to utilize a battery or other source of DC to excite the generator's field winding, and then some provision would have to be made to re-charge that battery when the generator was running.

A much more common design of AC generator uses *three* sets of stator windings to generate three AC voltages phase-shifted from one another by 120^o. The reason these three AC voltages are not in-phase with each other is precisely because the three stator poles are not physically aligned with each other, which means the magnetic poles of the spinning rotor will pass by each stator pole pair at different times:



As the generator's rotor spins counter-clockwise, stator winding pair "A" will reach its positive peak value before stator winding pair "B", and that before stator winding pair "C". This A-B-C order is called the *phase sequence* or *phase rotation* of the generator, and each stator winding set is simply called a "phase". Phase rotation is easiest to apprehend by viewing the schematic diagram, noting the phase order as you rotate counter-clockwise around the schematic (in the same direction as the rotor): at the top is "A" (arbitrarily defined as having a 0^o phase angle) followed by "B" 120 degrees later (-120^o or 240^o phase-shifted from "A") followed by "C" 120 degrees after that.

The phasor diagram also declares an A-B-C phase rotation: the blue vectors represent stator voltages at that instant in time when stator winding pair "A" is at its positive peak value (i.e. 0^o on a cosine wave), and in a phasor diagram it is the vectors themselves that rotate counter-clockwise so that a stationary observer would notice vector tips passing by in an A-B-C order.

As with single-phase generators, three-phase generators typically possess electromagnetic rotors rather than permanent-magnet rotors, and for the same reason: this provides a means to regulate the generator's output voltage independent of shaft speed.

3.2 Basic operating characteristics

Faraday's Law of Electromagnetic Induction is the basis for a generator's ability to convert mechanical energy into electrical energy: the rotation of the generator's shaft by a prime mover causes magnetized iron to move past stationary pieces of iron around which wires are wrapped into coil shapes, the variations in magnetic flux causing voltage to be induced in those coils. The amount of voltage induced depends on the number of turns of wire in each coil as well as the rate at which the magnetic flux varies. Flux rate-of-change is a function of how strongly magnetized the rotor is, as well as the speed at which the rotor turns. Written as a proportionality:

$$V_{output} \propto N_s N_f I_f S$$

Where,

V_{output} = Open-circuit output voltage of the stator winding(s)

N_s = Number of turns in the stator winding(s)

N_f = Number of turns in the field winding

I_f = Current passing through the field winding

S = Rotational speed of the generator shaft

For any generator that is already constructed, N_s and N_f are fixed, which means the only controllable variables for output voltage is field excitation current (I_f) and shaft speed (S).

The *frequency* of the AC output by a generator is a function of shaft speed and the number of magnetic poles on the rotor. In the simplest form of generator there will only be two poles on the rotor (one north, one south), and rotating its shaft 1 revolution per second will generate a sinusoidal output voltage with a frequency of 1 Hertz. Increasing the rotational speed will, of course, increase the output frequency. Increasing the number of magnetic pole-pairs on the rotor will do the same. A formula useful for relating AC frequency to these variables is as follows:

$$f_{output} = \frac{NS}{120}$$

Where,

f_{output} = Output frequency, in Hertz

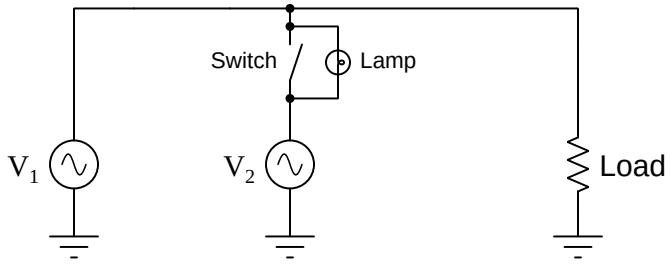
N = Number of magnetic poles on the rotor (minimum = 2)

S = Rotational speed of the generator shaft, in revolutions per minute (RPM)

Given a fixed number of poles on the rotor, the one and only variable affecting the frequency of a running AC generator is its shaft speed. Most AC electrical power systems require a tightly-controlled frequency for safe and efficient operation, which means all generators part of that system must spin at constant speeds. With rotational speed thus constrained, it should be clear to see why

it is advantageous for these generators to be equipped with electromagnetic field windings: to be able to regulate voltage as needed when there is no freedom to vary the speed.

Most electrical power systems incorporate multiple generators driven by different prime movers. In order to co-exist on the same "grid" these generators must all operate at the same frequency, or else they would fall in and out of phase with each other. This poses a problem when a new generator is started up, with the intention of joining to an already-running AC power grid. Since no machine is able to accelerate from a standstill to full speed *instantly*, there will be a period of time when every starting generator's frequency does not match the grid's. A practical solution to this problem is to monitor the voltage across the open contacts of the switch or circuit breaker disconnecting the generator from the rest of the grid, which will have a frequency equal to the *difference* between the generator's frequency and the grid's frequency. Traditionally this takes the form of an electric lamp connected in parallel with the switch contacts. In the following diagram, generator V_1 and the resistive load represent the "grid" while generator V_2 represents the new generator we are starting up:



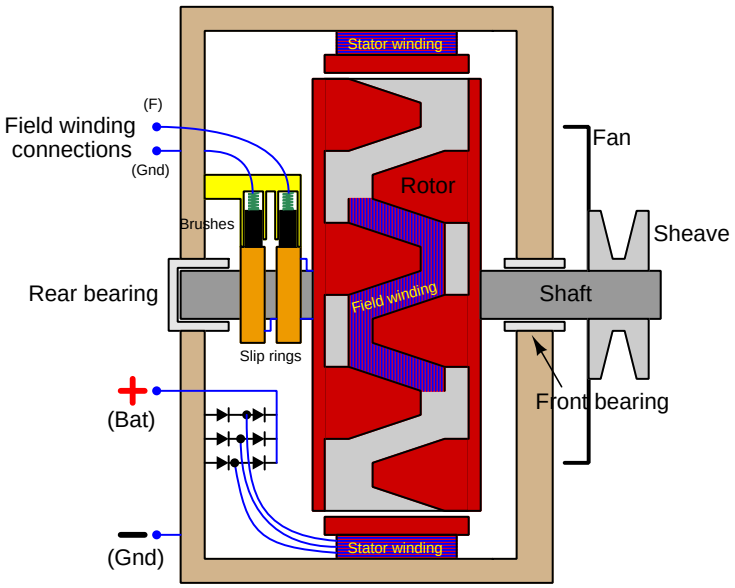
When the generator's frequency precisely matches the grid's, this voltage difference between the open switch contacts will have a steady AC value. If the two frequencies are unequal, this voltage will cycle at a slow rate making the lamp alternate between glowing and not glowing. If the two frequencies are equal but the phase angles are unequal, the lamp will steadily glow. If the two frequencies are equal and the phase angles are equal but the voltages are unequal, the lamp will also steadily glow. Only when all parameters are equal (frequency, phase, and voltage) will the lamp remain off.

Thus, the task of *synchronizing* an AC generator to an already-operating AC power system consists of adjusting the prime mover's speed and the field excitation current until a condition of zero (or nearly-zero) voltage across the open switch contacts is reached. At that time it is safe to close the switch and connect the generator to the grid. Once the switch is closed, all the generators will naturally act to keep each other in synchronization: if one tries to slow down for any reason, it will begin to operate as a motor and draw power from the other generators to maintain synchronization; if one tries to speed up, it will attempt to take on the entire grid as a load (including the other generators, making them act as motors) and that resulting burden will render impossible any actual increase in speed for the rogue generator.

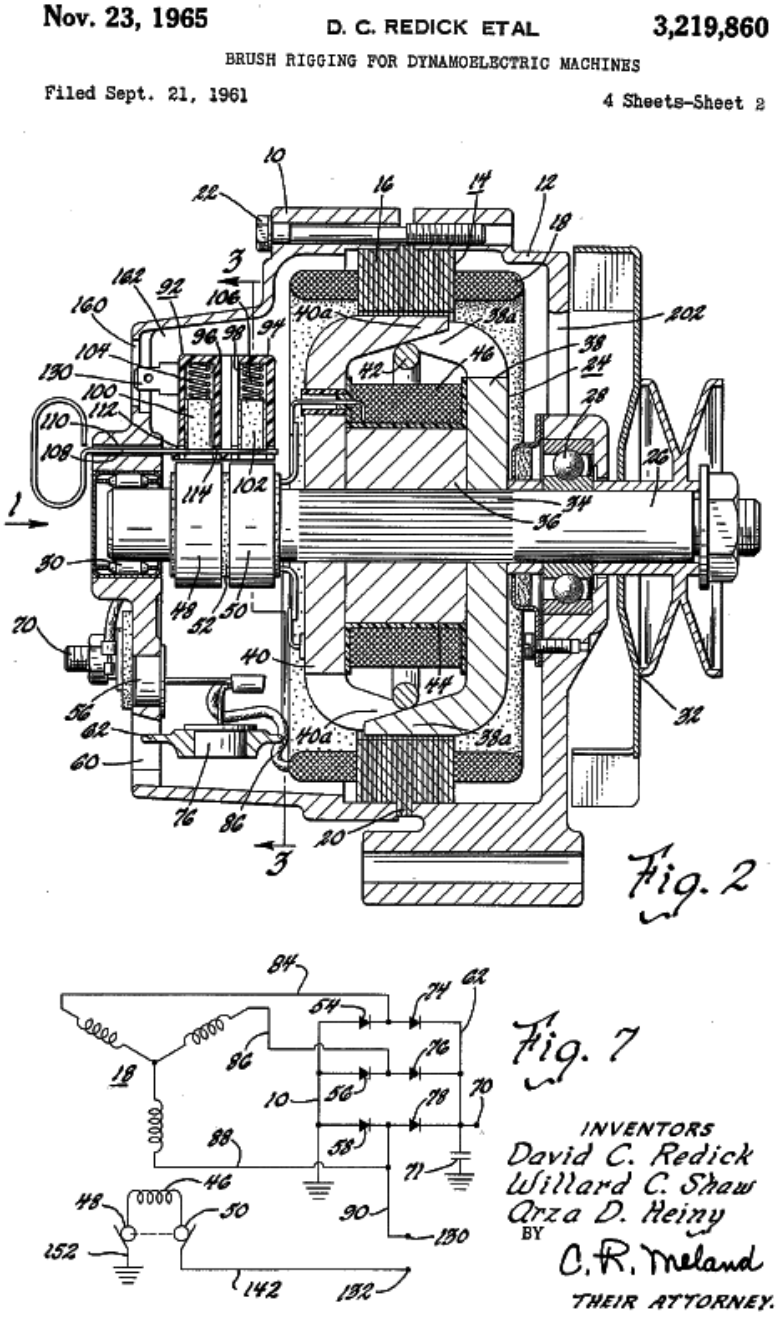
3.3 Delco-Remy 10DN alternator disassembly

The basic design features of AC generators – also known as *alternators* – are common to all sizes, which means we may learn all the elementary knowledge we might need from disassembling and inspecting small generators such as those used in automotive service. A very popular model of automotive AC generator ("alternator") is the model 10DN manufactured by Delco-Remy, used in a wide range of General Motors brand products (e.g. Chevrolet, Pontiac, Cadillac, Oldsmobile, etc.). These generators have three-phase stator windings connected in a "Wye" configuration, a rotating field energized by the automobile's 12-Volt electrical power network, and a set of six diodes built in to the frame of the generator designed to full-wave rectify the stator's three-phase output into DC suitable for powering the vehicle's electrical system. Many model 10DN generators also contain a built-in voltage regulator module, but the unit shown here does not have that feature, instead relying on external circuitry to modulate the rotor coil's energization.

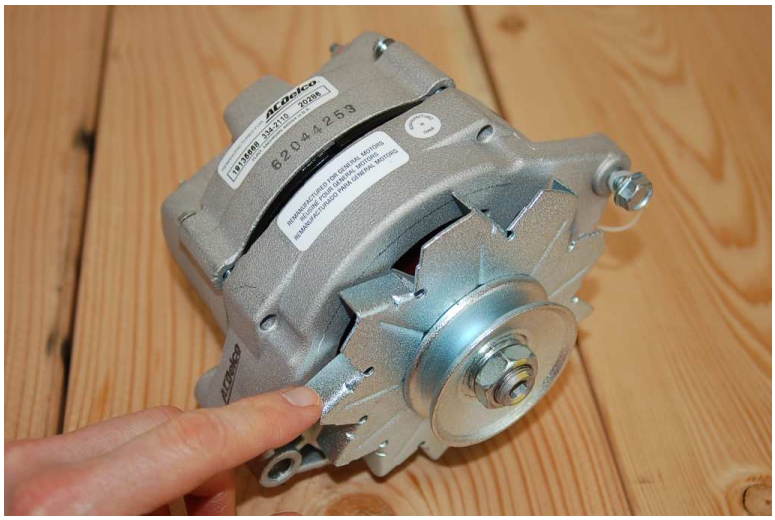
A simplified cross-sectional diagram of a generator based on the design of the Delco-Remy 10DN appears here:



A page from a 1965 patent awarded to David Redick, Willard Shaw, and Arza Heiny of the General Motors Corporation shows a detailed diagram of this same alternator:

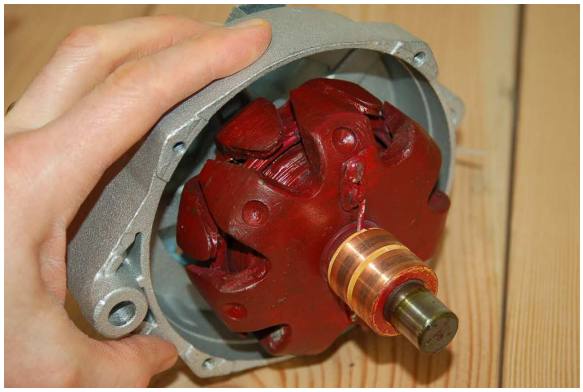


Next we see an external view of a Delco-Remy 10DN generator, complete with a sheave for belt-drive to the vehicle's engine and a centrifugal cooling fan designed to pull air through the case of the generator with the spinning motion of its shaft. My index finger happens to be touching one of the "fins" on this centrifugal fan assembly:



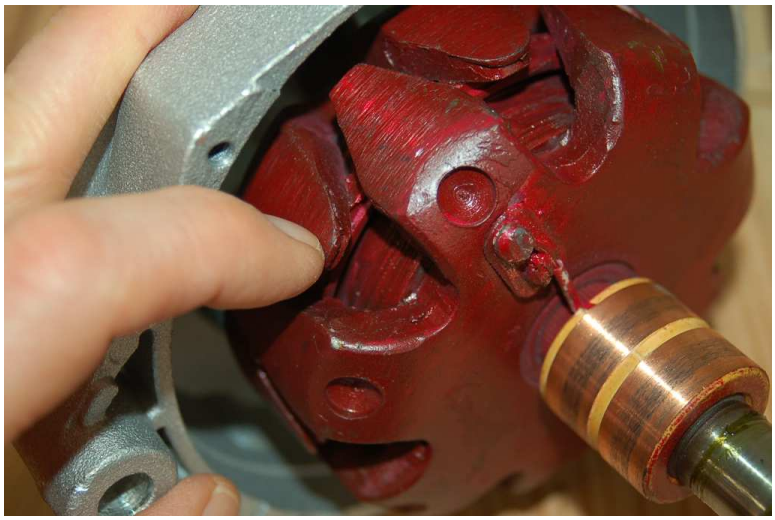
Connection terminals for the generator's electrical components are located on the back side of this unit, out of view of the camera.

Removing four screws allows the generator's case to be split open, and the rotor to be removed. The red-painted portion is the iron rotor, mounted on the shaft that is spun by the vehicle's engine. It is supported by a bearing at each end, and in this photograph you may see the shaft's end which used to be supported by a needle bearing in the rear of the unit but now is exposed and unsupported. The second bearing lies within the front half of the generator's frame, between the rotor assembly and the sheave/fan assembly:

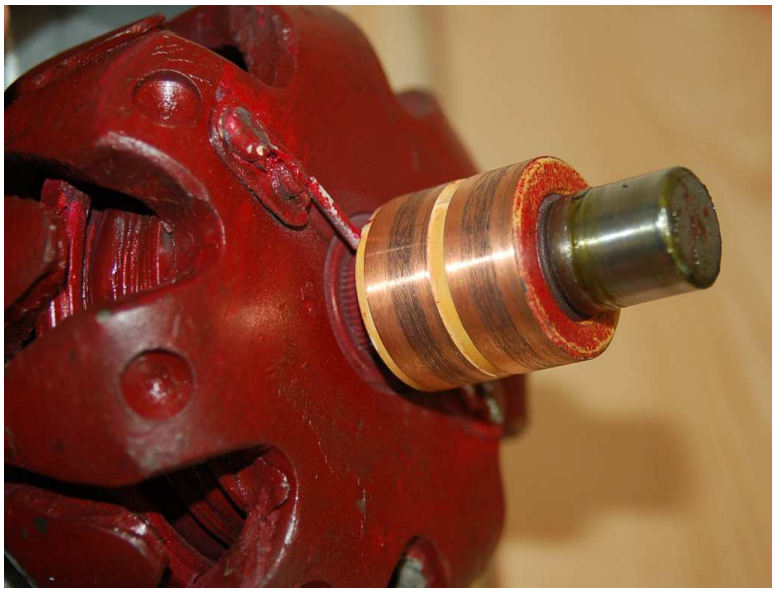


Looking closer at the rotor, we see the field coil (also painted red) inside the iron rotor. This coil is wound such that its centerline is also the centerline of the generator's shaft. When energized

by DC, it produces a "north" magnetic pole at one end and a "south" pole at the other. The two halves of the iron rotor assembly bring these north and south magnetic poles to the rotor's rim by way of fourteen interlacing "fingers", seven "north" and seven "south". These "fingers" rotating past the stator coils will induce voltage in the stator coils:



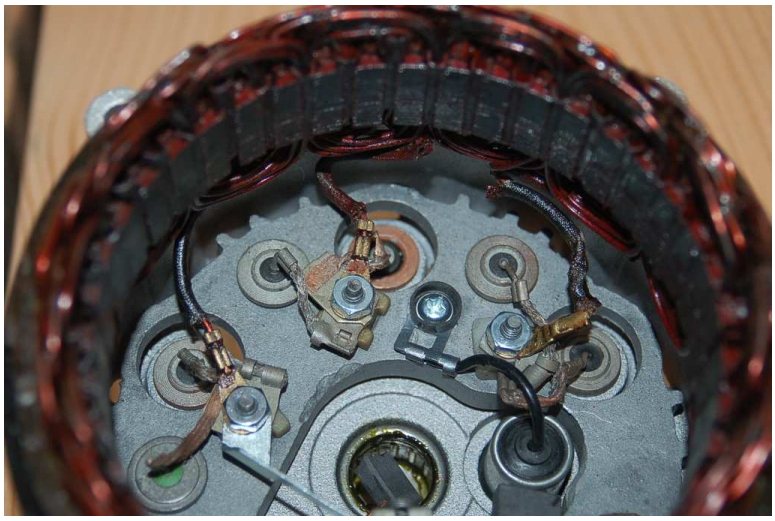
At one end of the rotor is a pair of copper "slip rings" where DC power connects to the rotor's field winding. When inserted in the generator frame, a pair of carbon "brushes" make contact with these rings to provide a sliding electrical contact, allowing external power to be fed to the field coil to magnetize that coil so that the generator will be able to produce electricity. In this photograph the wires leading from each slip ring to the field coil are easily seen:



It is important, especially for an automotive generator, to have an externally "excited" field coil rather than a permanent-magnet rotor. With external excitation it becomes possible to finely adjust the strength of the rotor's magnetic field in order to regulate the generator's output voltage with changing speed and load conditions. Automotive engines cover a broad range of speeds from idle to racing, and without voltage regulation the alternator would spend most of its time either outputting insufficient voltage or over-charging the vehicle's battery. The purpose of the generator's *voltage regulator* circuit is to reduce the rotor's external excitation if output voltage becomes too high, and increase excitation if the output voltage is too low.

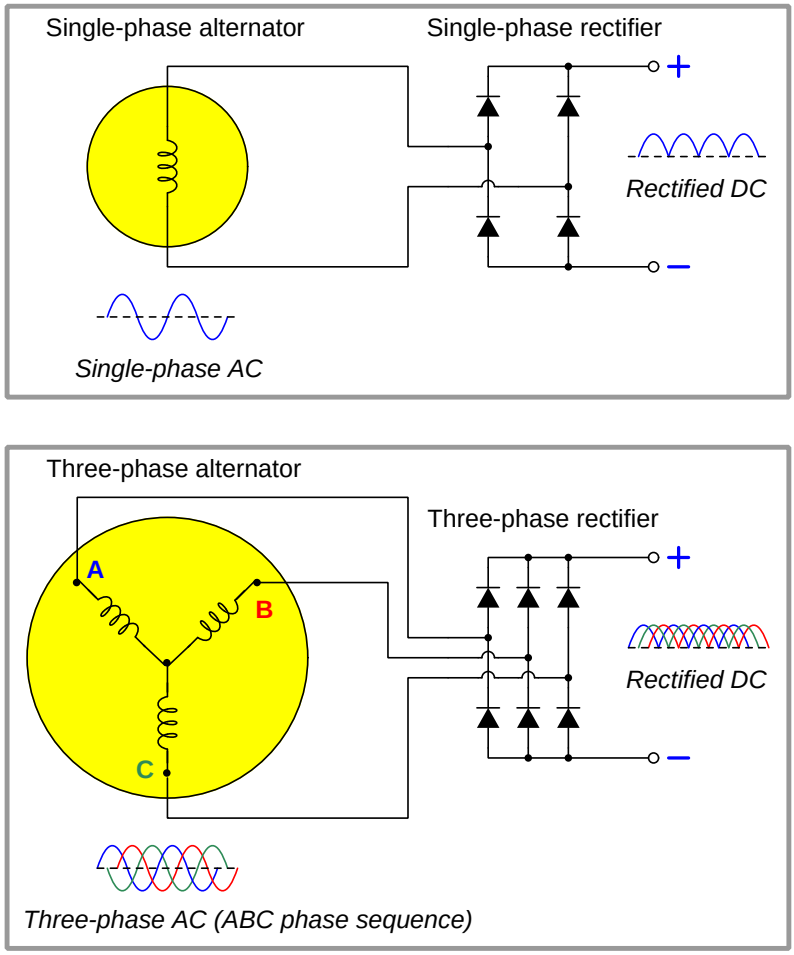
Leaving the front half of the generator frame with the attached rotor assembly and directing our attention to the rear half of the generator frame, we see the stator assembly as a set of iron poles and copper wires set into the circumference of the frame. The iron poles are painted black, while the copper wires are reddish in color from their enamel insulation:

Examining the stator closer, we clearly see the iron pole faces as well as the circular patterns of the stator coils wrapped around the poles. In the background we see three wires leaving the stator and connecting to two diodes each, forming the three-phase full-wave rectifier:



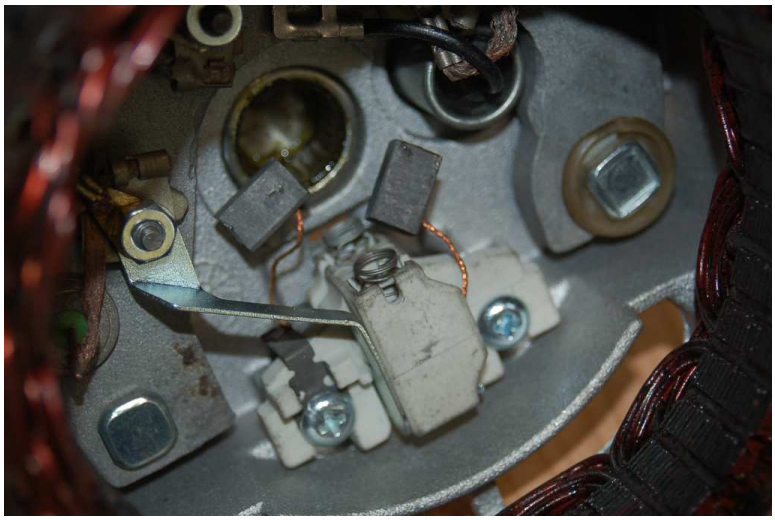
Three of these diodes press into the cast-aluminum body of the generator which acts as a common "ground" point for both power and control circuitry. The other three diodes press into a cast-aluminum sub-assembly isolated from the generator's main frame by insulating standoffs, this sub-assembly acting as a positive "bus" which will connect to the positive terminal of the vehicle's 12-Volt DC electrical system.

For review, we turn our attention to full-wave rectifier networks, contrasting single-phase rectification (top) against three-phase rectification (bottom):

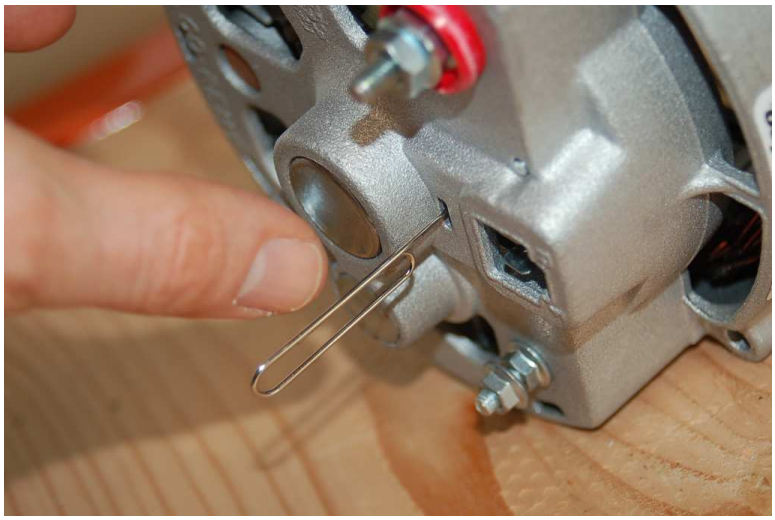


Note how three-phase rectification yields a much "smoother" rectified DC output due to the overlapping of the phase-shifted voltages. This is why automotive generators are all polyphase machines: to produce DC that pulses less than what would happen in a single-phase generator. This "smoother" DC power is beneficial for electronic equipment operating on the vehicle, such as engine control computers, radio systems, and other devices designed to be powered by pure DC.

Looking closer at the brush assembly, we see how the two carbon brushes have fallen out of their holder due to the removal of the rotor assembly. Normally the rotor is inserted into this half of the generator frame and the two carbon brushes maintain continuous contact with the copper slip rings with the help of two coil springs. Now, with the rotor gone, the brushes pop out of their holder to reveal the springs underneath as well as the wires connecting these brushes to external terminals on the generator:



A feature of the Delco-Remy 10DN alternator useful in reassembly is a hole drilled through the plastic brush-holder assembly, through which a stiff metal wire may be inserted to hold the two carbon brushes in place against the compression of their coil springs. This allows the rotor assembly to be re-inserted into the rear half of the generator frame, without the brushes getting in the way. A steel paper-clip, suitable straightened to act as this "keeper" wire, may be inserted at the rear of the generator:

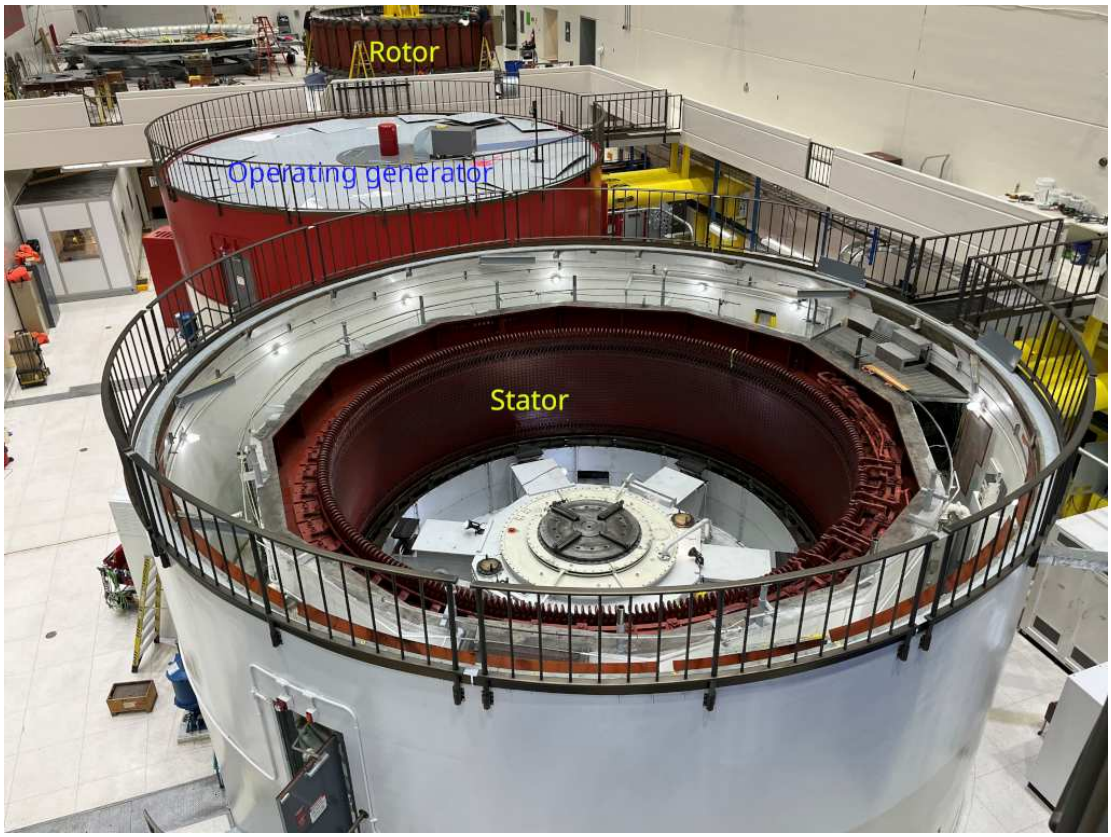


Once inserted, we see how this wire acts to hold the brushes down:

With the "keeper" wire in place, we may re-insert the rotor assembly, re-install the four screws clamping the two halves of the generator case together and then finally remove the wire to allow the brushes to spring "up" from their holder assembly to make contact with the rotor's slip rings.

3.4 Large hydroelectric generators

The following photograph was taken at a hydroelectric generating station, where water flowing downward from a reservoir spins turbines that turn AC generator shafts to output massive amounts of AC electric power. Here we see two generators, each rated at 100 million Watts (100 MW) output, the generator in the foreground disassembled for routine maintenance while the generator in the background is operating. Various stepladders positioned around the work area provide a sense of physical scale for these large machines, which incidentally are considered "small" for modern hydroelectric generating stations:



In the far background we see the rotor removed from the foreground generator, resting on an elevated concrete platform for access by maintenance personnel. As typical for hydroelectric generators these units are vertical-shaft in design, with a very large gantry crane built into the structure overhead for performing heavy maintenance work such as this. With the rotor removed, the stator is clearly visible in the foreground generator. Large yellow-painted conduits extending radially outward from each generator on the right-hand side house the conductors connecting each generator's stator windings to the generator bus in this station. Output voltage for each generator is 13.8 kV, stepped up to 500 kV by three-phase transformer banks located outside the generator building for transmission to distant substations.

Each of these generators has 32 poles in its rotor, making the rotational speed only 225 revolutions per minute (225 RPM) for an output frequency of 60 Hz. Aside from the number of poles and the sheer size of these machines, their design and construction is remarkably similar to the Delco-Remy 10DN generator explored in the previous section.

An interior photograph[4] of a much smaller hydroelectric power generating station – the Nooksack Falls power plant in Washington State, completed in 1906 – shows an open-frame horizontal-shaft generator manufactured by Westinghouse and rated at 1.5 megaWatts:

The main generator is the large circular machine directly coupled to the shaft coming from the turbine (encased by a curved sheet-metal frame), while a smaller belt-driven generator is the *exciter* tasked with providing DC power to the main generator's rotor. This photo was taken while the generator was spinning, which is why some of the parts appear blurry.

Handwheels visible atop the turbine housing control the position of "needle valves" sending river water at high velocity to buckets of a Pelton-style turbine. This style of turbine operates best at high pressures and low flow rates, suitable for the Nooksack Falls power plant which takes water from a relatively small waterway located a considerable elevation (approximately 63 meters) above the powerhouse. AC generators are fairly simple and rugged machines, which is why this power plant was able to operate for a duration of *over ninety years* before a fire damaged it. After repairs, the power plant continued to operate and is still in operation at the time of this writing (2026) one hundred and twenty years after its construction.

[4]Public-domain images courtesy of the Library of Congress.

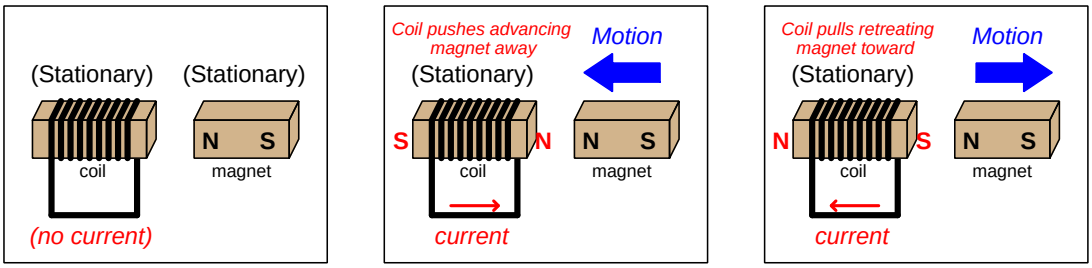
3.5 Lenz's Law in generators

Electromagnetic induction is where a time-varying magnetic field interacts with an electrical conductor to form a voltage. Electromagnetism is where an electric current passing through a conductor creates a magnetic field. What happens when these two phenomena occur at the same time in the same circuit? Imagine forming a conductive wire into a coil shape and then shorting the two ends of that wire coil together to create a complete circuit. If we then subject that wire coil to a changing magnetic field, we know the effect of electromagnetic induction will be to generate a voltage along the length of that coil, and as this voltage acts over the natural resistance of that wire it must create a current in the shorted wire circuit, and furthermore that this induced current must electromagnetically create its own magnetic field.

That induced current, and the magnetic field it creates, must interact in some way with the external magnetic field originally imposed on the coil, but how? Will the induced magnetic field oppose or reinforce the external field? As current only has two ways it could travel in our shorted-coil circuit, these are the only possible options. If we suppose the induced field reinforces the external field, it would mean that the combined fields' rate of change would also increase, leading to more induction, leading to stronger current, leading to more magnetic reinforcement, and so on to infinity. This makes no sense, as it would mean even the slightest provocation of a shorted coil by an external magnetic field would quickly result in its current climbing to infinite levels. This would plainly violate the Law of Energy Conservation, and so we know this scenario is not possible. Therefore, the only remaining option for our hypothetical coil is that the induced magnetic field must *oppose* the external field's rate of change.

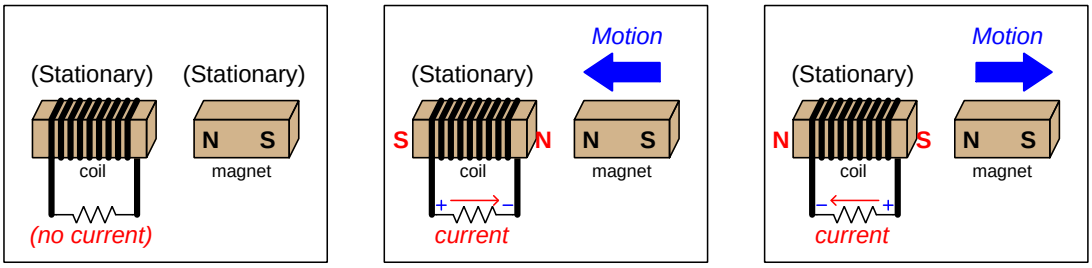
This general principle – that any induced effect must react in such a way as to oppose the initial cause in order to conserve energy – is known as *Lenz's Law*, and it plays a prominent role in electromagnetic generators of all types. Generators work by moving magnets past wire coils (called *windings*) or vice-versa, employing the relative motion between magnet and coil to produce voltage. If a generator is unloaded (i.e. open-circuited terminals) there will be no current as it spins even though its windings will exhibit induced voltage, and with no current possible there will be no reaction force against the spinning, and so we would expect the generator shaft to spin freely. As we load a generator (i.e. connect it to an electrical load such as a resistor), the magnetic field created by that current in the generator's own windings creates a reaction torque which makes the generator shaft more difficult to spin. A short-circuited generator is extremely difficult to turn, and in fact will act as a mechanical *brake*. This variation in shaft torque also makes sense by directly applying the Conservation of Energy: an unloaded generator conveys no electrical energy to any load, and so no energy should be required to spin its shaft other than to overcome bearing friction and aerodynamic drag; a loaded generator, by contrast, delivers electrical energy to a load and therefore must receive an input of mechanical work (i.e. rotation *and* torque) to supply that energy. A short-circuited generator's internal resistance functions as a very "heavy" load, which means it will grow hot as any prime mover attempts to spin it.

Examine the illustrations below showing a coil of wire facing a permanent magnet. In the left-hand illustration the magnet is stationary and therefore no induction occurs. In the center and right-hand illustrations the magnet moves, causing the coil to experience a varying magnetic field and thereby causing induction. The short-circuit permits current as a result of this induction, and we know any electric current through a coil produces its own magnetic field. Lenz's Law tells us this *induced* magnetic field must act to counter the motion of the permanent magnet:

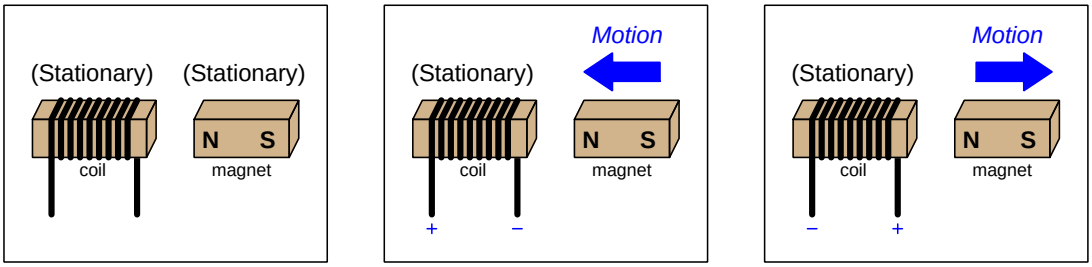


We can tell which way current must flow through the wire coil in the middle and right examples by applying the *Right-Hand Rule* of electromagnetism: by curling your fingers and pointing the thumb of your right hand, with the thumb pointing in the direction of magnetic north and the fingertips pointed in the direction of current (conventional flow notation) passing through the turns of the coil. Lenz's Law tells us which way the induced magnetic field must point to properly oppose the external field's change over time, and the Right-Hand Rule tells us which way the induced current must circulate to produce this reaction.

Inserting an electrical resistance into the coil's circuit diminishes the strength of this reaction, but does not alter its direction. Note how the coil functions as a *source* to the resistor's *load*:



If we break the circuit, no current may pass and therefore no opposing magnetic field can form. However, the coil must still generate a voltage in accordance with Faraday's Law of Electromagnetic Induction, and the polarity of that voltage will be the same as it would if there were a resistive load connected:



In case you were wondering, all these current directions and voltage polarities will reverse if we swap either the permanent magnet's polarity (i.e. magnetic south pole facing the coil) or the direction the coil is wrapped around its core. Reversing both of these parameters is equivalent to a double-negative, resulting in the same current directions and voltage polarities as shown above.

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,

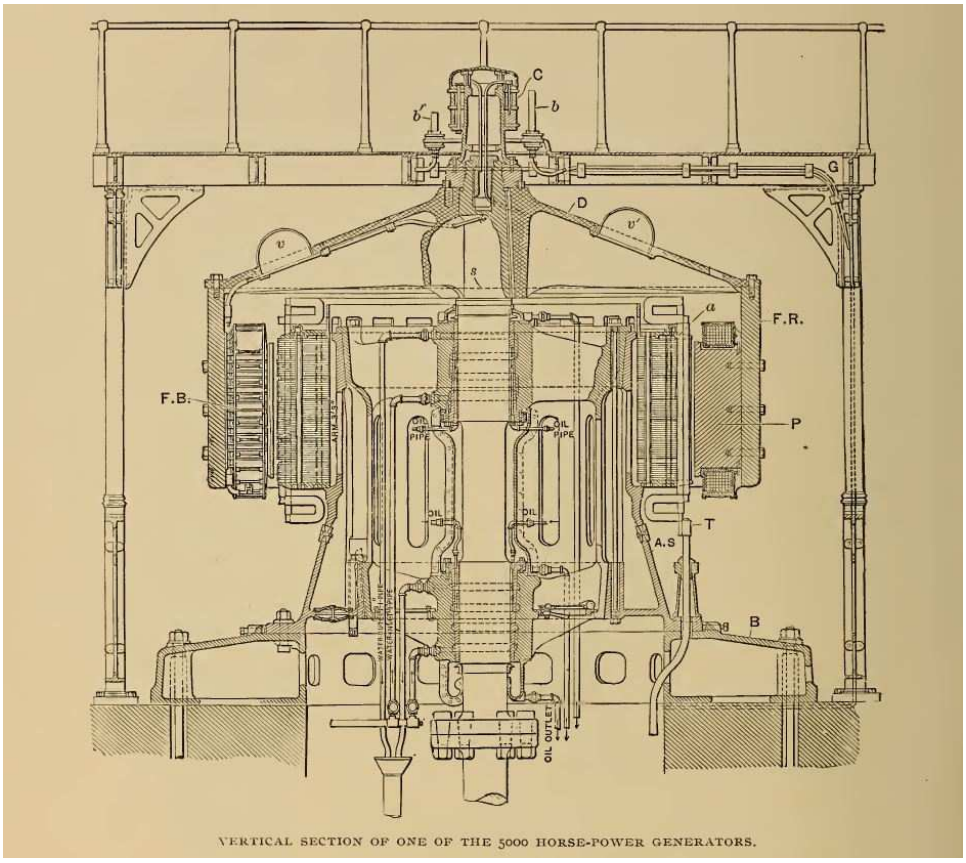
> It is of great advantage to the student of any subject to read the original memoirs on that subject, for science is always most completely assimilated when it is in its nascent state . . . `[page xi]`

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 Generators at Niagara Falls

The following photographs show a 5000 horsepower AC generator constructed for a hydroelectric power plant located at Niagara Falls in 1895. These came from an article in *Cassier's Magazine*, Volume 8, entitled "Electric Power Generation at Niagara" (written by Lewis Buckley Stillwell) on the design and construction of what was then an engineering marvel.

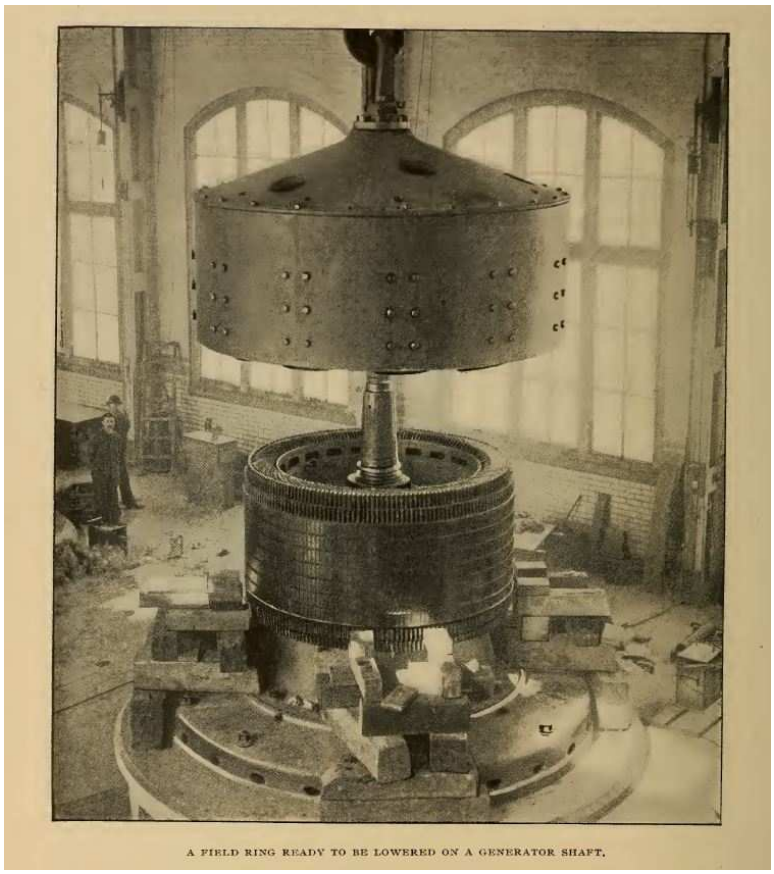
A cross-sectional drawing of one of the generators is shown below, from page 264 of the *Cassier's* article:



VERTICAL SECTION OF ONE OF THE 5000 HORSE-POWER GENERATORS.

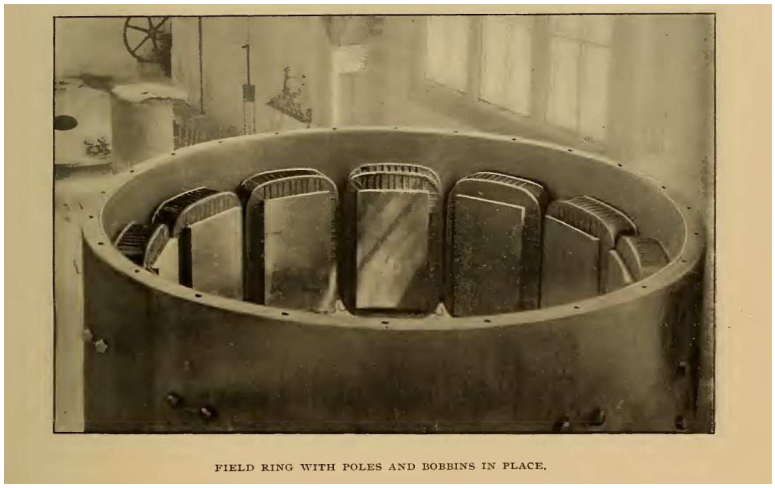
A very unusual (by modern standards) feature of this generator design is that the outer-most piece (called the *field ring*) was what revolved, and the stator (which the author called the "armature") *inside* the generator was stationary. This meant that the visible casing of the generator was revolving, typically at 250 revolutions per minute, as opposed to modern generator designs where the outer casing is stationary and the rotor spins within that casing hidden from both view and personal contact. The rotor's slip ring assembly is shown at C, with the two brush-holders at b and b'.

This rotating "field ring" is shown in the next photograph being lowered over the stationary armature (stator) by a crane during final assembly of a generator as shown on page 258 of the *Cassier's* article:



A FIELD RING READY TO BE LOWERED ON A GENERATOR SHAFT.

An interior view of this "field ring" prior to assembly appears below, from page 277 of the *Cassier's* article:

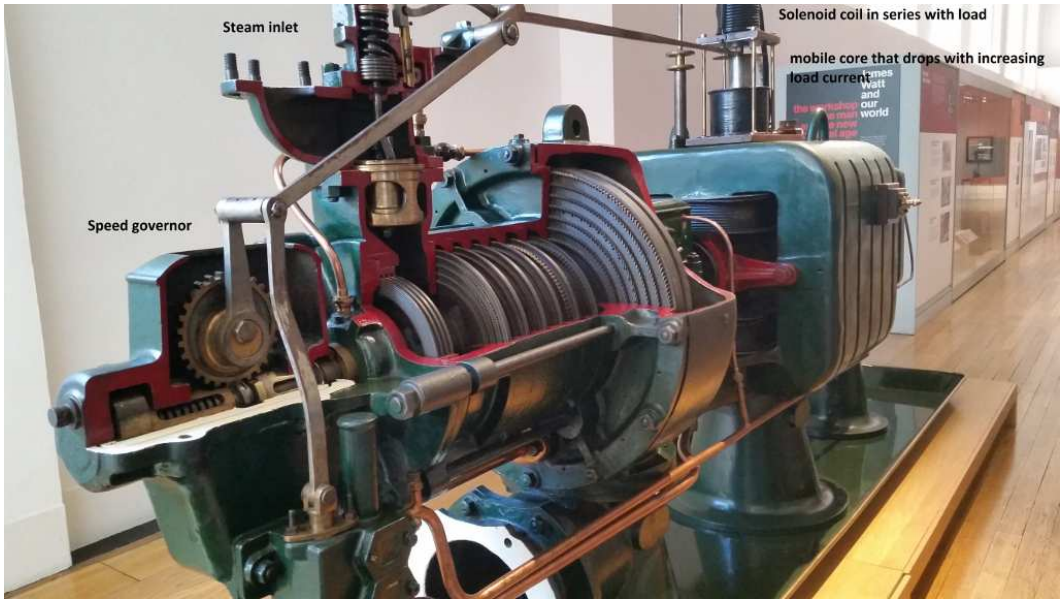


FIELD RING WITH POLES AND BOBBINS IN PLACE.

4.2 Solenoid-driven turbine control

Electromagnetism found widespread application soon after its discovery. Perhaps the most obvious of these 19th century applications include electric motors and electric generators, machines designed to convert electrical into mechanical energy, and mechanical into electrical energy, respectively.

In the following photograph[1] we see another, more subtle, application of electromagnetism. This photograph was taken within a museum, at an exhibit showcasing early electrical technology. In it we see a cutaway steam turbine engine coupled to a generator. Steam (most likely from a coal-fired boiler) drove the blades of the turbine, converting thermal energy into mechanical energy, which then spun the generator's shaft to convert into electrical energy:



The subtle application of electromagnetism suggested in the previous paragraph is the *solenoid coil* visible on the right-hand side of the image, linked to a lever arm which in turn influenced the speed governor mechanism for the turbine. A "solenoid" is nothing more than a coil of wire, typically wrapped around a cylindrical ferromagnetic core to produce strong magnetic fields. These magnetic fields, in turn, could be employed to attract other coils or ferromagnetic objects by way of magnetic attraction. This particular solenoid coil was wired in series with the output of the generator such that any changes in load current would immediately produce force on the lever arm to preload the governor mechanism and thereby alter the amount of steam fed to the turbine by the throttling valve mechanism near the steam inlet pipe. Any increase in load current, for example, would automatically result in more steam being fed to the turbine to provide more mechanical power to the generator.

[1] I am indebted to Mario Sotomaior for taking this photograph for me at a museum in London, England.

Speed regulation of such a generator is intended to stabilize the generator's output voltage. If the electrical load placed on this generator's output increases, the generator will become a "heavier" load for the turbine to drive, which in turn has a natural effect of slowing down the turbine. A slower-spinning generator outputs less voltage, all other factors being equal, and so stabilizing generator shaft speed helps the generator to maintain a more constant voltage. The governor assembly detects changes in turbine shaft speed and moves the throttling valve accordingly to correct for those disturbances. However, the governor alone is not the most effective way to stabilize generator output, as it cannot act until *after* the generator's shaft speed noticeably decreases. This is where the solenoid coil helps: by using load current to produce a mechanical force on the lever, any changes in load current *preemptively* adjust the throttling valve's position to increase or decrease steam flow as necessary to counteract the effects of electrical load changes. This means the task of restoring shaft speed does not rest solely with the mechanical governor, resulting in better dynamic stability for the whole generator system.

In control theory, this arrangement is known as *feedforward control*, in contrast to the governor's response being *feedback control*. Feedback control works to stabilize some measured quantity (called the *process variable*) by taking action *after* that measured quantity deviates from the desired level (called a *setpoint*). Feedforward control, however, takes action *before* that process variable has opportunity to deviate from its setpoint, based on the measurement of some other variable having a "loading" effect on the process variable. As you might expect, the combination of feedforward control offered by the load current solenoid and feedback control offered by the turbine's mechanical speed governor work well together to stabilize generator output when faced with rapid changes in load current.

Chapter 5

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?

5.1 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.

5.1.1 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.

5.1.2 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

Alternating current

Frequency

Direct current

Magnetic field

Electromagnetism

Faraday's Law of Electromagnetic Induction

Transformer

Polyphase

Wye connection

Synchronous operation

Rectifier

5.1.3 Induced voltage in stator winding

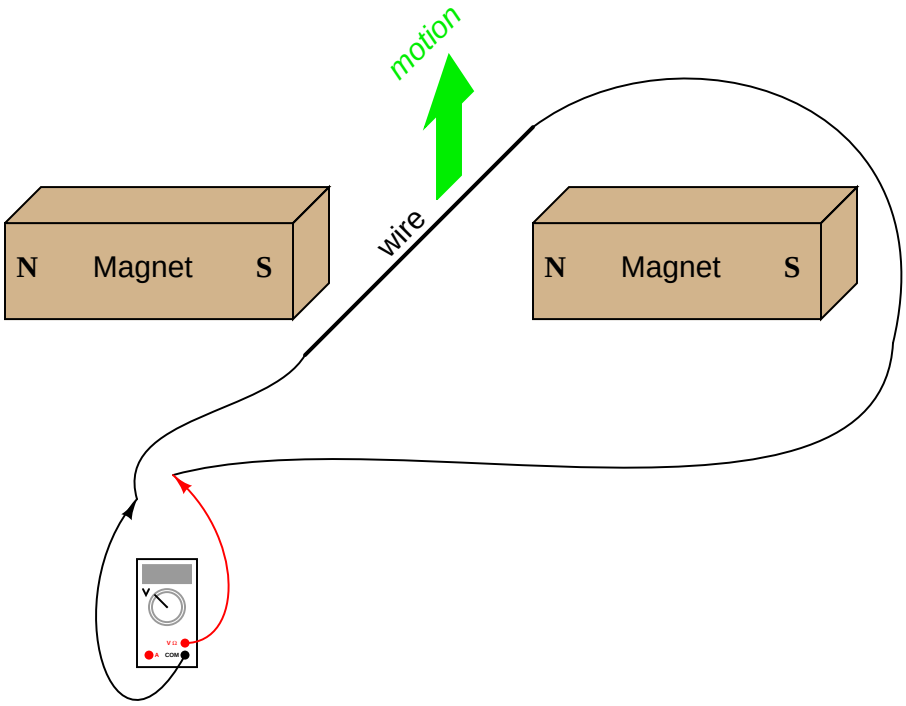
Examine any of the "mechanical diagrams" shown in the Tutorial of an AC generator, and then demonstrate how you could predict the polarity of the induced voltage as the rotor is turning in a specified direction and at some specified angle at a moment in time.

Challenges

- Explain why a generator becomes more difficult to turn as it powers a "heavier" load (i.e. a load drawing more current).

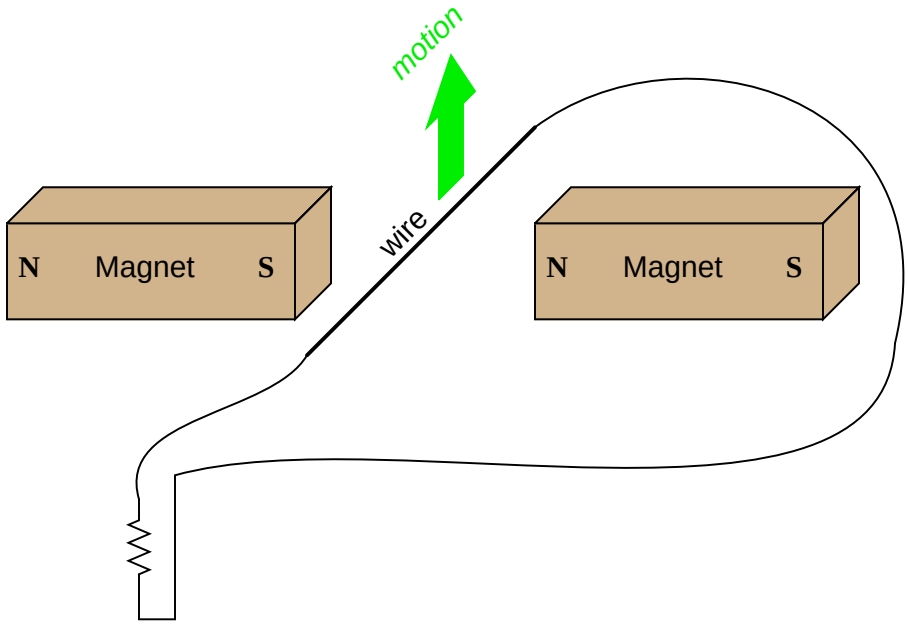
5.1.4 Moving wire and magnet

If this wire (between the magnet poles) is moved in an upward direction, what polarity of voltage will the meter indicate?



Describe the factors influencing the magnitude of the voltage induced by motion, and determine whether this is an example of an electric *motor* or an electric *generator*.

If this wire (between the magnet poles) is moved in an upward direction, and the wire ends are connected to a resistive load, which way will current go through the wire?



We know that current moving through a wire will create a magnetic field, and that this magnetic field will produce a reaction force against the static magnetic fields coming from the two permanent magnets. Which direction will this reaction force push the current-carrying wire? How does the direction of this force relate to the direction of the wire's motion? Does this phenomenon relate to any principle of electromagnetism you've learned so far?

Challenges

- What would happen if the resistor were replaced by a short?

5.1.5 Moving versus stationary coil

In order to make the most practical AC generator (or *alternator*, as it is also known), which design makes more sense: a stationary permanent magnet with a rotating wire coil, or a rotating permanent magnet with a stationary wire coil? Explain your choice.

Challenges

- Why are permanent-magnet alternators impractical for most applications?

5.2 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.

5.2.1 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.

5.2.2 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	

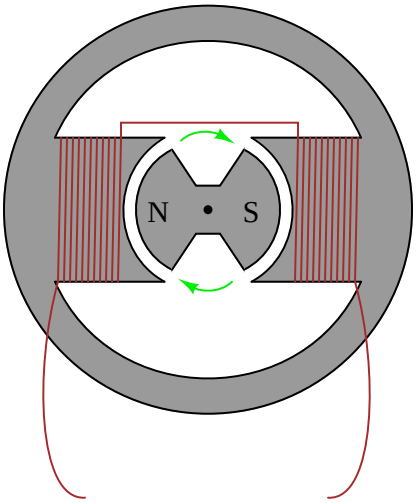
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

5.2.3 Generator frequency

If this generator is spun at 4500 RPM (revolutions per minute), what will be the frequency of its output voltage?



Calculate the output frequency at the same shaft speed supposing the rotor were replaced by one having four poles instead of two.

Challenges

- How many cycles of AC would be produced for every revolution of the shaft?

5.2.4 Poles and speed and frequency

How fast must a 12-pole AC generator spin in order to produce 60 Hz AC power?

How many poles does an alternator have if it generates 400 Hz power at a shaft speed of 6000 RPM?

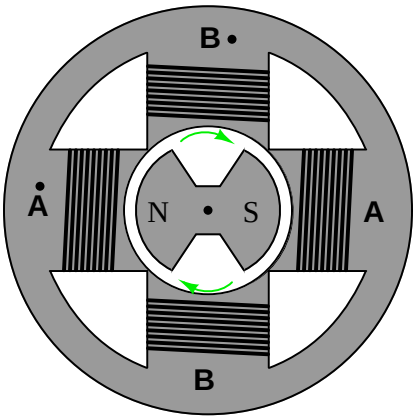
What frequency will be output by a 4-pole alternator spinning at a shaft speed of 1300 RPM?

Challenges

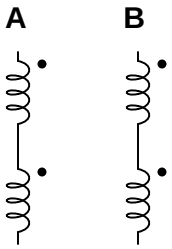
- Is it possible for an AC generator to have an odd number of poles?

5.2.5 Two-phase generator

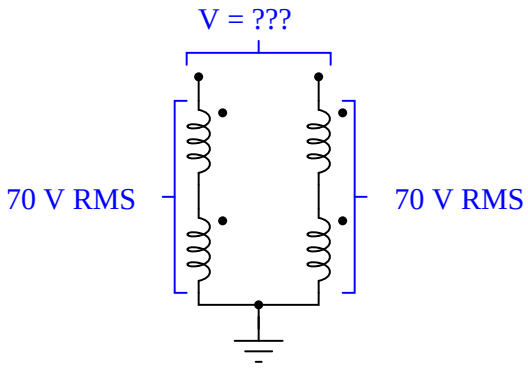
Suppose we have an alternator with two sets of windings, **A** and **B**:



Each pair of windings in each set is series-connected, so they act as just two separate windings:



If one end of each winding pair were connected together at a common ground point, and each winding pair output 70 volts RMS, how much voltage would be measured between the open winding pair ends?

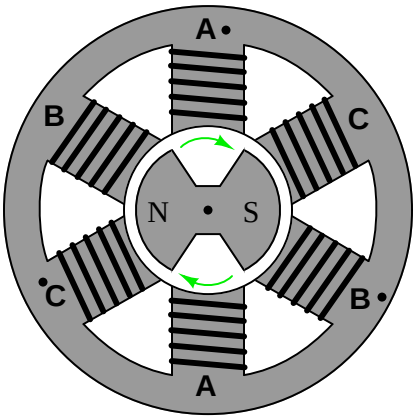


Challenges

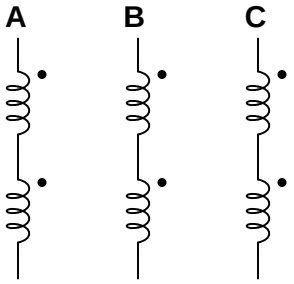
- Draw a phasor diagram showing the voltage of each stator winding as well as the output voltage.

5.2.6 Three-phase generator

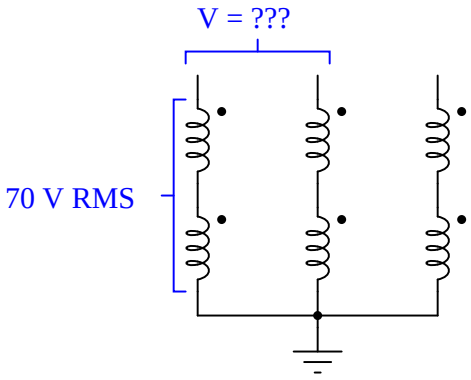
Suppose we have an alternator with three sets of windings, **A**, **B**, and **C**:



Each pair of windings in each set is series-connected, so they act as just three separate windings (pay close attention to the phase-marking dots!):



If one end of each winding pair were connected together at a common ground point, and each winding pair output 70 volts RMS, how much voltage would be measured between any two open wires?



Challenges

- Draw a phasor diagram showing the voltage of each stator winding as well as the output voltage.

5.3 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.

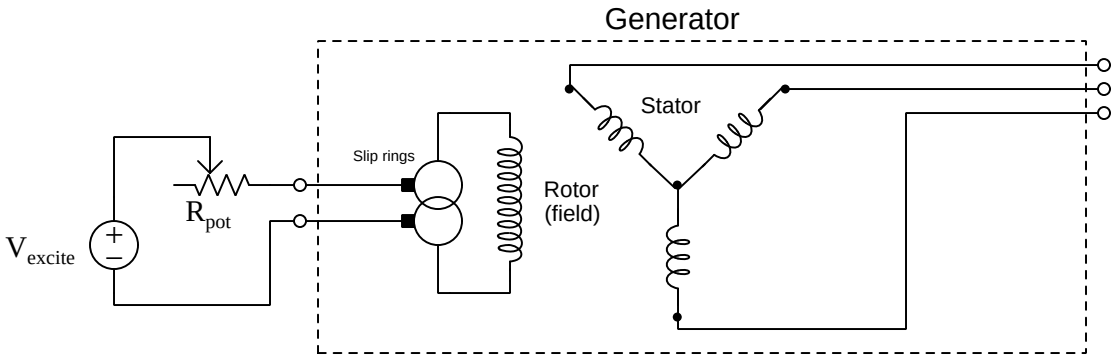
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

5.3.1 Effects of faults in manually-regulated generator

This AC generator's output is regulated manually by adjusting the potentiometer:



Identify the effects of each of the following faults, considered one at a time:

- R_{pot} fails open
- R_{pot} fails shorted
- Brush loses contact with slip ring
- Field winding fails open
- Stator winding fails open
- Prime mover stops turning

Challenges

- A good problem-solving strategy is to first determine the effect(s) of increasing and decreasing the resistance of R_{pot}. Describe these, and relate them to the listed faults.
- Can adjustments in R_{pot} affect the generator's frequency?

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.

18 March 2026 – corrected a typographical error courtesy of Wyatt Gleason. Also added some photos of the Nooksack Falls hydroelectric generating station from 1910.

18 January 2026 – added a new section to the Tutorial chapter showing photographs of 100 MW AC generators at a hydroelectric power plant.

17 October 2024 – added another sub-question (on prime mover failure) to the "Effects of faults in manually-regulated generator" Diagnostic Reasoning question. Also changed "10SI" to 10DN" for all alternator examples lacking an internal regulator.

27 September 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. Also added another sub-question to the "Poles and speed and frequency" Quantitative Reasoning question.

21 March 2023 – added a "Lenz's Law in generators" section to the Tutorial.

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.

16 November 2022 – added a Historical References section showing how a solenoid was used to help regulate generator speed on an antique steam-turbine generator.

14 July 2022 – fixed minor omission in image_5030 to more clearly show the location of the front bearing in the Delco-Remy 10SI alternator.

8 May 2021 – commented out or deleted empty chapters.

17 March 2021 – added some instructor notes.

15 March 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.

2-6 March 2021 – added questions.

1 March 2021 – document first created.

Index

Adding quantities to a qualitative problem, 58
Alternator, 15
Annotating diagrams, 57

Cassier's Magazine, 10
Checking for exceptions, 58
Checking your work, 58
Code, computer, 67
Conservation of Energy, 9, 26
Cut-out station, 10

Delco-Remy 10DN, 15
Dimensional analysis, 57
Diode, 15

Edwards, Tim, 68
Electromagnet, 11
Electromagnetic induction, 26
Electromagnetism, 26
Exciter, 11

Faraday's Law of Electromagnetic Induction, 9, 13, 28

General Motors, 15
Graph values to solve a problem, 58
Greenleaf, Cynthia, 35

How to teach with these modules, 65
Hwang, Andrew D., 69

Identify given data, 57
Identify relevant principles, 57
Induction, 26
Intermediate results, 57
Inverted instruction, 65

Knuth, Donald, 68

Lamport, Leslie, 68
Lenz's Law, 26
Limiting cases, 58
Load, 27

Magnetic flux, 9
Maxwell, James Clerk, 29
Metacognition, 40
Moolenaar, Bram, 67
Murphy, Lynn, 35

Open-source, 67

Permanent magnet, 11
Phase rotation, 12
Phase sequence, 12
Prime mover, 9–11
Problem-solving: annotate diagrams, 57
Problem-solving: check for exceptions, 58
Problem-solving: checking work, 58
Problem-solving: dimensional analysis, 57
Problem-solving: graph values, 58
Problem-solving: identify given data, 57
Problem-solving: identify relevant principles, 57
Problem-solving: interpret intermediate results, 57
Problem-solving: limiting cases, 58
Problem-solving: qualitative to quantitative, 58
Problem-solving: quantitative to qualitative, 58
Problem-solving: reductio ad absurdum, 58
Problem-solving: simplify the system, 57
Problem-solving: thought experiment, 57
Problem-solving: track units of measurement, 57
Problem-solving: visually represent the system, 57
Problem-solving: work in reverse, 58

Qualitatively approaching a quantitative problem, 58

Reading Apprenticeship, 35
Rectifier, 15
Reductio ad absurdum, 58, 64, 65
Right-Hand Rule, 27

Schoenbach, Ruth, 35
Scientific method, 40
Simplifying a system, 57
Socrates, 64
Socratic dialogue, 65
Source, 27
SPICE, 35
Stallman, Richard, 67
Stator winding, 11
Substation, 10

Thought experiment, 57
Torvalds, Linus, 67
Transmission line, 10

Units of measurement, 57

Visualizing a system, 57

Weber, 9
Winding, 26
Work in reverse to solve a problem, 58
WYSIWYG, 67, 68