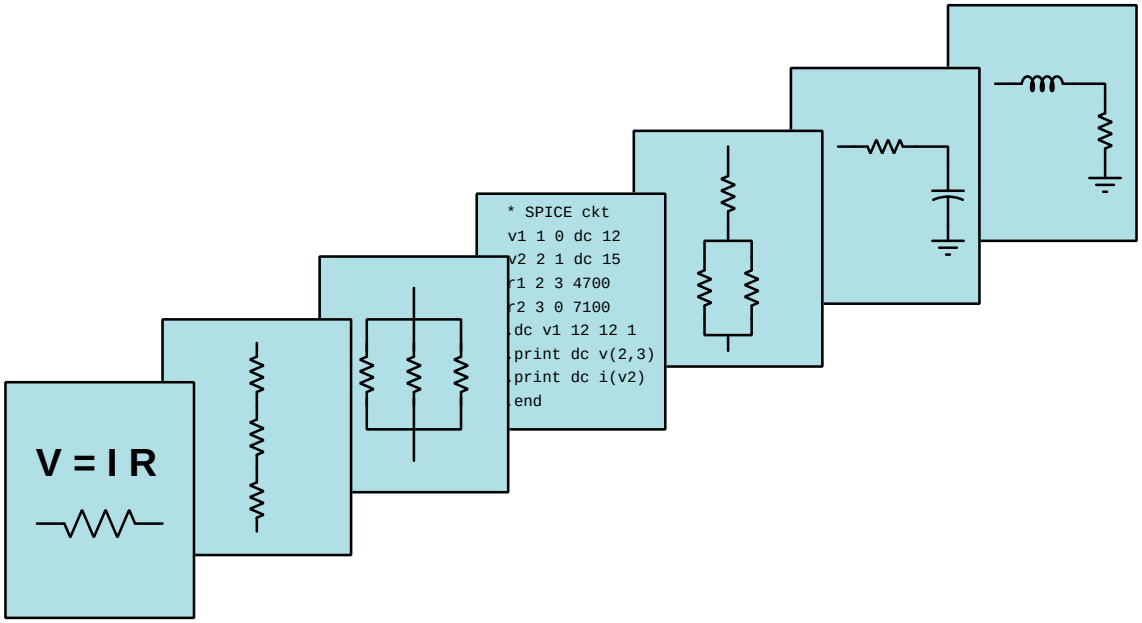
Modular Electronics Learning (ModEL) project



AC Motors

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Chapter 1

Introduction

1.1 Recommendations for students

The AC induction electric motor is arguably one of the most important machines ever designed. It literally powers modern industry, and may be found in a wide range of consumer products from kitchen appliances to electric vehicles. With only one moving part, and almost nothing to wear out, these electric motors are supremely reliable. Modern material selection and design have raised the typical energy efficiency of induction motors to approximately 90%, which means very little electrical energy gets "wasted" in the form of heat at the motor, but instead goes into doing the intended work.

Important concepts related to AC motors include **electromagnetism**, **rotating magnetic field**, motor and generator **poles**, **Lenz's Law**, **electromagnetic induction**, **slip**, **frequency**, **synchronous speed**, magnetic **coupling**, **speed** versus **torque**, **squirrel-cage** construction, **inrush current**, **polyphase** circuits, phase **sequence** or **rotation**, **capacitors**, **shading coils**, **Conservation of Energy**, **First Law of Thermodynamics**, **Second Law of Thermodynamics**, **efficiency**, and **horsepower**.

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?
- How is electricity used to create magnetic fields?
- Why can't an induction motor ever achieve synchronous speed on its own?
- How is a rotating magnetic field created inside of an AC motor?

- What determines the shaft speed of an AC induction motor?
- What determines the shaft speed of an AC synchronous motor?
- What factors influence the speed/torque characteristics for an induction motor?
- What does the term "squirrel cage" refer to in an induction motor's construction?
- How may the rotational direction of an AC motor be controlled?
- How do single-phase and three-phase motors differ from one another?
- What does it mean to "single-phase" a three-phase motor?
- How do we define efficiency for a device such as an electric motor?
- Is it possible for an electric motor to be 100% efficient?
- How fast will a "Design-D" induction motor spin when loaded at 200% of its full-load torque rating?
- How fast will a "Design-C" induction motor spin when loaded at 100% of its full-load torque rating?

1.2 Challenging concepts related to AC motors

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!
- **Confusing power factor and efficiency** – these two concepts are definitely related, but not synonymous. Efficiency is a ratio of energy directed out of a system toward useful work versus total energy put in to that system. Power factor, on the other hand, is a ratio of real power (P) to apparent power (S) in an AC circuit.
- **Motor inrush current** – the fact that all electric motors draw more current when starting to turn than they do when turning at full speed is often misinterpreted as a time-delay effect caused by the motor's inherent winding inductance. This is not true, and in fact if it were it would mean the motor would draw *less* current upon power-up and *more* current after some time had passed. The real explanation is rooted in the phenomenon of *counter-EMF* which occurs as the motor shaft begins to spin. Since counter-EMF is a speed-based phenomenon it means that inrush current can and will continue unabated if the motor shaft is not mechanically permitted to turn!

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** – Compute electrical parameters for AC motors

  Assessment – Calculate motor power based on PT and CT voltage/current measurements; e.g. pose problems in the form of the "Motor power based on PT and CT measurements" Quantitative Reasoning question.

- **Outcome** – Diagnose AC motor systems

  Assessment – Identify the effects of given faults on a capacitor-start AC motor; e.g. pose problems in the form of the "Effects of faults in a capacitor-start motor" Diagnostic Reasoning question.

- **Outcome** – Independent research

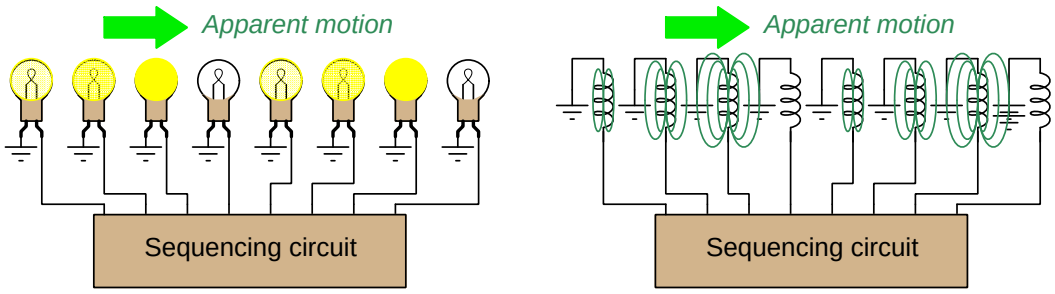
  Assessment – Locate AC motor datasheets and properly interpret some of the information contained in those documents including winding configuration, power ratings, power factor, speed, number of poles, etc.

Chapter 2

Tutorial

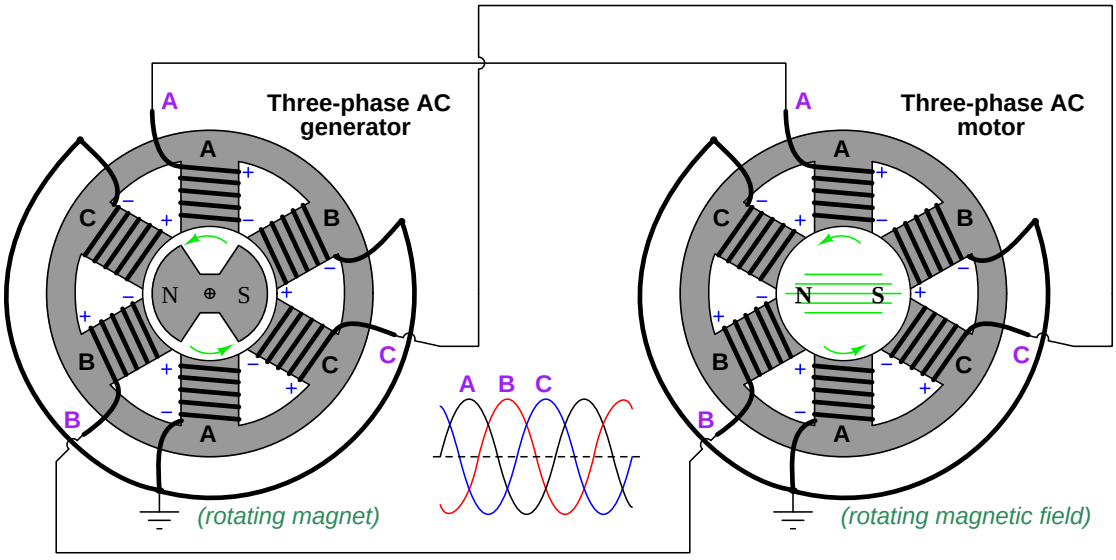
2.1 Rotating magnetic fields

Imagine a set of *chasing lights*: a string of stationary electric lamps sequentially energized by an electronic circuit so as to create the illusion of motion. The lamps obviously do not move, but their sequential illumination makes it *appear* as though one or more continuously-lit lamps move along in a particular direction. Now imagine a set of stationary electromagnet coils, or *stator windings*, energized by some similar electronic circuit so as to create a magnetic field that appears to move along from one coil to the next. Again, the windings themselves are motionless, but the combined effect of their magnetic fields growing and shrinking in sequence makes it appear as though one or more magnets move along in a particular direction.



Now consider a set of electromagnet coils arranged around the circumference of a circle, so that their pole faces point toward a common center. Energized in sequence, these stator windings create a magnetic field that *rotates* within the center of the circle. This rotating magnetic field is the basis of most AC motors, the stator windings being energized by out-of-phase AC currents to produce the sequential magnetization needed to create this illusory motion. A moving *rotor* situated between the stator poles follows this rotating magnetic field, and this is responsible for the mechanical motion of the electric motor.

The concept of a set of stator windings energized by out-of-phase AC currents creating a rotating magnetic field is easy to grasp if we consider the reverse process: a spinning magnet passing by sets of stator windings to create out-of-phase AC currents. This is precisely how polyphase[1] AC *generators* function: by spinning a magnetized rotor past sets of stator windings physically offset from each other. Each stator winding pair achieves peak voltage when it experiences the maximum rate-of-change from the moving rotor, but since these winding pairs are offset from one another their peaks are similarly offset (i.e. shifted out of phase). The rotating magnetic field generated by the stator windings of a three-phase *motor* is merely a reproduction of the rotor's magnetic field inside the *generator* supplying the three-phase power, as shown in the following illustration where a three-phase AC generator powers an identically-constructed AC motor:



If a permanently-magnetized rotor were placed within the center of the motor shown above, it would have to spin at the exact same speed as the generator's rotor, and we would call the motor *synchronous* in honor of this fact. For the generator and motor shown here, both possessing the minimum number of stator poles possible for three-phase machines (i.e. 2 poles arranged in pairs, per phase), a line frequency of 60 Hz equates to a shaft speed of 60 revolutions per second, or 3600 revolutions per minute (RPM). A machine with twice as many poles would spin half as fast for the same frequency. Thus, line frequency and pole count dictate the shaft speed of any synchronous motor. A simple mathematical formula relating shaft speed (S, in RPM) to frequency (f, in Hz) and number of poles (n) is as follows:

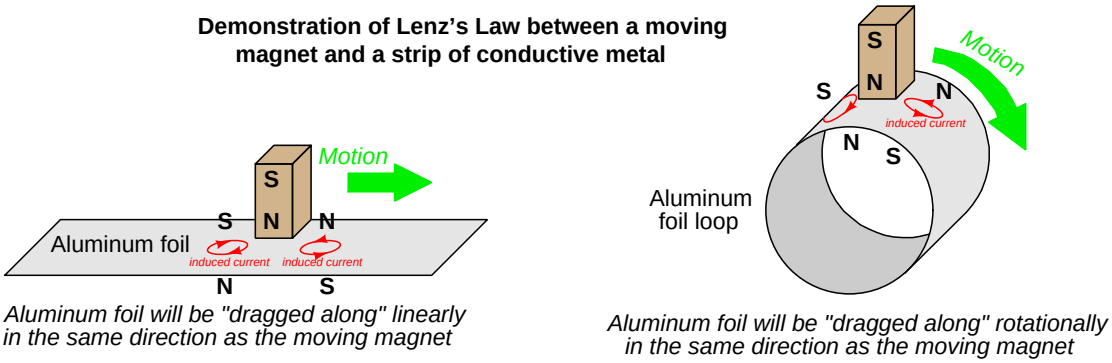
$$S = \frac{120f}{n}$$

[1] It is an interesting historical fact that polyphase AC electric power was actually *invented* for the purpose of designing this type of electric motor. Electric motors popular at the time utilized carbon brushes and commutator bars to conduct electricity to windings on a rotor, like DC motors, and suffered all the same problems of brush arcing, heat, and mechanical wear. The rotating-field motor bypassed all these problems by using phase-shifted AC currents to generate a rotating magnetic field that a brushless rotor could naturally follow.

2.2 Induction motor concepts

Synchronous AC motors with permanent-magnet rotors are impractical for all but low-power applications, due to the difficulty in getting the rotor up to full speed from a standstill without falling "out of step" with the stator's rotating field. A variation on this design called the *induction motor* solves this problem by replacing the permanently-magnetized rotor with an *electrically conductive* rotor. It is far from obvious why an electrically conductive object might be compelled to follow a moving magnetic field, and so some explanation is in order.

When a rotating magnetic field revolves around an electrically conductive object, electric currents are induced in that object. These induced currents generate their own magnetic fields, which act against the initial field in such a way that the object is "dragged along". This is known as *Lenz's Law*[2], and it is illustrated here in both linear and rotary forms:



In a "squirrel cage" style of induction motor, the rotor consists of an iron frame with aluminum bars laid along its circumference parallel to its axis, those bars "shorted" together at each end to form one circuit. If the stator's rotating magnetic field passes by faster than the rotor is turning, the induced currents in these bars create a torque[3] to move the rotor in the direction of that rotation. The rotor increases speed, but never quite reaches the same speed as the rotating field. The reason for this speed difference is Lenz's Law: in order for this torque to form, there must be currents induced in the rotor bars. In order for there to be induced currents, there must be *relative* motion between the rotating field and the rotor. If somehow the rotor were to achieve the same speed as the rotating field, induction would cease and so would the motivating torque. Induction motors, therefore, always run at slightly slower than synchronous speed in order to generate any torque. The difference in speed between the stator field's synchronous speed and the rotor's actual speed is called *slip*, and induction motor torque is a function of slip.

[2] Formally stated, Lenz's Law declares that any electric current induced by a varying magnetic flux will flow in such a direction as to generate its own magnetic flux to oppose that change.

[3] The term "torque" simply means "rotary force" as opposed to a *linear* force.

Slip is a phenomenon lending itself well to understanding by analogy. Imagine a sailboat traveling directly downwind, i.e. moving in exactly the same direction as the wind. Can the sailboat travel faster than the wind, in the same direction as the wind? Of course not. Can the sailboat travel exactly the same speed as the wind, in the same direction? At first this may seem possible, but it is only possible in a theoretical case where the boat experiences no drag whatsoever as it moves through the water. Real boats require constant force in order to maintain speed through the water, and therefore a sailboat moving in the same direction of the wind must travel slightly slower than the wind in order for the wind to "fill" its sails to generate that necessary driving force. If a sailboat happened to be equipped with a propulsion engine capable of providing this driving force, moving in the same direction of the wind at the same speed of the wind would result in the sails going "slack" and doing nothing useful to propel the boat.

It is no trivial task to predict how much slip an induction motor will experience in any given situation. The rotating magnetic field's speed is simple to calculate, being a strict function of AC frequency and the number of stator poles ($S = \frac{120f}{n}$). However, this merely sets an upper bound for shaft speed: the speed at which the induction motor generates no torque whatsoever. The actual shaft speed must be less than this synchronous speed, but how much less? A typical "two-pole[4]" induction motor operating at a power line frequency of 60 Hz has a synchronous speed of 3600 RPM, but the rotor typically achieves a full-load speed of only 3540 RPM. Similarly, a typical "four-pole" induction motor with a synchronous speed of 1800 RPM[5] may only attain a rotor speed of approximately 1760 RPM.

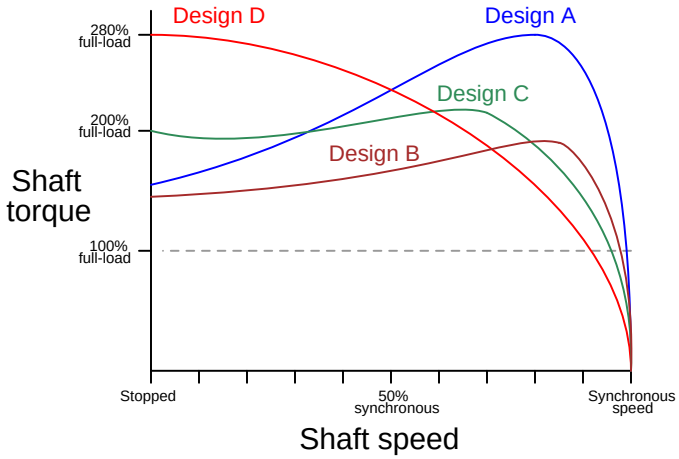
Mechanical loading is one factor affecting shaft speed and slip for an AC induction motor. The lighter the load (i.e. less torque demanded from the motor), the closer the shaft's speed will approach synchronous speed (i.e. less slip). The heavier the load, the more torque the motor must output, and this requires a greater slip speed which means the shaft speed will be further below synchronous speed. Like a sailboat experiencing drag from a partially-deployed anchor, its speed decreases until the wind fills its sails enough to generate a greater force equal to the drag. AC induction motor speed figures specified on the motor nameplate or datasheet document assume *full load conditions*, which means the motor shaft will spin that fast when it is outputting its maximum continuous-rated torque to a mechanical load. In other words, the advertised shaft speed for an AC induction motor is a lower bound limit. The real shaft speed for most operating conditions will be slightly faster than this, but never as fast as synchronous speed.

Rotor design is another factor affecting shaft speed and slip for an AC induction motor. The electrically-conductive bars within the rotor may be located at different radii from the shaft's center, and may be made thicker or thinner, at the time of manufacture. Bars closer to the rotor's outer surface will be tightly coupled to the stator poles, while bars "buried" deeper in the rotor toward the shaft center will experience a "looser" magnetic coupling with the stator. Thick bars have low resistance and will permit greater inductive currents, while thin bars have higher resistance and therefore weaker inductive currents.

[4] Two magnetic poles in the stator *per phase*, which is the lowest number possible because each phase naturally produces both a "north" and a "south" pole when energized. In the case of a three-phase induction or synchronous motor, this means a total of *six* magnetic stator poles.

[5] Doubling the number of magnetic poles increases the number of AC power cycles required for the rotating magnetic field to complete one full revolution. This effect is not unlike doubling the number of light bulbs in a chaser light array of fixed length, making it seem as though the light sequence is moving slower because there are more bulbs to blink along the same distance.

NEMA (the National Electrical Manufacturers' Association) has standardized four different speed/torque characteristics for AC induction motors, labeling them A, B, C, and D:



The most common NEMA design for industrial AC induction motors is Design B. Design C motors are typically specified for applications requiring high torque on start-up, such as air compressors and conveyor belts. Design D motors have poor speed control and efficiency characteristics, but produce the greatest torque at start-up compared against all the other motor design types. Elevator and crane motors are commonly of this design, where the extremely high starting torque is more important than steady speed regulation or continuous-run efficiency. Design A motors are used in specialty applications where good speed regulation is required. As is evident from the design A curve, maxmimum shaft torque is available at a higher speed than any of the other types, which means this design of induction motor will "fight" harder against slowing down than any of the others.

Induction motors are by far the most popular AC motor design in industry, and the common variant of the induction motor is *squirrel-cage*. A photograph of a small, disassembled three-phase AC induction "squirrel-cage" motor is shown here, revealing the construction of the stator windings and the rotor:

The stator windings are housed in the black-colored frame of the motor, seen on the left-hand side of this photograph. The rotor and front end-cover of the motor appear on the right-hand side. Close inspection of the rotor reveals the aluminum bars inset within an iron core, two cast-aluminum rings on either end of the rotor shorting those bars together to allow currents to flow in any direction from one bar to another.

Given the extremely simple construction of AC induction motors, they tend to be very reliable. So long as the stator coil insulation is not damaged by excessive moisture, heat, or chemical exposure, these motors will continue to operate indefinitely. The only "wearing" components are the bearings supporting the rotor shaft, and those are easily replaced when worn out. An induction motor operated within its rated limits should provide *decades* of faithful service.

2.3 Induction motor control

Starting a three-phase induction motor is as simple as applying full power to the stator windings. The stator coils will instantly produce a magnetic field rotating at a synchronous speed determined by the frequency of the applied AC power, and the rotor will experience a large torque as this high-speed (relative to the rotor's stand-still speed of zero) magnetic field induces large electric currents in it. As the rotor comes up to speed, the slip diminishes, weakening the induced currents and also the rotor's torque. Soon the rotor's speed settles at whatever value necessary to create enough slip to generate sufficient torque to sustain whatever mechanical load it is coupled to. As the mechanical load varies, the rotor's speed will vary accordingly, but never falling too far behind the synchronous speed. For all practical purposes, an AC induction motor is a "constant-speed" machine when powered by AC of fixed frequency.

The surge[6] of current during start-up of an induction motor is called *inrush* current, causing the rotor to produce a large mechanical torque. Inrush current is also known as *locked-rotor current*, and refers to the amount of current drawn by the motor when its shaft is stationary and full voltage is applied to its stator windings. As the rotor gains speed, the current reduces to a normal level, with the speed approaching the "synchronous" speed of the rotating magnetic field. If somehow the rotor achieves synchronous speed (i.e. the slip speed becomes zero), stator current will fall to an absolute minimum. If a mechanical power source "over-drives" a powered induction motor, forcing it to spin faster than synchronous speed, it will actually begin to function as a generator[7] and source electrical power to the connected circuit.

Reversing the rotational direction of a three-phase motor is as simple as swapping any two out of three power conductor connections. This has the effect of reversing the *phase sequence* of the power "seen" by the motor[8].

[6] Upwards of *several times* the normal running current!

[7] In this mode, the machine is called an *induction alternator* rather than an *induction motor*.

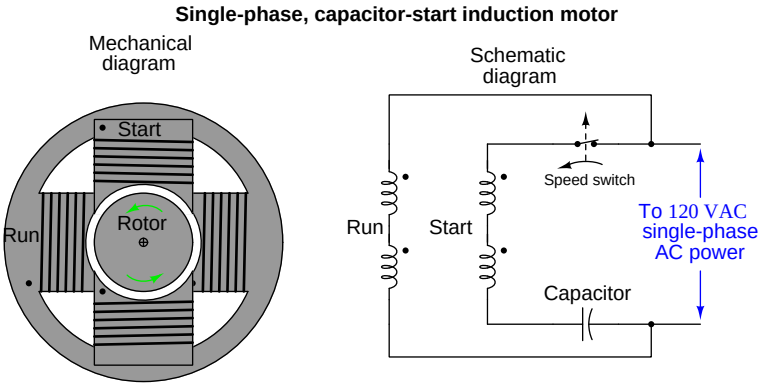
[8] This principle is not difficult to visualize if you consider the phase sequence as a repeating pattern of letters, such as `ABCABCABC`. Obviously, the reverse of this sequence would be `CBACBACBA`, which is nothing more than the original sequence with letters A and C transposed. However, you will find that transposing *any* two letters of the original sequence transforms it into the opposite order: for example, transposing letters A and B turns the sequence `ABCABCABC` into `BACBACBAC`, which is the same *order* as the sequence `CBACBACBA`.

2.4 Single-phase induction motors

An interesting problem to consider is how to make an AC induction motor function on *single-phase* power rather than polyphase power. After all, it is the three-step phase sequence of three-phase AC power that gives the stator windings' magnetic field its definite rotational direction. If we have only one sine wave supplied by the AC power source, is it possible to generate a truly *rotating* magnetic field? At best, it seems all we could ever produce with single-phase AC power is a *pulsing* or "blinking" magnetic field. If you imagine an array of "chasing lights" blinking on and off 180^o out of phase (i.e. `ABABABAB`), one could argue the sequence is marching from A to B, or alternatively from B to A – there is no definite direction to the lights' "motion."

In order to give the magnetic field within a single-phase stator assembly a definite rotation, we must *artificially create a second phase* within the motor itself. One common way to do this is to add a second set of stator windings offset from the first and energize those windings through a high-voltage capacitor, which creates a leading phase shift in winding current. This phase shift creates an out-of-step magnetic field in the second winding set, providing a definite direction of rotation. Once the motor comes up to speed, this auxiliary winding may be disconnected by a speed-sending switch, since a spinning motor will happily run[9] on single-phase AC. This is called a *capacitor-start* induction motor, and it is the design used for most single-phase AC induction motors requiring a high starting torque (e.g. pumps, shop grinders, drill presses, etc.).

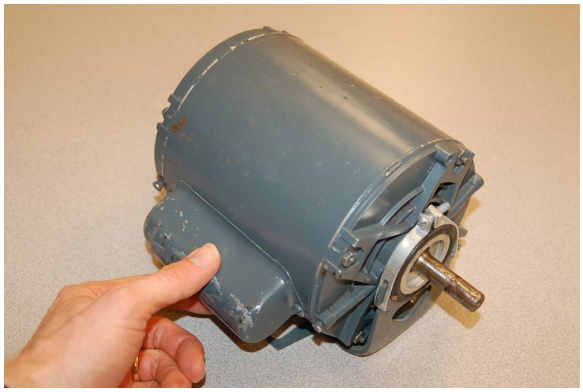
The following diagram shows the design of a single-phase, capacitor-start AC induction motor:



One of the major principles to grasp about AC induction motors is that they *must start as polyphase machines, although they may continue to run as single-phase machines.*

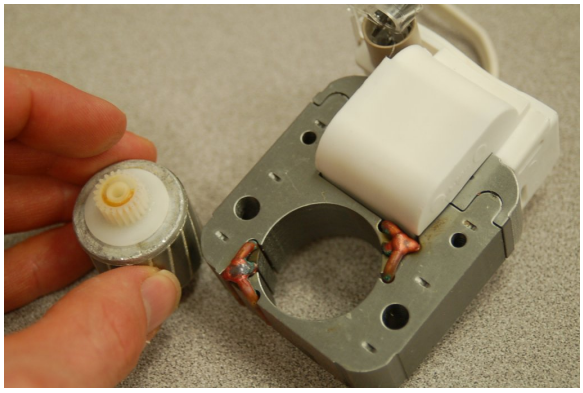
[9] I once encountered a washing machine induction motor with an "open" fault in the start winding. When energized, this motor remained still and hummed because it had no second phase to give its magnetic field a rotation. However, if you used your hand to give the motor a spin in either direction, *the motor would accelerate to full speed in that direction!*

A capacitor-start, single-phase electric motor is shown in the following photograph. My hand is touching the capacitor enclosure for the motor's starting winding. The speed switch is internal to the motor and cannot be seen in this photograph:



Capacitor-start motors are often designed in such a way that the starting winding draws much more current than the "run" winding, in order to provide a strong starting torque. This is important when the mechanical load being turned by the motor requires a great deal of torque to get moving, such as in the case of a reciprocating compressor or a fully-loaded conveyor belt. Due to this high current draw, starting windings are not rated for continuous duty, but rather must be de-energized shortly after starting the motor in order to avoid overheating.

Smaller AC motors, such as those used inside bench-top and rack-mount electronic equipment, use a completely different method for generating a rotating magnetic field from single-phase AC power. The following photograph shows one such motor, employing copper *shading coils* at the corners of the magnetic stator poles. The rotor has been removed, held by my fingers for inspection:



Instead of a capacitor creating a leading phase-shift for current through a special stator winding, this "shaded-pole" induction motor uses a pair of copper loops wrapped around the corners of the magnetic poles to produce a lagging phase shift in the magnetic field at those corners. The copper shading coils act as inductors, delaying the magnetic field through them by -90^o, creating

a secondary magnetic field that is out-of-step with the main magnetic field generated by the rest of the pole face. The out-of-step magnetic field together with the main magnetic field adjacent to it creates a definite direction of rotation[10].

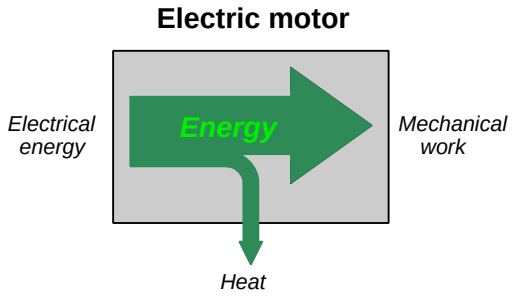
The fact that all AC induction motors must start as polyphase machines even though they can run as single-phase machines means that an AC motor designed to run on three-phase power may actually continue to run if one or more of its phases are "lost" due to an open wire connection or blown fuse. The motor cannot deliver full-rated mechanical power in this condition, but if the mechanical load is light enough the motor will continue to spin even though it no longer has multiple phases powering it! A three-phase motor, however, *cannot start from a stand-still* on just one phase of AC power. This loss of one or more phases to a polyphase AC induction motor is called *single-phasing*, and it may cause a great deal of trouble in an industrial facility. Three-phase electric motors that become "single-phased" from a fault in one of the three-phase power lines will refuse to start. Those that were already running under heavy (high-torque) mechanical load will stall. In either case, the stopped motors will simply "hum" and draw large amounts of current.

[10] For the shaded-pole motor shown in the photograph, the direction of rotation is counter-clockwise. The shaded poles are oriented counter-clockwise of center, which means their delayed magnetic fields create an "appearance" of rotation in that direction: the magnetic field achieves its peak strength first at the pole centers, and then later (delayed) at the shaded poles, as though there were an actual magnet rotating in that direction.

2.5 Electric motor efficiency

Electric motors are energy-conversion machines regardless of type, converting electrical energy into mechanical energy. Like all energy-conversion systems, there is an inevitable "spreading" or *dissipation* of energy into unintended forms. That is to say, electric motors cannot convert 100% of the given electrical energy into mechanical energy. While it is absolutely true that 100% of the energy input to an electric motor must ultimately be accounted (i.e. the Law of Energy Conservation, otherwise known as the *First Law of Thermodynamics*), it is also absolutely true that any process of energy converting from one form to another results in some of that energy converting to less-useful forms – a fact known as the *Second Law of Thermodynamics*. In other words, the Second Law of Thermodynamics declares the impossibility of transferring energy from a source to only one destination – some of that energy inevitably finds its way to other destinations. If you imagine energy transfer being analogous to transporting water in a bucket, the Second Law of Thermodynamics tells us *the bucket always leaks*.

If we monitor any energized electric motor we will find that it increases in temperature from its starting condition. This heat is the Second Law of Thermodynamics in action, a consequence of some of the electrical energy *not* becoming mechanical energy as it passes through the motor. Multiple mechanisms of "loss" exist in electric motors, including wire resistance in the windings, magnetic hysteresis in the iron core and frame, aerodynamic drag of the rotor, friction in the bearings, etc. We may summarize these effects in a simple diagram showing the flow of energy through the electric motor as arrows:



Energy efficiency is the term we give to the ratio of energy out of a system versus energy into a system. When operating under steady-state[11] conditions, this is equal to the ratio of *power* out versus in.

$$\text{Efficiency} = \frac{P_{out}}{P_{in}}$$

[11] When a machine operates under transient conditions (i.e. where power is unsteady over time) it becomes possible for power out to exceed power in, but that is only because some of that out-going energy comes from an internal store of energy inside the machine which will eventually be depleted. For example, imagine an electric motor running at full speed, then suddenly a clutch engages which connects the motor's shaft to some heavy mechanical load. During the initial moments following this engagement, the motor will output a large amount of power because its rotor is slowing down and in so doing giving up much of the kinetic energy it formerly stored, while still drawing a modest amount of electrical power from the source.

For example, an electric motor outputting 60 horsepower (44742 Watts, the conversion being 745.7 Watts per horsepower) of mechanical power to a load at an energy conversion efficiency of 93% will require 64.516 horsepower's worth of electrical power (48109.7 Watts) to energize.

Chapter 3

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.

3.1 Transformation of industry by electric motors

Technological innovation generally occurs as an answer to practical problems. The phrase *necessity is the mother of invention* certainly explains the rise of many new technologies, as solutions to pressing needs of individuals and/or society as a whole. This is most definitely the case with electric motors. The scientific discoveries of electromagnetism and electromagnetic induction may have remained laboratory curiosities if not for the incentives of industry to employ cheaper and safer methods of transferring mechanical power to do useful work.

The following pair of photographs shows the machinery within a textile mill, in this particular case a silk-weaving factory, powered by mechanical shafts and belt drives turned by a centrally-located steam engine (left), and later powered by electric motors (right). These images were taken from the text *Electric Motors – their action, control and application* published in 1919. The contrast between these two images, in terms of mechanical complexity and employee safety alone, is stark:

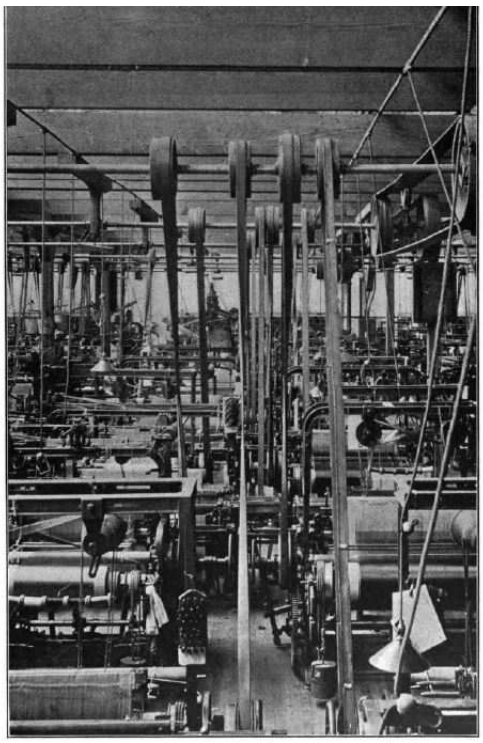


PLATE A.—SILK-WEAVING SHED WITH BELT DRIVE.

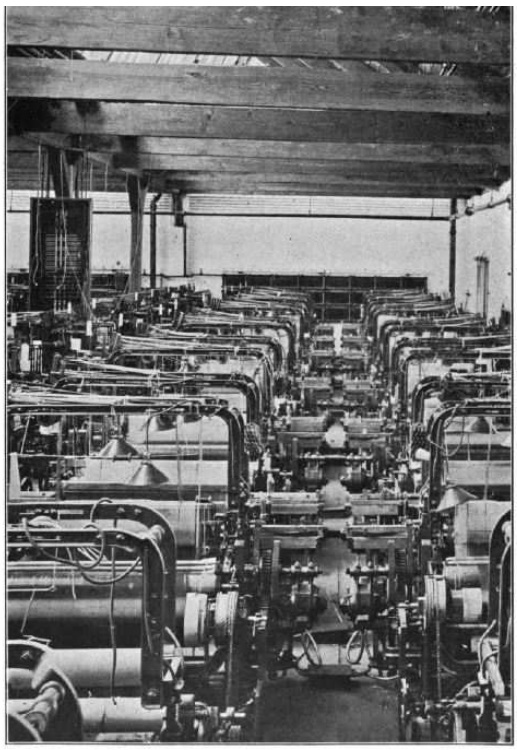


PLATE B.—THE SAME SILK-WEAVING SHED WITH MOTOR DRIVE.

Perhaps the most obvious improvement in factory conditions resulting from the replacement of mechanical drive systems with electric is that of personnel safety. All those open belts posed significant hazard to anyone working nearby. Anyone unfortunate enough to get an article of clothing or a limb caught up in one of those moving belts faced a grim fate.

The authors of this text presented a long list of advantages for the use of electric motor drives over mechanical shaft and belt drives, many of which are simply not apparent to anyone innocent of shaft- and belt-driven industrial environments. Given that it is highly unlikely any reader of *this* text will have that sort of personal experience, it is worthwhile to recount some of the advantages of electric motor drives cited by the authors of *Electric Motors – their action, control and application.* If nothing else, it gives a glimpse of early industrial work environments and engineering considerations:

- **Energy efficiency** – long mechanical shafts with journal bearings as well as belt drives incur substantial frictional power losses. Even considering the inefficiencies of converting a steam engine's mechanical power to electric power (via a generator) and then back to mechanical power again (via a motor), electric drive systems still used less fuel to do the same work as mechanical drive systems!

- **Lower building cost** – structures containing belt-driven machinery needed to support the weight of driveshafts from their ceiling beams, necessitating framework capable of bearing this load. Furthermore, as structures tend to settle over time, misalignments of shafts and belts would occur as the building aged. These problems disappear entirely with electric motors.

- **Building placement** – in a mechanical-drive factory, the steam engine needed to be located immediately adjacent to the factory floor where its power would be used. This is not the case with electric drives, as the generator building could be located a considerable distance from the factory floor, with wires connecting the two.

- **Expansion** – on a similar note, factory facilities are much easier to expand with electric motor drive than with mechanical drive, since building placement and distance from the power source are no longer limited.

- **Portable machinery** – small machines such as grinders may be made portable with electric motor drives, but this is impossible with shaft- and belt-drive.

- **Clear overhead space** – the elimination of shafts from the ceiling of factory buildings made lighting much easier. This advantage is plainly visible in the comparative photographs of the silk mill before and after electric motors. It also facilitated the use of overhead cranes for maintenance and/or production work.

- **Hygiene** – one of the advantages of electric motor drives most difficult to perceive by modern readers is improved air quality and general cleanliness on the factory floor. Apparently, shaft bearings constantly dripped lubricant, and belts continually generated fine dust. Not only did this pose breathing hazards to employees, but the pall of dust and oil would contaminate the very product(s) manufactured, especially in a place such as a textile mill where the last thing you want applied to new silk is *dust and oil*. As an example of improved working conditions, the 1914 text cites a 40% reduction in lost employee time due to sickness at the Government Printing Office in Washington DC following the retrofit of electric motors to printing machinery. Another working condition improvement was noise reduction, as electric motors run much quieter than shafts and belts.

- **Reliability** – electric motors, even those of circa 1914, were generally more reliable than a belt drive. Furthermore, when an electric motor failed it only affected the one machine it operated,

and repairs could be made while the rest of the machinery on the factory floor continued to operate. This was not the case with machines driven from a common shaft, which had to be stopped to replace *any* belt along the shaft's length.

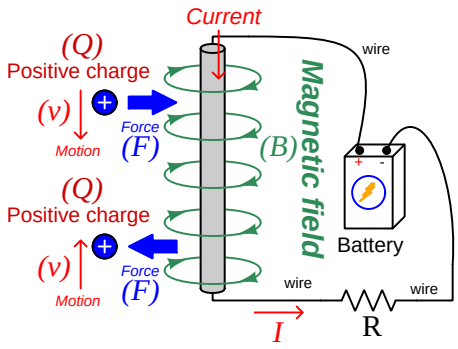
- **Speed control** – when multiple machines are powered by a common shaft, they must all run at the same speed, or be individually equipped with *transmissions* allowing speed adjustment. Electric motors, on the other hand, are relatively easy to control the speed of. An interesting behavioral note made by the authors of the 1914 text is that *what is convenient gets used*: electric motor speed controls usually take the form of a simple knob or dial that may be turned, while shifting a mechanical transmission requires manipulation of large and cumbersome levers. Human operators were found to make frequent adjustments to electric drive speed controls in order to improve efficiency and/or production, while they would be more reluctant to do the same with clumsy mechanical speed controls. This simple fact translated to improved production with electric drives.

- **Turndown** – this refers to the ability to run only *portions* of a factory's machinery after hours, during holidays, or during labor strikes. This would be inefficient in a mechanical-drive system because the (large) common steam engine would have to be run at full speed even if just one machine on the factory floor needed to operate. However, with electric drives it was possible to run a small auxiliary generator just large enough to power the reduced machinery, without having to turn the shafts of all the other machines.

As a result of these advantages, it was found that factories generally increased their production output by 20 to 30 percent following retrofit to electric motor drive.

3.2 Magnetic field quantities

A useful definition of magnetic field (B) is in terms of the force (F, called the *Lorentz force*) exerted on a moving electric charge (Q) influenced by that field:



$$\vec{F} = Q\vec{v} \times \vec{B}$$

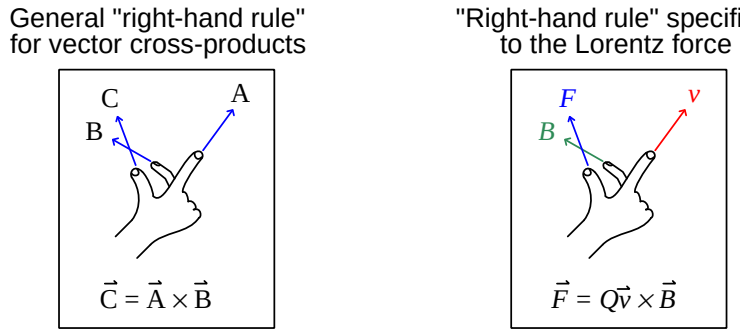
Where,

$\vec{F}$ = Force exerted on the charge (Newtons)
Q = Charge quantity (Coulombs[1])
$\vec{v}$ = Velocity of moving charge (meters per second)
$\vec{B}$ = Magnetic field (Tesla, Webers per square meter, or Newtons per Ampere-meter)

The small "arrow" symbols above the variables for force and velocity and magnetic field in the equation denote those variables as *vector quantities*, having both magnitude and direction. Charge is a *scalar quantity* having only magnitude but no direction, and as a scalar quantity when multiplied by the velocity vector it simply magnifies the magnitude but does not alter the direction. The "cross-product" ($\times$) is a specific form of vector multiplication, and it results in a product at right angles to the vector directions of both terms. Therefore, the force and velocity and electric field vectors never all point in the same direction.

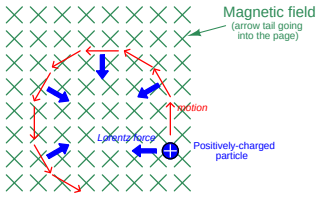
[1] One Coulomb of electric charge is equal to 6.2415×10^{18} electrons.

Vector cross-products conveniently relate to the fingers of the right hand, which is where the "right-hand rule" originates:



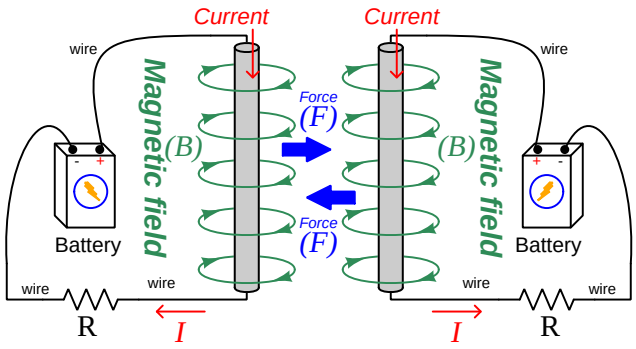
When holding the index finger, middle finger, and thumb of your right hand perpendicular to each other, your index finger points in the direction of the velocity vector ($\vec{v}$), your middle finger in the direction of the magnetic field vector ($\vec{B}$), and your thumb in the direction of the force vector ($\vec{F}$). A simple mnemonic I use to remember these relationships of fingers to vectors is that the **I**ndex finger points in the direction of current[2] (I), the **M**iddle finger points in the direction of the **m**agnetic field (B), and the **Th**umb points in the direction of the **th**rust (i.e. force) acting upon the moving charge.

The Lorentz force's effect on electrically-charged particles in motion has many applications, from redirecting the paths of charged-particle beams in particle accelerator machines, to bending the trajectory of electron beams in a cathode-ray tube (CRT), to forcing electrons to travel in spiral or circular trajectories inside of magnetron (microwave oscillator) tubes. An illustration of a positively-charged particle curving perpendicular to a magnetic field appears here:



[2]Some textbooks speak of a "left-hand rule" which is intended to make sense of electric charge motion (current) in terms of *electron flow*. As we know, electrons are the only real mobile charge carriers within metal conductors, and so technically "electron flow" notation is most physically accurate when describing the motion of electric charges in metallic circuits. However, the right-hand rule is a *mathematical definition* for vector cross products, the concept of the cross product arising in the late 18th century when electrical science was still in its infancy. Early explorers of electricity used the established mathematical tools of their time and applied it to their work with electric currents and magnetism. At that time, charge carriers in metal wires were assumed to be "positive" and this is how the motion of positively-charged carriers became associated with the first vector of the cross-product. As a result of this assumption which was later proven false, we have two different conventions for denoting the motion of electricity: electron-flow which is *physically* accurate (for metal wires, at least), and conventional flow which is *mathematically* accurate. This, perhaps more than any other reason, is why educational programs designed for mathematically rigorous fields (e.g. electrical engineering) exclusively use conventional flow notation rather than electron flow notation to denote the direction of current.

If the moving charge in question is not a single charged particle but rather part an electric *current* passing through a conductor parallel to the first, both conductors will experience a mutually-attracting force given by the following equation:



$$\vec{F} = I\vec{l} \times \vec{B}$$

Where,

$\vec{F}$ = Force exerted on both conductors (Newtons)

I = Current (Amperes)

$\vec{l}$ = Length of wire (meters)

$\vec{B}$ = Magnetic field (Tesla, or Webers per square meter, or Newtons per Ampere-meter)

The point-charge Lorentz force equation and the two-conductor Lorentz force equation are not that different from one another. Dimensional analysis validates this: the Lorentz force on a moving charge uses that charge quantity (Coulombs) multiplied by the point-charge's velocity in meters per second to give Coulomb-meters per second for the first term:

$$Q\vec{v} = [\mathrm{C}]\left[\frac{\mathrm{m}}{\mathrm{s}}\right] = \left[\frac{\mathrm{C} \cdot \mathrm{m}}{\mathrm{s}}\right]$$

The Lorentz force on a current-carrying conductor uses the current (Amperes, which is Coulombs per second) multiplied by length in meters, for the same composite units of Coulomb-meters per second:

$$I\vec{l} = \left[\frac{\mathrm{C}}{\mathrm{s}}\right][\mathrm{m}] = \left[\frac{\mathrm{C} \cdot \mathrm{m}}{\mathrm{s}}\right]$$

This dimensional equivalence makes conceptual sense as well: an electrically-charged particle moving through empty space is an electric current in its own right, and an electric current flowing through a conductor is just a collection of charged particles moving through space (just not *empty* space). In either case, the basis for the Lorentz force remains the same: the moving charge(s) create their own magnetic field, which reacts with the magnetic field of the original current-carrying wire to produce forces acting on both.

If the two currents flow in the same direction, their mutual forces *attract*. If the two currents flow in opposite directions, their mutual forces *repel*. This is the basis of electric motors: causing

mechanical motion by electro-magnetic attraction and repulsion. It also represents an interesting contrast with electric fields:

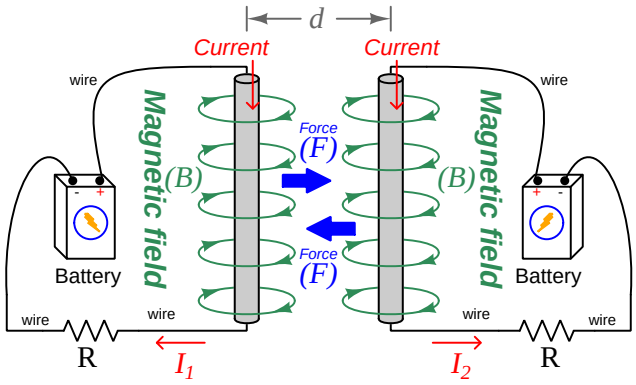
With electric fields, opposite *charges* attract and like *charges* repel.

With magnetic fields, opposite *poles* attract and like *poles* repel.

With parallel currents, opposite *directions* repel and like *directions* attract[3].

Two parallel current-carrying conductors of length l and separated by a distance d will generate a mutual force proportional to both their currents:

$$F = l\frac{\mu I_1 I_2}{2\pi d}$$



[3]That is, assuming it's *like* charges moving in these directions! If the charges in question are opposite each other – for example electrons in one circuit and holes in another – then like directions will repel and opposite directions will attract!

The circular loops surrounding the current-carrying conductors in the previous illustrations represent the magnetic lines of *flux* (Φ_B) surrounding each of those conductors. The magnetic field (B) is related to magnetic flux by area (A), the field being a measurement of how densely-packed those flux lines are per unit area. For this reason, magnetic field (B) is more properly known as *magnetic flux density*:

$$\vec{B} = \frac{\Phi_B}{\vec{A}}$$

Where,

$\vec{B}$ = Magnetic field or flux density (Tesla, Webers per square meter, or Newtons per Ampere-meter)

Φ_B = Magnetic flux (Webers)

$\vec{A}$ = Area over which flux is distributed (square meters)

An older unit of measurement for magnetic flux density B is the *Gauss* which is much smaller than a Tesla, with one Tesla equivalent to 10,000 Gauss. To put things into perspective, the Earth's natural magnetic field has a strength of approximately one-half of one Gauss[4].

Magnetic field strength is an inverse function of distance from any current-carrying wire, and also depends on the magnetic permeability of the space adjacent to the wire:

$$B = \frac{\mu I}{2\pi d}$$

Where,

B = Magnetic field or flux density (Tesla, Webers per square meter, or Newtons per Ampere-meter)

μ = Magnetic permeability of the surrounding space (Tesla-meters per Ampere, $4\pi \times 10^{-7}$ for empty space)

I = Current (Amperes)

d = Distance from conductor (meters)

[4]Using the online *Magnetic Field Calculator* application provided by NOAA (the National Oceanic and Atmospheric Administration) at `https://ngdc.noaa.gov/geomag/calculators/magcalc.shtml#igrfwmm`, applying the World Magnetic Model WMM modeling algorithm for years 2019-2024, the total magnetic field strength at my home is 53,584.4 nano-Tesla (53,584.4 nT or 0.535844 Gauss), and presently (May 2020) decaying at a rate of -104.1 nT per year.

The relation of magnetic *flux* to current through a conductor follows a similar equation:

$$\Phi = \frac{\mu A I}{2\pi d}$$

Where,

Φ = Magnetic flux (Webers)

μ = Magnetic permeability of the surrounding space (Tesla-meters per Ampere, $4\pi \times 10^{-7}$ for empty space)

A = Area over which flux is distributed (square meters)

I = Current (Amperes)

d = Distance from conductor (meters)

As this equation makes clear, the amount of magnetic flux surrounding a current-carrying conductor depends not only on the amount of current, but also on the sampled area, the distance from the wire, and also the surrounding material. Most[5] substances (gas, liquid, solid) have permeability values greater than that of empty space, and so this means magnetic flux is usually *enhanced* by the presence of matter around the current-carrying conductor.

The total magnetic flux enclosed by a circular wire loop follows a similar equation:

$$\Phi = \frac{\pi \mu I r}{2}$$

Where,

Φ = Magnetic flux (Webers)

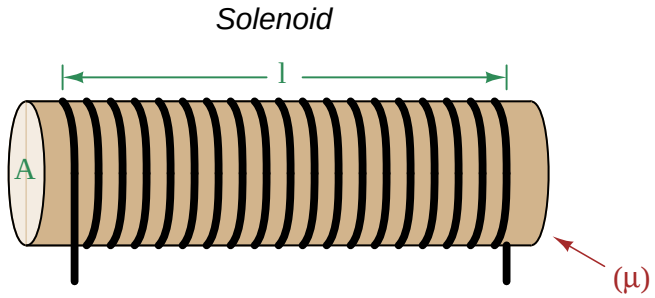
μ = Magnetic permeability of the surrounding space (Tesla-meters per Ampere, $4\pi \times 10^{-7}$ for empty space)

I = Current (Amperes)

r = Radius of circular loop (meters)

[5] Interestingly, superconducting materials *forbid* magnetic fields inside of their bulk, and so the permeability value of any superconductor must be zero!

A common form of electromagnet known as a *solenoid* takes the form of a wire coil wrapped in such a way as to form a long[6] cylinder, often wrapped around a plastic frame, and often with a ferromagnetic material such as iron in the center:



The amount of magnetic flux, and the flux density, within the interior of a current-carrying solenoid are given by the following formulae:

$$\Phi = \frac{\mu N A I}{l} \qquad\qquad B = \frac{\mu N I}{l}$$

Where,

Φ = Magnetic flux (Webers)

B = Magnetic field or flux density (Tesla, Webers per square meter, or Newtons per Ampere-meter)

μ = Magnetic permeability of the surrounding space (Tesla-meters per Ampere, $4\pi \times 10^{-7}$ for empty space)

N = Number of turns of wire in the coil

A = Cross-sectional area of solenoid coil (square meters)

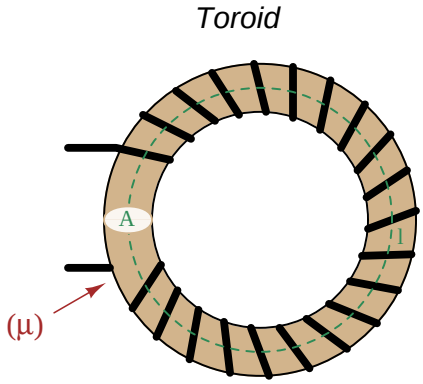
I = Current (Amperes)

l = Length of solenoid coil (meters)

These formulae have interesting implications for solenoid design. Note how a shorter (i.e. smaller length l) solenoid identical in all other respects will generate a stronger magnetic field for a given current. Note also how the flux density (B) remains constant with increasing cross-sectional area (A) if all other factors are equal, and that this necessarily means a greater amount of total magnetic flux (Φ) for a greater area A.

[6] These magnetic field formulae apply perfectly to a solenoid coil that is closely-packed (i.e. each turn adjacent to the next) and infinitely long. Therefore, they only approximate real solenoid behavior. This fact may be understood by performing a thought experiment where we decrease the solenoid coil's length to zero, in which case the formulae predict an *infinite* amount of magnetism for any amount of current at all, which of course cannot be true.

Another common form of electromagnet known as a *toroid* is really just a solenoid bent in a circle so that its two ends meet[7] cylinder, often wrapped around a plastic frame, and often with a ferromagnetic material such as iron in the center. Toroids have the unusual property of *containing* their magnetic flux lines extremely well, unlike solenoids, wires, and simple coils which all radiate magnetic fields. They find application as energy-storage devices, or as electromagnets suitable for applying magnetic fields to specimens placed *inside* the toroid's cross-section:



The amount of magnetic flux, and the flux density, within the interior of a current-carrying toroid are identical to that within an otherwise identical otherwise identical solenoid having a length (l) equal to the toroid's circumference:

$$\Phi = \frac{\mu N A I}{l} \qquad\qquad B = \frac{\mu N I}{l}$$

Where,

Φ = Magnetic flux (Webers)

B = Magnetic field or flux density (Tesla, Webers per square meter, or Newtons per Ampere-meter)

μ = Magnetic permeability of the surrounding space (Tesla-meters per Ampere, $4\pi \times 10^{-7}$ for empty space)

N = Number of turns of wire in the coil

A = Cross-sectional area of toroid (square meters)

I = Current (Amperes)

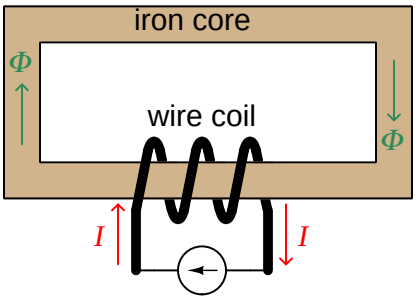
l = Circumference of toroid (meters)

If we wish to substitute toroid radius (r) for circumferential length (l), the formulae become the following:

$$\Phi = \frac{\mu N A I}{2\pi r} \qquad\qquad B = \frac{\mu N I}{2\pi r}$$

[7] Again, the magnetic field formulae are only accurate for a toroidal coil that is closely-packed (i.e. each turn adjacent to the next) and infinitely long, and therefore only approximate real toroid behavior. This fact may be understood by performing an equivalent thought experiment as before where we decrease the toroid's circumference to zero and absurdly end up with *infinite* magnetism for a finite current.

Many applications of electromagnetism involve conductive *coils* wrapped around some form of ferromagnetic core material, the purpose of that core being to provide a higher-permeability pathway for the magnetic flux than would exist otherwise through air, and the purpose of the wire coil being to intensify the amount of magnetism developed by the electric current beyond what would be possible with a straight current-carrying wire. These magnetic cores typically form a closed loop, or *magnetic circuit* for the lines of magnetic flux to naturally form a closed path. A simple example appears here:



The amount of magnetic flux (Φ) present in the magnetic "circuit" formed by the iron core depends on many factors. First and foremost is the amount of electric current (in Amperes) passing through the wire coil and the number of turns that coil makes around the iron core. The product of this current and the number of turns is called the *magnetomotive force* or *mmf* of the magnetic circuit, analogous to "electromotive force" or "emf" often used as a synonym for voltage in an electric circuit. Not surprisingly, the standard metric unit of measurement for magnetomotive force is the *Ampere-turn*.

However, magnetomotive force alone does not fully describe the current's effect on magnetism within the iron core. The total length of the magnetic circuit is also an important factor, since a longer path distributes that magnetomotive force over a greater distance. The quotient of magnetomotive force and magnetic circuit length is called *magnetic field intensity*, symbolized by the variable H and expressed in units of *Ampere-turns per meter*.

Magnetic permeability (μ) relates magnetic field intensity (H) to the magnetic flux density (B) within the core material, such that a greater permeability will result in higher flux density for any given amount of field intensity. Permeability is a property of the core material and not its geometry, mathematically defined as the ratio of flux density to field intensity: $\mu = \frac{B}{H}$

Magnetic reluctance ($\Re$) relates magnetomotive force (mmf) to magnetic flux (Φ), and is related not only to the core material's permeability but also its geometry. It is mathematically defined as the ratio of magnetomotive force to magnetic flux: $\Re = \frac{\text{mmf}}{\Phi}$

If all this seems confusing, you are in good company. Not only are there many magnetic variables, some related to physical geometry and others not, but there are *two different sets of metric units* appropriate for expressing each! The older units were based on the centimeter-gram-second (CGS) version of the metric system, while the newer units are based on the meter-kilogram-second or SI (Système International) version of the metric system.

Quantity	**Symbol**	**SI unit**	**CGS unit**
Magnetomotive force	mmf	Ampere-turn (A-t)	Gilbert (Gb)
Flux	Φ	Weber (Wb)	Maxwell (Mx)
Field intensity	H	Ampere-turns per meter (A-t/m)	Oersted (Oe)
Flux density	B	Tesla (T)	Gauss (G)
Permeability	μ	Tesla-meters per Ampere-turn (T-m/A-t)	Gauss per Oersted (G/Oe)
Reluctance	$\Re$	Ampere-turns per Weber (A-t/Wb)	Gilberts per Maxwell (G/Mx)

Magnetomotive force (mmf) and magnetic flux (Φ) may be thought of as the "raw" measures of magnetism, with Ampere-turns and Webers being their respective SI metric units. Reluctance ($\Re$) is the ratio of the two for any given magnetic circuit with known dimensions and core material. Simply put, reluctance tells you how many Ampere-turns of magnetomotive force will be necessary to create one Weber of magnetic flux in a given space.

Magnetic field intensity (H) and magnetic flux density (B) may be thought of as the "normalized" measures of magnetism, with Ampere-turns per meter and Tesla being their respective SI metric units. H and B relate to mmf and flux by the physical dimensions of the magnetic circuit (length and cross-sectional area, respectively). Permeability is the ratio of the two for any given magnetic core material. Simply put, permeability tells you how many Tesla of magnetic field (i.e. flux density, or Webers of flux per square meter or cross-sectional core area) you will obtain for one Ampere-turn per meter of magnetic field intensity applied to a given core material.

Conversion between the newer SI and the older CGS metric units are as follows:

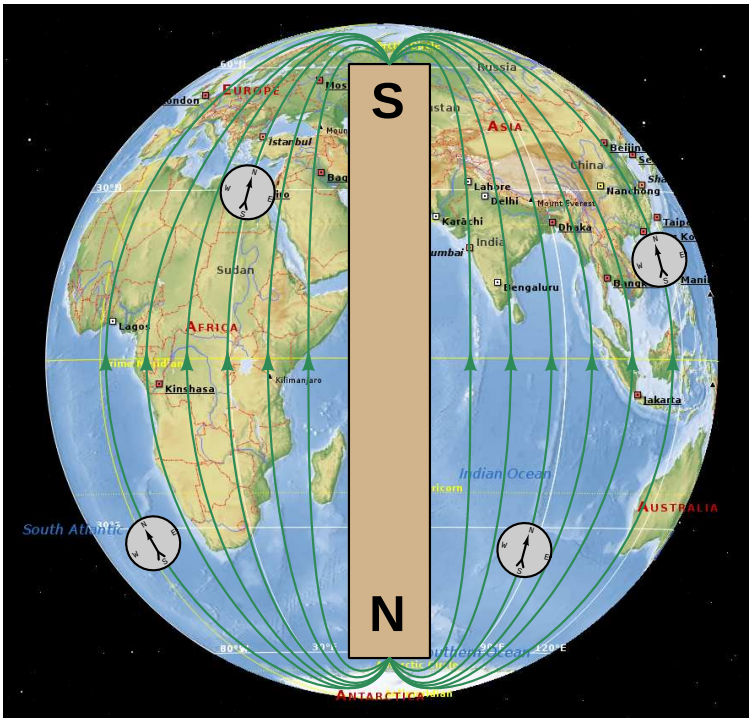
Quantity	**Conversion equivalence**
Magnetomotive force (mmf)	1 Ampere-turn = $\frac{4\pi}{10}$ Gilberts
Magnetic flux (Φ)	1 Weber = 10^8 Maxwells
Magnetic field intensity (H)	1 Ampere-turn/meter = $\frac{4\pi}{1000}$ Oersteds
Magnetic flux density (B)	1 Tesla = 10^4 Gauss
Permeability (μ)	1 Tesla-meter/Ampere-turn = $\frac{10^7}{4\pi}$ Gauss/Oersteds
Reluctance ($\Re$)	1 Ampere-turn/Weber = $\frac{4\pi}{10^9}$ Gilberts/Maxwell

3.3 Defining magnetic north and south

Magnetic pole-pairs are always called *north* and *south*, and this naming hails from the days of navigation by magnetic compass, where a magnetized iron needle would point toward the geographic north pole of the Earth (i.e. toward the Arctic region).

The compass's needle itself is, of course, nothing more than a small magnet with north and south poles. These poles naturally align with the Earth's own magnetic field. Confusion tends to arise when we consider the well-known behavior of magnetic poles to attract when they are opposite and repel when they are identical. Whichever end of a compass needle points toward the Arctic region of the Earth must have the opposite type of magnetic pole as that end of the Earth, and the same must be said of the Antarctic-pointing end of the compass needle.

By convention we have come to identify magnetic north and magnetic south in terms of a compass needle's ends: that is to say, the Arctic-pointing end of a compass needle is magnetic north while the Antarctic-pointing end of that same needle is magnetic south. This means the Earth itself must have a magnetically-south Arctic and a magnetically-north Antarctic. The following illustration shows this relationship:



Fortunately for anyone using a magnetic compass to map magnetic fields created by circuits and/or by permanent magnets, discerning the direction of the magnetic field vectors is extremely simple: *the arrow symbol shown on the compass is the vector-direction of the magnetic field.* Note in the above illustration how each of the compass needles points in the same direction as the respective magnetic flux vector, from Antarctic to Arctic.

3.4 Early description of three-phase motor

An interesting description of a prototype three-phase electric power system installed in Frankfort, Germany is found on page 454 of Volume 1 of *Cassier's Magazine*, which was an engineering periodical published from 1891 to the early 1900's out of London, England. The article in which this quote is found is called "The Transmission of Power" written by Carl Hering, describing the innovative features of a three-phase electric power system, particularly with reference to electric motors:

> Time will not permit a detailed discussion of this three-phase system here; it will suffice to say that it consists of three simple alternating currents, – one in each wire, – the waves or impulses in the three wires following each other in succession similarly to the relative motions of the three cranks of a three-cylinder steam engine, or the pistons of a three-plunger pump. Such a set of currents produces a *rotating* magnetic field, while the simple alternating current produces merely an *oscillating* field. The rotating field furthermore has a definite direction of rotation. It is this feature of a rotating magnetic field as distinguished from an oscillating one which renders it particularly well adapted to run motors. The ordinary simple alternating current motor may be said to be analogous to a steam-engine with one crank, having its slide-valve operated by an independent rapidly running engine ; it has a dead point from which it will not start, but after it is up to speed it will run very steadily. The rotating field motor, on the other hand, is analogous to a three-crank engine operating its own valves. There is no dead point, and it can start itself, even with full load. `[page 454]`

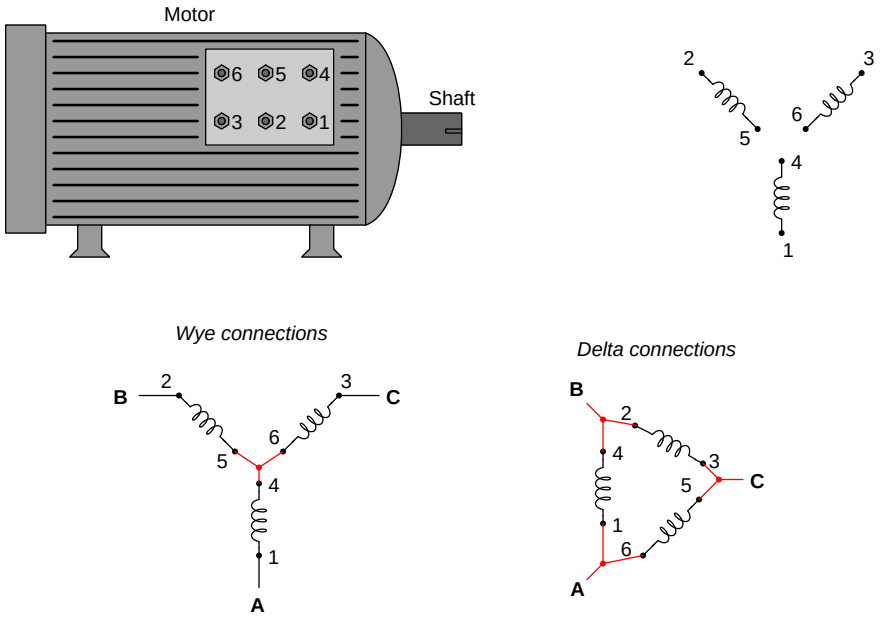
Chapter 4

Derivations and Technical References

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

4.1 6-lead AC induction motors

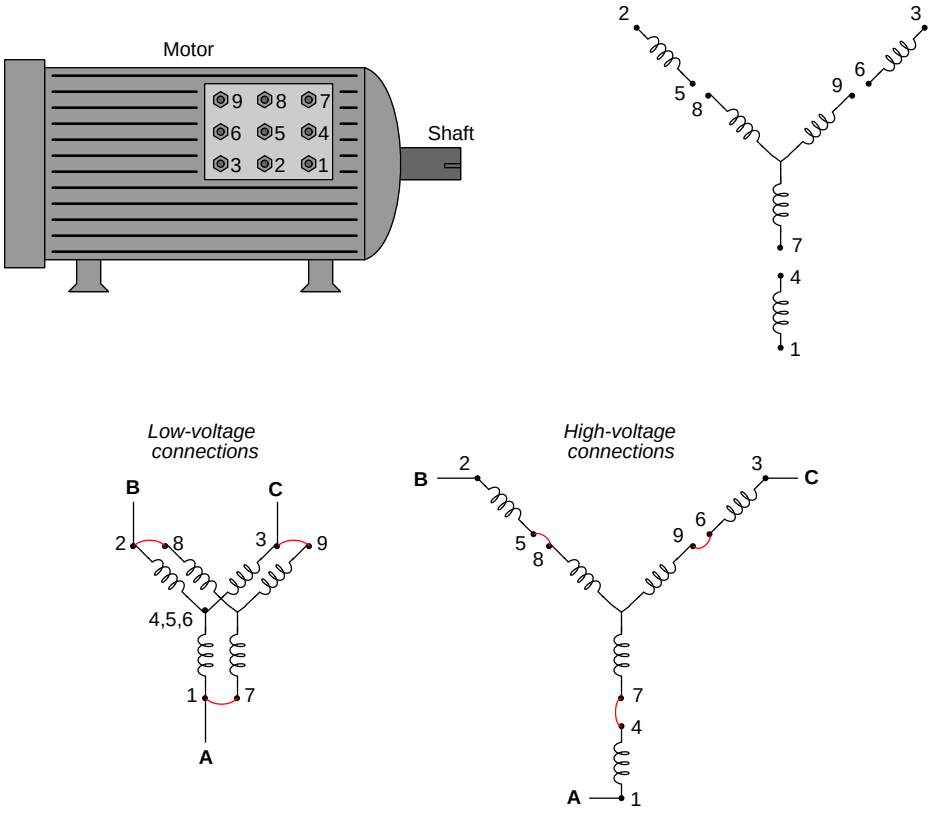
The following illustrations show a 6-lead wye-wound AC induction motor. Stator phase windings each have their own individual terminals, allowing the end-user to wire it either as a wye or a delta:



If each individual stator winding were rated for a maximum of 240 Volts, we would have two line voltage options: 240 Volts for the delta and 416 Volts for the wye. This is a simple function of $\sqrt{3}$, given that line voltage is $\sqrt{3}$ larger than phase voltage for any balanced wye network.

4.2 9-lead AC induction motors

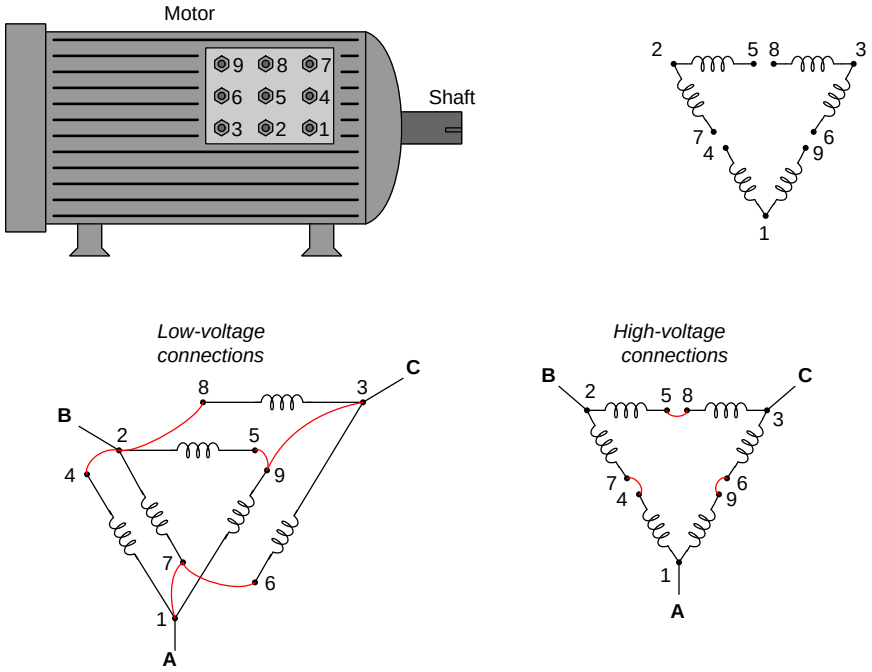
The following illustrations show a 9-lead wye-wound AC induction motor. Six winding pairs exist in this motor's stator, which may be connected either in series or in parallel for different operating voltages:



In the high-voltage configuration, winding pairs are connected in series; in the low-voltage configuration, winding pairs are connected in parallel.

If each individual stator winding were rated for a maximum of 120 Volts, we would have two line voltage options: 208 Volts for the low-voltage connections and 416 Volts for the high. This is a simple function of balanced wye networks and of series-connected elements: line voltage for any balanced wye network is $\sqrt{3}$ greater than phase voltage, and if two identical loads are connected in series they will together drop double the amount of voltage of each one individually.

The following illustrations show a 9-lead delta-wound AC induction motor. Six winding pairs exist in this motor's stator, which may be connected either in series or in parallel for different operating voltages:

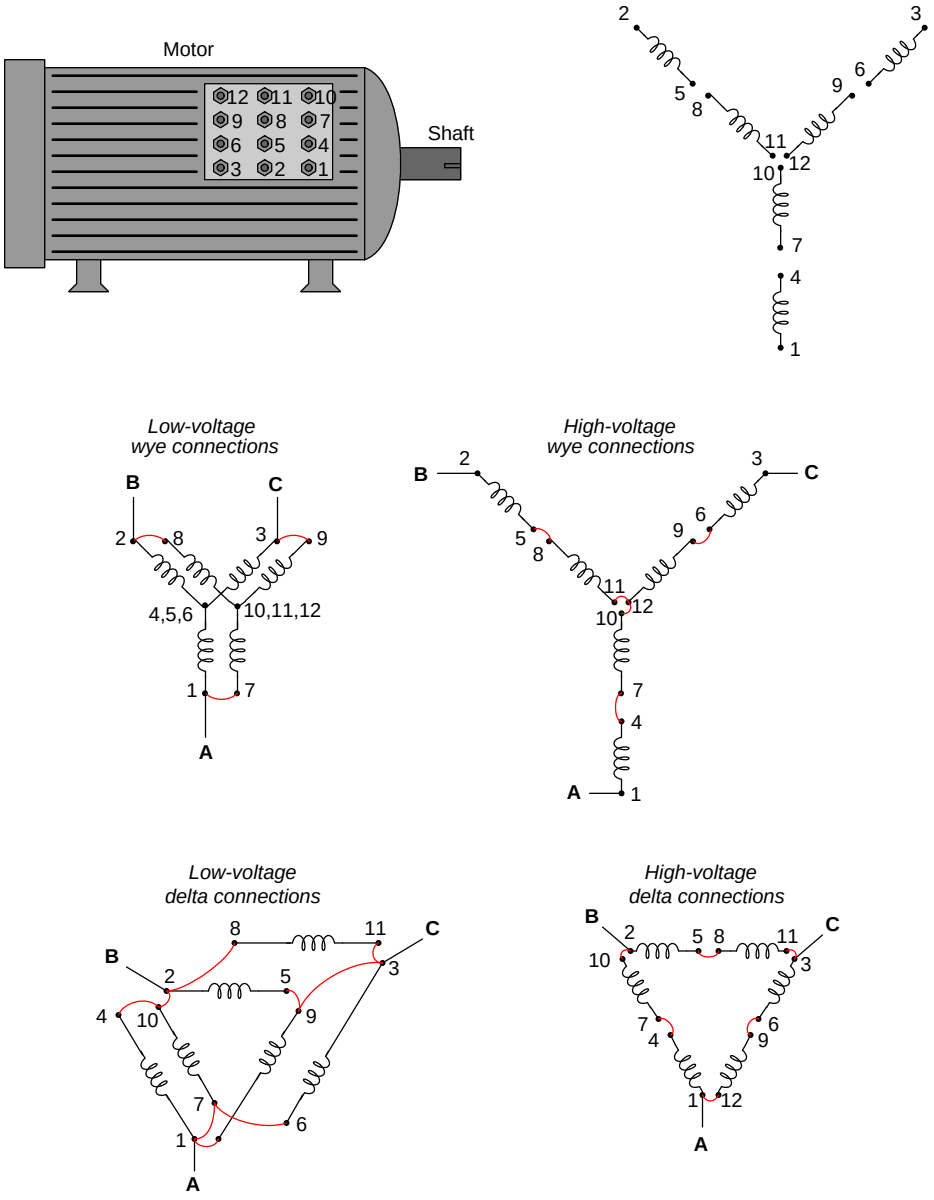


In the high-voltage configuration, winding pairs are connected in series; in the low-voltage configuration, winding pairs are connected in parallel.

If each individual stator winding were rated for a maximum of 240 Volts, we would have two line voltage options: 240 Volts for the low-voltage connections and 480 Volts for the high. This is a simple function of series-connected elements: two identical loads connected in series will together drop double the amount of voltage of each one individually.

4.3 12-lead AC induction motors

The following illustrations show a 12-lead AC induction motor. Six winding pairs exist in this motor's stator, which may be connected either in wye or in delta configurations, *and* either series or in parallel for different operating voltages:



As with 9-lead AC motors, the high-voltage configurations for a 12-lead motor connects winding pairs in series; parallel for the low-voltage configurations.

Each of the four possible wiring configurations results in a unique line voltage, given a voltage rating for each individual stator coil. Supposing a coil voltage rating of 120 Volts, we have the following line voltage options:

- Delta connections, low-voltage = 120 Volts ($V_{line} = V_{coil}$)
- Wye connections, low-voltage = 208 Volts ($V_{line} = \sqrt{3}V_{coil}$)
- Delta connections, high-voltage = 240 Volts ($V_{line} = 2V_{coil}$)
- Wye connections, high-voltage = 416 Volts ($V_{line} = 2\sqrt{3}V_{coil}$)

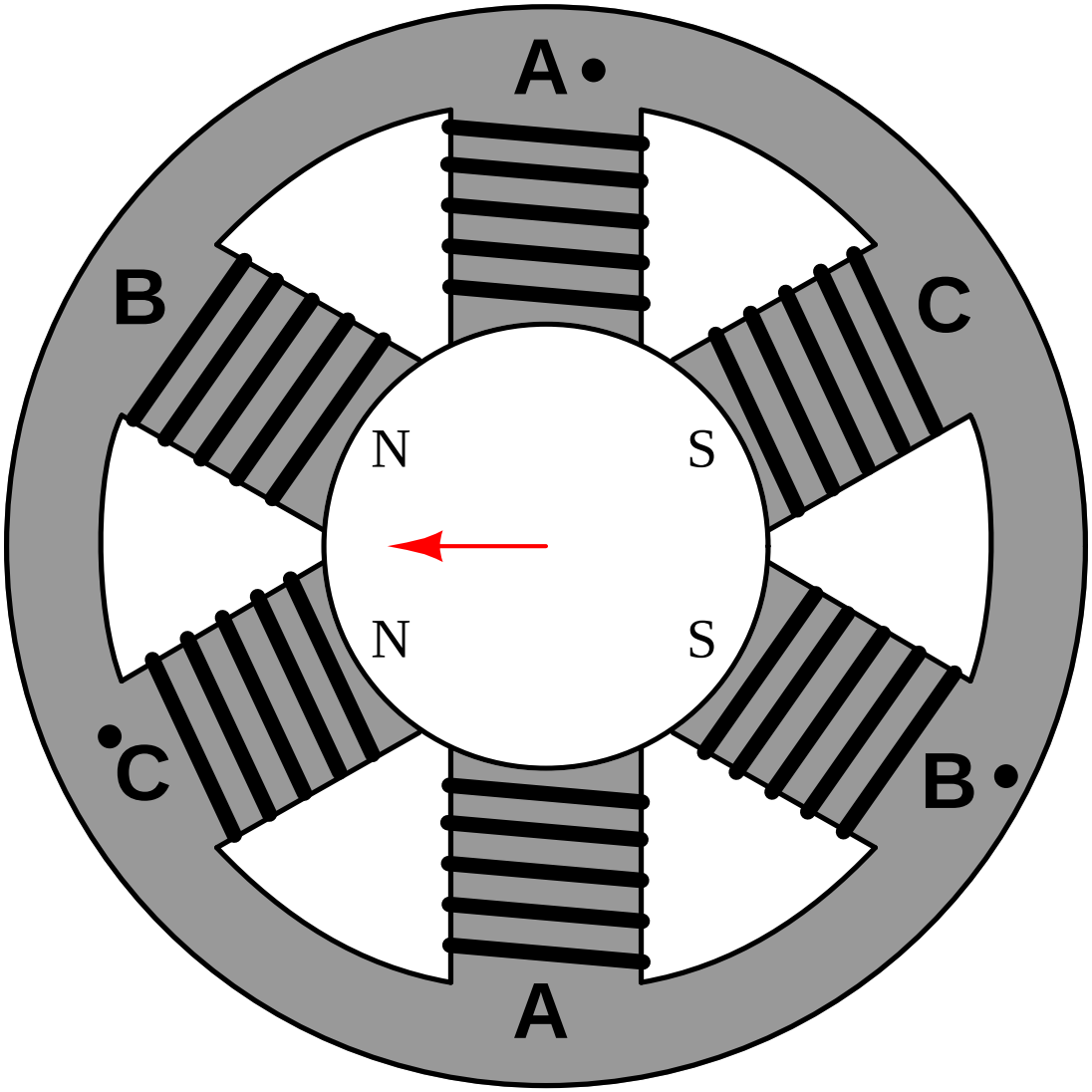
Chapter 5

Animations

Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

5.1 Rotating magnetic field animated

The following animation shows how the "rotating" magnetic field of a three-phase AC induction motor is produced by the interaction of three stator winding sets energized with different phases (A, B, and C) of a three-phase AC power source. A red arrow shows the direction of the *resultant* magnetic field created by the interaction of the three winding sets.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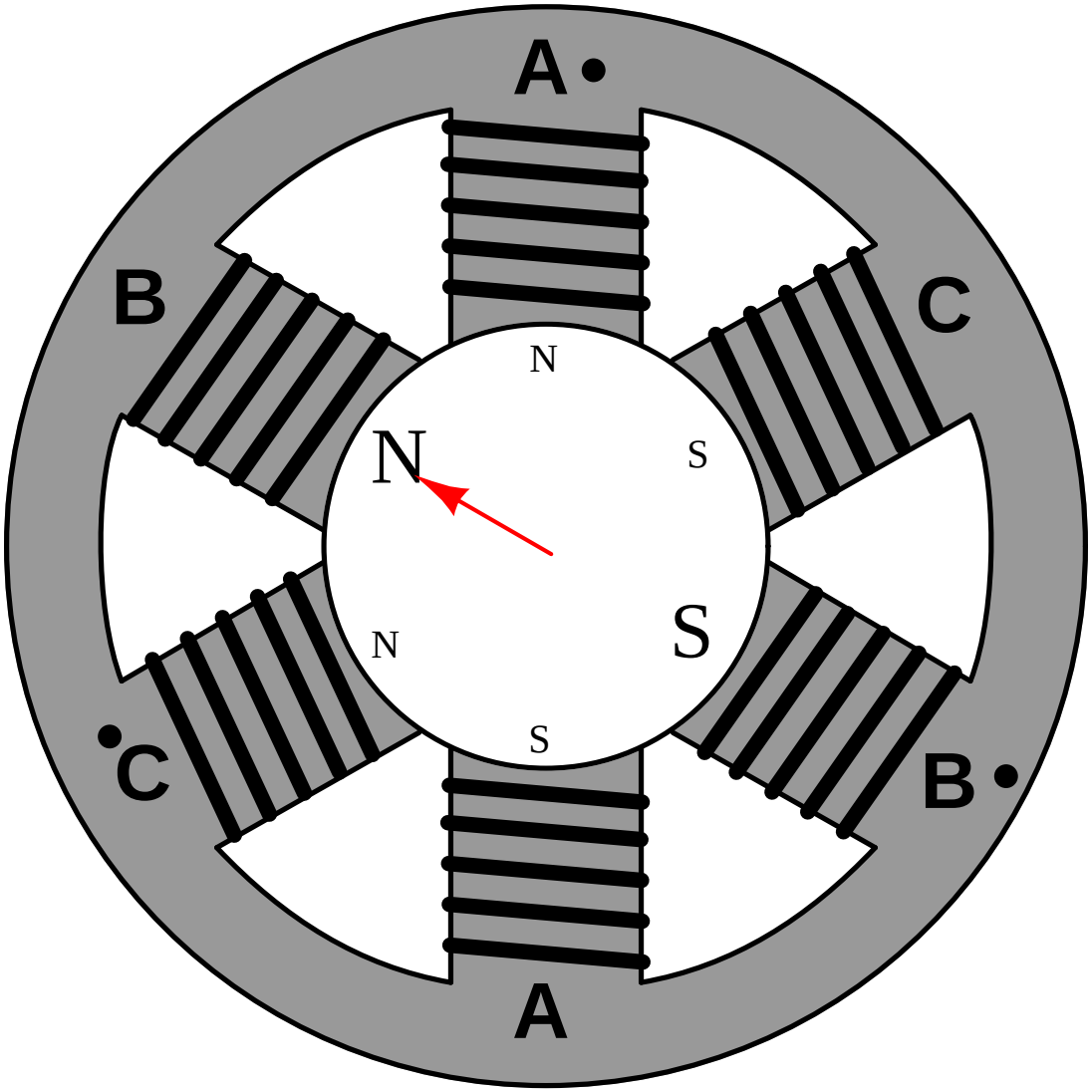
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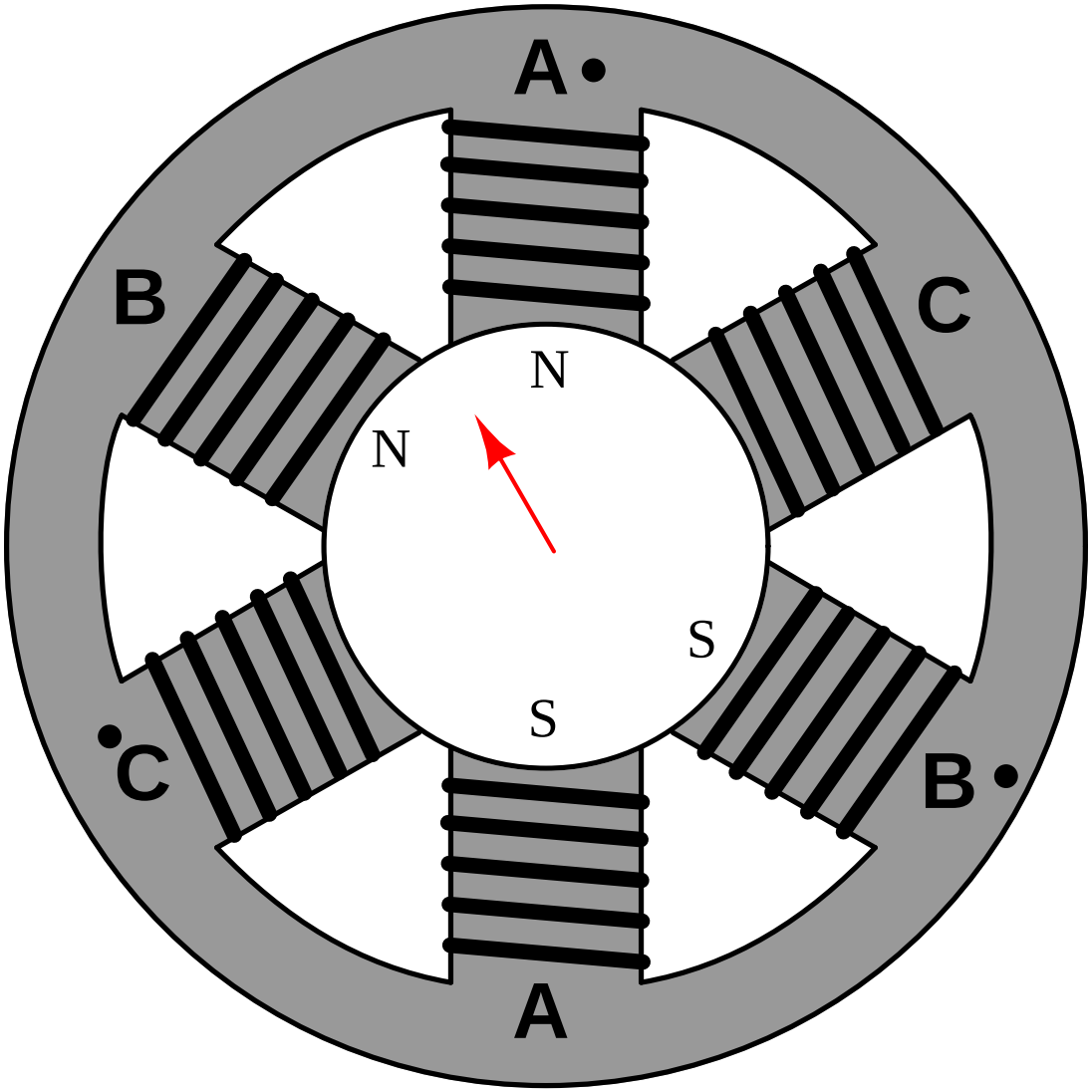
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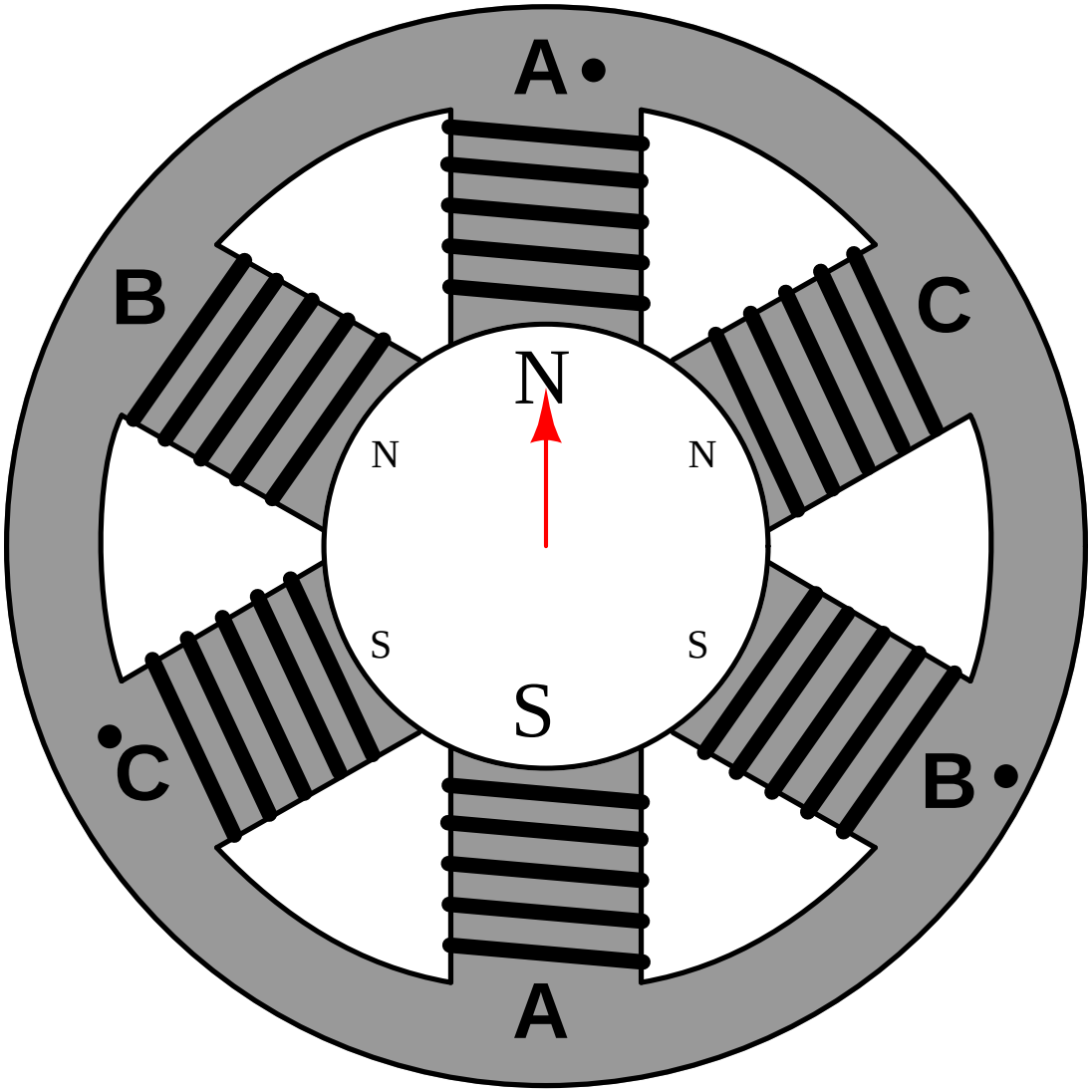
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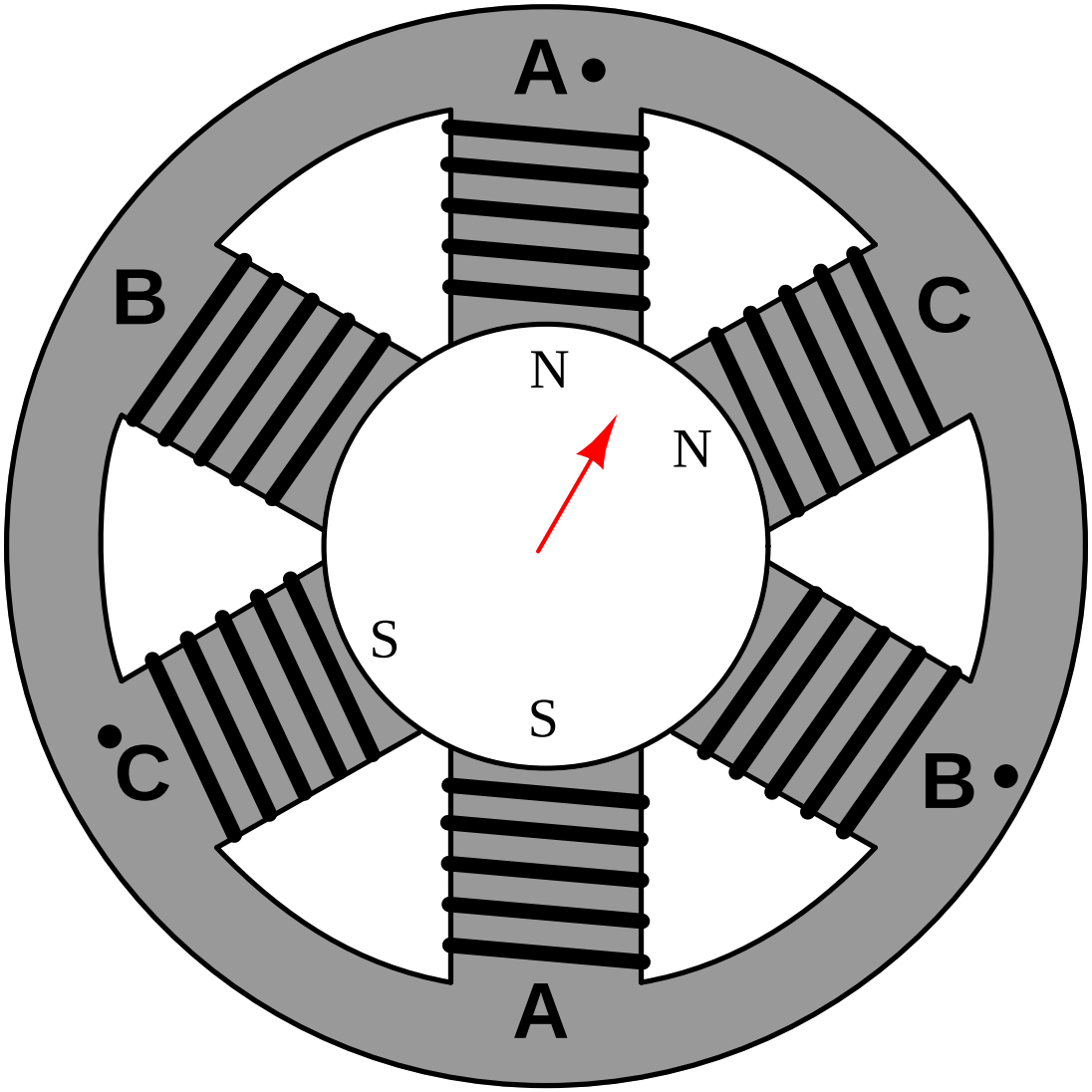
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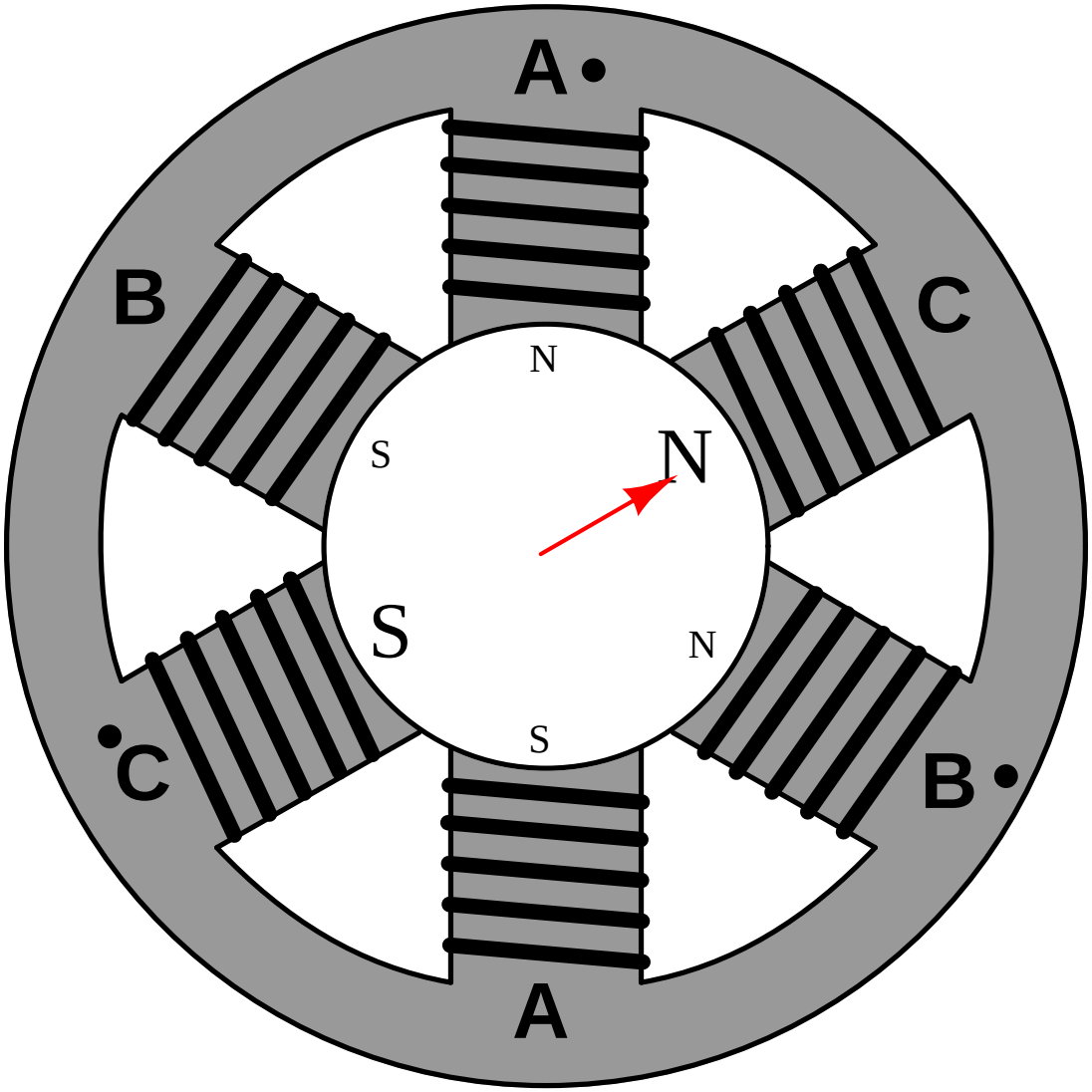
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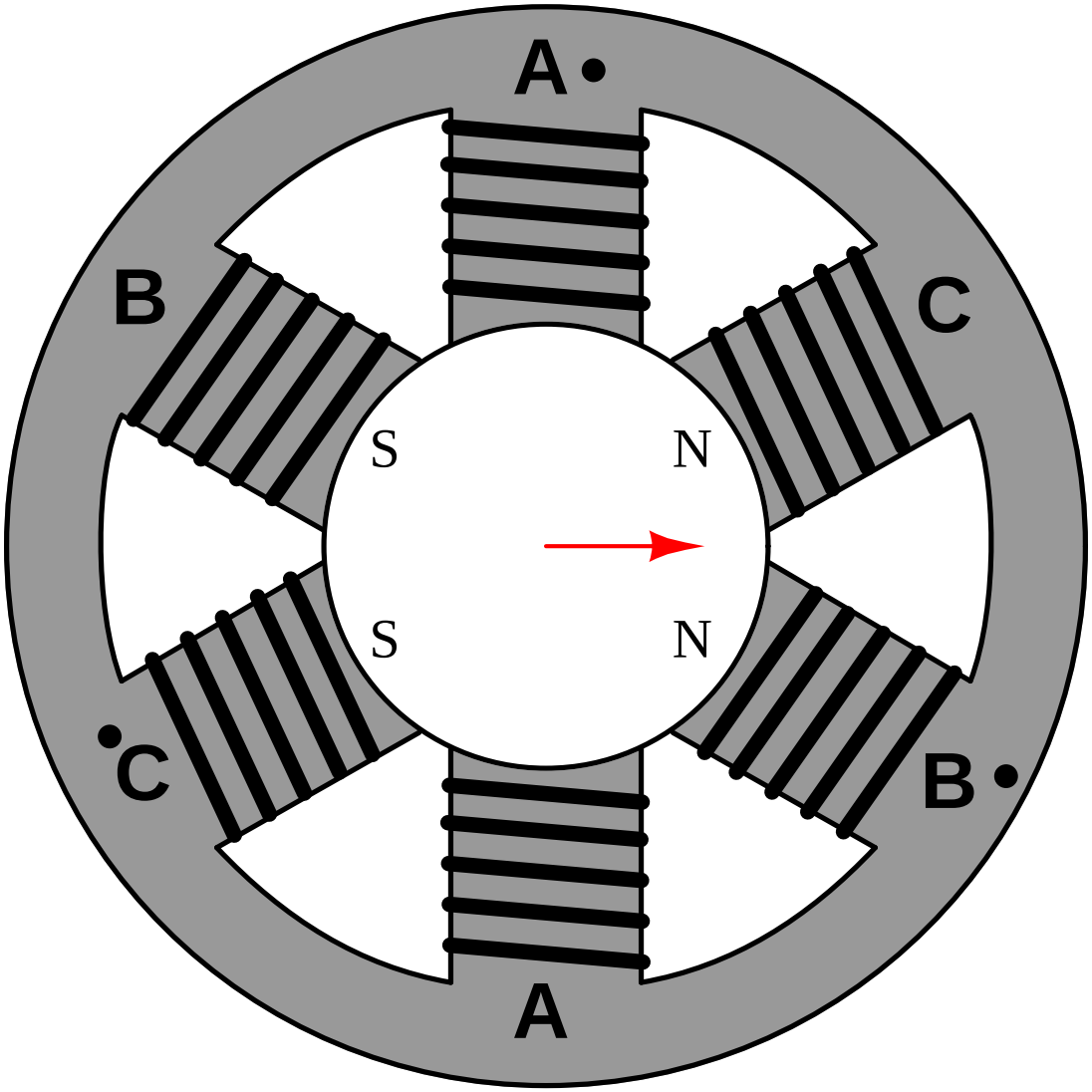
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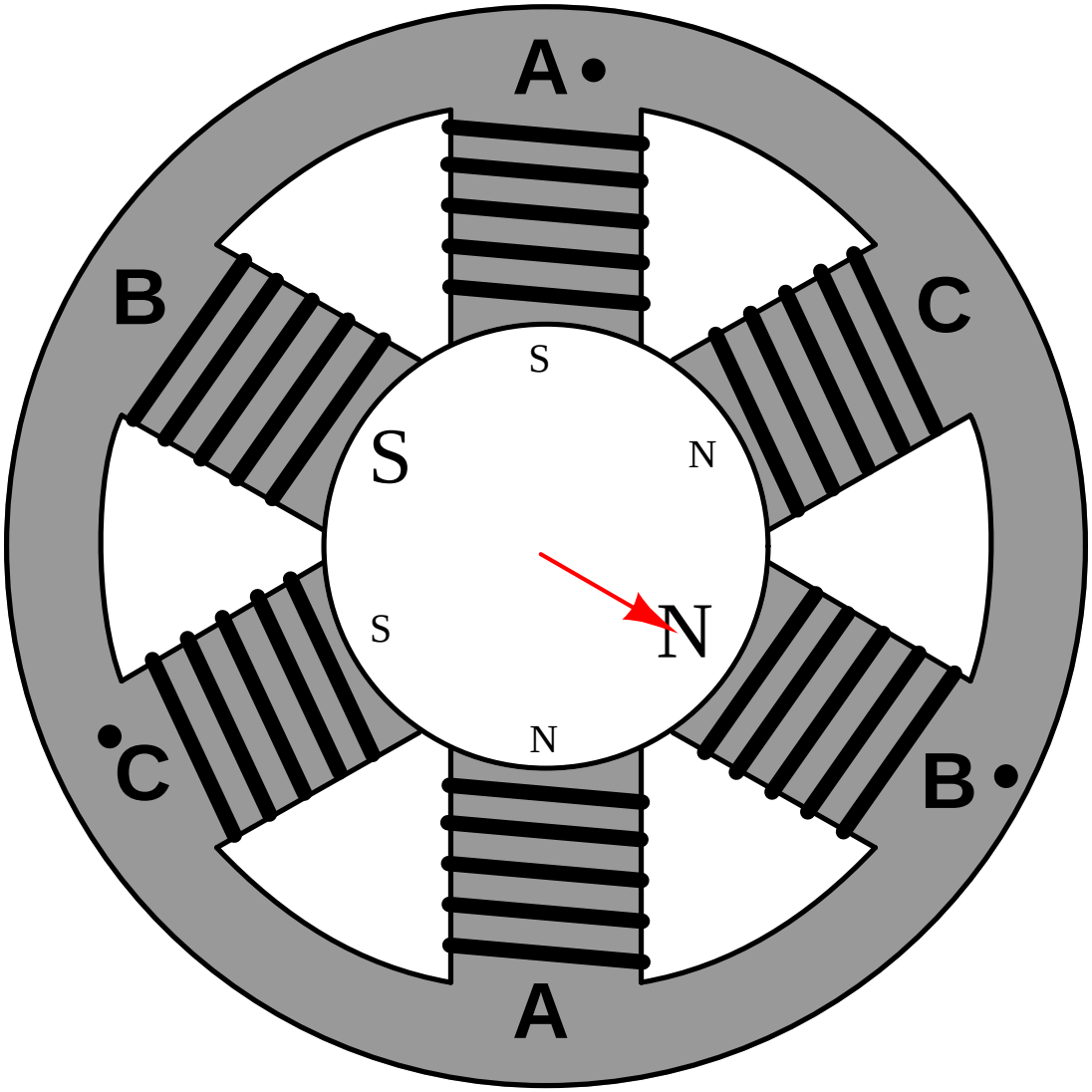
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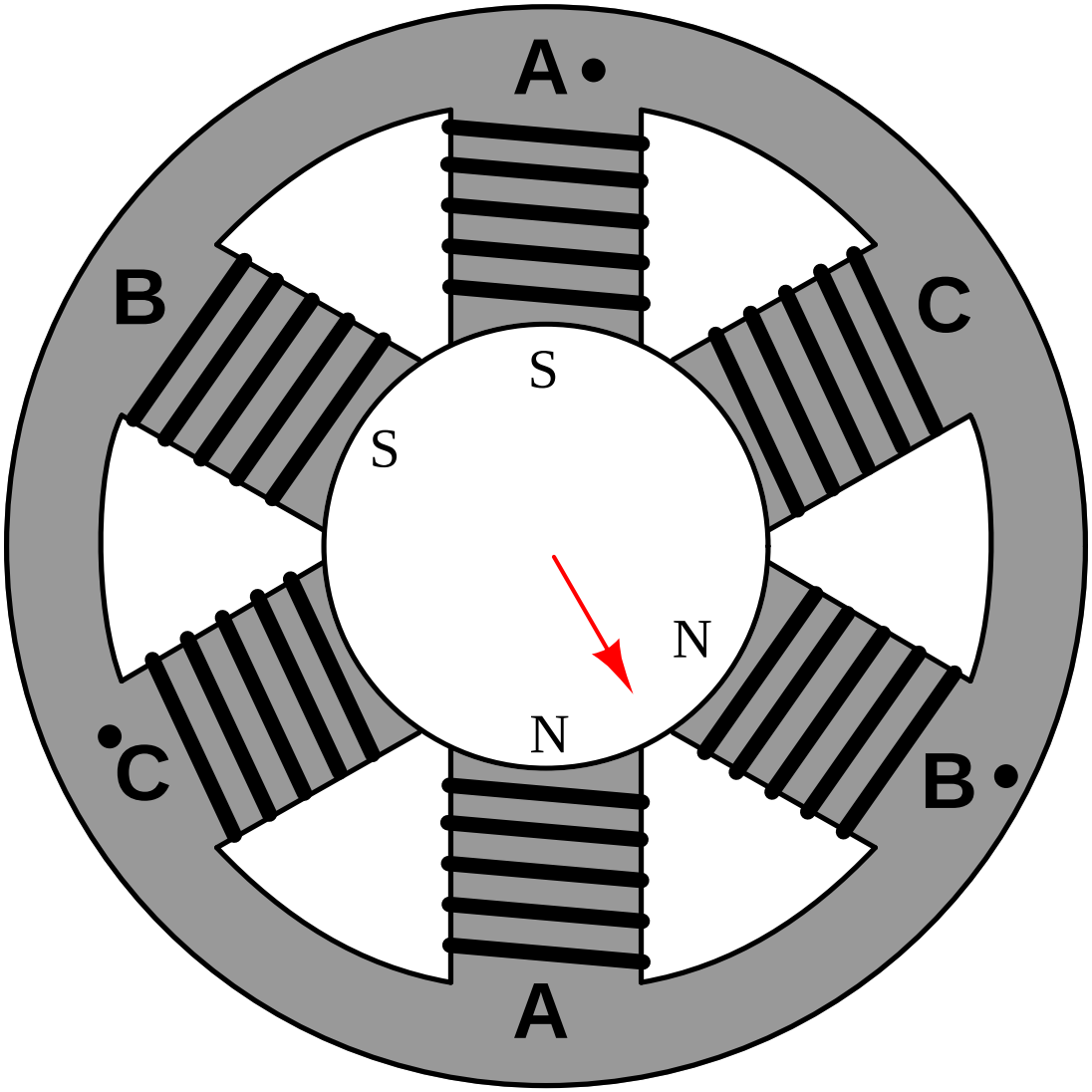
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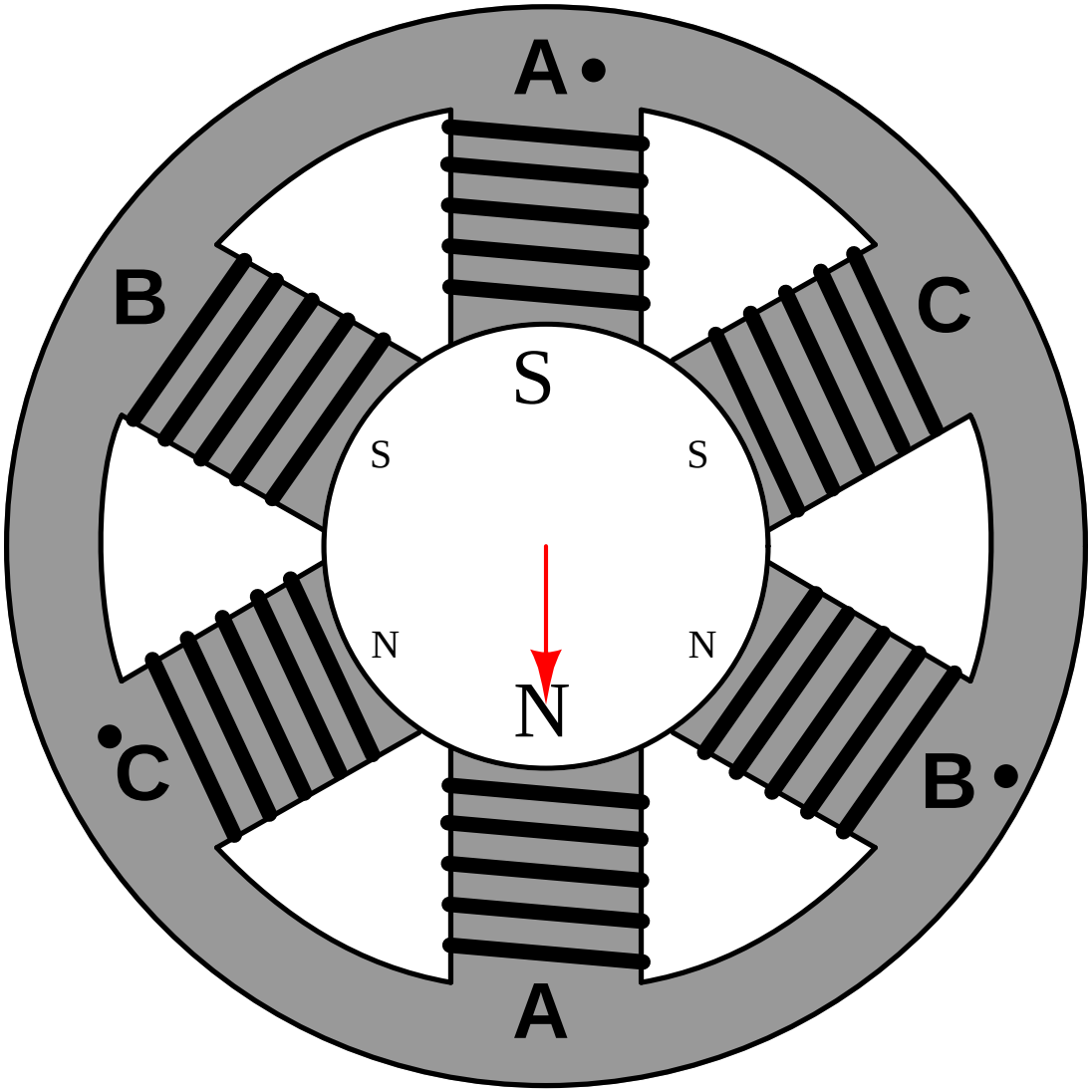
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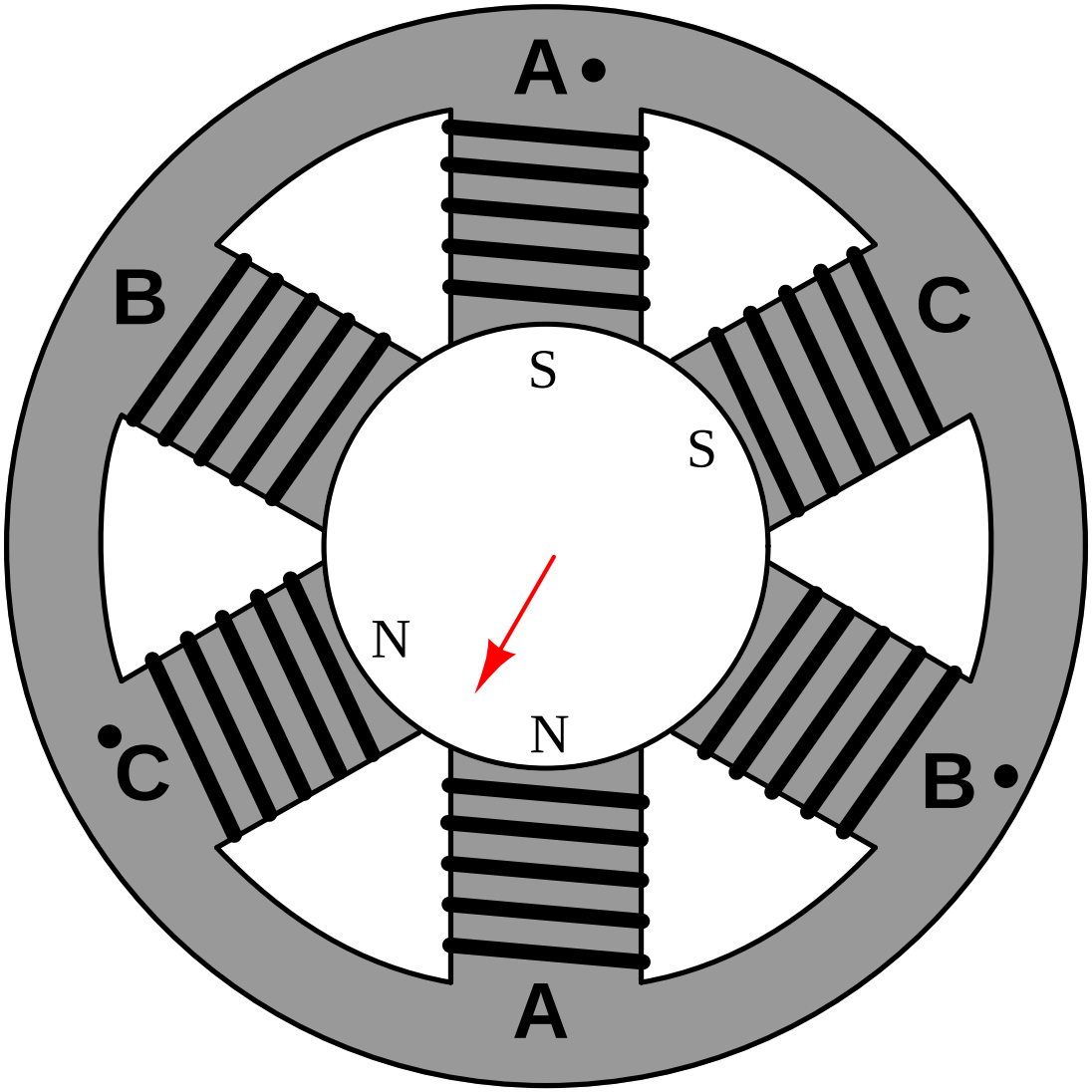
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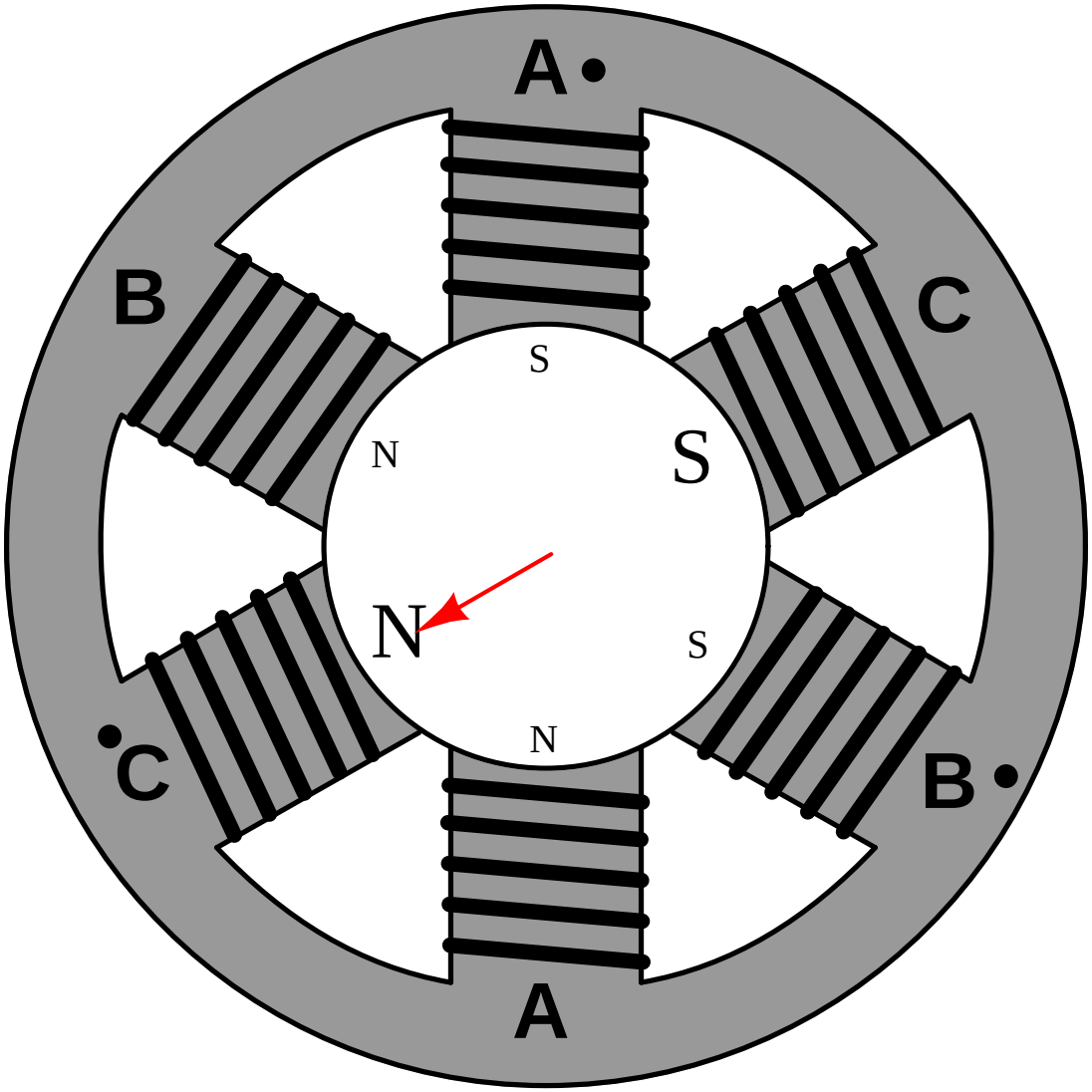
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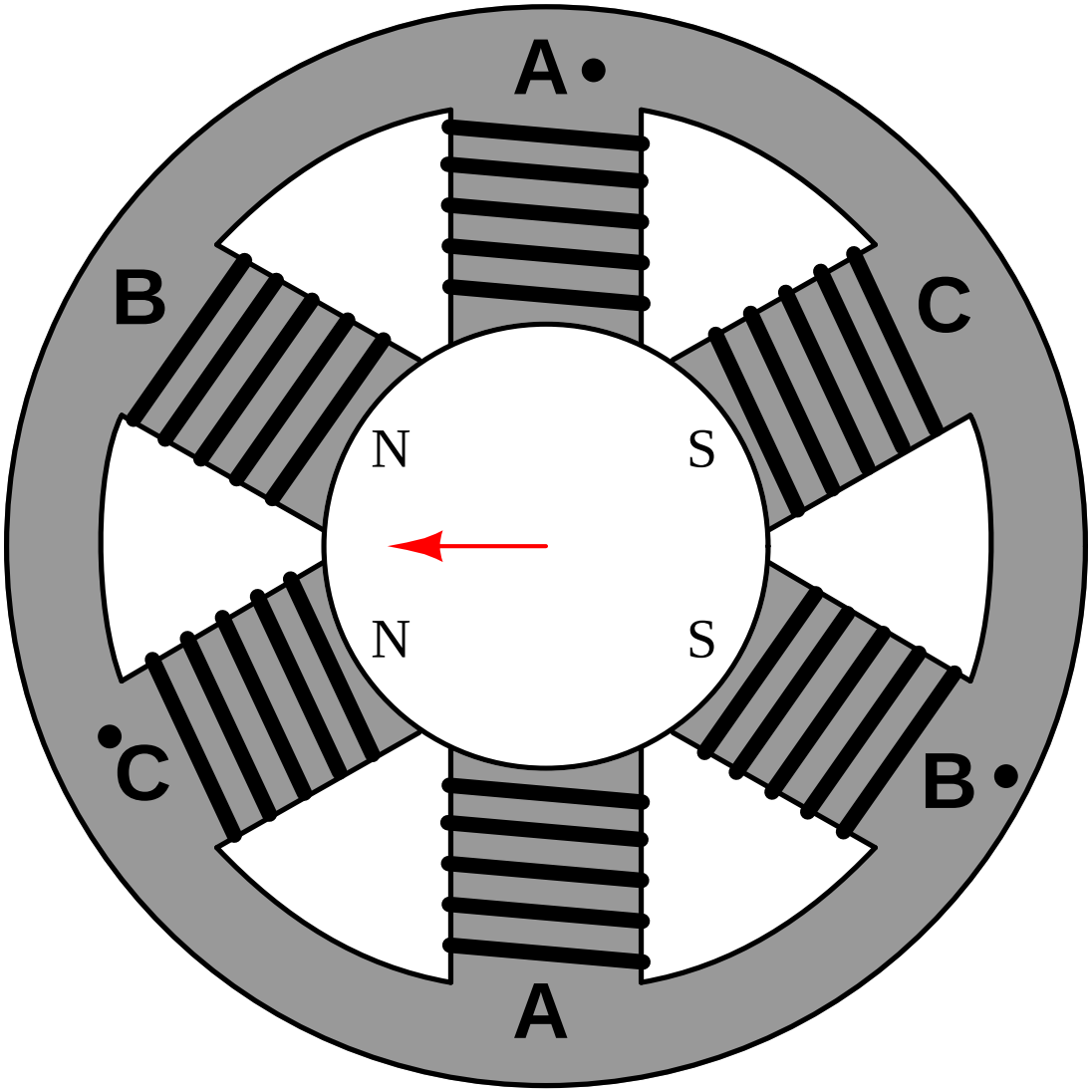
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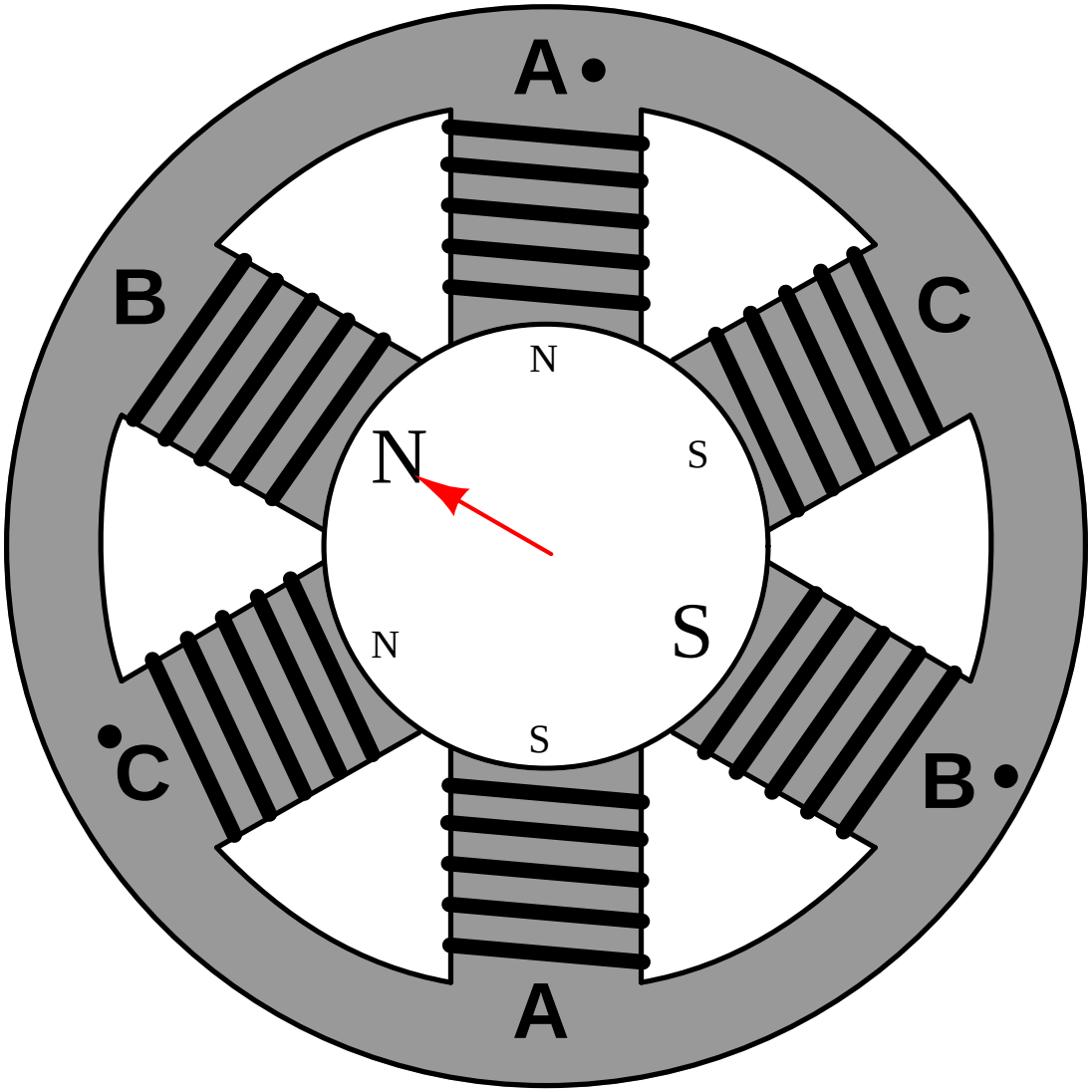
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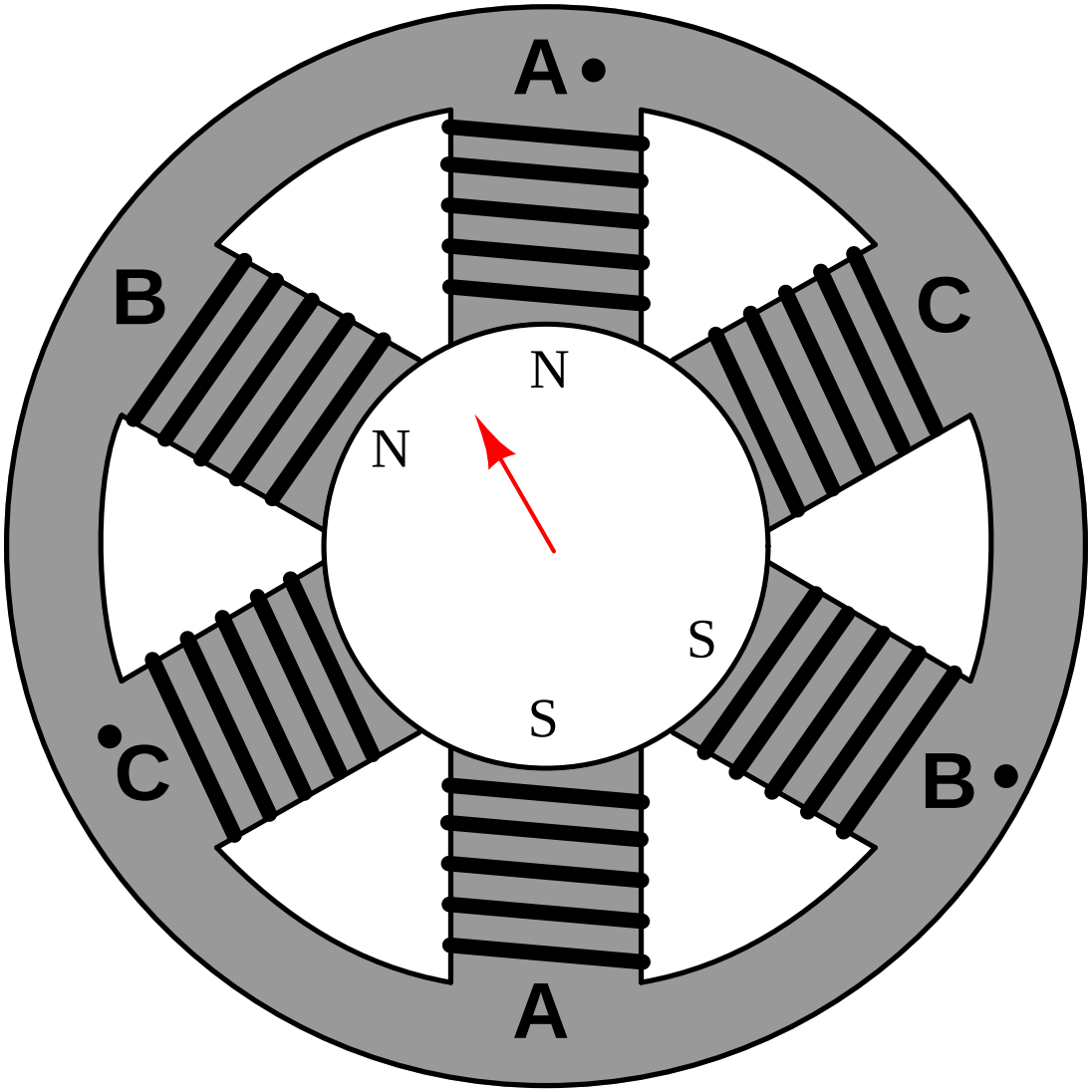
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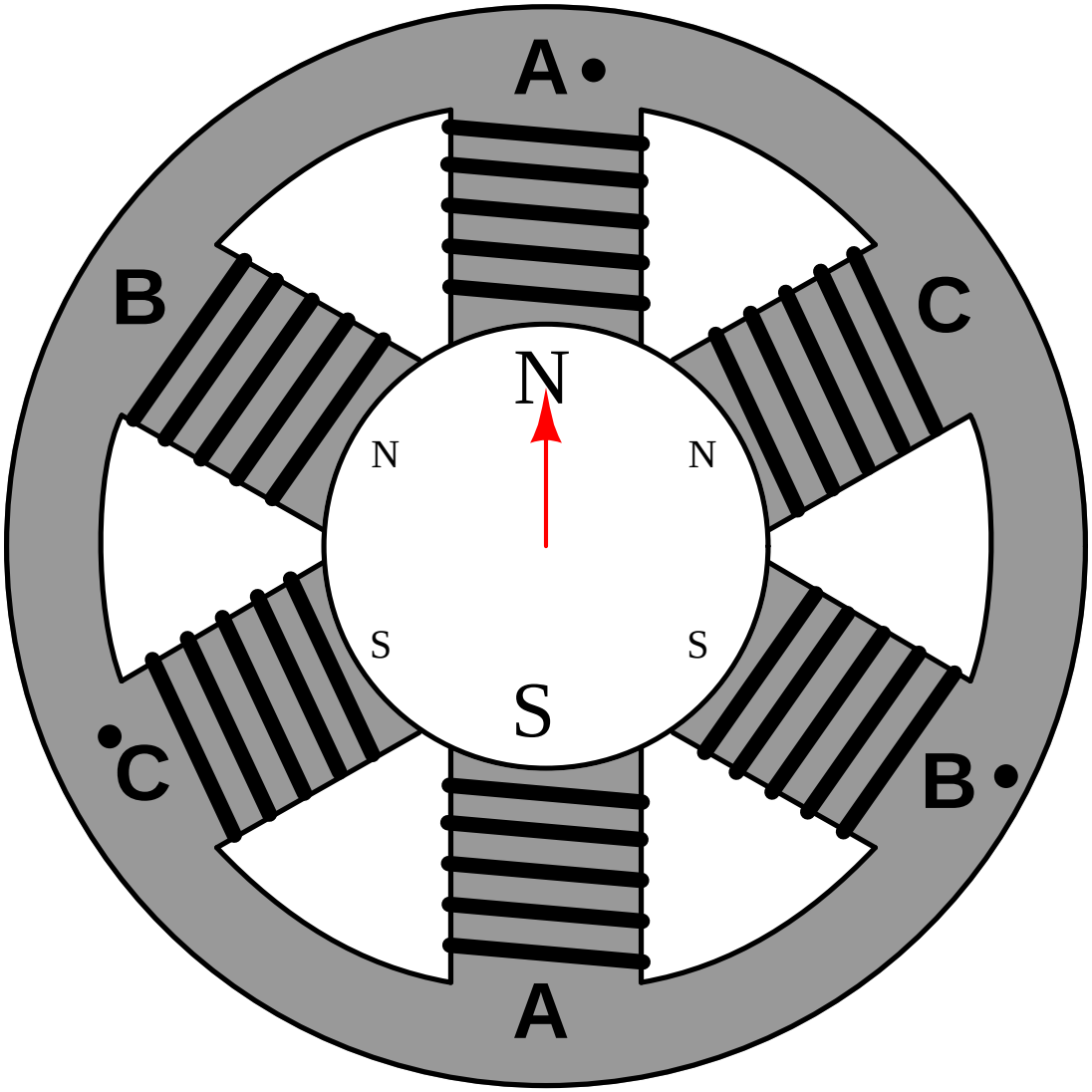
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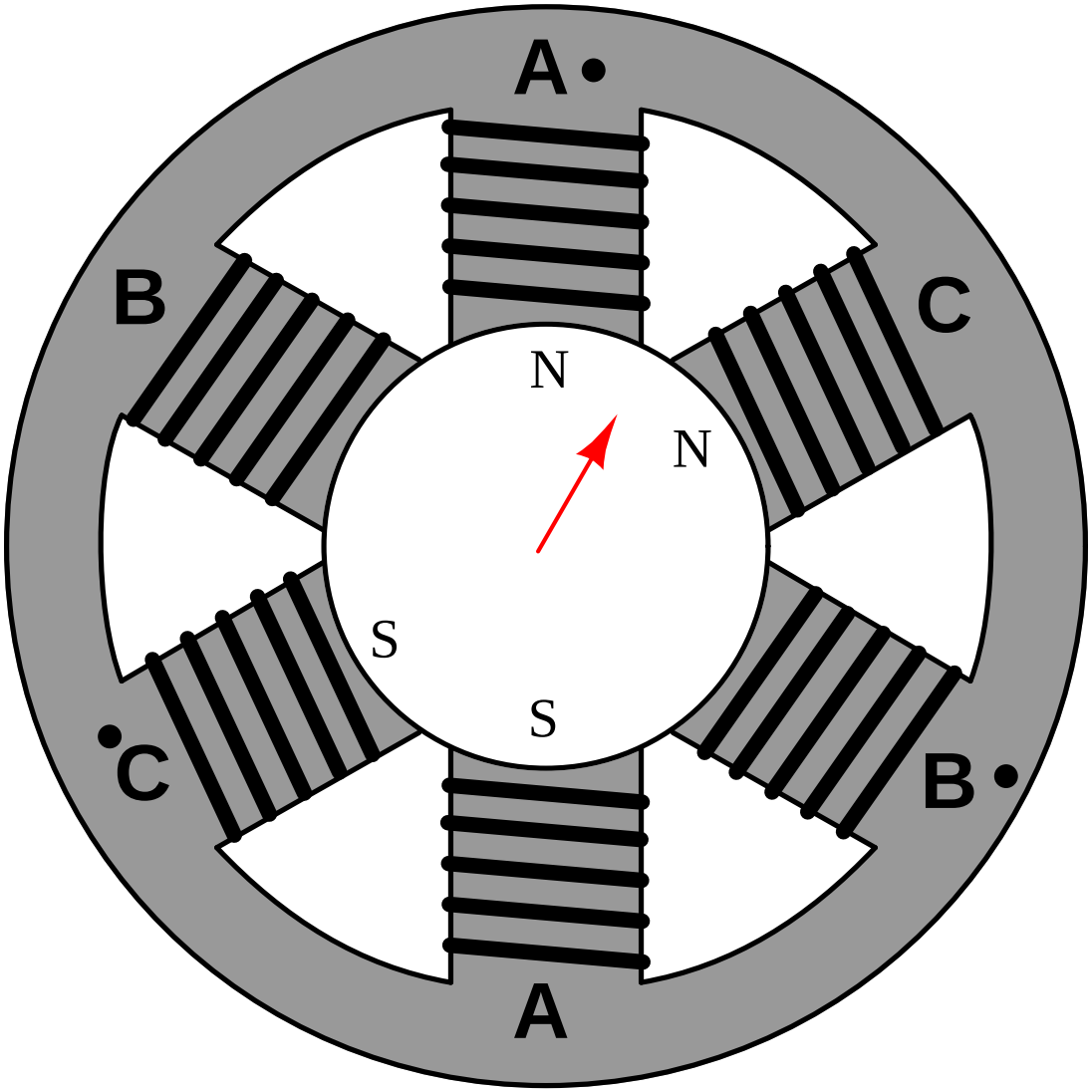
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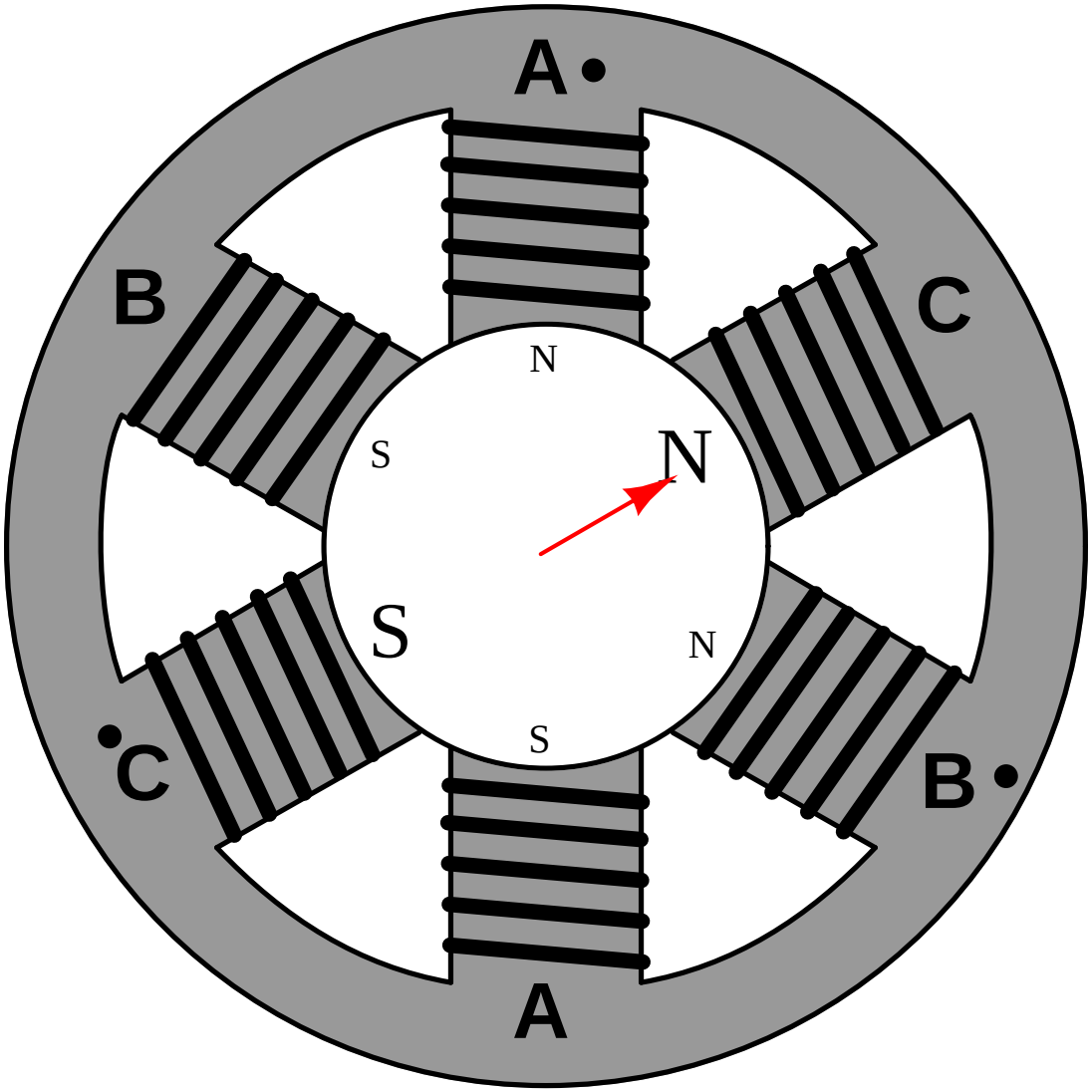
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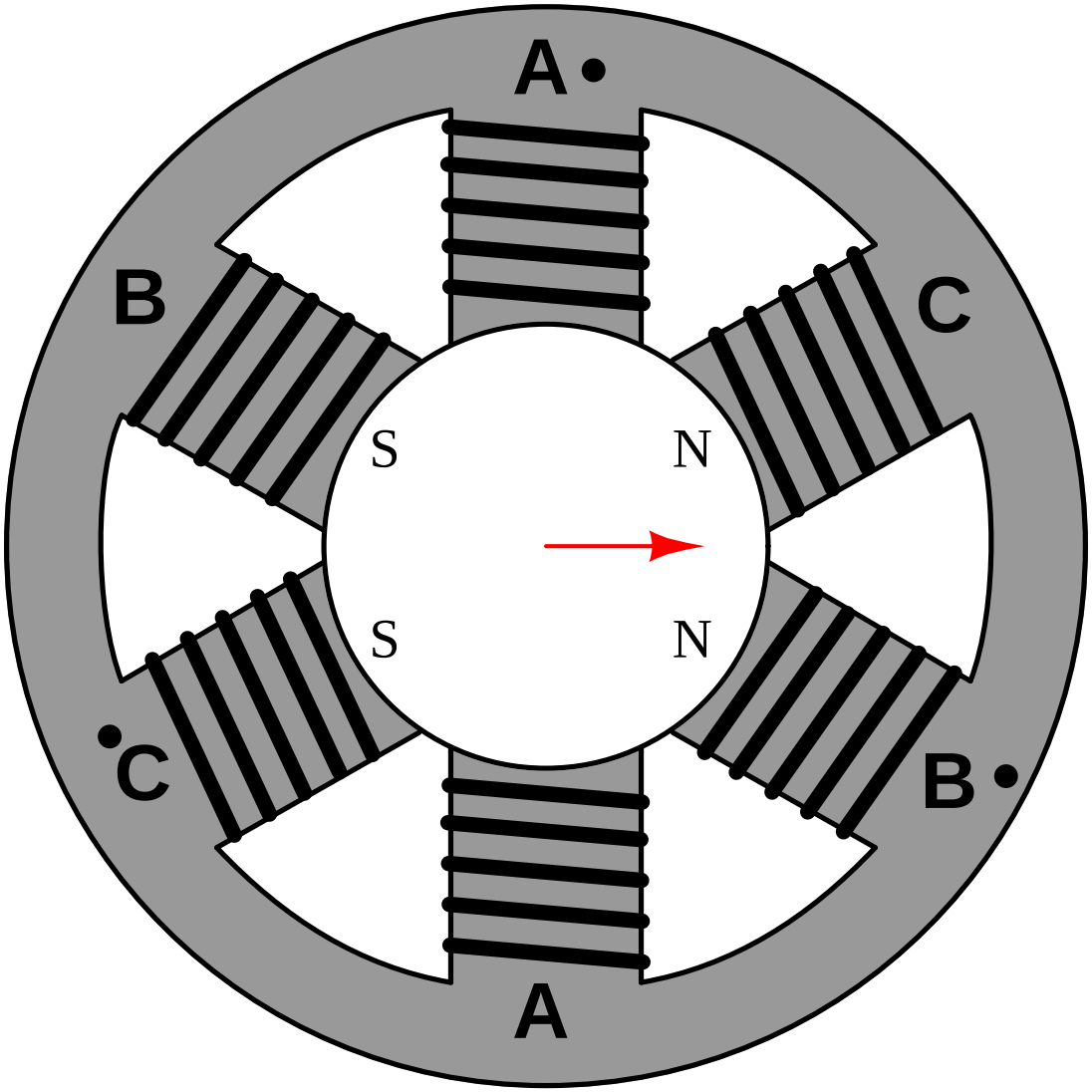
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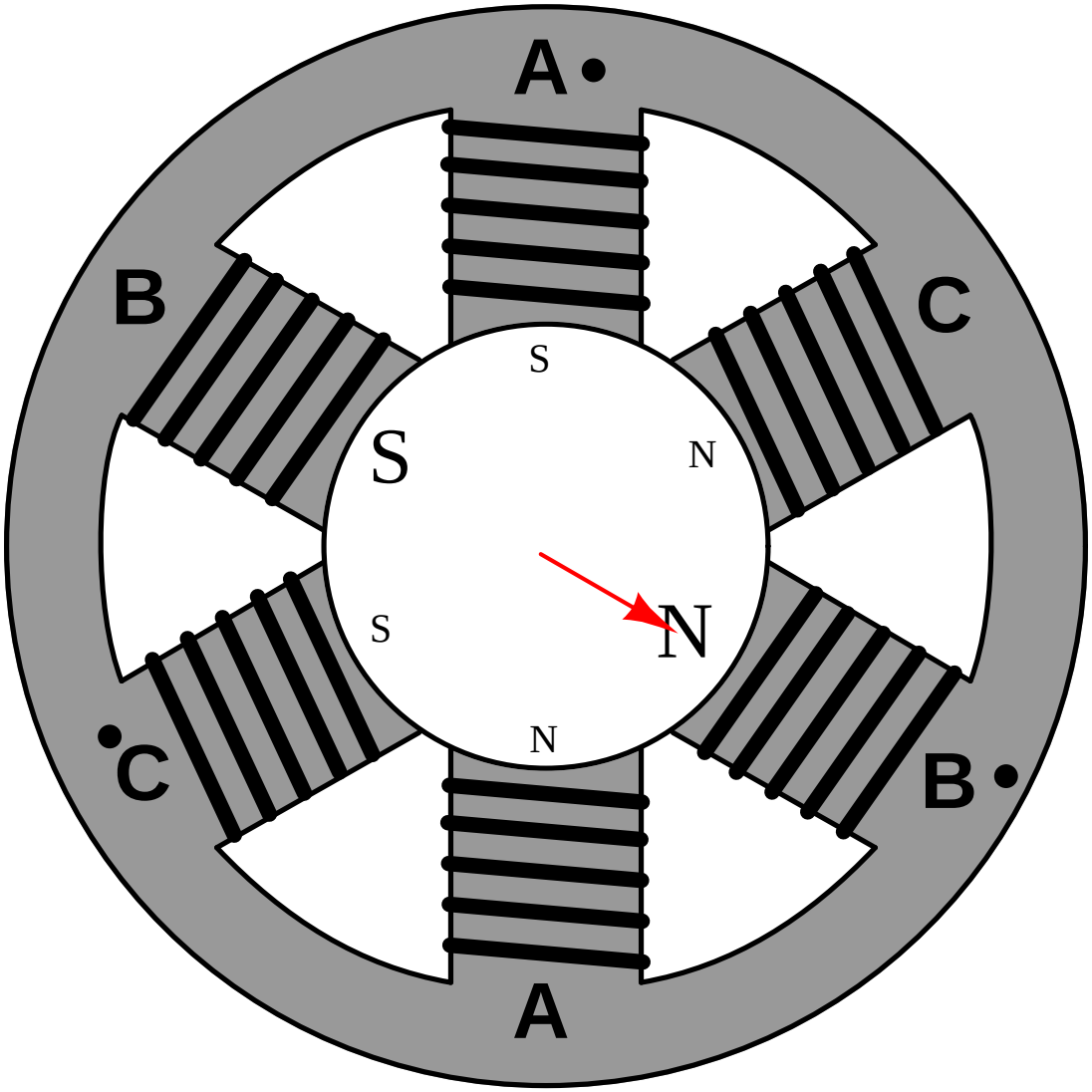
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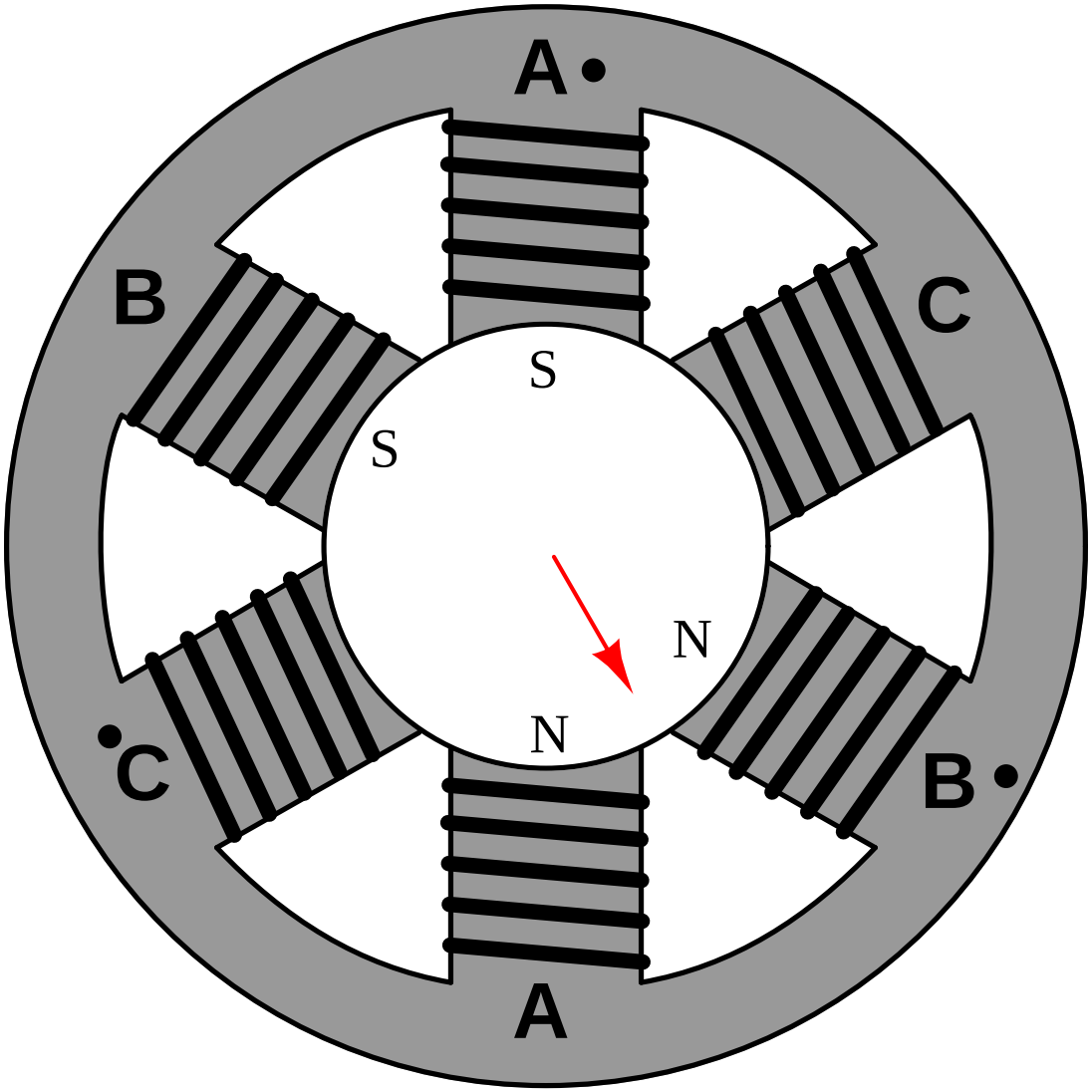
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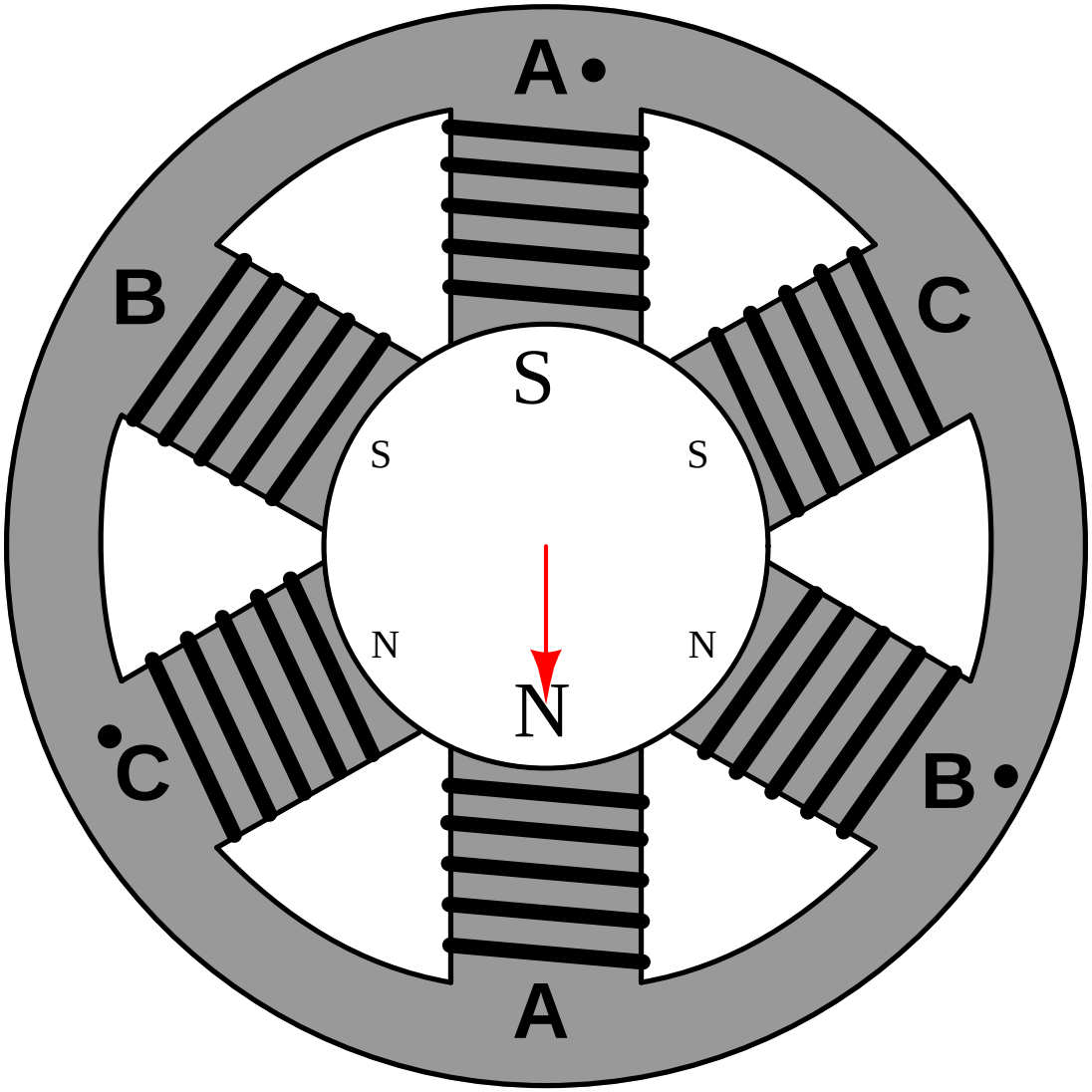
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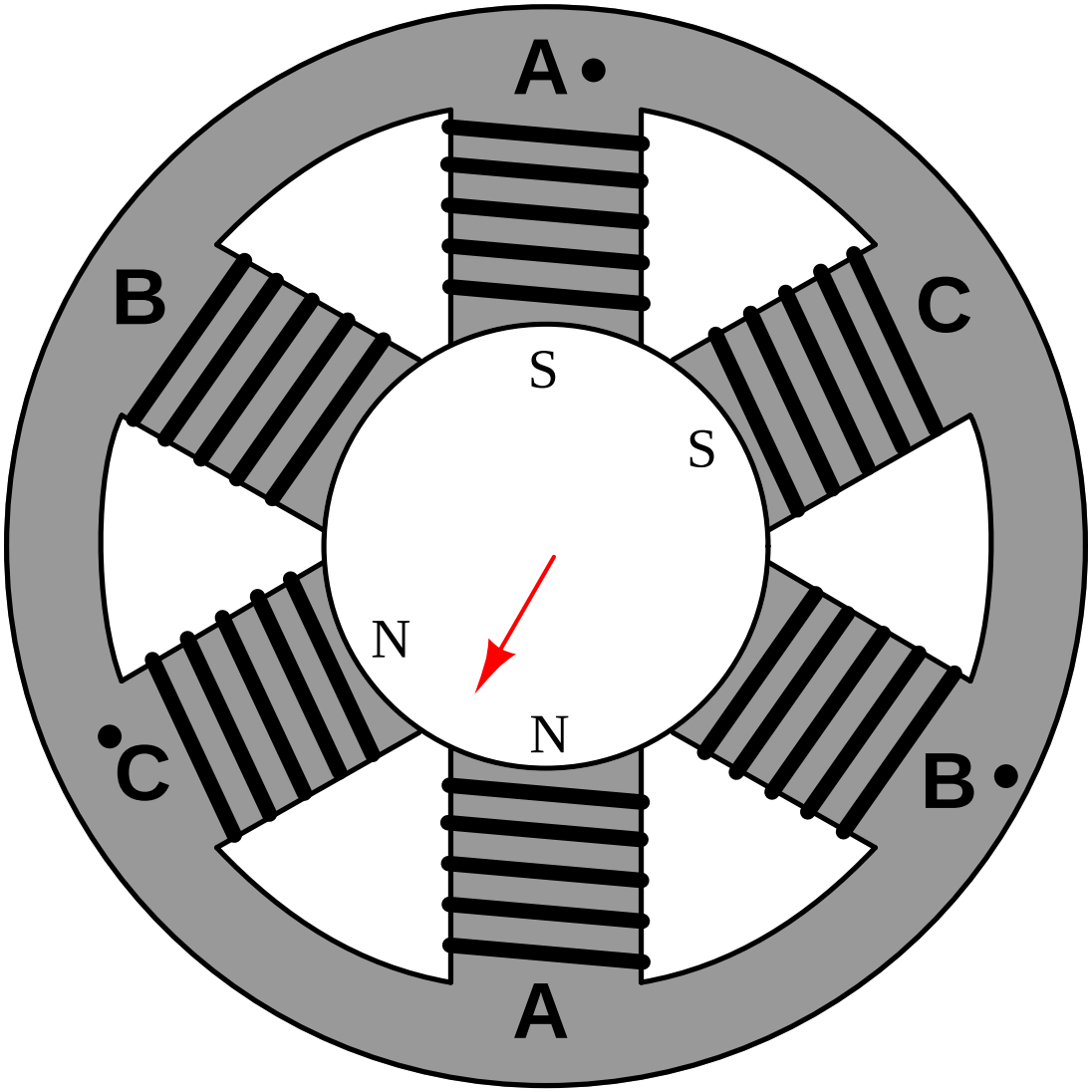
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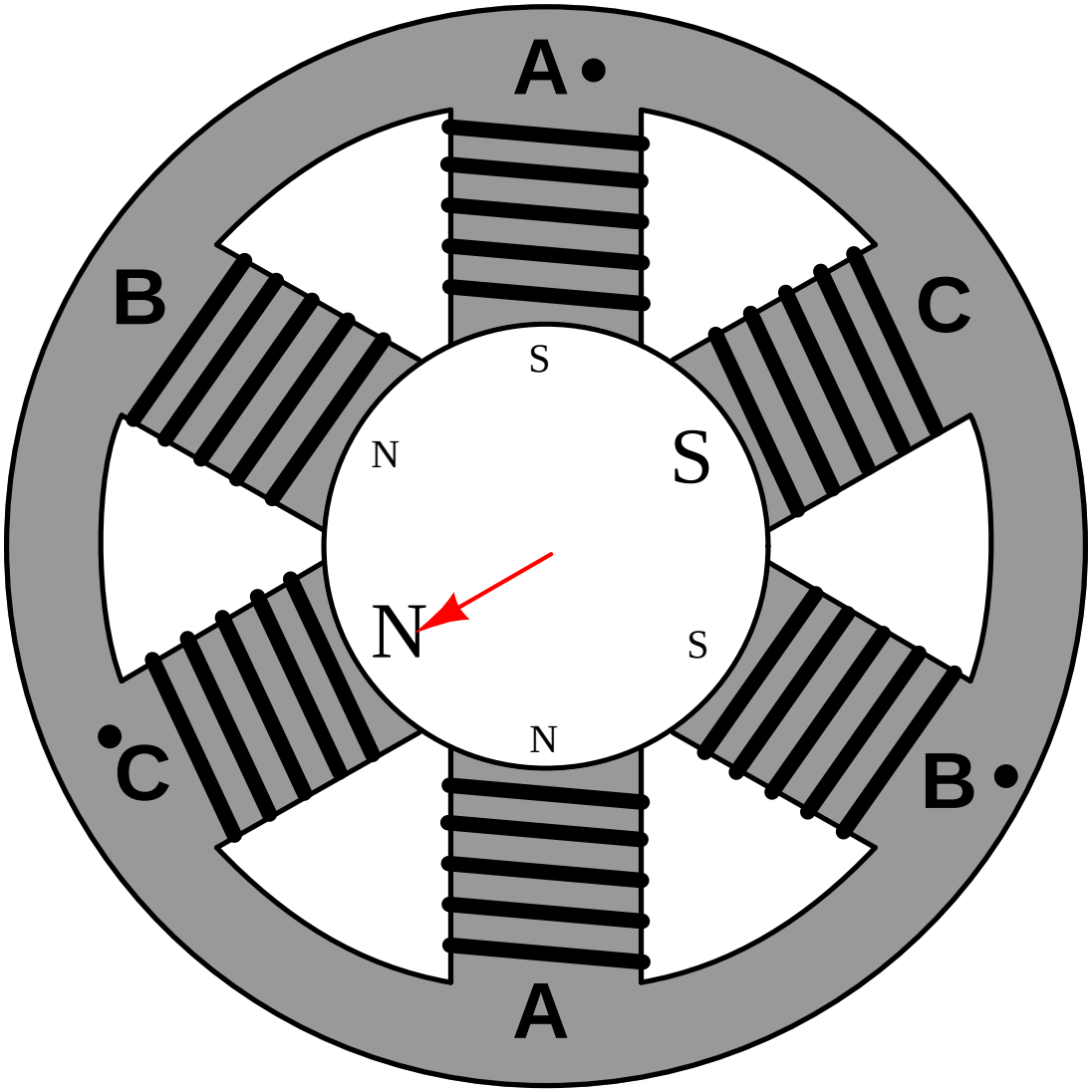
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Chapter 6

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

6.1 Conceptual reasoning

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

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

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

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

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

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

6.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

6.1.2 Foundational concepts

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

Energy

Conservation of Energy

First Law of Thermodynamics

Second Law of Thermodynamics

Rotating magnetic field

Synchronous operation

Lenz's Law

Induction motor

Slip speed

Upper and lower bound

Squirrel cage

Inrush current

Induction generator

Reversing a three-phase motor

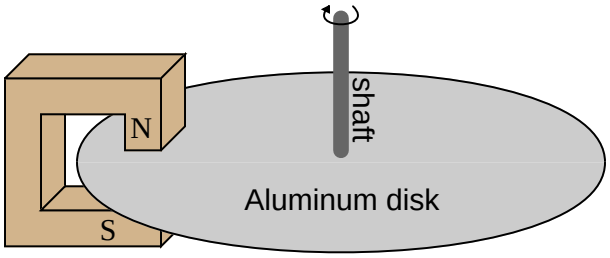
Single-phase induction motor operation

Single-phasing a polyphase motor

Energy efficiency

6.1.3 Drag magnet

Electromechanical watt-hour meters use an aluminum disk that is spun by an electric motor. To generate a constant "drag" on the disk necessary to limit its rotational speed, a strong magnet is placed in such a way that its lines of magnetic flux pass perpendicularly through the disk's thickness:



The disk itself need not be made of a ferromagnetic material in order for the magnet to create a "drag" force. It simply needs to be a good conductor of electricity.

Explain the phenomenon accounting for the drag effect, and also explain what would happen if the roles of magnet and disk were reversed: if the magnet were moved in a circle around the periphery of a stationary disk.

Challenges

- Explain how this relates to an AC induction motor.
- Sketch approximate paths of currents induced in the face of the aluminum disk as it spins in the direction shown.

6.1.4 Animation of rotating magnetic field

Refer to section 5.1 beginning on page 42 to view a flip-book animation showing how a set of three-phase stator windings create a rotating magnetic field vector. The red-colored arrow is the field vector, pointing in the direction of maximum magnetic "north". The "N" and "S" letters by each pole face grow and shrink in size proportional to the strength of each pole pair's magnetic field. Flip page-by-page through this animation to watch how the rotating magnetic field develops as a result of the three pole-pairs' energization by three-phase AC currents.

Examine just one of these pole-pairs (either A and A', or B and B', or C and C') and comment on how its magnetic field grows and shrinks.

Explain how the combined effect of the three pole-pairs creates the magnetic field vector.

Challenges

- Explain how to reverse the direction of a three-phase motor, and what this would look like when viewed in an animation such as this.

6.1.5 Electric water pump nameplate example

The nameplate on an electric water pump provides the following data:

- 110 V / 60 Hz
- Single-phase
- 1/2 HP
- 3400 RPM
- Max. Lift = 22 ft
- Max. Head = 115 ft
- Max. Flow = 12 Gal/min
- 1" outlet

Calculate the amount of line current expected in the motor's power wiring.

Identify whether this is an *induction* motor or a *synchronous* motor. If it were the *other* type of motor, how would the nameplate data differ?

Determine the number of *poles* in the stator of this motor. Does it have 2 poles, 4 poles, 6 poles, or more poles?

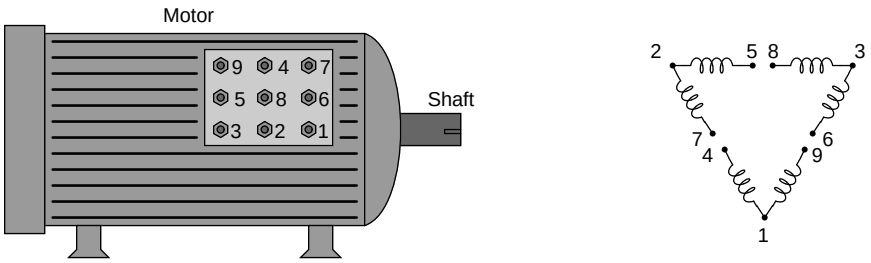
Calculate the *slip* speed of this motor.

Challenges

- Given the fact that we know this is a water pump, what do you suppose the Max. Lift and Max. Head ratings refer to?
- How fast would you expect this motor to spin if it were energized by 50 Hz instead of 60 Hz?

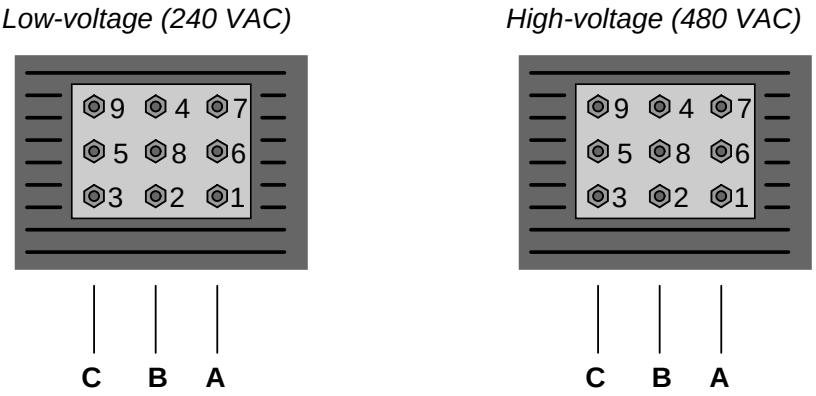
6.1.6 9-lead Delta motor connections

Three-phase electric motors are often equipped with a set of electrical terminals for configuring different voltage ranges and/or base speeds. Different configurations consist of different patterns of "jumper" wires connecting these terminals together. For example, here is an illustration of a three-phase electric motor with nine stud-and-nut terminals for connecting a set of six wire windings (coils) in two different configurations, one for low voltage (240 Volts AC) and one for high voltage (480 Volts AC):



When connecting the terminals for high-voltage operation, the goal is to have a "delta" configuration with two series-connected windings in each side of the triangle. When connecting the terminals for low-voltage operation, the goal is to have two parallel "delta" winding sets.

Sketch the proper power conductor and jumper connections for low-voltage operation and for high-voltage operation:

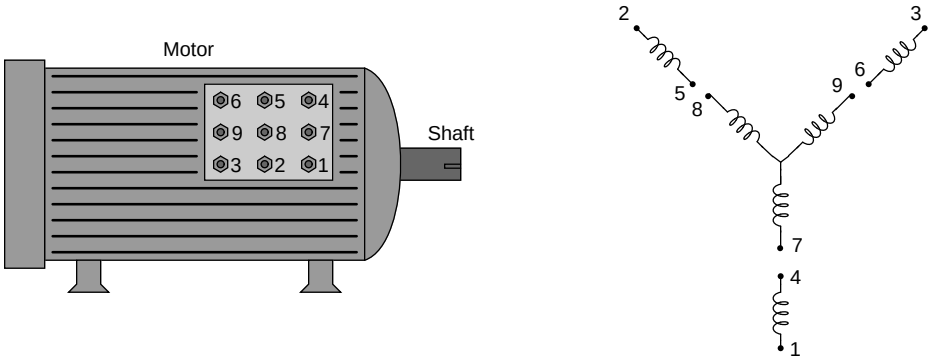


Challenges

- How is this similar to connecting the primary windings of a control power transformer for 240 Volts versus 480 Volts?

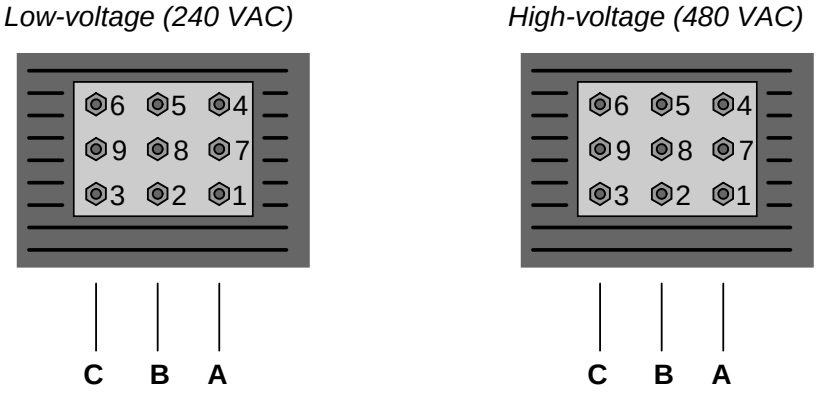
6.1.7 9-lead Wye motor connections

Three-phase electric motors are often equipped with a set of electrical terminals for configuring different voltage ranges and/or base speeds. Different configurations consist of different patterns of "jumper" wires connecting these terminals together. For example, here is an illustration of a three-phase electric motor with nine stud-and-nut terminals for connecting a set of six wire windings (coils) in two different configurations: one for low voltage (240 Volts AC) and one for high voltage (480 Volts AC):



When connecting the terminals for high-voltage operation, the goal is to have a "wye" configuration with two series-connected windings in each leg. When connecting the terminals for low-voltage operation, the goal is to have two parallel windings in each leg of the "wye".

Sketch the proper power conductor and jumper connections for low-voltage operation and for high-voltage operation:



Challenges

- How is this similar to connecting the primary windings of a control power transformer for 240 Volts versus 480 Volts?

6.2 Quantitative reasoning

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

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

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

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

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

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

6.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

6.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

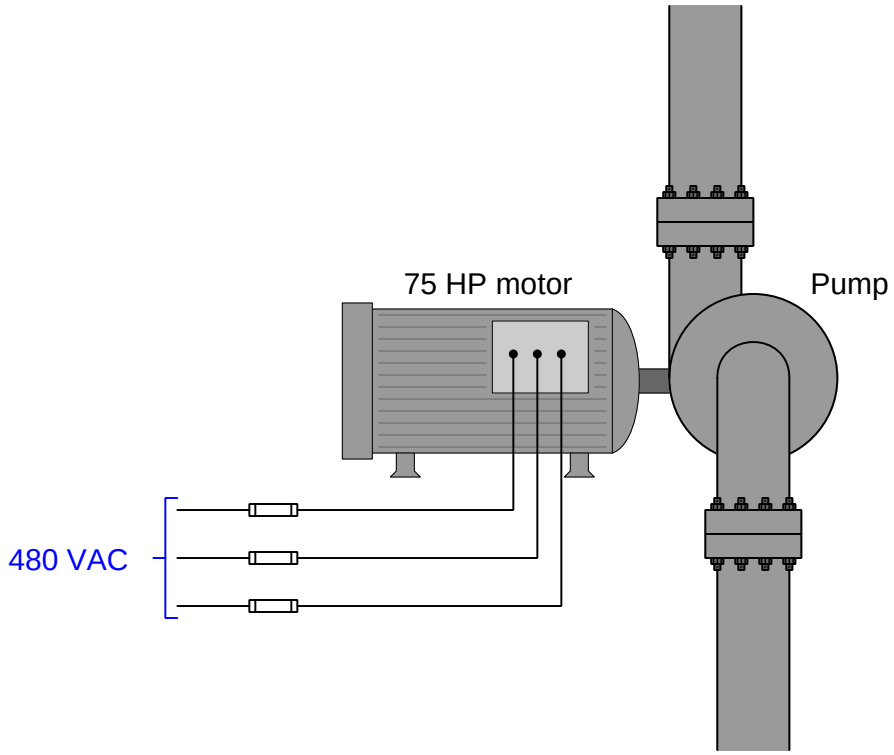
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

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

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

6.2.3 Electric water pump efficiency

Suppose a 75 horsepower electric motor powered by three-phase 480 VAC power is used to turn a pump:



Using the conversion factor of 746 watts to one horsepower, calculate the amount of AC line current drawn by the motor at full power (assuming perfect motor efficiency).

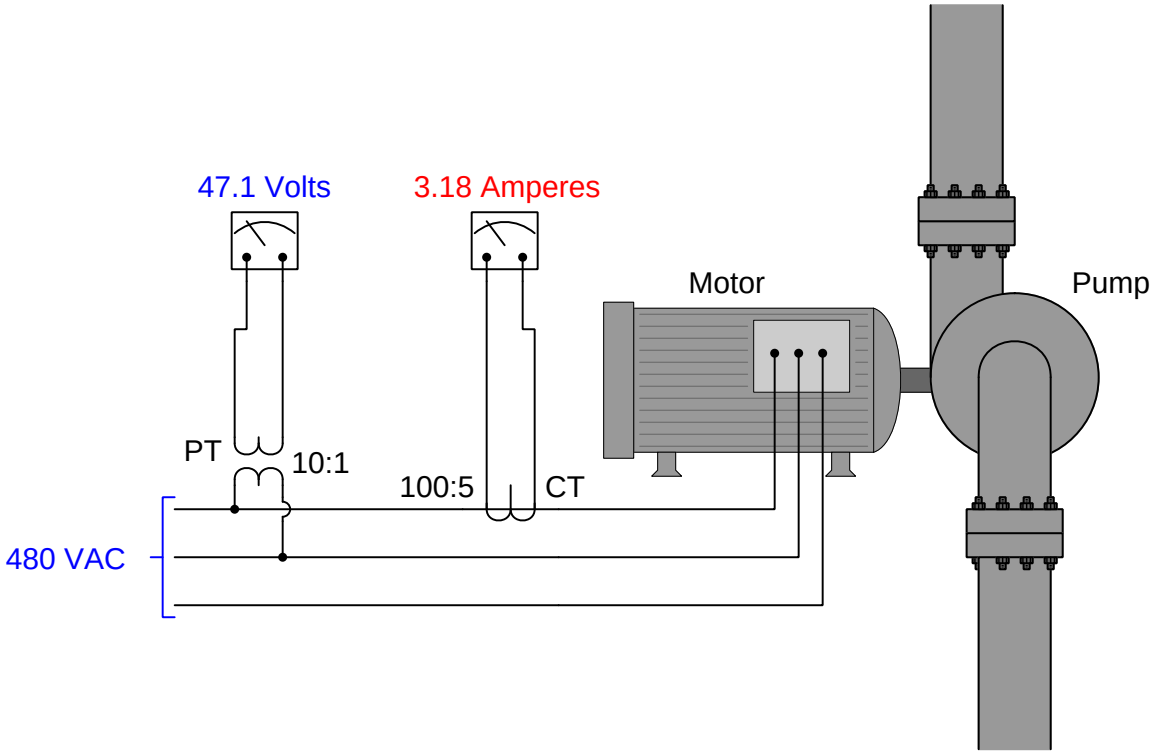
Now, suppose the motor is only 92% efficient instead of being perfect. How much line current will this realistic motor draw while delivering the same amount of mechanical power (75 HP) to the water pump?

Challenges

- Explain why we do not have to know whether the motor is internally wound Wye or Delta to calculate line current in either case.
- Given that we know energy is always conserved, what happens to the electrical energy represented by the 8% of motor inefficiency?

6.2.4 Motor power based on PT and CT measurements

Suppose a three-phase 480 VAC electric motor is used to turn a pump, while a pair of instrument transformers are connected to the motor's lines to provide voltage and current measurements at stepped-down values (i.e. safer for panel meters than full line voltage and full line current):



A *current transformer* (CT) with a ratio of 100:5 is used to measure line current. A *potential transformer* (PT) with a ratio of 10:1 is used to measure line voltage. Based on this measurement (assuming the motor presents a balanced load), calculate the following:

- The electrical power delivered to the motor (in horsepower)
- Assuming 93% efficiency, the mechanical power output by the motor (in horsepower)
- Assuming 93% efficiency, the heat dissipation of the motor (in kilowatts)

Challenges

- Identify any assumptions made in these calculations.

6.2.5 Stroboscope measuring motor speed

A *stroboscope* is a bright strobe light designed to be used for measuring the shaft speed of a rotating machine. When flashed at the same frequency as the shaft's rotation, the effect is to make a mark placed on the shaft appear as though it is stationary even while it is spinning. The flashing rate of a stroboscope is adjustable, usually by turning a small knob.

Suppose a stroboscope is used to "freeze" the rotation of an AC motor's shaft, and the flash frequency noted on the adjustment knob is 29.3 Hz. Calculate the speed of the motor shaft, and then determine both the number of poles inside this motor and whether or not it is an *induction* motor or a *synchronous* motor. Assume the motor's line frequency is 60 Hz.

Challenges

- Stroboscopes must be used with caution, because it is possible to be wrong by any whole-numbered factor. For example, a stroboscope flashing at *half* the frequency of the shaft's rotation will also result in the shaft appearing to stand still! Explain how you could properly adjust the flashing frequency of a stroboscope to ensure it is actually flashing once per shaft revolution.
- Explain how you could build your own stroboscope.

6.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

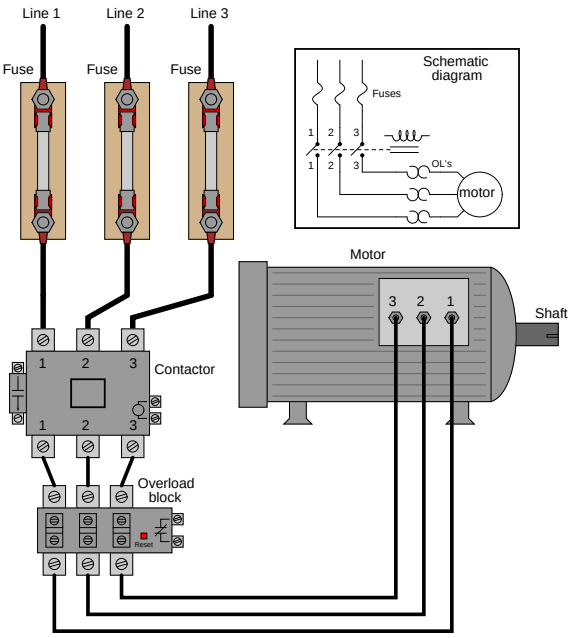
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

6.3.1 Humming motor

Examine this three-phase motor control circuit (sometimes referred to as a "bucket"), where fuses protect against overcurrent faults, a three-pole relay (called a *contactor*) turns power on and off to the motor, and a set of overload heaters detect mild overcurrent conditions. Control circuit wiring has been omitted for simplicity's sake. Only the power wiring is shown:



After years of faithful service, one day this motor refuses to start. It makes a "humming" sound when the contactor is energized (relay contacts close), but it does not turn. A mechanic checks it out and determines that the shaft is not seized, but is free to turn. The problem must be electrical in nature!

You are called to investigate. Using a clamp-on ammeter, you measure the current through each of the lines (immediately after each fuse) as another start is once again attempted. You then record the three current measurements:

Line	Current
1	52.7 A
2	51.9 A
3	0.0 A

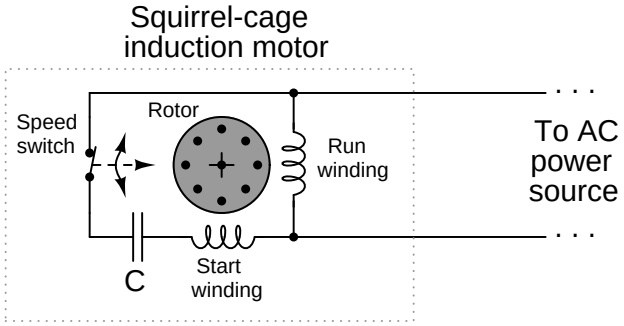
Determine at least two possible faults, either one fully capable of causing the motor's refusal to start and the three current measurements taken. Then, decide what your next measurement(s) will be to isolate the exact location and nature of the fault.

Challenges

- Is there a way we could have determined a lack of current in line 3 without the use of a clamp-on ammeter, using a multimeter incapable of directly measuring current over 10 Amperes?

6.3.2 Effects of faults in a capacitor-start motor

Examine the following schematic diagram for a single-phase "squirrel-cage" AC induction motor:



Predict how this motor will behave for each of the following faults (considered independently):

- Capacitor failed open
- Capacitor failed shorted
- Speed switch failed open
- Speed switch failed shorted
- Run winding failed open
- Run windings failed shorted

Challenges

- Explain the purpose of the capacitor in this motor.

Chapter 7

Projects and Experiments

The following project and experiment descriptions outline things you can build to help you understand circuits. With any real-world project or experiment there exists the potential for physical harm. *Electricity can be very dangerous in certain circumstances, and you should follow proper safety precautions at all times!*

7.1 Recommended practices

This section outlines some recommended practices for all circuits you design and construct.

7.1.1 Safety first!

Electricity, when passed through the human body, causes uncomfortable sensations and in large enough measures[1] will cause muscles to involuntarily contract. The overriding of your nervous system by the passage of electrical current through your body is particularly dangerous in regard to your heart, which is a vital muscle. Very large amounts of current can produce serious internal burns in addition to all the other effects.

Cardio-pulmonary resuscitation (CPR) is the standard first-aid for any victim of electrical shock. This is a very good skill to acquire if you intend to work with others on dangerous electrical circuits. You should never perform tests or work on such circuits unless someone else is present who is proficient in CPR.

As a general rule, any voltage in excess of 30 Volts poses a definitive electric shock hazard, because beyond this level human skin does not have enough resistance to safely limit current through the body. "Live" work of any kind with circuits over 30 volts should be avoided, and if unavoidable should only be done using electrically insulated tools and other protective equipment (e.g. insulating shoes and gloves). If you are unsure of the hazards, or feel unsafe at any time, stop all work and distance yourself from the circuit!

A policy I strongly recommend for students learning about electricity is to *never come into electrical contact*[2] *with an energized conductor, no matter what the circuit's voltage*[3] *level!* Enforcing this policy may seem ridiculous when the circuit in question is powered by a single battery smaller than the palm of your hand, but it is precisely this instilled habit which will save a person from bodily harm when working with more dangerous circuits. Experience has taught me that students who learn early on to be careless with safe circuits have a tendency to be careless later with dangerous circuits!

In addition to the electrical hazards of shock and burns, the construction of projects and running of experiments often poses other hazards such as working with hand and power tools, potential

[1] Professor Charles Dalziel published a research paper in 1961 called "The Deleterious Effects of Electric Shock" detailing the results of electric shock experiments with both human and animal subjects. The threshold of perception for human subjects holding a conductor in their hand was in the range of 1 milliampere of current (less than this for alternating current, and generally less for female subjects than for male). Loss of muscular control was exhibited by half of Dalziel's subjects at less than 10 milliamperes alternating current. Extreme pain, difficulty breathing, and loss of all muscular control occurred for over 99% of his subjects at direct currents less than 100 milliamperes and alternating currents less than 30 milliamperes. In summary, it doesn't require much electric current to induce painful and even life-threatening effects in the human body! Your first and best protection against electric shock is maintaining an insulating barrier between your body and the circuit in question, such that current from that circuit will be unable to flow through your body.

[2] By "electrical contact" I mean either directly touching an energized conductor with any part of your body, or indirectly touching it through a conductive tool. The only physical contact you should ever make with an energized conductor is via an electrically insulated tool, for example a screwdriver with an electrically insulated handle, or an insulated test probe for some instrument.

[3] Another reason for consistently enforcing this policy, even on low-voltage circuits, is due to the dangers that even some low-voltage circuits harbor. A single 12 Volt automobile battery, for example, can cause a surprising amount of damage if short-circuited simply due to the high current levels (i.e. very low internal resistance) it is capable of, even though the voltage level is too low to cause a shock through the skin. Mechanics wearing metal rings, for example, are at risk from severe burns if their rings happen to short-circuit such a battery! Furthermore, even when working on circuits that are simply too low-power (low voltage and low current) to cause any bodily harm, touching them while energized can pose a threat to the circuit components themselves. In summary, it's generally wise (and *always* a good habit to build) to "power down" *any* circuit before making contact between it and your body.

contact with high temperatures, potential chemical exposure, etc. You should never proceed with a project or experiment if you are unaware of proper tool use or lack basic protective measures (e.g. personal protective equipment such as safety glasses) against such hazards.

Some other safety-related practices should be followed as well:

- All power conductors extending outward from the project must be *firmly* strain-relieved (e.g. "cord grips" used on line power cords), so that an accidental tug or drop will not compromise circuit integrity.
- All electrical connections must be sound and appropriately made (e.g. soldered wire joints rather than twisted-and-taped; terminal blocks rather than solderless breadboards for high-current or high-voltage circuits). Use "touch-safe" terminal connections with recessed metal parts to minimize risk of accidental contact.
- Always provide overcurrent protection in any circuit you build. *Always.* This may be in the form of a fuse, a circuit breaker, and/or an electronically current-limited power supply.
- Always ensure circuit conductors are rated for more current than the overcurrent protection limit. *Always.* A fuse does no good if the wire or printed circuit board trace will "blow" before it does!
- Always bond metal enclosures to Earth ground for any line-powered circuit. *Always.* Ensuring an equipotential state between the enclosure and Earth by making the enclosure electrically common with Earth ground ensures no electric shock can occur simply by one's body bridging between the Earth and the enclosure.
- Avoid building a high-energy circuit when a low-energy circuit will suffice. For example, I always recommend beginning students power their first DC resistor circuits using small batteries rather than with line-powered DC power supplies. The intrinsic energy limitations of a dry-cell battery make accidents highly unlikely.
- Use line power receptacles that are GFCI (Ground Fault Current Interrupting) to help avoid electric shock from making accidental contact with a "hot" line conductor.
- Always wear eye protection when working with tools or live systems having the potential to eject material into the air. Examples of such activities include soldering, drilling, grinding, cutting, wire stripping, working on or near energized circuits, etc.
- Always use a step-stool or stepladder to reach high places. Never stand on something not designed to support a human load.
- When in doubt, *ask an expert.* If anything even seems remotely unsafe to you, do not proceed without consulting a trusted person fully knowledgeable in electrical safety.

7.1.2 Other helpful tips

Experience has shown the following practices to be very helpful, especially when students make their own component selections, to ensure the circuits will be well-behaved:

- Avoid resistor values less than 1 kΩ or greater than 100 kΩ, unless such values are definitely necessary[4]. Resistances below 1 kΩ may draw excessive current if directly connected to a voltage source of significant magnitude, and may also complicate the task of accurately measuring current since any ammeter's non-zero resistance inserted in series with a low-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Resistances above 100 kΩ may complicate the task of measuring voltage since any voltmeter's finite resistance connected in parallel with a high-value circuit resistor will significantly alter the total resistance and thereby skew the measurement. Similarly, AC circuit impedance values should be between 1 kΩ and 100 kΩ, and for all the same reasons.

- Ensure all electrical connections are low-resistance and physically rugged. For this reason, one should avoid *compression splices* (e.g. "butt" connectors), solderless breadboards[5], and wires that are simply twisted together.

- Build your circuit with **testing** in mind. For example, provide convenient connection points for test equipment (e.g. multimeters, oscilloscopes, signal generators, logic probes).

- Design permanent projects with **maintenance** in mind. The more convenient you make maintenance tasks, the more likely they will get done.

- **Always document and save your work**. Circuits lacking schematic diagrams are more difficult to troubleshoot than documented circuits. Similarly, circuit construction is simpler when a schematic diagram precedes construction. Experimental results are easier to interpret when comprehensively recorded. Consider modern videorecording technology for this purpose where appropriate.

- **Record your steps** when troubleshooting. **Talk to yourself** when solving problems. These simple steps clarify thought and simplify identification of errors.

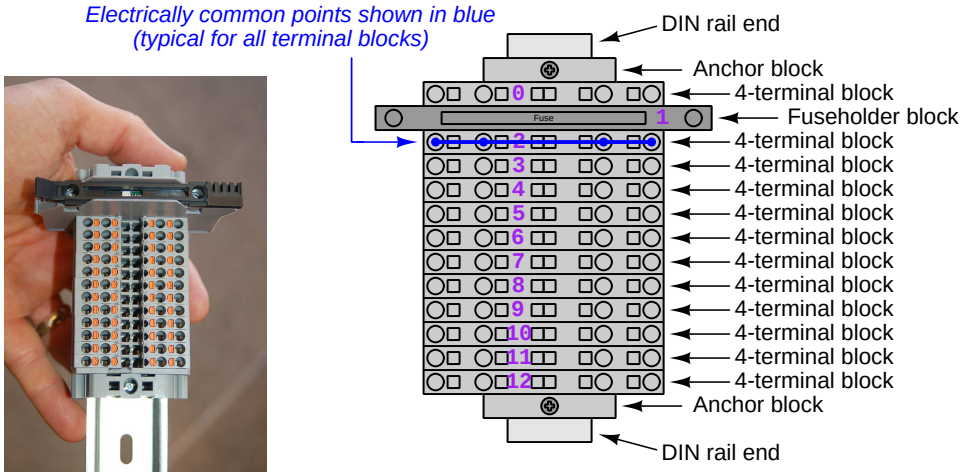
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary resistor value much greater than 100 kΩ is an electrostatic *drain resistor* used to dissipate stored electric charges from body capacitance for the sake of preventing damage to sensitive semiconductor components, while also preventing a path for current that could be dangerous to the person (i.e. shock).

[5] Admittedly, solderless breadboards are very useful for constructing complex electronic circuits with many components, especially DIP-style integrated circuits (ICs), but they tend to give trouble with connection integrity after frequent use. An alternative for projects using low counts of ICs is to solder IC sockets into prototype printed circuit boards (PCBs) and run wires from the soldered pins of the IC sockets to terminal blocks where reliable temporary connections may be made.

7.1.3 Terminal blocks for circuit construction

Terminal blocks are the standard means for making electric circuit connections in industrial systems, and are also quite useful for student-built experiments, providing a robust alternative to solderless breadboards[6]. Terminal blocks provide highly reliable connections rated for significant voltage and current magnitudes, and they force the builder to think carefully about component placement which is an important mental practice. Terminal blocks designed to mount on standard 35 mm DIN rail[7] come in many types and capabilities.

Every student of electricity should build their own terminal block array consisting of several terminal blocks where each block has at least 4 connection points all electrically common to each other[8] and at least one terminal block that is a fuse holder for overcurrent protection. A pair of anchoring blocks hold all terminal blocks securely on the DIN rail, preventing them from sliding off the rail. Each of the terminals should bear a unique number starting from 0. An example is shown in the following photograph and illustration:



Screwless terminal blocks (using internal spring clips to clamp wire and component lead ends) are preferred over screw-based terminal blocks, as they reduce assembly and disassembly time, and also minimize repetitive wrist stress from twisting screwdrivers. Some screwless terminal blocks require the use of a special tool to release the spring clip, while others such as the Phoenix Contact model 3211019 blocks shown in the photograph provide buttons[9] for this task which may be pressed using the tip of any suitable tool such as a small screwdriver or multimeter test probe tip.

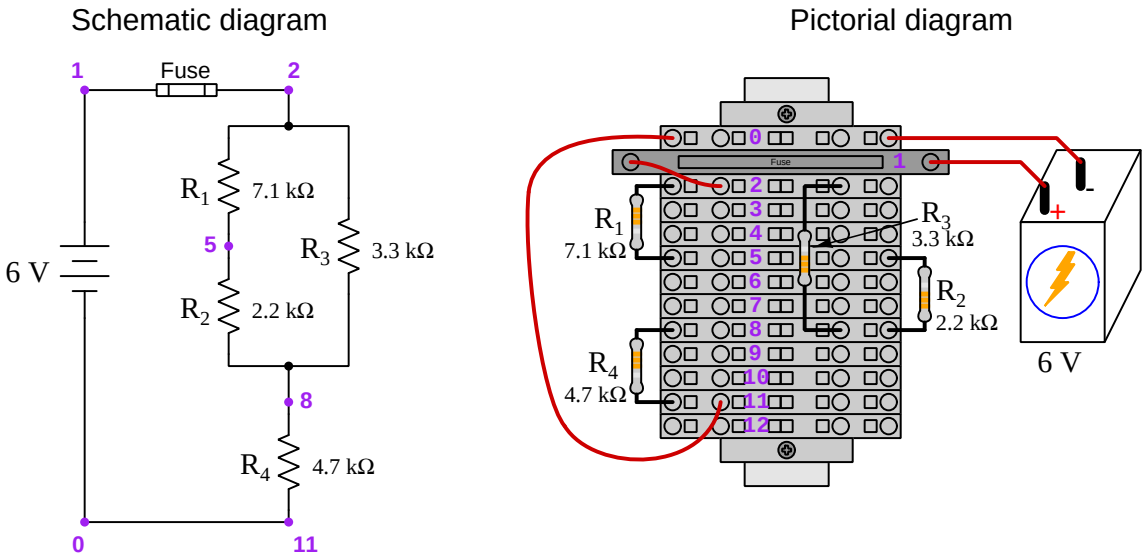
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use wires to connect the socket pins to terminal blocks. This also accommodates *surface-mount* components, which solderless breadboards do not.

[7] DIN rail is a metal rail designed to serve as a mounting point for a wide range of electrical and electronic devices such as terminal blocks, fuses, circuit breakers, relay sockets, power supplies, data acquisition hardware, etc.

[8] Sometimes referred to as *equipotential*, *same-potential*, or *potential distribution* terminal blocks.

[9] The small orange-colored squares seen in the above photograph are buttons for this purpose, and may be actuated by pressing with any tool of suitable size.

The following example shows how such a terminal block array might be used to construct a series-parallel resistor circuit consisting of four resistors and a battery:



Numbering on the terminal blocks provides a very natural translation to SPICE[10] netlists, where component connections are identified by terminal number:

```
* Series-parallel resistor circuit
v1 1 0 dc 6
r1 2 5 7100
r2 5 8 2200
r3 2 8 3300
r4 8 11 4700
rfuse 1 2 0.01
rwire 0 11 0.01
.op
.end
```

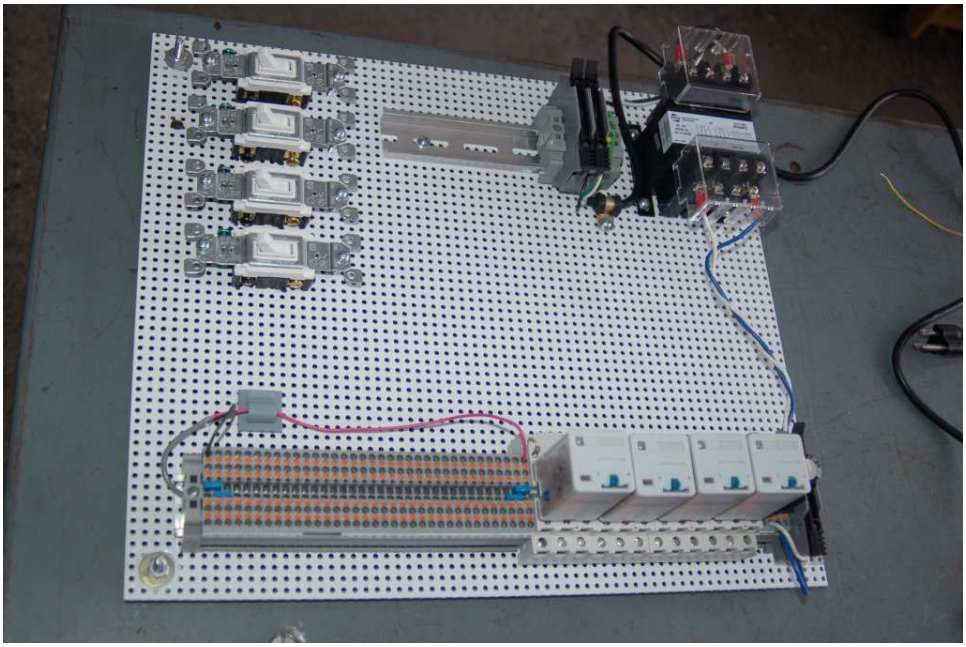
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low value of 0.01 Ohm appropriate to their real-life resistance values.

Listing all components and wires along with their numbered terminals happens to be a useful documentation method for any circuit built on terminal blocks, independent of SPICE. Such a

[10] SPICE is computer software designed to analyze electrical and electronic circuits. Circuits are described for the computer in the form of *netlists* which are text files listing each component type, connection node numbers, and component values.

"wiring sequence" may be thought of as a *non-graphical description* of an electric circuit, and is exceptionally easy to follow.

An example of a more elaborate terminal block array is shown in the following photograph, with terminal blocks and "ice-cube" style electromechanical relays mounted to DIN rail, which is turn mounted to a perforated subpanel[11]. This "terminal block board" hosts an array of thirty five undedicated terminal block sections, four SPDT toggle switches, four DPDT "ice-cube" relays, a step-down control power transformer, bridge rectifier and filtering capacitor, and several fuses for overcurrent protection:



Four plastic-bottomed "feet" support the subpanel above the benchtop surface, and an unused section of DIN rail stands ready to accept other components. Safety features include electrical bonding of the AC line power cord's ground to the metal subpanel (and all metal DIN rails), mechanical strain relief for the power cord to isolate any cord tension from wire connections, clear plastic finger guards covering the transformer's screw terminals, as well as fused overcurrent protection for the 120 Volt AC line power and the transformer's 12 Volt AC output. The perforated holes happen to be on $\frac{1}{4}$ inch centers with a diameter suitable for tapping with 6-32 machine screw threads, their presence making it very easy to attach other sections of DIN rail, printed circuit boards, or specialized electrical components directly to the grounded metal subpanel. Such a "terminal block board" is an inexpensive[12] yet highly flexible means to construct physically robust circuits using industrial wiring practices.

[11] An electrical *subpanel* is a thin metal plate intended for mounting inside an electrical enclosure. Components are attached to the subpanel, and the subpanel in turn bolts inside the enclosure. Subpanels allow circuit construction outside the confines of the enclosure, which speeds assembly. In this particular usage there is no enclosure, as the subpanel is intended to be used as an open platform for the convenient construction of circuits on a benchtop by students. In essence, this is a modern version of the traditional *breadboard* which was literally a wooden board such as might be used for cutting loaves of bread, but which early electrical and electronic hobbyists used as platforms for the construction of circuits.

[12] At the time of this writing (2019) the cost to build this board is approximately $250 US dollars.

7.1.4 Conducting experiments

An *experiment* is an exploratory act, a test performed for the purpose of assessing some proposition or principle. Experiments are the foundation of the *scientific method*, a process by which careful observation helps guard against errors of speculation. All good experiments begin with an *hypothesis*, defined by the American Heritage Dictionary of the English Language as:

> An assertion subject to verification or proof, as (a) A proposition stated as a basis for argument or reasoning. (b) A premise from which a conclusion is drawn. (c) A conjecture that accounts, within a theory or ideational framework, for a set of facts and that can be used as a basis for further investigation.

Stated plainly, an hypothesis is an *educated guess* about cause and effect. The correctness of this initial guess matters little, because any well-designed experiment will reveal the truth of the matter. In fact, *incorrect* hypotheses are often the most valuable because the experiments they engender lead us to surprising discoveries. One of the beautiful aspects of science is that it is more focused on the process of *learning* than about the status of *being correct*[13]. In order for an hypothesis to be valid, it must be testable[14], which means it must be a claim possible to refute given the right data. Hypotheses impossible to critique are useless.

Once an hypothesis has been formulated, an experiment must be designed to test that hypothesis. A well-designed experiment requires careful regulation of all relevant variables, both for personal safety and for prompting the hypothesized results. If the effects of one particular variable are to be tested, the experiment must be run multiple times with different values of (only) that particular variable. The experiment set up with the "baseline" variable set is called the *control*, while the experiment set up with different value(s) is called the *test* or *experimental*.

For some hypotheses a viable alternative to a physical experiment is a *computer-simulated experiment* or even a *thought experiment*. Simulations performed on a computer test the hypothesis against the physical laws encoded within the computer simulation software, and are particularly useful for students learning new principles for which simulation software is readily available[15].

[13] Science is more about clarifying our view of the universe through a systematic process of error detection than it is about proving oneself to be right. Some scient*ists* may happen to have large egos – and this may have more to do with the ways in which large-scale scientific research is *funded* than anything else – but scientific *method* itself is devoid of ego, and if embraced as a practical philosophy is quite an effective stimulant for humility. Within the education system, scientific method is particularly valuable for helping students break free of the crippling fear of *being wrong*. So much emphasis is placed in formal education on assessing correct retention of facts that many students are fearful of saying or doing anything that might be perceived as a mistake, and of course making mistakes (i.e. having one's hypotheses disproven by experiment) is an indispensable tool for learning. Introducing science in the classroom – *real* science characterized by individuals forming actual hypotheses and testing those hypotheses by experiment – helps students become self-directed learners.

[14] This is the principle of *falsifiability*: that a scientific statement has value only insofar as it is liable to disproof given the requisite experimental evidence. Any claim that is unfalsifiable – that is, a claim which can *never* be disproven by any evidence whatsoever – could be completely wrong and we could never know it.

[15] A very pertinent example of this is learning how to analyze electric circuits using simulation software such as SPICE. A typical experimental cycle would proceed as follows: (1) Find or invent a circuit to analyze; (2) Apply your analytical knowledge to that circuit, predicting all voltages, currents, powers, etc. relevant to the concepts you are striving to master; (3) Run a simulation on that circuit, collecting "data" from the computer when complete; (4) Evaluate whether or not your hypotheses (i.e. predicted voltages, currents, etc.) agree with the computer-generated results; (5) If so, your analyses are (provisionally) correct – if not, examine your analyses and the computer simulation again to determine the source of error; (6) Repeat this process as many times as necessary until you achieve mastery.

Thought experiments are useful for detecting inconsistencies within your own understanding of some subject, rather than testing your understanding against physical reality.

Here are some general guidelines for conducting experiments:

- The clearer and more specific the hypothesis, the better. Vague or unfalsifiable hypotheses are useless because they will fit *any* experimental results, and therefore the experiment cannot teach you anything about the hypothesis.
- Collect as much data (i.e. information, measurements, sensory experiences) generated by an experiment as is practical. This includes the time and date of the experiment, too!
- *Never* discard or modify data gathered from an experiment. If you have reason to believe the data is unreliable, write notes to that effect, but never throw away data just because you think it is untrustworthy. It is quite possible that even "bad" data holds useful information, and that someone else may be able to uncover its value even if you do not.
- Prioritize *quantitative* data over *qualitative* data wherever practical. Quantitative data is more specific than qualitative, less prone to subjective interpretation on the part of the experimenter, and amenable to an arsenal of analytical methods (e.g. statistics).
- Guard against your own bias(es) by making your experimental results available to others. This allows other people to scrutinize your experimental design and collected data, for the purpose of detecting and correcting errors you may have missed. Document your experiment such that others may independently replicate it.
- Always be looking for sources of error. No physical measurement is perfect, and so it is impossible to achieve *exact* values for any variable. Quantify the amount of uncertainty (i.e. the "tolerance" of errors) whenever possible, and be sure your hypothesis does not depend on precision better than this!
- Always remember that scientific confirmation is provisional – no number of "successful" experiments will prove an hypothesis true for all time, but a single experiment can disprove it. Put into simpler terms, *truth is elusive but error is within reach.*
- Remember that scientific method is about *learning*, first and foremost. An unfortunate consequence of scientific triumph in modern society is that science is often viewed by non-practitioners as an unerring source of truth, when in fact science is an ongoing process of challenging existing ideas to probe for errors and oversights. This is why it is perfectly acceptable to have a failed hypothesis, and why the only truly failed experiment is one where nothing was learned.

The following is an example of a well-planned and executed experiment, in this case a physical experiment demonstrating Ohm's Law.

```
Planning Time/Date = 09:30 on 12 February 2019

HYPOTHESIS: the current through any resistor should be exactly proportional
to the voltage impressed across it.

PROCEDURE: connect a resistor rated 1 k Ohm and 1/4 Watt to a variable-voltage
DC power supply.  Use an ammeter in series to measure resistor current and
a voltmeter in parallel to measure resistor voltage.

RISKS AND MITIGATION: excessive power dissipation may harm the resistor and/
or pose a burn hazard, while excessive voltage poses an electric shock hazard.
30 Volts is a safe maximum voltage for laboratory practices, and according to
Joule's Law a 1000 Ohm resistor will dissipate 0.25 Watts at 15.81 Volts
(P = V^2 / R), so I will remain below 15 Volts just to be safe.

Experiment Time/Date = 10:15 on 12 February 2019

DATA COLLECTED:
  (Voltage)    (Current)         (Voltage)   (Current)
   0.000 V   =  0.000 mA          8.100    =  7.812 mA
   2.700 V   =  2.603 mA          10.00 V  =  9.643 mA
   5.400 V   =  5.206 mA          14.00 V  =  13.49 mA

Analysis Time/Date = 10:57 on 12 February 2019

ANALYSIS: current definitely increases with voltage, and although I expected
exactly one milliAmpere per Volt the actual current was usually less than
that.  The voltage/current ratios ranged from a low of 1036.87 (at 8.1 Volts)
to a high of 1037.81 (at 14 Volts), but this represents a variance of only
-0.0365% to +0.0541% from the average, indicating a very consistent
proportionality -- results consistent with Ohm's Law.

ERROR SOURCES: one major source of error is the resistor's value itself.  I
did not measure it, but simply assumed color bands of brown-black-red meant
exactly 1000 Ohms.  Based on the data I think the true resistance is closer
to 1037 Ohms.  Another possible explanation is multimeter calibration error.
However, neither explains the small positive and negative variances from the
average.  This might be due to electrical noise, a good test being to repeat
the same experiment to see if the variances are the same or different.  Noise
should generate slightly different results every time.
```

The following is an example of a well-planned and executed *virtual* experiment, in this case demonstrating Ohm's Law using a computer (SPICE) simulation.

```
Planning Time/Date = 12:32 on 14 February 2019

HYPOTHESIS: for any given resistor, the current through that resistor should be
exactly proportional to the voltage impressed across it.

PROCEDURE: write a SPICE netlist with a single DC voltage source and single
1000 Ohm resistor, then use NGSPICE version 26 to perform a "sweep" analysis
from 0 Volts to 25 Volts in 5 Volt increments.

    * SPICE circuit
    v1 1 0 dc
    r1 1 0 1000
    .dc v1 0 25 5
    .print dc v(1) i(v1)
    .end

RISKS AND MITIGATION: none.

DATA COLLECTED:
       DC transfer characteristic  Thu Feb 14 13:05:08  2019
    ------------------------------------------------------------
    Index   v-sweep         v(1)            v1#branch
    ------------------------------------------------------------
    0       0.000000e+00    0.000000e+00    0.000000e+00
    1       5.000000e+00    5.000000e+00    -5.00000e-03
    2       1.000000e+01    1.000000e+01    -1.00000e-02
    3       1.500000e+01    1.500000e+01    -1.50000e-02
    4       2.000000e+01    2.000000e+01    -2.00000e-02
    5       2.500000e+01    2.500000e+01    -2.50000e-02

Analysis Time/Date = 13:06 on 14 February 2019

ANALYSIS: perfect agreement between data and hypothesis -- current is precisely
1/1000 of the applied voltage for all values.  Anything other than perfect
agreement would have probably meant my netlist was incorrect.  The negative
current values surprised me, but it seems this is just how SPICE interprets
normal current through a DC voltage source.

ERROR SOURCES: none.
```

As gratuitous as it may seem to perform experiments on a physical law as well-established as Ohm's Law, even the examples listed previously demonstrate opportunity for real learning. In the physical experiment example, the student should identify and explain why their data does not perfectly agree with the hypothesis, and this leads them naturally to consider sources of error. In the computer-simulated experiment, the student is struck by SPICE's convention of denoting regular current through a DC voltage source as being *negative* in sign, and this is also useful knowledge for future simulations. Scientific experiments are most interesting when things *do not* go as planned!

Aside from verifying well-established physical laws, simple experiments are extremely useful as educational tools for a wide range of purposes, including:

- Component familiarization (e.g. *Which terminals of this switch connect to the NO versus NC contacts?*)
- System testing (e.g. *How heavy of a load can my AC-DC power supply source before the semiconductor components reach their thermal limits?*)
- Learning programming languages (e.g. *Let's try to set up an "up" counter function in this PLC!*)

Above all, the priority here is to inculcate the habit of hypothesizing, running experiments, and analyzing the results. This experimental cycle not only serves as an excellent method for self-directed learning, but it also works exceptionally well for troubleshooting faults in complex systems, and for these reasons should be a part of every technician's and every engineer's education.

7.1.5 Constructing projects

Designing, constructing, and testing projects is a very effective means of practical education. Within a formal educational setting, projects are generally chosen (or at least vetted) by an instructor to ensure they may be reasonably completed within the allotted time of a course or program of study, and that they sufficiently challenge the student to learn certain important principles. In a self-directed environment, projects are just as useful as a learning tool but there is some risk of unwittingly choosing a project beyond one's abilities, which can lead to frustration.

Here are some general guidelines for managing projects:

- Define your goal(s) before beginning a project: what do you wish to achieve in building it? What, exactly, should the completed project *do*?
- Analyze your project prior to construction. Document it in appropriate forms (e.g. schematic diagrams), predict its functionality, anticipate all associated risks. In other words, *plan ahead*.
- Set a reasonable budget for your project, and stay within it.
- Identify any deadlines, and set reasonable goals to meet those deadlines.
- Beware of *scope creep*: the tendency to modify the project's goals before it is complete.
- Document your progress! An easy way to do this is to use photography or videography: take photos and/or videos of your project as it progresses. Document failures as well as successes, because both are equally valuable from the perspective of learning.

7.2 Experiment: Measure DC motor inrush current using DMM

When full power is applied to any resting motor, that motor will draw an abnormally large amount of current (called *inrush* current) as it starts to move. This is true for all motor types, AC and DC. Your task is to devise and execute an experiment demonstrating this phenomenon on a small DC ("hobby" type) electric motor, and using the Min/Max capture feature of a digital multimeter (DMM) to do so.

EXPERIMENT CHECKLIST:

- Prior to experimentation:
  - ☑ Write an hypothesis (i.e. a detailed description of what you expect will happen) unambiguous enough that it could be disproven given the right data.
  - ☑ Write a procedure to test the hypothesis, complete with adequate controls and documentation (e.g. schematic diagrams, programming code).
  - ☑ Identify any risks (e.g. shock hazard, component damage) and write a mitigation plan based on best practices and component ratings.
- During experimentation:
  - ☑ Safe practices followed at all times (e.g. no contact with energized circuit).
  - ☑ Correct equipment usage according to manufacturer's recommendations.
  - ☑ All data collected, ideally quantitative with full precision (i.e. no rounding).
- After each experimental run:
  - ☑ If the results fail to match the hypothesis, identify the error(s), correct the hypothesis and/or revise the procedure, and re-run the experiment.
  - ☑ Identify any uncontrolled sources of error in the experiment.
- After all experimental re-runs:
  - ☑ Save all data for future reference.
  - ☑ Write an analysis of experimental results and lessons learned.

Challenges

- Science is an *iterative* process, and for this reason is never complete. Following the results of your experiment, what would you propose for your *next* hypothesis and *next* experimental procedure? Hint: if your experiment produced any unexpected results, exploring those unexpected results is often a very good basis for the next experiment!

- What constitutes "normal" current for your DC motor? How can you tell?
- A common electric motor performance parameter is *locked-rotor current*. Use your experimental apparatus to measure this current value.

7.3 Experiment: Measure DC motor inrush current using DSO

When full power is applied to any resting motor, that motor will draw an abnormally large amount of current (called *inrush* current) as it starts to move. This is true for all motor types, AC and DC. Your task is to devise and execute an experiment demonstrating this phenomenon on a small DC ("hobby" type) electric motor, and using a digital storage oscilloscope (DSO) to do so.

EXPERIMENT CHECKLIST:

- Prior to experimentation:
  - ☑ Write an hypothesis (i.e. a detailed description of what you expect will happen) unambiguous enough that it could be disproven given the right data.
  - ☑ Write a procedure to test the hypothesis, complete with adequate controls and documentation (e.g. schematic diagrams, programming code).
  - ☑ Identify any risks (e.g. shock hazard, component damage) and write a mitigation plan based on best practices and component ratings.
- During experimentation:
  - ☑ Safe practices followed at all times (e.g. no contact with energized circuit).
  - ☑ Correct equipment usage according to manufacturer's recommendations.
  - ☑ All data collected, ideally quantitative with full precision (i.e. no rounding).
- After each experimental run:
  - ☑ If the results fail to match the hypothesis, identify the error(s), correct the hypothesis and/or revise the procedure, and re-run the experiment.
  - ☑ Identify any uncontrolled sources of error in the experiment.
- After all experimental re-runs:
  - ☑ Save all data for future reference.
  - ☑ Write an analysis of experimental results and lessons learned.

Challenges

- Most oscilloscope probes are not configured to measure current, but rather voltage. A valid technique for obtaining a current measurement using a voltage-sensing instrument is to place a *shunt resistor* in series with the current to be measured, and use the instrument to sense voltage across that resistor. What criteria determine the appropriate size of shunt resistor for any application?

- Science is an *iterative* process, and for this reason is never complete. Following the results of your experiment, what would you propose for your *next* hypothesis and *next* experimental procedure? Hint: if your experiment produced any unexpected results, exploring those unexpected results is often a very good basis for the next experiment!

7.4 Experiment: Measure AC motor inrush current using CT

When full power is applied to any resting motor, that motor will draw an abnormally large amount of current (called *inrush* current) as it starts to move. This is true for all motor types, AC and DC. Your task is to devise and execute an experiment demonstrating this phenomenon on an AC electric motor, using a current transformer (CT) to convert the motor's line current into a smaller value for an instrument to read.

If this experiment is being done within a formal course, your instructor will identify an appropriate AC motor to measure current through, provide a suitable CT, and ensure proper lock-out/tag-out (LOTO) procedures are followed.

EXPERIMENT CHECKLIST:

- Prior to experimentation:
  - ☑ Write an hypothesis (i.e. a detailed description of what you expect will happen) unambiguous enough that it could be disproven given the right data.
  - ☑ Write a procedure to test the hypothesis, complete with adequate controls and documentation (e.g. schematic diagrams, programming code).
  - ☑ Identify any risks (e.g. shock hazard, component damage) and write a mitigation plan based on best practices and component ratings.
- During experimentation:
  - ☑ Safe practices followed at all times (e.g. no contact with energized circuit).
  - ☑ Correct equipment usage according to manufacturer's recommendations.
  - ☑ All data collected, ideally quantitative with full precision (i.e. no rounding).
- After each experimental run:
  - ☑ If the results fail to match the hypothesis, identify the error(s), correct the hypothesis and/or revise the procedure, and re-run the experiment.
  - ☑ Identify any uncontrolled sources of error in the experiment.
- After all experimental re-runs:
  - ☑ Save all data for future reference.
  - ☑ Write an analysis of experimental results and lessons learned.

Challenges

- Science is an *iterative* process, and for this reason is never complete. Following the results of your experiment, what would you propose for your *next* hypothesis and *next* experimental procedure? Hint: if your experiment produced any unexpected results, exploring those unexpected results is often a very good basis for the next experiment!

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.

22 March 2026 – typographical error corrections courtesy of Wyatt Gleason.

9 November 2024 – added a new "Challenging concept" to the Introduction chapter on motor inrush current.

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.

10 March 2024 – added more questions to the Introduction chapter.

23 October 2023 – divided the Tutorial into sections.

5 July 2023 – added Technical Reference sections on magnetic units and also definitions of magnetic north and south.

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

8 May 2021 – commented out or deleted empty chapters.

18 March 2021 – minor additions to the Introduction chapter, and minor edits to wording of certain questions, including proper capitalization of "Volts".

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.

20 May 2019 – added another Quantitative Reasoning problem.

1 May 2019 – moved motor starter Experiments from mod_acmotor to mod_acstarter.

27 April 2019 – added HP/Watts conversion factor to Tutorial, as well as sailboat analogy for understanding induction motor "slip" and animation (from mod_vfd) for the magnetic field within a three-phase motor. Also added discussion of A/B/C/D motor designs, and added details to the question on stroboscope interpretation.

22 July 2020 – incorporated "Transformation of industry by electric motors" into its own technical reference file to be shared amongst multiple modules.

30 March 2019 – added experiments.

29 March 2019 – added questions, and added discussion of motor efficiency to the Tutorial.

10 March 2019 – completed the Foundational Concepts list.

30 December 2018 – added 12-lead motor diagram to Technical Reference chapter.

29 December 2018 – added 6-lead and 9-lead motor diagrams to Technical Reference chapter.

24 November 2018 – added historical reference to the transformation of a silk weaving shop due to electric motors. Also clarified inrush current as being synonymous with locked-rotor current.

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

October 2018 – document first created.

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