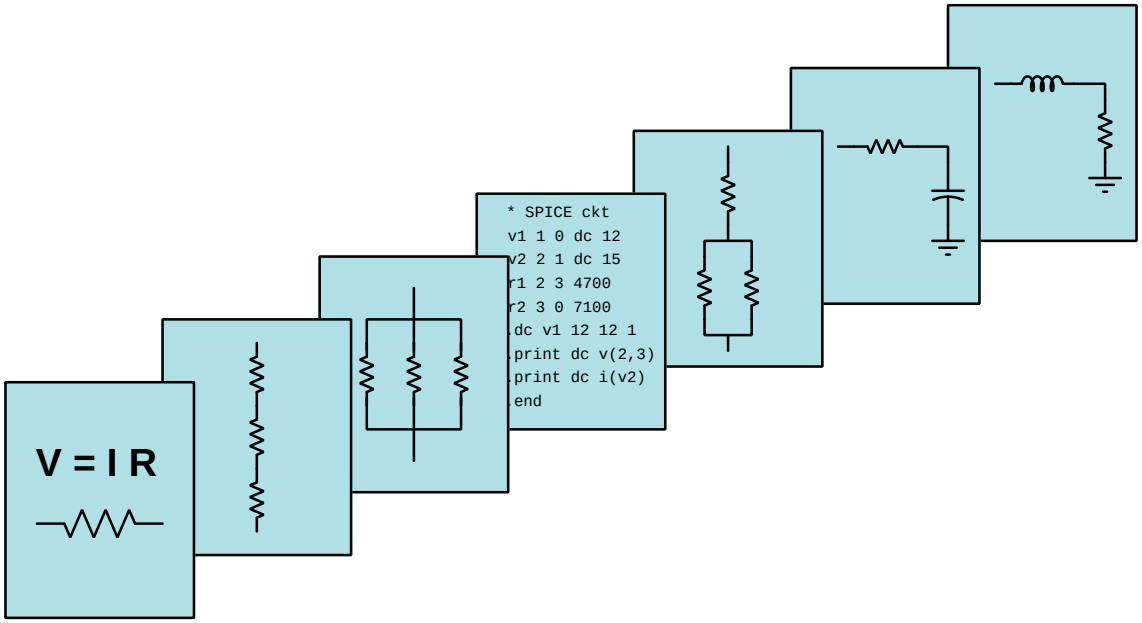
Modular Electronics Learning (ModEL) project



AC Induction Motor Starters

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Chapter 1

Introduction

1.1 Recommendations for students

AC induction electric motors are the workhorses of modern industry, providing mechanical power for a wide range of applications. The simple construction the AC induction motor, with stationary "stator" windings and only one moving mechanical component (the "rotor"), gives it outstanding reliability. Induction motors are quite energy-efficient as well, with conversion efficiencies over 95% for larger sizes. With so many induction motors serving so many different applications, it is important to understand the various methods used to control their operation. That is the subject of this module: circuits used to control the starting and stopping of AC induction motors.

Important concepts related to AC motor control circuits include electromagnetic **relays**, **inrush current**, **contactors**, **arc flash** and **arc blast**, **overload detection**, thermal overload **heaters**, **current transformers**, **Ohm's Law**, **Joule's Law**, **auxiliary contact**, **seal-in contact**, **latching circuits**, **ladder diagrams**, motor **reversal**, **interlocking**, **process switches**, **electromagnetism**, electromagnetic **induction**, **counter-EMF**, , , **reduced-voltage starting**, **time-delay** relays, **autotransformers**, properties of **Wye networks**, properties of **Delta networks**, and **thyristors**.

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

- How might an experiment be designed and conducted to measure the inrush current of an AC motor? 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 measure (or infer) the counter-EMF generated by an AC motor at a particular speed? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- What is the difference between a *starter* and a *bucket*?
- How can we reverse the rotation of a three-phase AC motor?
- How does thermal overload protection work for an AC motor?

- What is the function of a *current transformer*?
- Why does a motor continue to run even when the momentary-contact pushbutton switch is released?
- What function does an *interlock* serve?
- What are some different types of interlocks?
- What does the "Hand" position represent for a Hand-Off-Auto switch?
- How are digital networks applied to modern motor controls?
- Why might "across-the-line" starting not be optimal?
- Why does motor current decrease with shaft speed?
- How may an induction motor be forced to operate as a generator?
- How does an electronic "soft-starter" function?

1.2 Challenging concepts related to AC induction motor starters

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

- **Purpose of thermal overloads** – thermal overloads are designed to warm up with excessive motor current and to trip (open) a switch contact which then turns the contactor off and stops the motor. The overload "heaters" themselves, however, are *not* fuses! Although the heaters are in series with the motor terminals like fuses would be, these heaters are not designed to burn open the way fuses are. Instead, they merely get warm and by that (low) heat trip the overload contact which shuts off the contactor.

- **Seal-in contacts** – the simplest and most common way to make momentary-contact "Start" and "Stop" switches latch a motor's state on and off is to wire an auxiliary contact from the contactor in parallel with the Start switch to "seal in" that circuit once the contactor energizes. This, however, complicates analysis of the circuit by granting it *states*. State-based logic is more complex than combinational logic because the status of state-based logic depends not only on input conditions but also on past history. This means a person must analyze the circuit before and after input condition changes to determine how it will respond.

- **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!

- **Autotransformers** – an autotransformer is a transformer using a single winding rather than two or more electrically-isolated windings. By tapping into the one winding it becomes possible to power the load from a different number of turns than what the source connects to, thereby granting a step ratio for voltage and current. That step ratio is still calculated on the basis of load winding turns versus source winding turns, the only difference being a lack of electrical isolation between source and load because the smaller of those turns are shared with both circuits.

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** – Design a three-phase motor starter circuit

  Assessment – Sketch wire placement in a pictorial diagram for a circuit employing an electromechanical contactor to control the operation of a three-phase AC motor; e.g. pose problems in the form of the "Sketching connections for a three-phase starter" Conceptual Reasoning question.

- **Outcome** – Diagnose a faulted AC motor control circuit

  Assessment – Determine the probability of various component faults in an AC motor control circuit given symptoms and measured values; e.g. pose problems in the form of the "Faulted lift station pump control" and "Faulted wye/delta starter" Diagnostic Reasoning questions.

- **Outcome** – Independent research

  Assessment – Locate motor starter manuals and properly interpret some of the information contained in those documents including maximum motor horsepower, auxiliary contact arrangements, etc.

Chapter 2

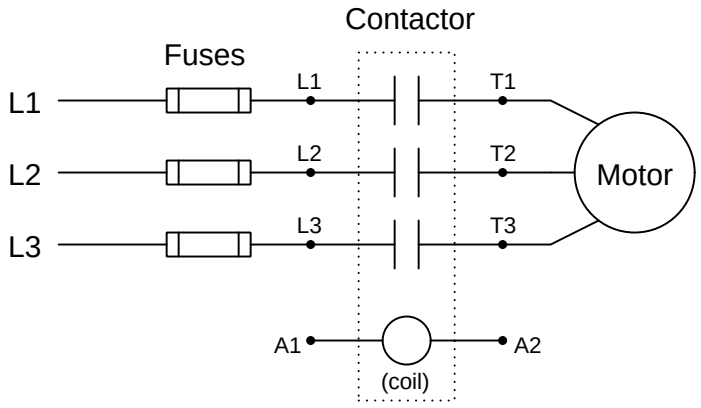
Tutorial

This tutorial discusses various techniques and technologies used for on-off ("discrete") control of three-phase AC induction motors.

2.1 Motor contactors

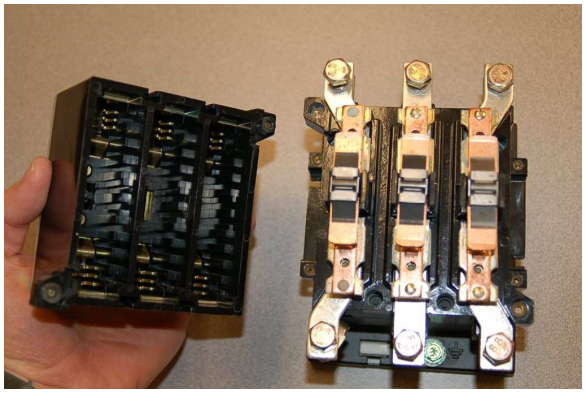
To start up and shut down a three-phase AC induction motor, any three-pole switch with a suitable current rating will suffice. Simply closing the switch to send three-phase power to the motor will cause it to start up, while opening the three-pole switch will cut power to the motor to make it turn off. If we desire to have *remote* start and stop control over a three-phase motor, we need a special relay with switch contacts big enough to safely conduct the motor's inrush current over many start and stop cycles. Large, high-current-rated electromechanical relays built for this very purpose are commonly referred to as *contactors*.

A schematic diagram of a three-phase contactor connected to a three-phase motor (with fuses for overcurrent protection) is shown here. The three-phase AC voltage source will connect to terminals L1, L2, and L3:

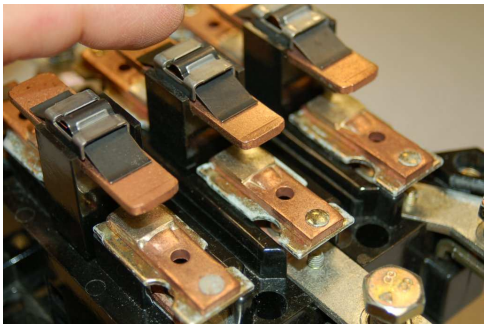


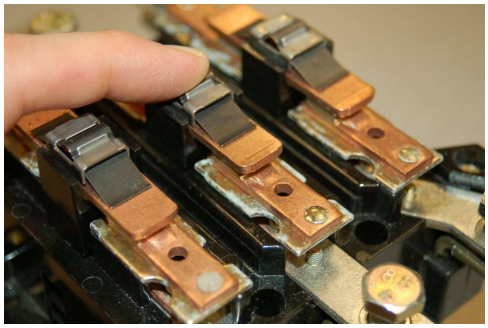
Energizing terminals A1 and A2 of the contactor magnetizes its electromagnet coil, causing all three switch contacts to simultaneously close and thereby send three-phase AC power to the motor. De-energizing the coil causes it to de-magnetize, releasing the armature and enabling a return spring inside the contactor to snap all three contacts to the open (off) position.

A contactor rated at 75 horsepower (at 480 Volt AC 3-phase power) is shown here, both assembled and with the top cover removed to reveal the three sets of high-current electrical switch contacts:



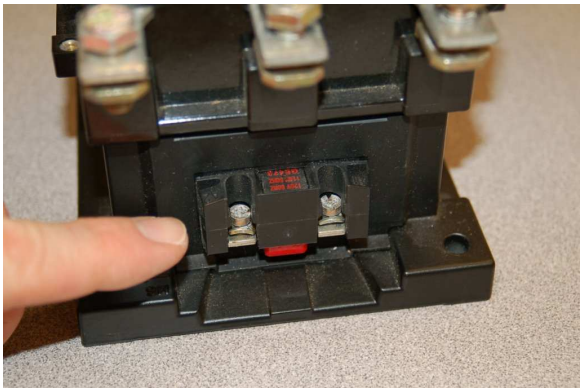
Each phase switch contact is actually a series pair of contacts that make and break simultaneously with the actuation of a ferrous armature attracted by an electromagnet coil in the base of the contactor assembly. The operation of the three contact sets may be seen in this pair of photographs, the left-hand image showing the contacts in their normal (open) state, and the right-hand image showing the contacts closed (the armature "pulled in") by the force of my finger:





Of course, it would be very dangerous to touch or manually actuate the contacts of a motor starting relay with the cover removed as shown. Not only would there be an electric shock hazard from touching any one of the bare copper contacts, but the arcing produced by closing and opening such contacts would pose *arc flash* and *arc blast* hazards. This is why all modern motor contactors are equipped with *arc shield* covers. The non-conducting arc shields provide separate chambers for each of the three power contact sets, so that no arc may pass between adjacent contacts to form a phase-to-phase fault.

Below the main power connection terminals (L1-L3, T1-T3) on this contactor are two small screw terminals (commonly denoted A1 and A2) providing connection points to the electromagnet coil actuating the contactor:



Like most three-phase contactors, this one's coil is rated for 120 Volts AC. Although the electric motor may operate on three-phase, 480 Volt AC power, the contactor coil and the rest of the control circuitry operates on a lower voltage for reasons of safety. Like all electromechanical relays, motor contactors use a low-power signal to control higher-power electric current to the load. This "amplifying" action enables relatively small control switches, PLCs, and relay circuits to start and stop relatively large (high-current) electric motors.

2.2 Motor overload protection

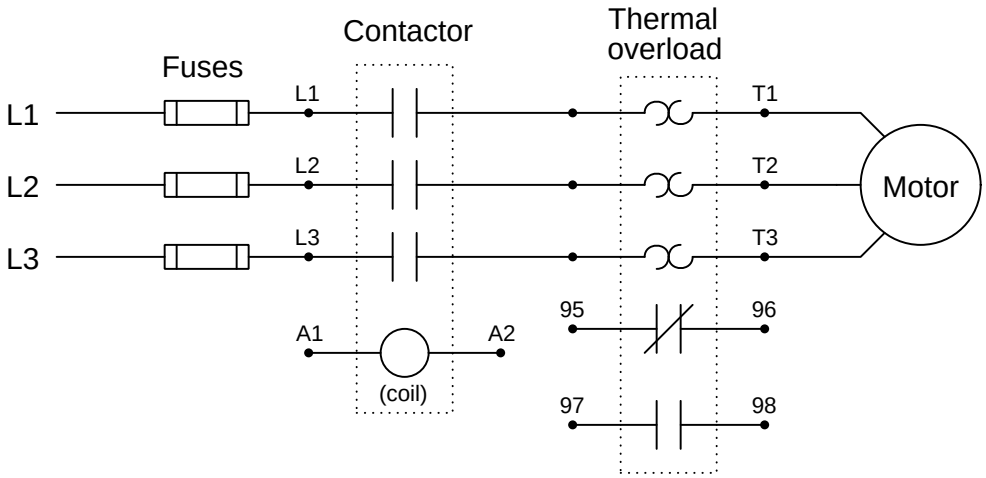
In addition to a contactor, any motor control circuit must also contain some form of overcurrent protection. At minimum this takes the form of fuses, one per phase of the three-phase power circuit as previously shown. However, fuses and circuit breakers alike are only intended to protect electrical conductors against overcurrent in the event of faults, such as a short-circuit developing within a motor's winding(s). An electric motor operated under mechanical over-load conditions may draw enough current to cause damage, but less current than what a fuse would be rated for protecting the conductors feeding current to and from the motor. Therefore, another device is needed to provide overload protection to the motor.

A very simple and common overload protective device is known as an *overload heater*, consisting of resistive elements connected in series with the three lines of a 3-phase AC motor, designed to heat and to cool at rates modeling the thermal characteristics of the motor itself. These heating elements operate a temperature-sensitive switch, which when triggered open by excessive temperature will interrupt current to the contactor's coil, causing the contactor to spring-return to its "off" state and interrupt power to the motor.

Some elaboration is in order here, as there exists much confusion over the roles of fuses, circuit breakers, and thermal overload heaters. Fuses and circuit breakers tend to be fast-acting devices, intended to interrupt overcurrent resulting from an electrical fault such as a phase-to-ground or phase-to-phase short circuit. As such, they are sized to protect the wiring delivering power to a load, not (necessarily) the load itself. Thermal overload heaters, by contrast, are specifically designed to protect an electric motor from damage resulting from mild overcurrent conditions, such as what might be experienced if the motor becomes mechanically overloaded. The sizing of overload heaters is unrelated to wire ampacity, and therefore unrelated to the ratings of the fuses or circuit breakers delivering line power to the motor.

Another important distinction is that fuses and circuit breakers directly interrupt motor current, while thermal overloads do not. A thermal overload "heater" merely becomes warm, and its heat causes an adjacent thermal switch to open, which in turn signals the contactor to turn off. This distinction is worth noting because a very common misconception among industrial electricians is that overload heaters are supposed to burn open like fuses in the event of an overcurrent condition, and *this is not true*. Overload heaters simply command the contactor to interrupt current during mild overload conditions for the purpose of protecting the motor from thermal damage; fuses, by contrast, function by violently burning open during heavy overload conditions for the purpose of protecting power conductors from thermal damage.

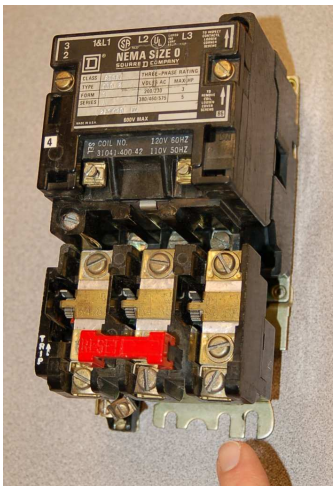
A schematic diagram of a three-phase overload connected to a three-phase contactor and three-phase motor is shown here:

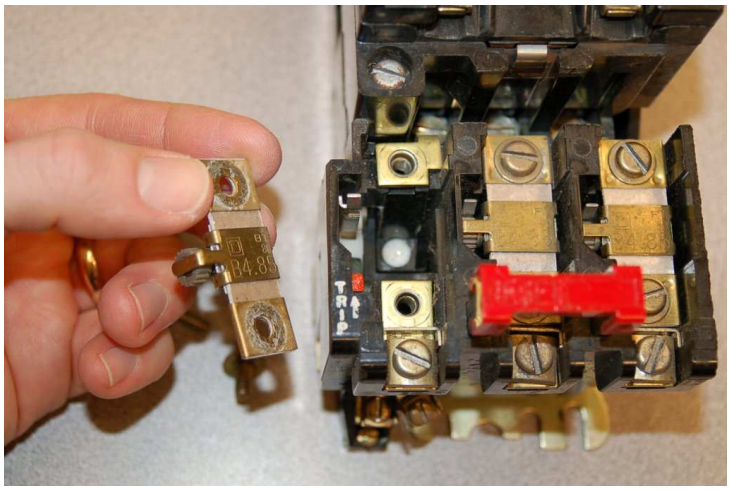


Both contacts inside the overload assembly will remain in their resting ("normal")[1] states so long as the heater elements (the back-to-back "hook" symbols seen in the above diagram) remain cool. If one or more of the resistive heaters becomes too warm, however, the contacts will actuate and change state. The normally-closed overload contact (terminals 95 and 96) is typically wired in series with the contactor coil (terminals A1 and A2), so that a detected overload condition forces the contactor to de-energize and interrupt power to the motor.

[1] For an in-depth review of contact "normal" states, refer to page 52.

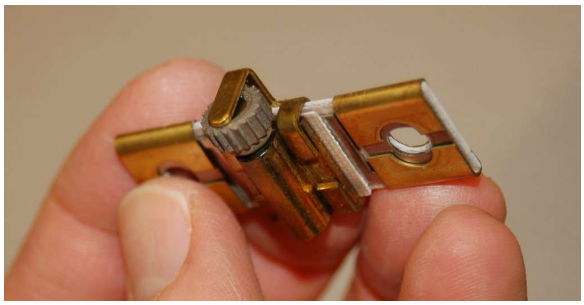
The following photograph shows a three-phase contactor relay joined together with a set of three "overload heaters" through which all of the motor's current flows. The overload heaters appear as three brass-colored metal strips near a red push-bar labeled "Reset". The entire assembly – contactor plus overload heaters – is referred to as a *starter*:





Removing one of the heater elements, as shown in the right-hand photograph, reveals its mechanical nature: a small toothed wheel on one side engages with a lever when it is bolted into place in the overload assembly. That lever connects to a spring-loaded mechanism charged by the manual actuation of the red "Reset" push-bar, which in turn actuates a small set of electrical switch contacts.

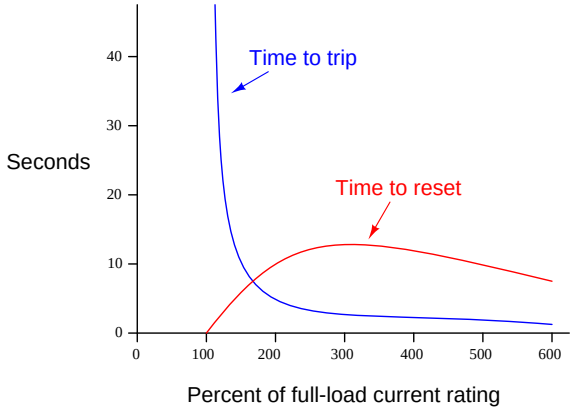
The purpose of the overload heater is to heat up as the motor draws excessive current. The small toothed wheel is held in place by a rod immersed in a solidified mass of solder, encased in a brass cylinder underneath the heater strip. The next photograph shows the underside of the heater element, with the toothed wheel and brass cylinder plainly visible:



If the heater element becomes too hot (due to excessive motor current), the solder inside the brass cylinder melts, allowing the toothed wheel to spin. This releases spring tension in the overload mechanism, allowing the small electrical switch to spring to its open state. This open "overload contact" interrupts current to the contactor's electromagnet coil, causing the contactor to de-energize and the motor to stop.

Manually pressing the "Reset" push-bar will re-set the spring mechanism and re-close the overload contact, allowing the contactor to energize once more, but only once the overload heater element has cooled down enough for the solder inside the brass cylinder to re-solidify. Thus, this simple mechanism prevents the overloaded motor from being immediately re-started after a thermal overload "trip" event, giving it time to cool down as well.

A typical "trip curve" for a thermal overload unit is shown here, with time plotted against the severity of the overcurrent level:

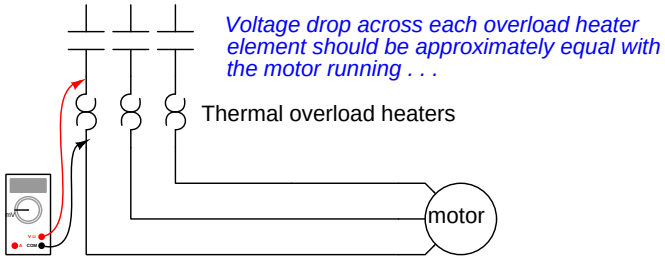


In contrast to a circuit breaker or fuse – which is sized to protect the power wiring from overcurrent heating – the overload heater elements are sized specifically to protect the *motor*. As such, they act as miniature thermal models of the motor itself, heating to the "trip" point just as fast as the motor itself will heat to the point of maximum rated temperature, and taking just as long to cool to a safe temperature as the motor takes. Again, note how overload heaters differ from breakers and fuses in that they do not directly interrupt motor current[2] as fuses or breakers do. Rather, each overload heater serves the simple purpose of *warming* proportionately to the magnitude and time duration of motor overcurrent, causing an adjacent electrical contact to open, which in turn triggers the contactor to open and interrupt motor current. Overload heaters also differ from circuit breakers in that they cannot be immediately reset; they require cool-down time (just as the motor does) before they may be returned to their typical state.

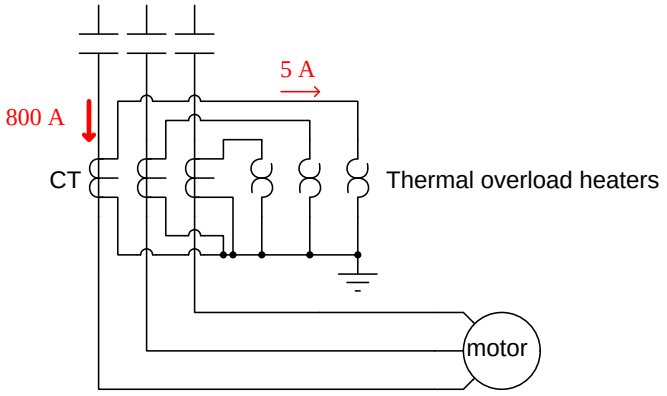
Of course, overload heaters only work to protect the motor from thermal overload if they experience similar ambient temperature conditions. If the motor is situated in a very hot area, whereas the overload elements are located in a climate-controlled "motor control center" (MCC) room, they may fail to protect the motor as designed. Conversely, if the overload heaters are located in a hot room while the motor is located in a freezing-cold environment (e.g. the MCC room lacks air conditioning while the motor is located in a freezer), they may "trip" the motor prematurely.

[2] This is not to say overload heaters cannot fail open, because they can and will under extraordinary circumstances. However, opening like a fuse is *not* the design function of an overload heater.

A useful fact to remember for motor control circuit diagnosis is that overload heaters are nothing more than low-value resistors. As such, they will drop small amounts of voltage (usually quite a bit less than 1 Volt AC) under full load current. This voltage drop may be used as a simple, qualitative measure of motor phase current. By measuring the voltage dropped across each overload heater (with the motor running), one may ascertain whether or not all phases are carrying equal currents. Of course, overload heaters are not precise enough in their resistance to serve as true current-measuring "shunts," but they are more than adequate as qualitative indicators of relative phase current, to aid you in determining (for instance) if the motor suffers from an open or high-resistance phase winding:



When the motor in question is large, and its line current and/or voltage levels are high enough to render overload heaters impractical for direct conduction of motor current, a common practice is to use overload heaters of proportionately smaller size and energized them through *current transformers* (*CTs*) rather than by motor line current directly. The following diagram shows an example of this, where three 800:5 ratio CTs transform high motor line current into current signals 160 times smaller to the overload heaters:



Current transformers not only make possible thermal protection of very large motors using overload heaters of small size, but they also provide electrical isolation[3] between the motor line

[3]Electrical "isolation" refers to the lack of any conductive connection between two points in an electrical system. As with any transformer, a CT uses *magnetism* rather than a direct conductive connection to transfer electrical energy from primary to secondary windings, and so the primary and secondary windings of a transformer are said to be "isolated" from each other. Note the grounded secondary circuits of the CTs shown, maintaining the electrical potential of all points within those circuits at or near zero so long as the overload heaters all have continuity.

conductors and the overload heaters. This increases safety for anyone working near or with these overload heaters when the motor's normal line voltage is dangerously high.

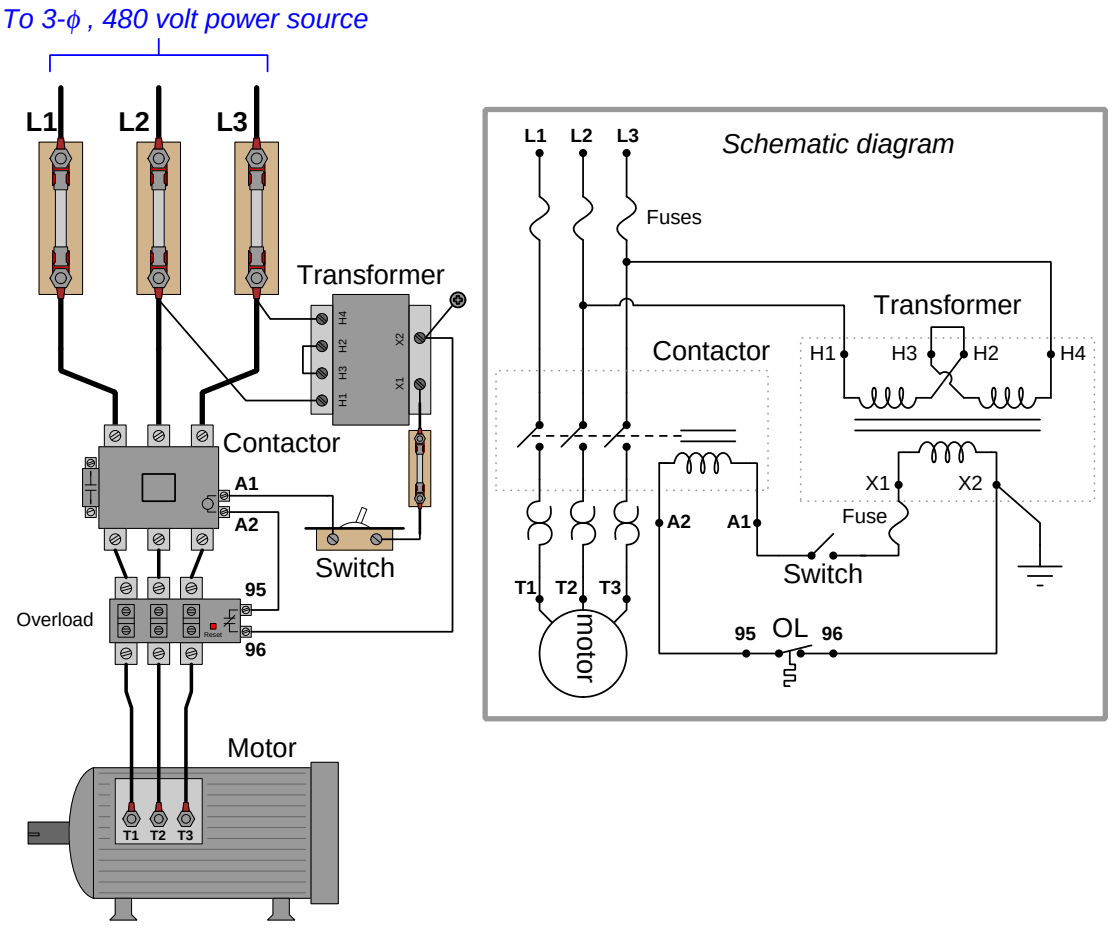
A very important safety rule when working with a current transformers is to never leave its secondary winding open if there is any chance current may flow through the primary. The proper function of a CT is to act as a *current source*[4] to its load (e.g. AC ammeter, overload heater), and if the connection to that load becomes severed the CT can and will output a dangerously high voltage in its effort to push that current through the air gap of the "open" circuit.

As useful as thermal overload "heaters" are for motor protection, more effective technologies exist. A more direct way to detect motor overload is to monitor the temperature of the motor's stator windings using temperature sensors embedded in the motor's stator, reporting winding temperature to an electronic "trip" unit tasked with the same control responsibilities as an overload heater assembly. This sophisticated approach is used on large (thousands of horsepower) electric motors, and/or in critical applications where motor reliability is paramount. Vibration-monitoring equipment used to sense excessive vibration in rotary machines is often equipped with such temperature-sensing "trip" modules just for this purpose. Not only can motor winding temperatures be monitored, but also bearing temperatures and other temperature-sensitive machine components so that the protective function extends beyond the health of the electric motor.

[4] Recall that the definition of a current source is an electrical component designed to output a constant electric current regardless of load resistance. An ideal current source will therefore develop as much voltage as Ohm's Law dictates ($V = IR$) to push current through its load.

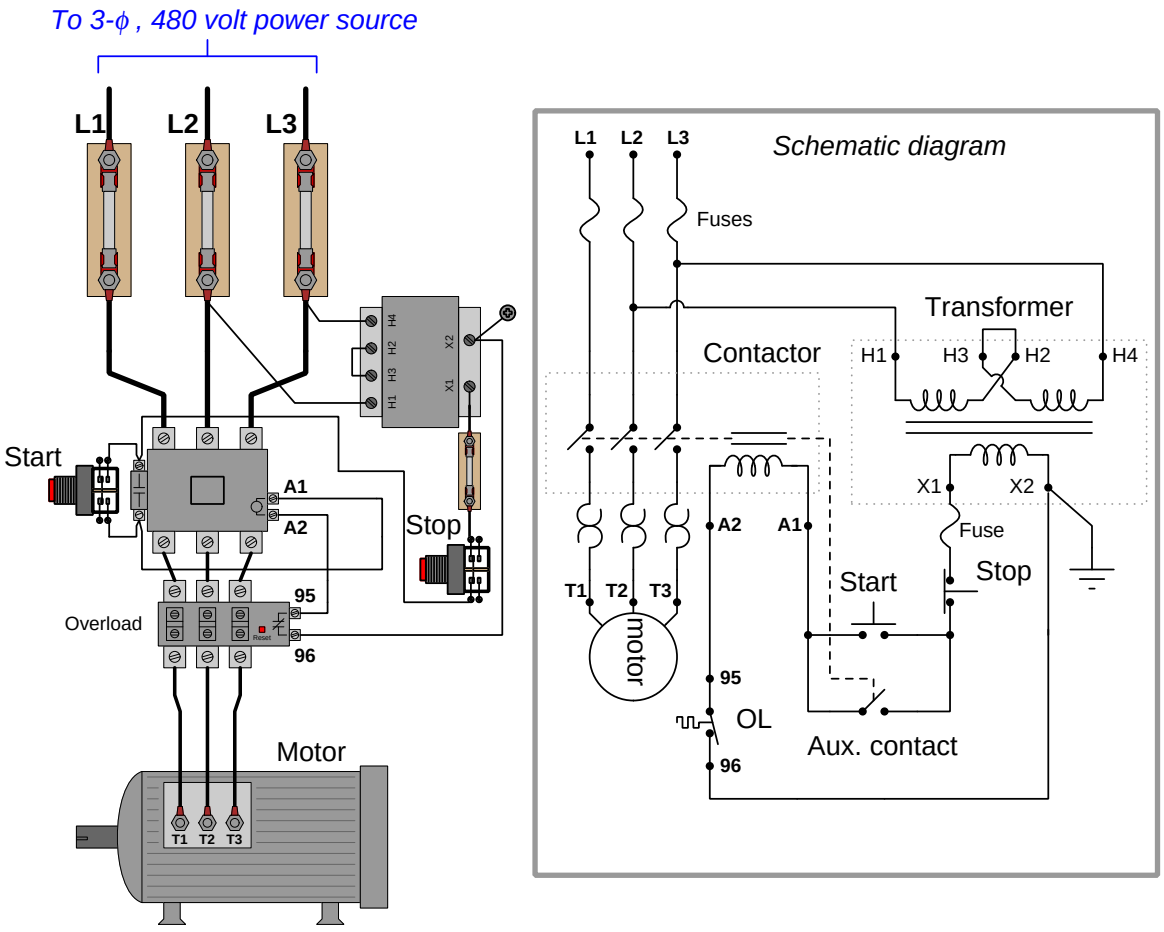
2.3 Latching motor starters

A simple three-phase, 480 Volt AC motor-control circuit is shown here, both in pictorial and schematic form. This entire assembly consisting of contactor, overload block, control power transformer, power fuses (or alternatively, a circuit breaker) and associated components is informally referred to as a *bucket*:



Note how a *control power transformer* steps down the incoming line voltage (480 Volts AC) to 120 Volts AC to power the contactor coil. Furthermore, note how the overload ("OL") contact is wired in series with the contactor coil so that a thermal overload event forces the contactor to de-energize and thus interrupt power to the motor even if the control switch is still in the "on" position. The overload heaters appear in the schematic diagram as pairs of back-to-back "hook" shapes, connected in series with the three "T" lines of the motor. Remember that these "OL" heater elements do not directly interrupt power to the motor in the event of an overload, but rather signal the "OL" contact to open up and de-energize the contactor.

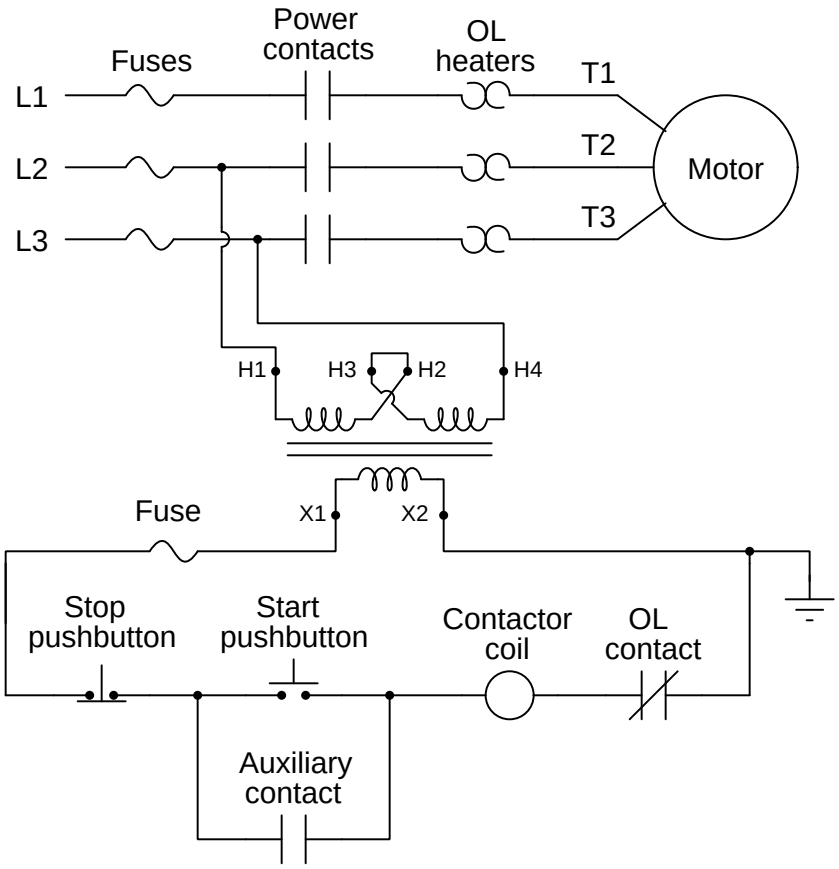
It should be noted that a toggling-style of switch is necessary in order for the motor to continue to run after a human operator actuates the switch. The motor runs when the switch is in the closed state, and stops when the switch opens. An alternative to this design is to build a *latching* circuit allowing the use of momentary contact switches (one to start, and one to stop). A simple latching motor control circuit is shown here:



In this circuit, an *auxiliary contact* actuated by the motor contactor is wired in parallel with the "Start" pushbutton switch, so that the motor contactor continues to receive power after the operator releases the switch. This parallel contact – sometimes called a *seal-in contact* – latches the motor in an "on" state after a momentary closure of the "Start" pushbutton switch.

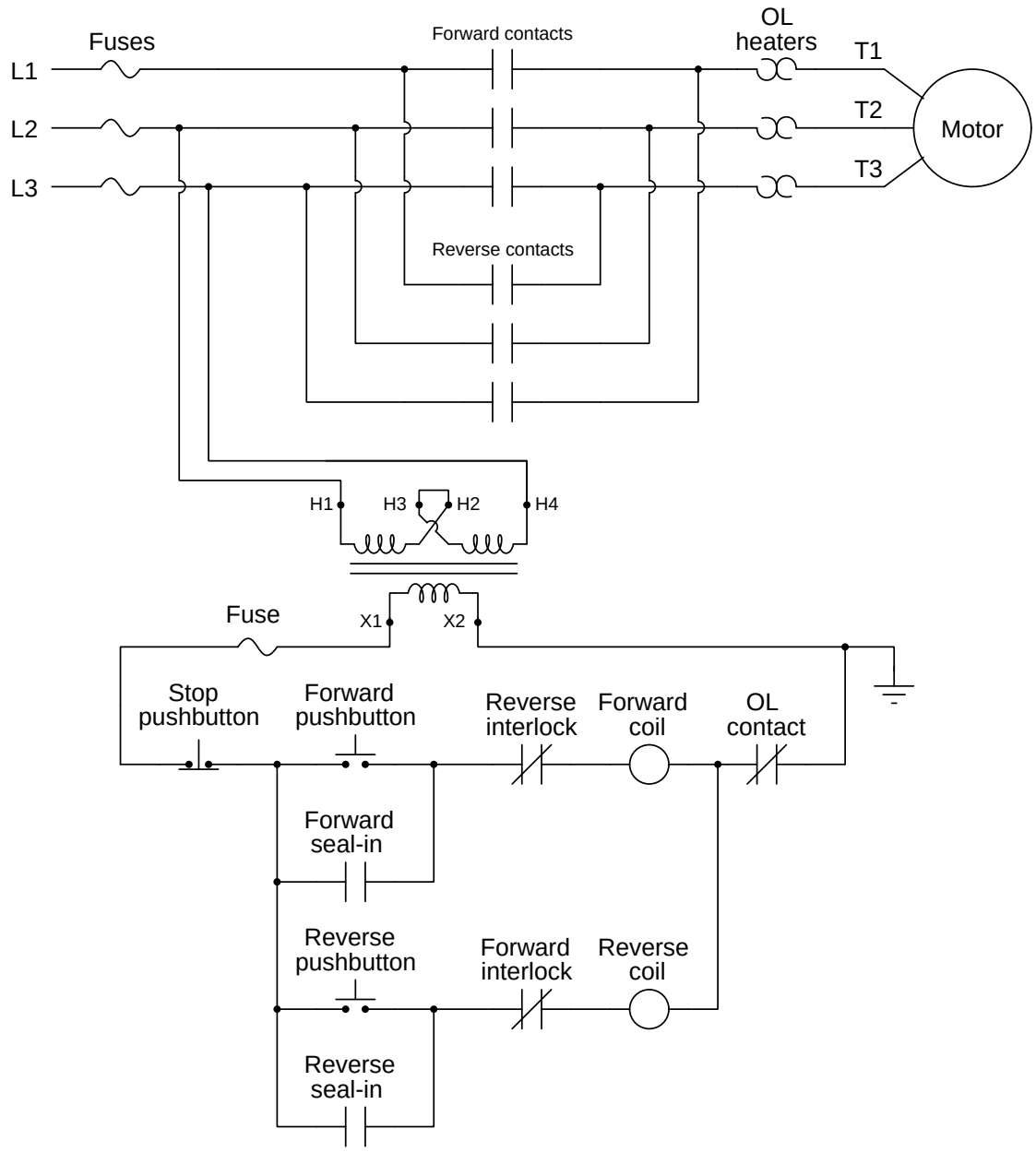
A normally-closed "Stop" switch provides a means to "un-latch" the motor circuit. Pressing this pushbutton switch opens the control circuit, forcing current to halt through the coil of the contactor, which then opens the three motor power contacts as well as the auxiliary contact used to maintain the contactor's energized state.

A simple *ladder diagram* showing the interconnections of all components in this motor control circuit makes this system easier to understand:



Most on/off motor control circuits in the United States are some variation on this wiring theme, if not identical to it. A programmable logic controller (PLC) may also be used to provide the latching function rather than an auxiliary contact on the contactor. Once a PLC is included in the motor control circuit, a great many automatic control features may be added to enhance the system's capabilities. Examples include timing functions, motor cycle count functions, and even remote start/stop capability via a digital network connecting to operator interface displays or other computers.

In applications where reversing motor control is desired, a pair of contactors may be wired together as shown here:



Note how motor reversal is accomplished by swapping phases L1 and L3: in the forward direction, power line conductor L1 connects to motor terminal T1, L2 connects to T2, and L3 connects to T3.

In the reverse direction L2 still connects to T2, but L1 now connects to T3 and L3 now connects to T1. Recall the principle that swapping *any two phases* in a three-phase power system reverses the phase rotation, which in this case make the electric motor spin the other direction.

With two contactors, the control circuit now contains two coils to actuate those contactors: one marked "forward" and the other marked "reverse". Separate "forward" and "reverse" pushbutton switches send power to those coils, and separate seal-in auxiliary contacts connected in parallel with their respective pushbuttons latch each one.

An important feature of this reversing starter circuit is the inclusion of *interlock* contacts in each rung of the circuit. In the forward-control circuit, a normally-closed auxiliary contact actuated by the "reverse" contactor is wired in series, and vice-versa in the reverse-control circuit. The purpose of an "interlock" is to prevent incompatible events from happening, in this case preventing the actuation of the "reverse" contactor when the "forward" contactor is already actuated, and vice-versa. If both contactors were to be simultaneously actuated, it would result in a direct phase-to-phase fault (short-circuit) between L1 and L3!

Some reversing motor contactors provide a feature called *mechanical interlocking*, where the motion of the armature in each contactor is restrained in such a way that both cannot actuate simultaneously. This usually takes the form of a "rocking beam" lever preventing one contactor armature from being pulled in while the other contactor's armature is pulled in, similar to a "see-saw" playground toy where only one end can be down at any given time. It is not uncommon for both electrical and mechanical interlocking to be used in the same reversing starter, as a measure of extra protection.

2.4 Digital motor controls

A modern trend in motor control is the use of digital networks to both command the contactor as well as monitor the motor's operating status remotely. This next photograph[5] shows a digitally monitored and controlled "bucket," using DeviceNet as the control network:

Using a digital network standard such as Ethernet, DeviceNet, Modbus, Profibus, or any number of others to monitor and control a motor brings a host of benefits for maintenance and operations. Control wiring is vastly simplified with digital networks, as a single network cable is able to address multiple motor buckets. The "smart" network interface module installed in the bucket may be designed to monitor such parameters as line voltage, line current, phase imbalance, and power factor to report these values to the host control system via the network.

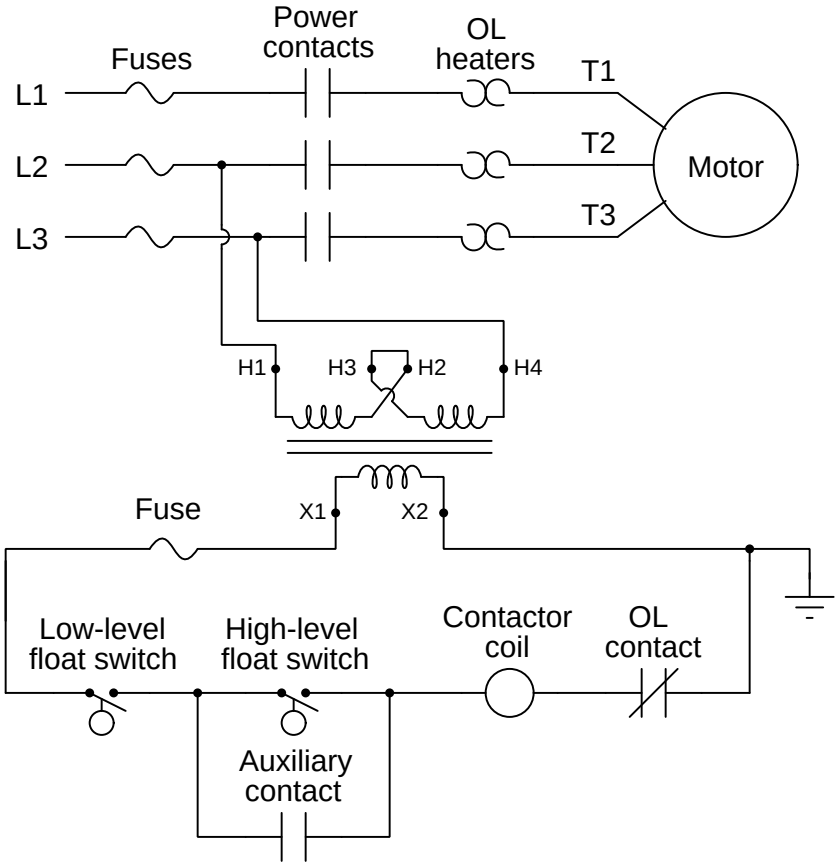
[5] This bucket was still under construction at the time the photograph was taken. As such, none of the motor leads have been connected, which is why there are no power conductors exiting the bottom of the bucket. Instead, all you see are three terminals ready to accept heavy-gauge motor leads.

It is common for the network interface module inside the bucket to have its own digital display for local indication of these parameters as well. A close-up photograph of a Square-D "Motor Logic Plus" unit shows some of its locally-accessible features:

The PLC connected to the network is able to access all these values as well, reporting them to operations and/or maintenance personnel as desired. Instead of individual wires running between the PLC and the motor starter to command each motor to run and stop, the PLC simply transmits "start" and "stop" commands over the digital network to individually addressed digital starter modules. The network wiring may simply be paralleled ("daisy-chained") between units, such that several buckets reside on the same physical network, each one programmed with a unique address. A PLC connected to this same network is thus able to access and control all parameters for all motors on that network.

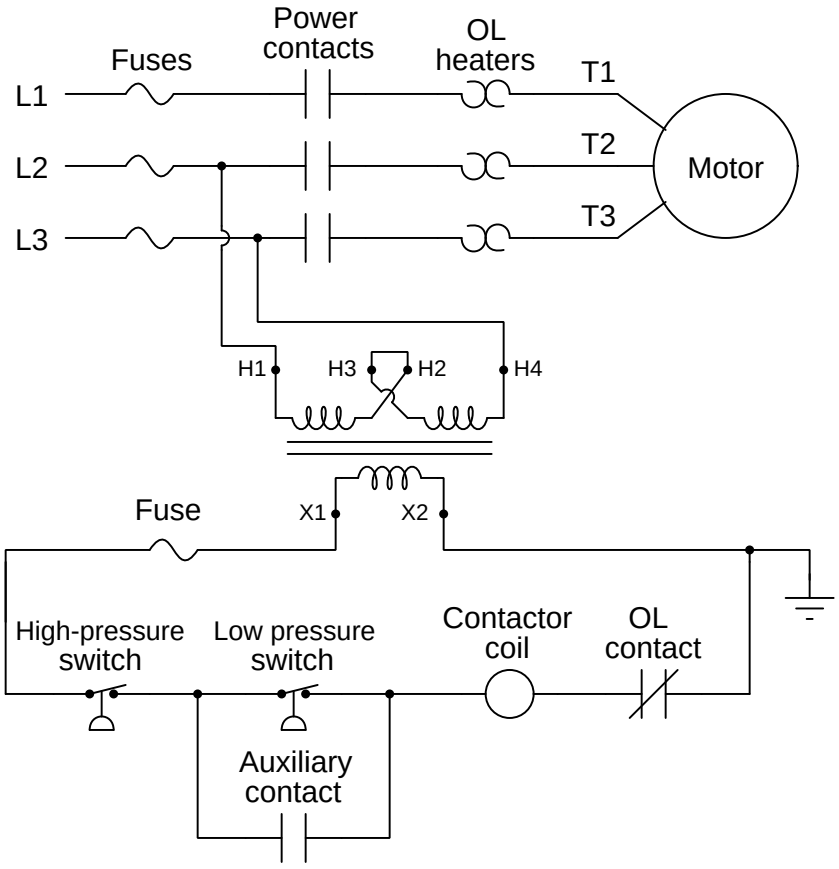
2.5 Automatic motor starting

The previous section explored manual (pushbutton or toggle switch) control of AC induction motors, but there are many applications in which we desire the motor to start and stop *automatically*. Such an application would be a sump pump motor control system, where the motor must automatically energize to pump water out of a collection sump if ever the water level rises too high, and shut off again when the water level has been pumped down to a nearly-empty sump condition. In the following ladder-logic diagram we see such an automatic motor starter system, where normally-open float-type levels switches have replaced the customary "start" and "stop" pushbutton switches:



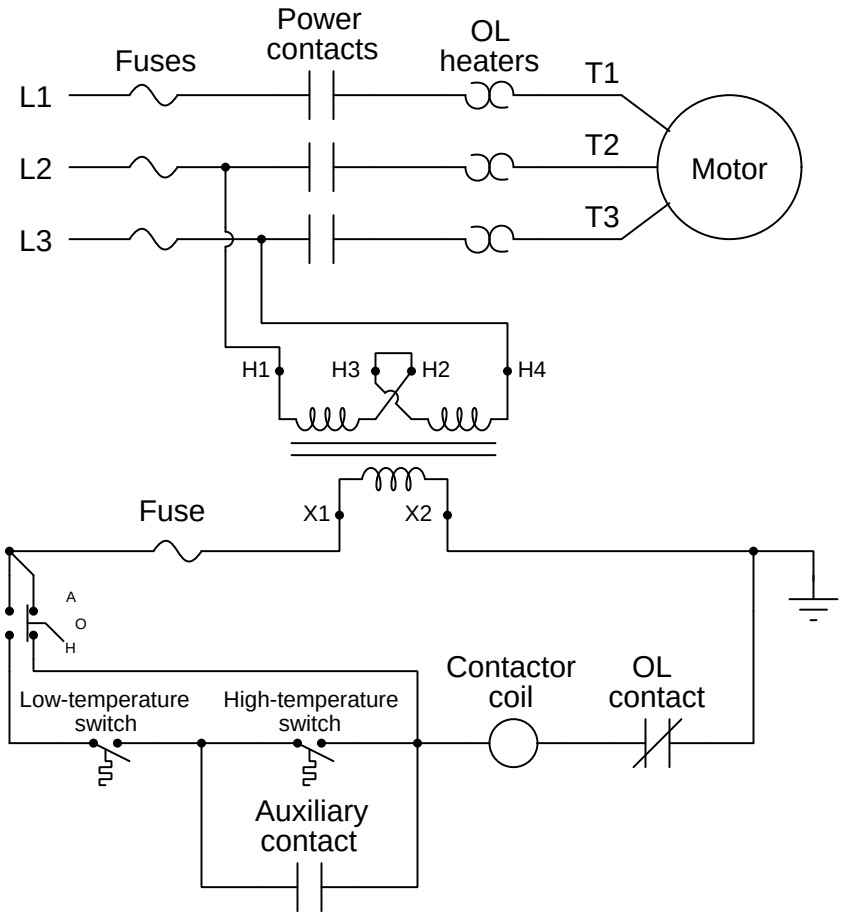
When the sump is nearly full, both float switches are wet and will be in their closed states, thus starting the pump motor. As water level in the sump decreases, the "high" float switch will be the first one to go dry and return to its "normal" open state. However, the motor continues to run because the seal-in contact maintains power to the contactor coil. The pump continues to move water out of the sump until the "low" float switch goes dry, at which point the control circuit opens and the contactor de-energizes. Water level must accumulate in the sump until both float switches are wet in order to re-start the pump motor.

Other types of process switches may be used to control a latching motor starter circuit. Take for example the following air compressor motor starter circuit, designed to maintain adequate compressed air in a storage vessel (called a *receiver tank*). Instead of two normally-open level-sensing float switches, we have two normally-closed *pressure*-sensing switches to trigger the starting and stopping of the air compressor motor:



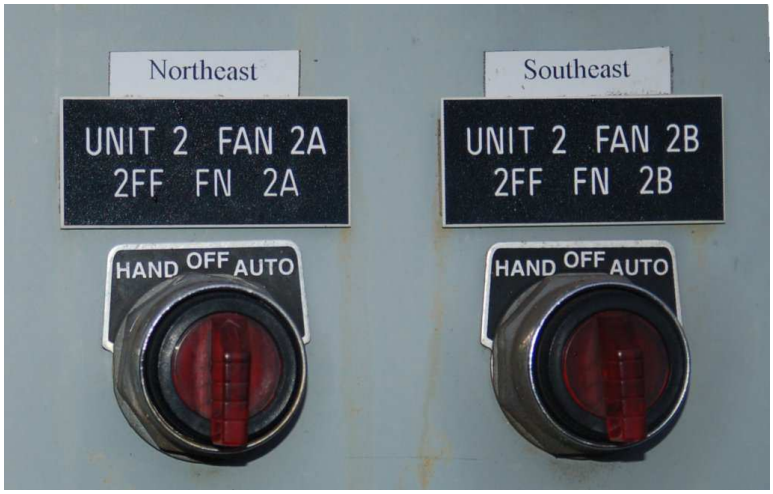
When the receiver tank's air pressure is low, both of these pressure switches will be in their closed states. This starts up the compressor motor, which pumps air into the receiver tank to raise its pressure. As pressure increases, the "low" switch is the first one to be actuated out of its "resting" condition and into its open state, but the compressor motor continues to run because the seal-in contact maintains power to the contactor coil. The motor continues to run until air pressure accumulates high enough to trip the "high" pressure switch, which shuts off the motor when it opens. The motor remains off until the receiver tank's pressure falls below the "low" pressure switch's setting, at which point the motor re-starts and the cycle continues.

A common feature added to industrial automatic motor-starter systems is a three-position manual switch called a *Hand-Off-Auto* (HOA) switch, the purpose of this switch being to provide a means for a human operator to override the starter's automatic functionality. When placed in the "Auto" position, the starter should act as it normally does, starting and stopping the motor based on physically-sensed conditions. When placed in the "Off" position, the motor is forced to shut off and remain in that state. When placed in the "Hand" position, the motor is forced to start up and remain running. A Hand-Off-Auto switch is shown in the following ladder-logic diagram, providing manual override for an automatic cooling fan motor:



With the HOA switch in the "A" (automatic) position, the motor starter circuit starts the motor when the temperature is high enough to close both temperature switches, and shuts off the motor when the temperature falls low enough to open both temperature switches, maintaining the last state during any period when temperature is between the low- and high-switch trip settings. With the HOA switch in the "O" (off) position, the control circuit is electrically open and the motor cannot run. With the HOA switch in the "H" (hand) position as shown in the diagram, both temperature switches are bypassed and the motor is forced to run.

A pair of HOA selector switches used to control industrial cooling fans are shown in the following photograph. Both switches happen to be in their "Off" positions in this photograph:

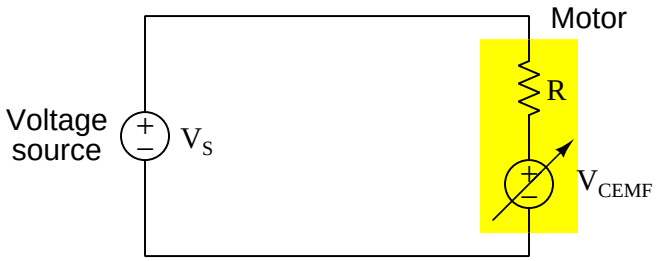


2.6 Inrush current

Any basic motor starter that starts up the motor by connecting the motor's leads straight to the power line conductors is called an *across-the-line starter*. Such starter circuits are simple and easy to understand, but when line voltage is directly applied across the terminals of a stationary electric motor the amount of current the motor initially draws from the source will be unusually high. This high level of motor current is called *inrush current*, or alternatively *locked-rotor current*, and is upwards of several times the motor's full-load operating current value. This abnormally-high current tapers down to regular values as the motor's shaft speed increases from a standstill to full speed. Inrush current poses a significant problem for electric motor starting, and it is for the purpose of mitigating this inrush current that so-called *soft-starting* techniques were developed for electric motors. The purpose of this section is to explain, in general terms applicable to all electric motors, the origin of this inrush current.

When electric current passes through a conductor a magnetic field is produced, and this phenomenon is called *electromagnetism*. When a conductor moves through a magnetic field it generates a voltage, and this is called *electromagnetic induction*. Both of these phenomena occur within an operating electric motor: electromagnetism is used to create the magnetic fields necessary to generate the attractive and repulsive forces creating *torque* (mechanical twisting force) at the motor's shaft, and when the motor's rotor spins within the magnetic field produced by its stationary windings, induced voltages result.

We may formulate a crude electrical model of an energized electric motor using two voltage sources and a single resistance. The fact that these two voltage sources are DC rather than AC is of no consequence – inrush current is based on principles common to both DC and AC motors, and since DC is easier to comprehend than AC we will use DC for our crude model:



V_S represents the voltage of the electrical power source which will energize the motor. R represents the resistance (or *impedance*, for an AC motor) of the motor windings. V_{CEMF} is something called *Counter-EMF*[6], and it represents the voltage induced inside the motor's windings by the rotation of the shaft. You will notice that the polarity of V_{CEMF} opposes the polarity of the source voltage, which is why V_{CEMF} is referred to as a *counter* voltage. The magnitude of V_{CEMF} depends on two varying factors: the motor's shaft speed and the intensity of the magnetic field through which the rotor spins. When the motor shaft is stationary, as it is at the first moment of energization, V_{CEMF} will be zero.

The amount of current passing through this model circuit is a simple function of Ohm's Law: the difference between the two voltage sources divided by the motor's resistance:

$$I = \frac{V_S - V_{CEMF}}{R}$$

When the motor shaft is stationary, as it is initially during start-up or during any condition where the shaft is mechanically bound from turning (i.e. a *locked rotor* condition), V_{CEMF} will be zero and motor current will simply be limited only by V_S and R. This is the locked-rotor current, or *inrush current* value.

As the motor begins to turn, electromagnetic induction begins to take effect on the windings: the shaft's rotation causes the windings to experience a moving magnetic field, thus generating a voltage counter to the polarity of the energizing source voltage. This counter-EMF (V_{CEMF}) rises in value as the motor increases speed, and this opposing voltage has the effect of decreasing the apparent voltage across the motor's winding resistance in accordance with Kirchhoff's Voltage Law. With $V_S - V_{CEMF}$ now less than it was at start-up, the motor current as predicted by Ohm's Law must also be less, which is why motor current falls off as the motor's shaft speed increases.

If the motor has no mechanical load attached and is able to spin freely, its shaft speed will rise to the point where $V_S - V_{CEMF}$ is minimal, and its current will likewise be at a minimum value. As the motor becomes mechanically loaded, its shaft speed slows somewhat, thereby diminishing V_{CEMF}, increasing the difference $V_S - V_{CEMF}$, and increasing current. This is why motor current varies proportionately to mechanical load.

If some external engine or other mechanical power source causes the energized electric motor to speed up past its full rated speed, the motor's counter-EMF may rise to exceed the source voltage,

[6] The term "EMF" simply refers to *electro-motive force*, which is synonymous with *voltage*.

at which point $V_S - V_{CEMF}$ becomes a negative quantity and current reverses direction: i.e. the motor now becomes a *generator*. Note that this effect occurs with every type of electric motor, DC and AC alike, and is a direct consequence of counter-EMF.

Viewing an electric motor as both a voltage source and a resistive load, packaged together in one unit, explains why it draws large amounts of current during start-up and locked-rotor conditions, and also explains why it may serve as a generator if over-sped by a mechanical source.

Resistive heat dissipation is a function of the *square* of current as described by Joule's Law ($P = I^2R$), and so even modest amount of "overcurrent" in an electric motor result in dramatic temperature rises. Motor overheating is the principal threat of inrush current, which is why we must find ways to reduce inrush current for large electric motors. A secondary effect of inrush current is the generation of very high torque (twisting force) at the motor's shaft, and so any technique reducing inrush current will also result in reducing the motor's starting torque. This can be beneficial to the mechanical components coupled to the motor's shaft (e.g. couplings, belts, gears, sprockets, etc.) by reducing the amount of stress and wear experienced during motor start-up.

According to our simple model, inrush (locked-rotor) current may be mitigated in two different ways: by increasing R or decreasing V_S. Every form of "soft-starting" for electric motors take one of these two forms.

2.7 Inrush-limited starting

Multiple techniques exist to limit inrush current for AC induction motors during start-up. Some of these techniques involve decreasing the amount of voltage impressed across the motor's terminals, while others achieve the same end by inserting impedance into the motor circuit to limit current. The term *reduced-voltage starting* is often used to describe all of these methods.

A summary of inrush-limiting motor starting techniques is shown here, most of these techniques relying on the use of multiple[7] contactors (i.e. a "start" contactor and a "run" contactor at minimum) to switch power to the motor:

- Resistance starting
- Reactance starting
- Autotransformer starting
- Part-winding starting
- Wye-Delta starting
- Electronic soft-starting

[7] Close inspection of the diagrams for these multiple-contactor circuits will reveal an important difference compared to reversing motor starters: the contactors for reduced-voltage starters maintain the same phase sequence to the motor, whereas the contactors in a reversing starter circuit swap two of the three phases in order to achieve reversal of shaft direction.

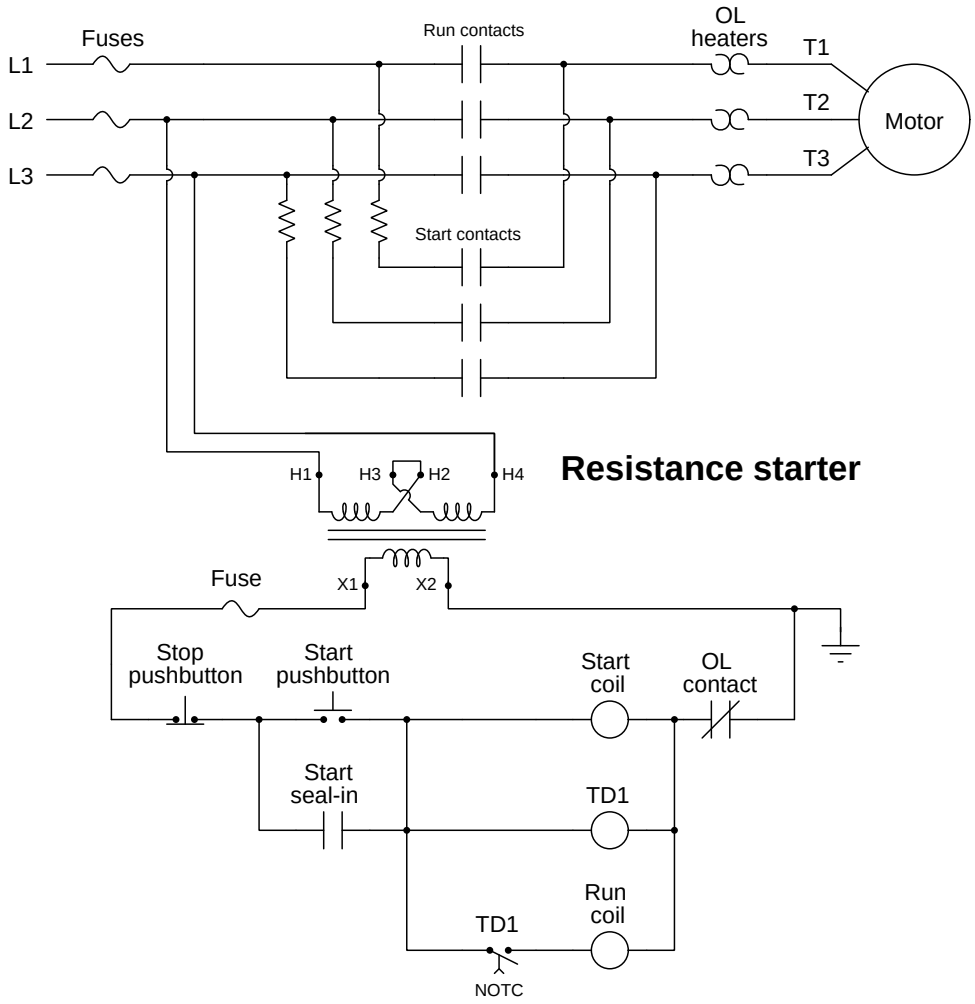
Resistance and *reactance* starting both work by temporarily inserting impedance in series with the motor windings during start-up, making the motor appear as if it possessed greater impedance and thereby reducing inrush current.

Autotransformer starting works by inserting devices called autotransformers into the motor circuit, reducing voltage *and* boosting current to the motor's terminals in order to decrease inrush current as seen from the source. Unlike resistance or reactance starting, autotransformer starting makes it possible for the motor to receive more current than the source provides during start-up, which improves motor starting torque while still holding source inrush current to a minimum.

Part-winding and *wye-delta* starting both require special motors with more than three terminals (T1, T2, and T3). Each starter circuit energizes the motor's stator windings in different configurations during the start-up period versus the run period, the effect being reduced current during start-up.

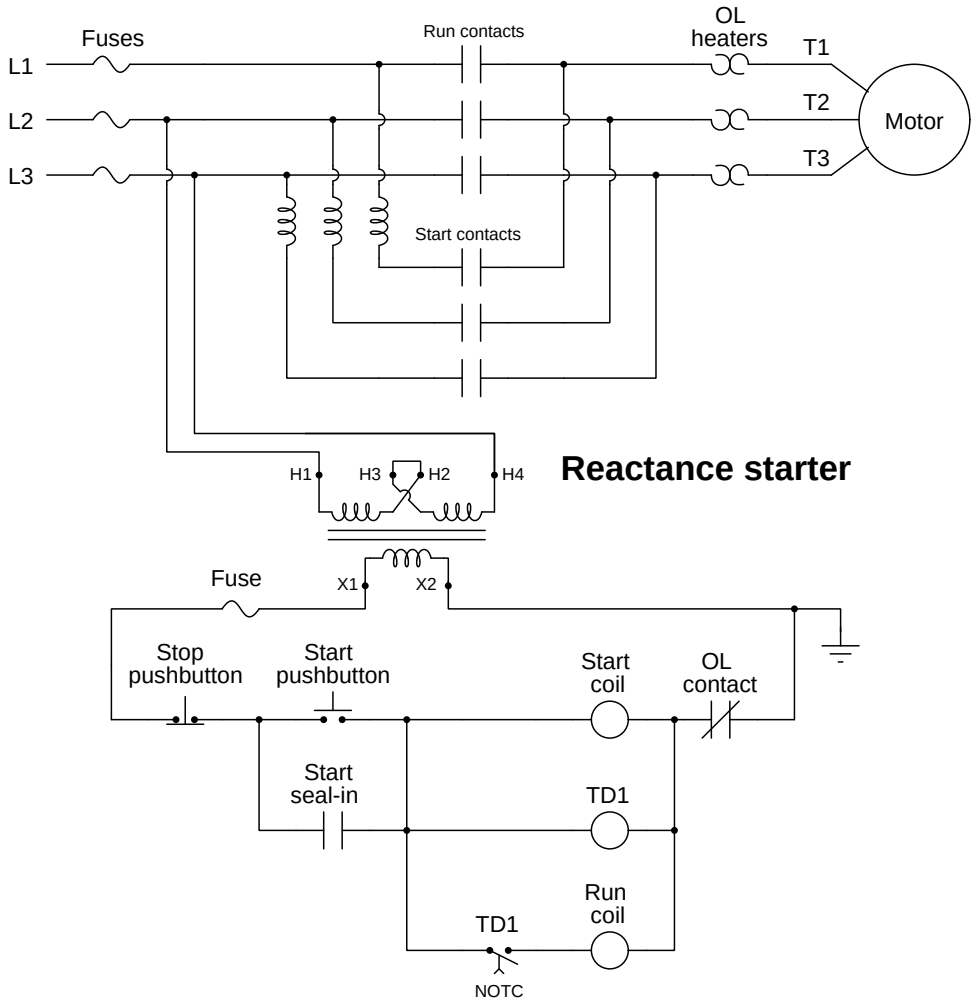
A modern technique called *electronic soft-starting* uses semiconductor switching devices such as SCRs and TRIACs to switch current on and off very rapidly to the motor during start-up, and then apply full power afterward.

Perhaps the simplest technique for limiting inrush current is to initially insert series resistance into the motor circuit upon start-up, then at some later time switch to a direct connection between the electrical power source and the motor. The following diagram shows an example of this technique applied to a three-phase unidirectional motor starter circuit:



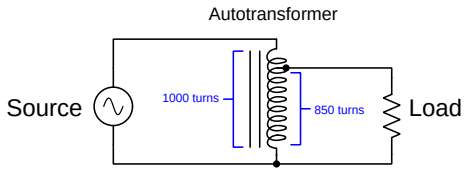
This circuit contains two three-pole contactors, one sending power to the motor through a set of resistances and the other sending power directly to the motor. A time-delay relay (TD1) in the control circuit delays energization of the "Run" contactor for some set amount of time appropriate to the motor and its application. Alternatively, a normally-open *speed switch* mechanically coupled to the motor's shaft could substitute for the time-delay relay contact, closing to energize the "Run" contactor only when the motor shaft has reached some minimum speed.

A very similar strategy uses reactors (i.e. inductors) instead of resistors to impede current during the start-up period. The advantage here is that inductors dissipate less[8] heat than resistors, minimizing the problem of temperature rise within the starter's enclosure:



[8] An ideal inductor, just like an ideal capacitor, is purely reactive which means it does not dissipate energy but rather borrows and returns energy from/to the circuit. If we were to use ideal inductors in this starter circuit, they would release no heat to the enclosure at all. However, real inductors possess wire resistance as well as magnetic losses, both resulting in some heat dissipation. Still it will not be as much heat dissipation as if we had used resistors.

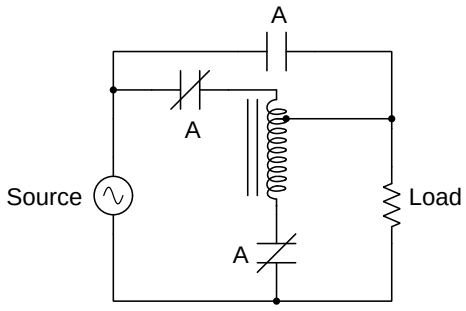
A more sophisticated means of reducing inrush current uses devices called *autotransformers* rather than resistors or inductors. An "autotransformer" functions much like a regular transformer except that it uses a single coil of wire rather than multiple coils to achieve step-up and step-down of voltage and current. To review, a simple autotransformer circuit is shown in the following schematic diagram, using a single coil of wire possessing 1000 turns, with a "tap" connection at 850 turns for connection of a load:



The AC voltage source connects across the full 1000 turns of the coil, while the load resistance connects across only 850 turns of that same coil. This means the load will receive 85% (i.e. $\frac{850}{1000}$) of the source's voltage, while at the same time experiencing approximately 117% (i.e. $\frac{1000}{850}$) of the source's current. In an autotransformer-based starter circuit, the load is the electric motor rather than a resistor, and the end result is reduced voltage to the motor and reduced current from the source. The motor actually receives more current than the source provides during start-up, allowing it to generate more torque for any given amount of source current, which is an advantage over resistance or reactance starting methods if we care more about reducing inrush current than about reducing mechanical stress on the motor. Also, the autotransformer may be equipped with multiple taps allowing for reconfiguration of start-up voltage reduction.

Contactor switching is more complex for autotransformer starters than for resistance or reactance starters, because the autotransformer cannot be operated in parallel with full-voltage to the motor as is the case with resistance or reactance starters. In a resistance/reactance starter, no harm results from simultaneously closing both "Start" and "Run" contact sets, but with an autotransformer these two modes must be made mutually exclusive.

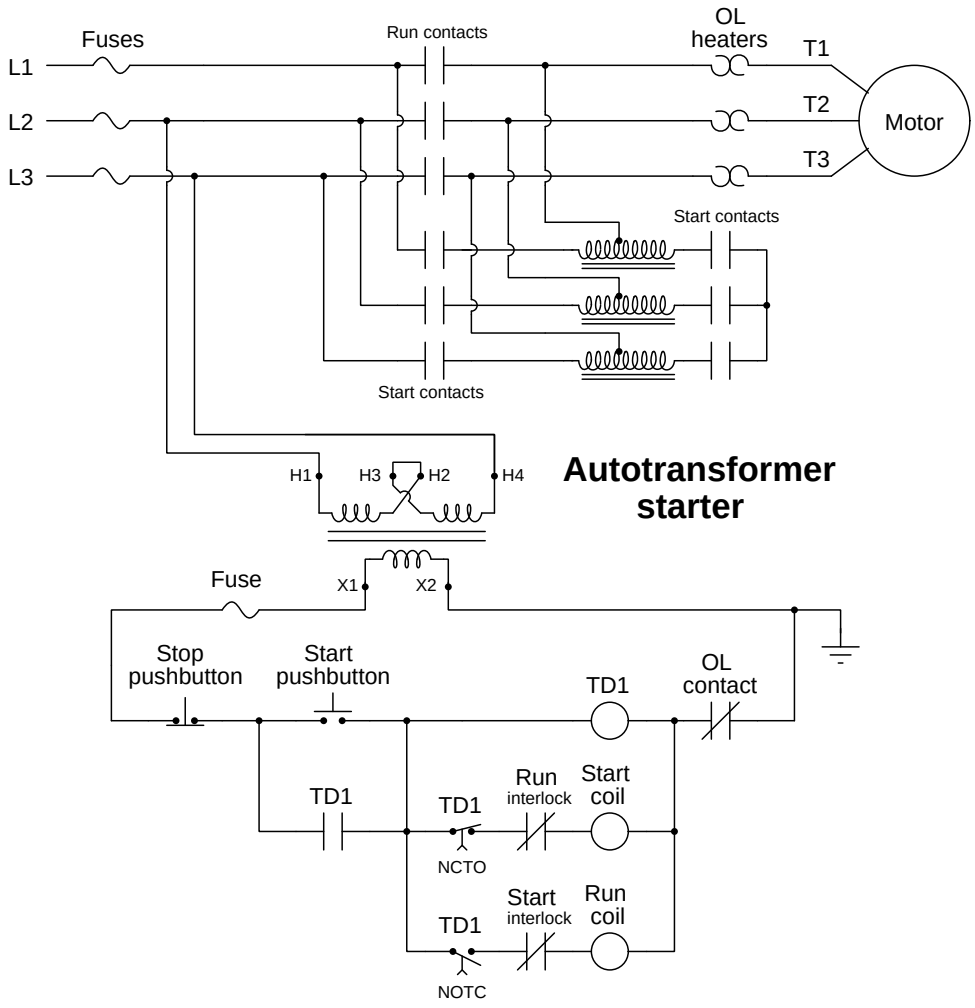
Another simple schematic diagram illustrates this principle, showing three contacts from the same relay "A" controlling the load's power:



When relay "A" is de-energized, its normally-closed contacts will be closed and its normally-open contact open, feeding power through the autotransformer and to the load. When relay "A" energizes, though, its normally-closed contacts both open and its normally-open contact closes, disconnecting

the autotransformer coil at both ends (NC contacts) and bypassing (NO contact) power directly to the load from the source.

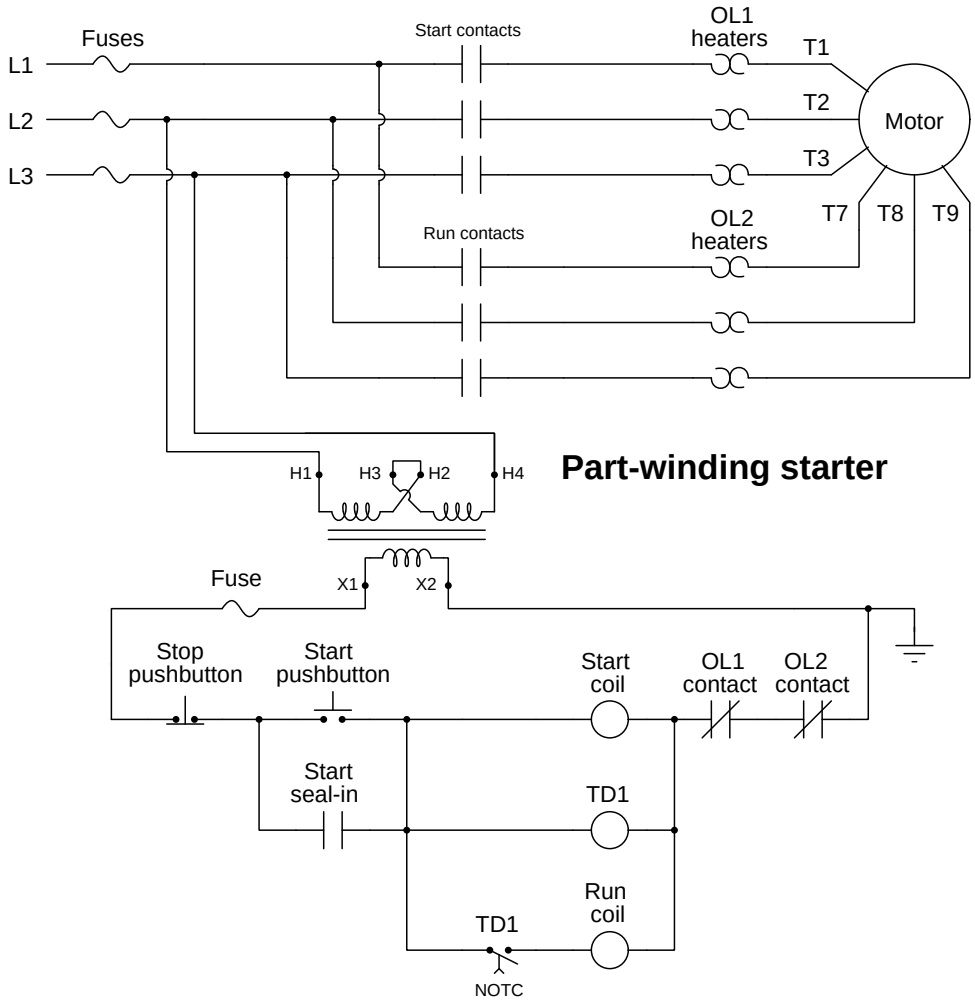
The following diagram shows a motor starter circuit with three autotransformers connected in a Wye network:



Note the timed sequencing provided by relay TD1: an instantaneous contact provides seal-in, while two timed contacts operated by the same coil control power to the Start and Run contactor coils. Normally-closed *interlock* contacts provide additional security against the possibility of both Start and Run contactors simultaneously energizing, which would harm[9] the autotransformers.

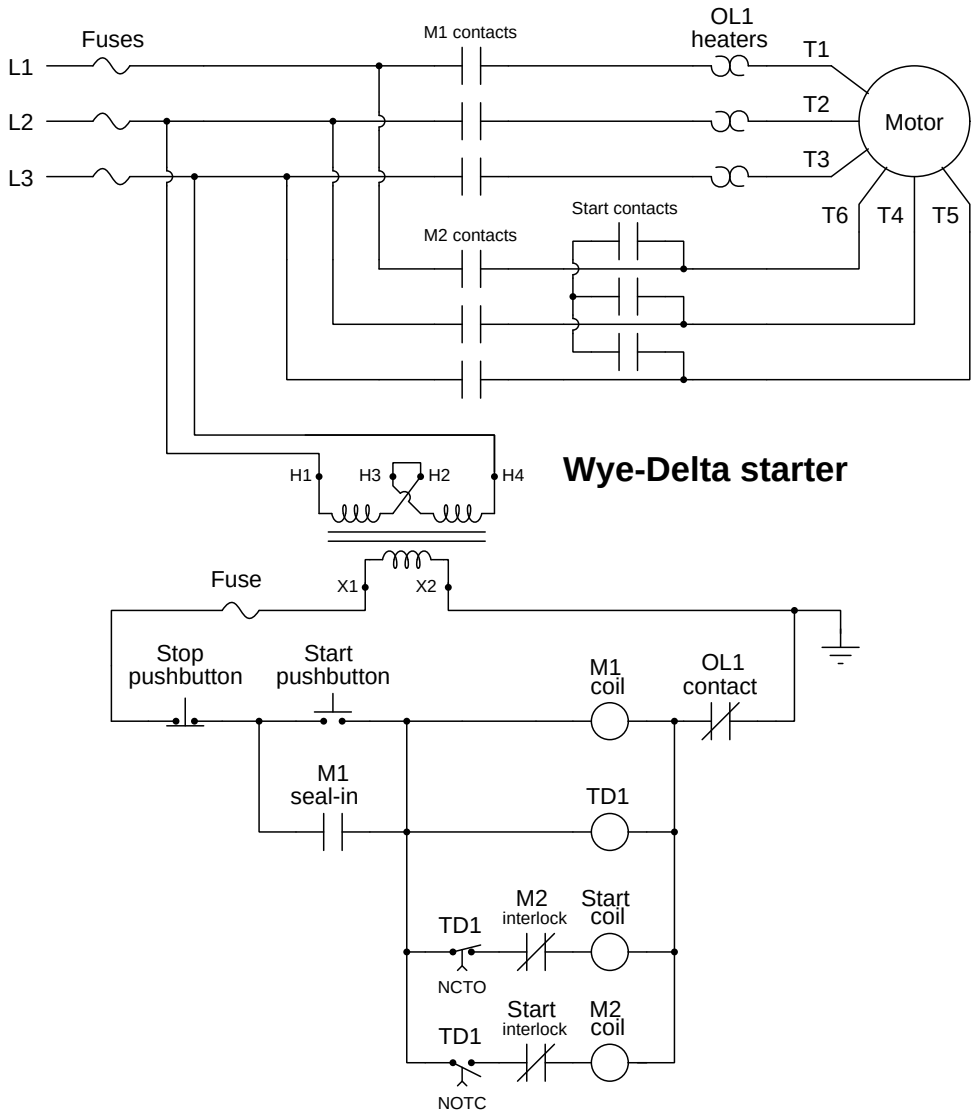
[9] If both Start and Run contact sets were simultaneously closed, each autotransformer would experience a short-circuit across part of its winding. In this particular schematic, the shorted portion would be the left side of the tap. Such a short-circuit would result in a very large amount of current passing through the shorted portion of each winding, very likely destroying the autotransformers if an overcurrent protection device did not first intervene.

Some AC induction motors are equipped with multiple windings for the express purpose of limiting inrush current while starting – essentially two independent sets of stator windings sharing a common rotor and frame. If each winding set is equipped with its own dedicated across-the-line contactor, the two contactors may be closed in sequence resulting in a two-stage start-up. An example diagram showing such a *part-winding* starter circuit appears here:

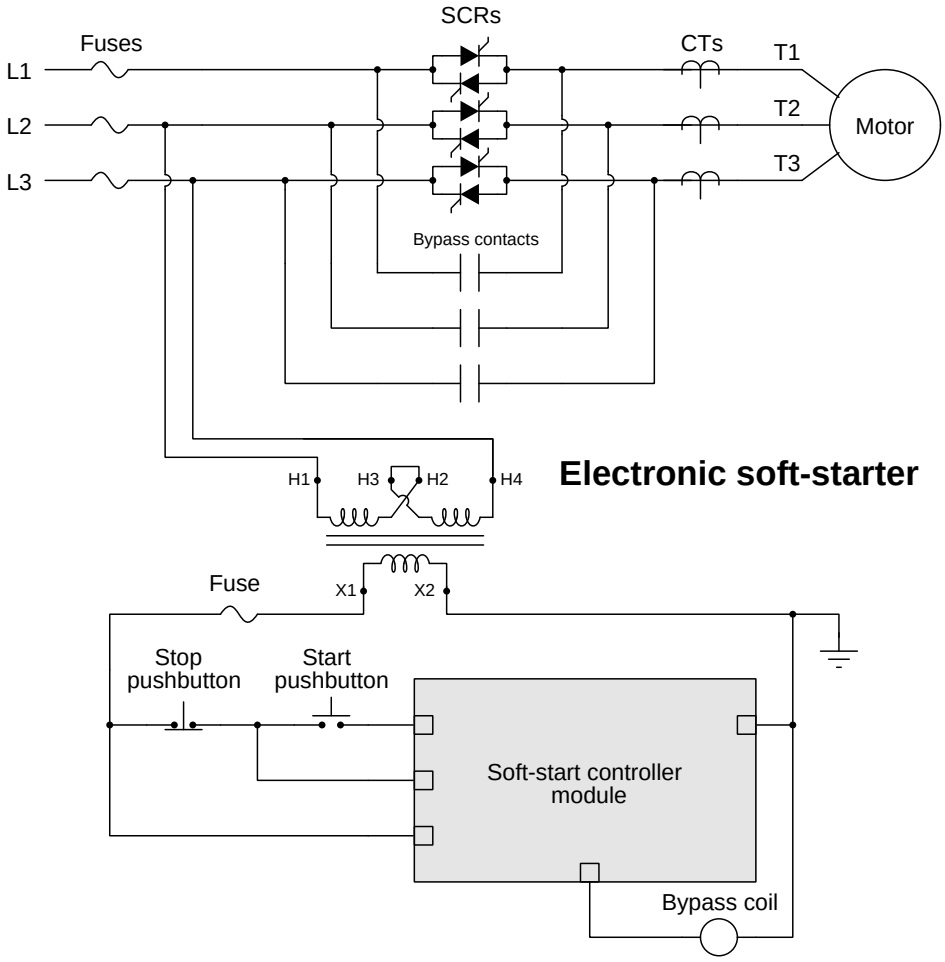


Note the use of two sets of overload heater elements and two overload contacts, each one dedicated to the protection of its respective stator winding set.

Another method for limiting inrush current utilizes a "6-lead" induction motor where the three stator phase windings are not pre-wired in either a delta or a wye configuration, but may be made so by making the appropriate connections (shown on page 66) between six numbered terminals. The starter circuit first energizes the motor in the wye configuration where each stator coil receives $\frac{1}{\sqrt{3}}$ of the full line voltage, then after some period of time switches to delta to impress full line voltage across each stator coil:



A thoroughly modern solution to the problem of motor inrush current is to use semiconductor switching devices to *rapidly pulse power on and off* to the starting motor, as opposed to applying full power. This is typically referred to as *electronic soft-starting*. The following diagram shows power components and the solid-state controller module as it may appear in this starting technique:



The controller module contains all the digital "firing control" circuitry used to trigger the gates of the SCRs, as well as monitor motor current through a set of current transformers (CTs)[10] thus eliminating the need for thermal overload elements. Digital SCR firing allows very precise control over the amount of electrical power delivered to the motor during start-up, enabling the end-user to flexibly configure the soft-starter for virtually any starting profile desired. Additionally, these controllers may provide *soft-stop* capability, where power is gradually shut off to the motor.

[10] Connections between the CTs and the soft-start controller have been omitted in this diagram for simplicity. Real CT secondary terminals should *never* be left unconnected, as the CT requires a low-resistance circuit through which to send its transformed current.

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 References on induction motor starting

The second edition of *Electric Motors – their action, control and application* written by Francis Crocker and Morton Arendt in 1914 describes induction motor inrush current and several methods for its mitigation in chapter 15, beginning on page 202. Note the use of legacy electrical terms, such as *pressure* to represent what we now call *voltage*.

> The fact that an induction motor is substantially a transformer with a short-circuited secondary causes difficulty in starting, especially when its terminals are directly connected to full line pressure. For example: the locked saturation curves of an induction motor, as shown in Fig. 111 (p. 195), indicate that direct application of the full line pressure to the stator terminals, with the rotor short-circuited and standing still, produces an inrush primary current which is nearly five times rated value. Such excessive current is likely to injure the insulation of the windings and should be avoided. In addition to this, the power factor of this current is very low, bring about thirty to forty per cent. It also affects the line regulation, causing voltage fluctuation. Consequently, when the motor to be started is of even moderate size (over 1 h.p.) some means should be employed to limit the inrush current to reasonable values.
>
> Two general forms of rotor windings are employed in practice as already stated on pp. 181-2, and as a result two methods of starting have been developed which depend respectively upon:
>
> - (a) Reduction of Line Voltage.
> - (b) Resistance Control.
>
> Starting by means of reduced line voltage is adopted when squirrel-cage rotors are employed, and it is generally accomplished through the introduction of an *auto-transformer* or *compensator* into the primary circuit. The underlying principle of this type of starter will be understood by referring to Fig. 114. The device is equivalent to a single-coil step-down transformer, the ratio of transformation being that existing between the total number of turns across which the primary terminals are connected and those between which the load is placed. In the specific instance illustrated in Fig. 114, the primary potential is 440 volts, the secondary voltage is 176, secondary current 200 amperes, and primary current 80 amperes. The voltage across the stator terminals is only a frac- [page 202]

tion of the line potential, when the switch is placed in the starting position, but after the motor has approximately reached its rated speed, the switch is thrown over *rapidly* into the *running* position, the stator winding being then directly connected to the supply voltage.

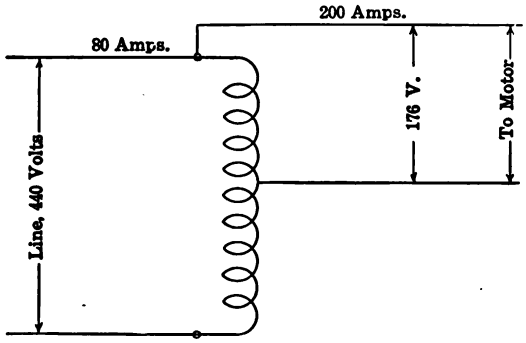


FIG. 114. — SIMPLE AUTO-TRANSFORMER CONNECTIONS.

The compensator windings for a three-phase motor consist of three coils, one for each phase, each coil being placed upon a separate leg of a laminated iron core. Each coil is provided with three or more taps, so that a number of sub-voltages may be obtained, any one of which may be selected for permanent connection to the throw-over

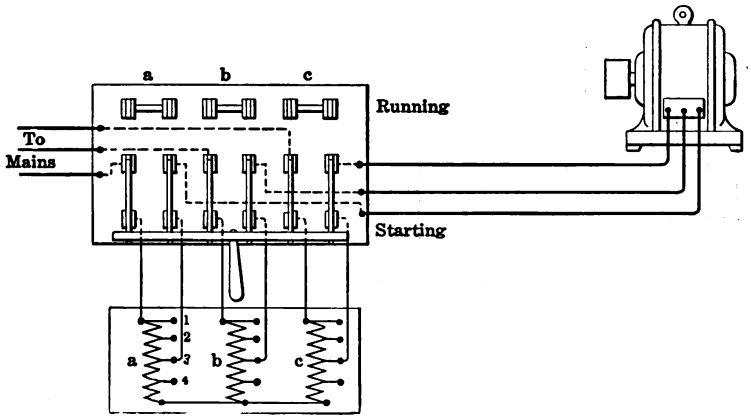


FIG. 115. — CONNECTIONS OF STARTING COMPENSATOR FOR THREE-PHASE INDUCTION MOTOR.

switch, according to service conditions. The three coils of the compensator are Y-connected, the supply line to the three free ends and the starting connections of the motor to the taps being as shown in Fig. 115. To meet various requirements, compensators are generally provided with taps giving potentials approximately equal to [page 203]

40, 58, 70 and 80 per cent of the line voltage, though the 70 per cent value meets most of the commercial requirements, as it gives practically full load torque for starting. The line currents with the above taps are respectively 16, 34, 50 and 64 per cent of that which would be drawn by the motor if no compensator were employed. The chief objection to the compensator is its cost, being about 25 per cent of that of the motor. It has been suggested that this expense could be reduced by using one compensator for starting a number of motors, the method recommended being as follows : [1] A throw-over switch is provided for each motor to be started, and a three-pole compensator supply switch. Only one motor can be started at a time, thus avoiding the line disturbance caused by simultaneous starting of two or more motors, each motor switch being thrown into the running position as soon as the machine

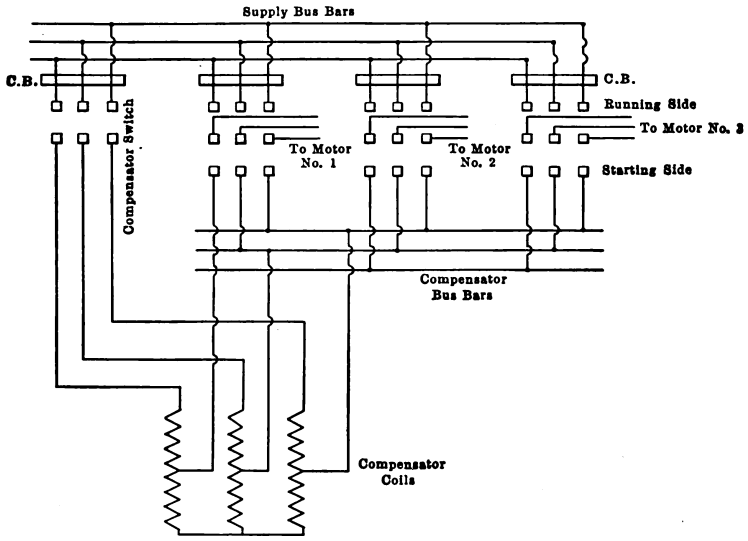


FIG. 116.—CONNECTIONS FOR STARTING SEVERAL MOTORS BY MEANS OF ONE COMPENSATOR.

approximates normal speed. When all motors have been started, the compensator supply switch should be opened. The diagram (Fig. 116) shows the method of connecting three motors to one compensator. [page 204]

[1] G. Stevenson, Journal Institution of Electrical Engineers, Vol. XLI, 1908, p. 685.

Star-Delta Method. – Three-phase motors maybe started without a compensator, by Y-connecting the stator windings at starting, and employing delta connections for running, the change being rapidly made by means of a special throw-over or double-throw four point switch. The connections for such a starting scheme are illustrated in Fig. 117. By this method the voltage per phase at starting is only $1 \div \sqrt{3}$ or 58 per cent of the line voltage. It follows, then, that the starting current and torque are also reduced. For example, con-

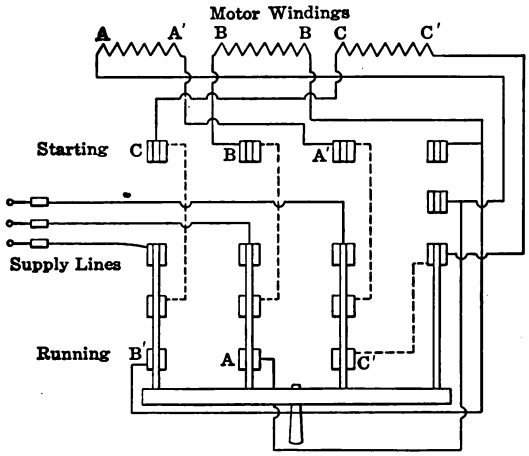


FIG. 117. — CONNECTIONS FOR STARTING THREE-PHASE INDUCTION MOTOR. STATOR Y-CONNECTED FOR STARTING.

sider the 20-h.p. motor already referred to; the starting current with Y-connection would be only one-third of that taken if the motor were thrown directly on the line with delta-connected stator, or it would be $(470 \div 3) \div 97 = 1.62$ times full load current.[2] The starting torque being proportional to the square of the potential difference employed, would give a value of torque equal to one-third of the value obtained with full line voltage.

Boucherot Method. – An excellent method for starting induction motors provided with squirrel-cage rotors is that devised by M.P. Boucherot. The general scheme is to employ the ordinary form of stator as the primary, and to provide a rotor with several squirrel-cage windings of graded resistance and reactance varying from high resistance with low inductance to low resistance with high [page 205]

[2]Rated load current equals 97 amperes.

inductance. The high resistance circuits are the seats of large induced currents at starting, while those of high inductance have only small currents, because at standstill their reactance is high. The starting is due to the high resistance windings. As the rotor speeds up from standstill, the frequency of the secondary e.m.f. decreases; consequently the reactance of the windings diminishes, and all circuits carry current, that of the highly inductive circuits becoming relatively larger, because their resistance is extremely low. Thus the advantages of a high resistance rotor for starting are secured, while the poor speed regulation and low efficiency of such a winding under varying load are avoided by the fact that the low resistance (high reactance) windings are the working ones.

A double squirrel-cage winding is usually found to be sufficient to meet practical requirements, Fig. 118 showing a rotor punching

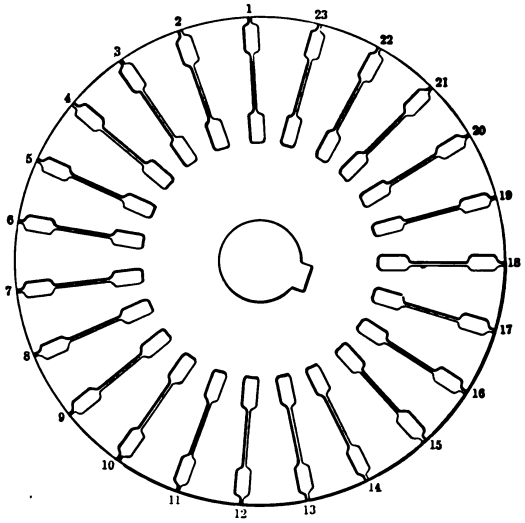


FIG. 118. — ROTOR LAMINATIONS OF A BOUCHEROT MOTOR.

of such a motor. The radial openings joining the upper and lower slots are designed to prevent the occurrence of excessive magnetic leakage with respect to the inner winding. Copper bars are placed in the outer series of holes, and these are connected by means of high resistance end rings formed of German silver or other resistance alloy. Copper bars of larger cross section than those of the outer [page 206]

group are placed in the inner series of slots, and these are connected by low resistance end rings. The speed-torque curves of such a motor are illustrated in Fig. 119;[3] of these, curve A represents the action when the motor is op-

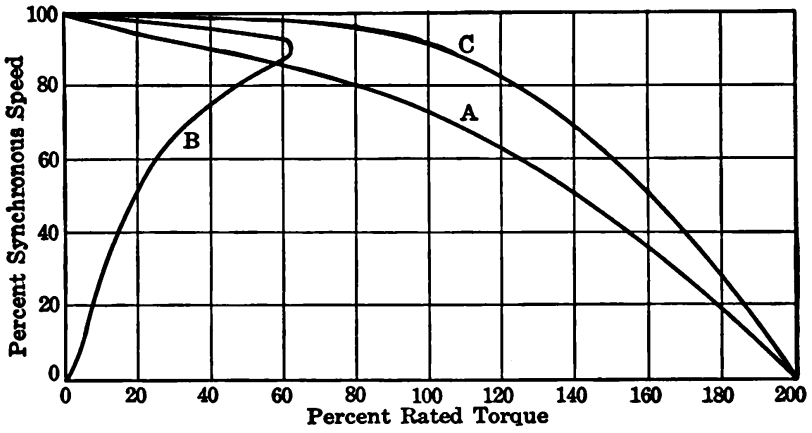


FIG. 119. — SPEED-TORQUE CURVES OF A BOUCHEROT INDUCTION MOTOR.

erated with only the outer or high resistance winding active. In this case the starting torque available is nearly twice that at rated load, and the slip at rated load is about 25 per cent. Curve B indicates the speed-torque relations when the inner or highly reactive winding only is used. Under this condition the motor has practically no starting torque, while the maximum available torque when running is only 60 per cent of the rated value, and the corresponding slip is 6 per cent. The speed torque characteristic of the motor with both windings active is shown in curve C. The starting torque then obtained is substantially twice that existing at rated load. The speed regulation is excellent, a slip of but 6 per cent occurring at rated load.

It is surprising that this method of control is not more widely employed, since the efficiency of the motor thus designed is high, the starting torque good, and the control extremely simple, all that is necessary to start the motor being the closing of an ordinary supply switch.

Resistance Control. – It was shown in the discussion of the torque equation of the induction motor (p. 181) that the starting torque of this type of machine may be varied by changing the resistance of its secondary winding. With this method of control the starting torque can be made to have any value, up to the maximum ; [page 207]

[3] Electric Motors, H. M. Hobart, p. 330, London, 1910.

that is, two or three times the rated load torque. In the case of small machines (3 to 5 horsepower), in which no speed regulation is required, provision may be made to locate the special resistance grids in the annular space between rotor core and shaft, employing for this purpose an overhung core. For example, the three free ends of the rotor winding are connected to three resistance grids placed within the rotor spider. This resistance is subsequently cutout, by operating a lever which engages a collar free to slip longitudinally upon the shaft. This collar moves over the resistance grids, gradually reducing their value, until they are completely short-circuited. This method, while applicable to small machines, is not advisable for large ones on account of excessive PR loss in the resistances, which if confined within the rotor would produce extreme heating and perhaps ultimately injure the motor. Consequently, in large machines, or in the case of those whose speed is to be adjusted, the regulating resistances are placed external to the motor, connections being made to the free ends of the Y-rotor winding by means of three slip-rings and brushes, Fig. 120. This type of resistance control, owing to the presence of the slip-rings, is commercially known as the slip-ring method.

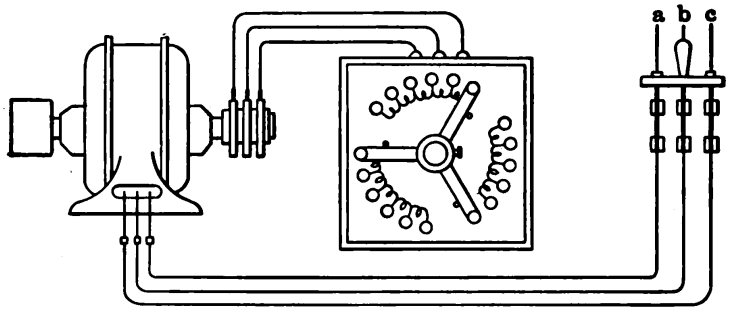


FIG. 120. — CONNECTIONS OF SLIP-RING STARTING DEVICE.

The slip of an induction motor at a given torque varies directly as the secondary copper losses (p. 190); hence if the rotor resistance per phase winding be doubled, the slip for any given torque will be increased 100 per cent; if the resistance be increased to three times its initial value, the slip will be thrice its former amount, etc. The curves shown in Fig. 121 are obtained from the speed-torque curve of Fig. 113, and they correspond to secondary rotor resistances of one, one and one-half, two, four, five and eight times that existing with the rotor short-circuited. These externally added resistances [page 208]

are Y-connected and the movable contact arms cut out resistance equally in each of the branches, as shown in Fig. 120.

The amount of external resistance needed to obtain any given starting torque within the range of the motor's capabilities can be readily determined from the speed-torque curve obtained when the rotor is operated with its windings short-circuited. For example, it is desired to have the typical motor operate so that it will give, as a maximum, approximately rated torque when starting; and Fig. 113 shows that rated torque exists when the slip is eight per cent.

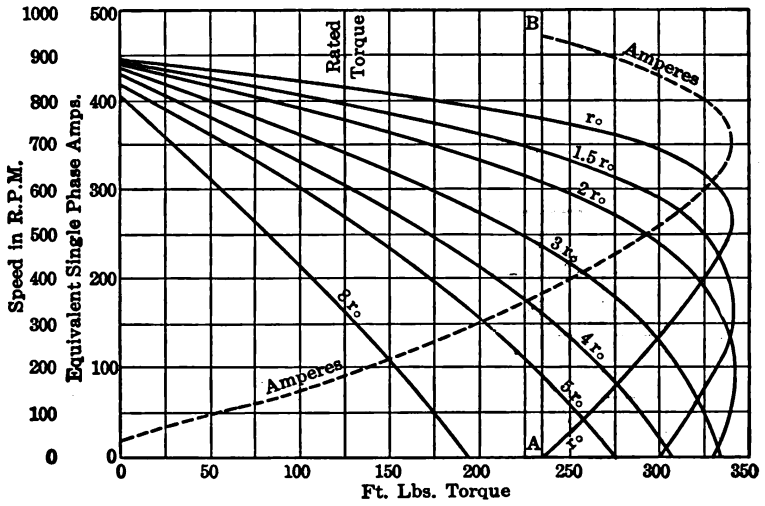


FIG. 121. — SPEED-TORQUE CURVES OF A 20-H.P. INDUCTION MOTOR, WITH VARIOUS VALUES OF ROTOR RESISTANCE.

Hence to have this torque developed at standstill, the desired resistance of the rotor circuit must be such as to increase the slip about twelvefold. However, since the resistance per phase winding of the rotor is .044 ohm, approximately .5 ohm additional must be placed in each branch. Similarly, if it be desired that the motor exert the maximum torque available at starting, the necessary external resistance can be also determined directly from the speed-torque curve of Fig. 113. The slip at maximum torque is 40 per cent, therefore to have 100 per cent slip and same torque, the rotor resistance must be increased to about 2.5 times its initial value, that is, a total of .044 X 2.5 = ,110 ohm must be placed in each phase circuit of the rotor. [page 209]

3.2 Early AC motor overload protection

In the early 1900's[4] the Westinghouse Electric & Manufacturing Company published a book called *Silent Sentinels* describing what was then the state-of-the-art in automatic electric power system protection, particularly focused on specialized *protective relays* manufactured by Westinghouse for this purpose. Section 5 ("Protection of Alternating-Current Apparatus) of chapter III ("Alternating-Current Systems") discusses the protection of AC electrical device windings from overtemperature:

> **Temperature Protection of Windings** – Inasmuch as the overheating of the windings in electrical apparatus is closely related to overcurrent protection, the overcurrent protection is often adequate to provide the necessary temperature protection. In some cases, however, it is more desirable to furnish protective apparatus which will include in its operation, not only the load on the apparatus, but also the existing temperature of the windings. In other cases, the temperature of the winding alone is taken as the determining factor in the operation of a temperature protective scheme. [page 33]
>
> In most of the larger generating stations or substations, where constant supervision of the operation of the various machines is possible, temperature indicating devices are used to show the attendant when the temperature of the windings in question becomes such that some means should be used to reduce it. Such indications are usually provided by means of exploring coils imbedded in the windings of the apparatus serving either to actuate a signal when the temperature reaches some predetermined point, or to operate some temperature indicating instrument. Thus when the critical degree of heat is indicated, the operator may relieve the condition either by reducing the load on the apparatus, or by increasing any existing cooling means, such as the flow of air or water, as the case may be.
>
> **Oil-Filled Thermal Relays** – Where manual supervision is not possible, such as in automatic substation equipment, and in plants using numerous motors, it is necessary to have temperature protection that will disconnect the apparatus when any predetermined conditions exist. A common scheme for providing such protection is to apply in a protective relay a heating element with thermal characteristics similar to those of the machine to be protected. A current proportional to the load current in the apparatus itself flows through the heating element of the relay. The characteristics of this element are such that its temperature will be approximately the same as that of the protected apparatus under all loads and at all times. When the temperature of this element reaches the critical point, it serves to trip the apparatus off the line. The Westinghouse BA and BD oil-filled thermal relays serve to provide this class of protection. [page 34]

[4] The copy I possess has no date of publication, only an ink stamping on the cover saying it was received on 6 August 1928 by the P.P. & C. Company Power Department of Kennewick, Washington. Therefore, all I can say as to this book's date is that it was prior to August 1928. Inside this book it mentions the first Westinghouse induction-type overload protective relay as being introduced in 1902. The latest date mentioned inside this book is the year 1916 when Westinghouse introduced the type CR reverse-power relay.

A diagram showing the internal construction of a type BA oil-filled thermal relays appears on page 63 of *Silent Sentinels*. This relay design used multiple *bimetal elements* which would physically distort when heated, their movement actuating a switch contact which would be wired to the trip coil of a circuit breaker, automatically tripping that breaker (open) in the event of overheating:

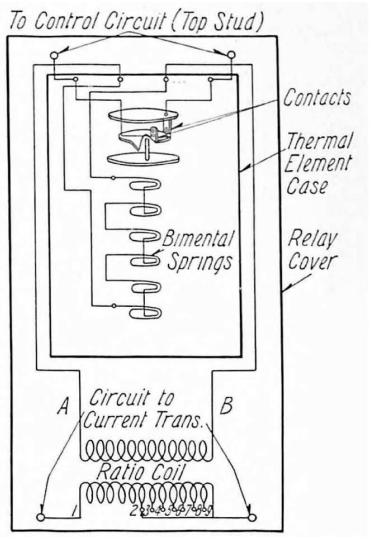


FIGURE 126.—INTERNAL CONNECTIONS OF TYPE BA RELAY.

The wires and bimetal elements within this particular relay were not large enough to directly carry the line current of a large generator, motor, or transformer, and so the type BA relay was designed to receive a stepped-down proportion of the line current from a *current transformer*, or *CT*. The "thermal element case" of this relay was filled with oil, providing enough mass to delay its warming and cooling so as to possess similar thermal dynamics as the machine being protected.

Additional explanatory text for this relay appears on page 63 of *Silent Sentinels*:

> Another type of temperature relay which does not require the use of exploring coils embedded in the windings of the apparatus to be protected has been developed. This type depends upon the expansion of a bi-metal element. The element has characteristics such that it heats up at the same rate as the windings of the apparatus to be protected. In order to further duplicate the temperature rise of the protected apparatus, the bi-metallic element is immersed in oil and the walls of the container are such that the dissipation of heat will be, approximately, the same as in the case of the apparatus to be protected. The operation of the relay is simple. When the bi-metallic element heats to a certain temperature it expands sufficiently to operate the relay, closing its contacts. [page 63]

A more direct method of sensing machine winding temperature is described for the Westinghouse type CT relay:

> **Type CT Temperature Relay** – Another scheme used for the temperature protection of windings is to have the protective apparatus dependent on the current flowing at any given time, and also at the same time on the temperature within the windings of the apparatus to be protected. In such a scheme, the temperature is usually determined by means of copper exploring coils buried in the windings, and connected in some sort of bridge arrangement, so that the change in the resistance of the exploring coils, due to any change in the temperature of the windings, will give the proper temperature indication to the protective relay by using the change in the resistance values to cause a flow of current. In addition to this, a current proportional to the current flowing in the apparatus, flows through another winding of the relay, and thus the following three conditions are necessary before the apparatus is disconnected from the source of power. First, the temperature of the windings of the apparatus must be above the value for which the relay is set to operate; second, the current flowing in the apparatus must be above the normal value; and third, these two conditions must have existed for a given period of time. Thus the liability of the machines being disconnected upon the occurrence of a transient overload is guarded against. The CT temperature relay provides such protection, and embodies the necessary characteristics to assure maximum continuity of service.
>
> The simplest form of overtemperature protection is that in which the temperature of the surrounding material is alone used as an indication of the temperature of the winding, and is taken as the determining factor in the operation of any protective relays used. Such a scheme is used largely in the protection of transformers where the exploring coils, expansion bulbs, or whatever means are used for measuring the temperature of the surrounding material, may be embedded between the coils of the transformers in such a way that an approximate indication of the temperature of the windings is secured. The HM thermostat relay is sometimes used for this purpose. [page 34]

An illustration showing the internal construction and application of a type CT temperature relay is shown on page 34. Please note that "zig-zag" symbols shown in electrical power diagrams refer to *coils* (windings) and not *resistors* as is the case with electronic schematic diagrams:

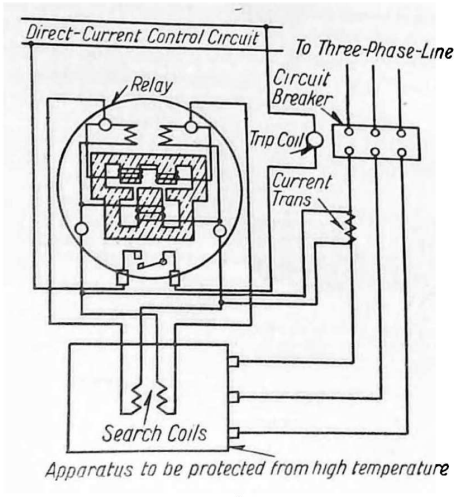


FIGURE 60—CONNECTIONS FOR PROTECTING WINDINGS FROM OVERHEATING WITH CT TEMPERATURE RELAY.

An illustration showing the internal construction and application of a type HM "expansion bulb" temperature relay to the protection of a mechanical bearing also appears on page 34:

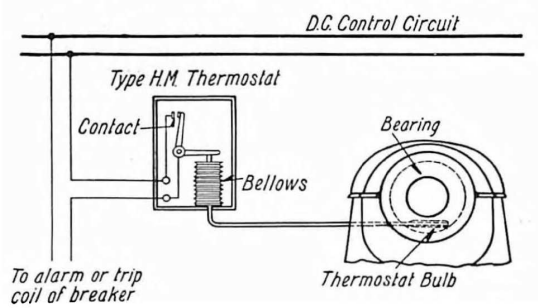


FIGURE 61—SCHEMATIC DIAGRAM OF TYPE HM THERMOSTAT INSTALLATION

An "expansion bulb" is a hollow metal tube, sealed at one end and connected to a long and narrow *capillary tube* at the other, leading to a bellows. The bulb and capillary tube are filled with some fluid, either gas or liquid, which expands when heated. Thus, as the bulb experiences an increase in temperature, the fluid expands to actuate the bellows, which in the case of the type HM relay works to close a switch contact signaling an overtemperature condition at the protected device.

Chapter 4

Derivations and Technical References

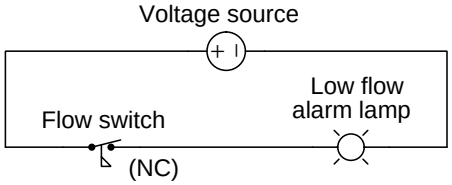
This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

4.1 Normal status of a switch contact

An perennial source of confusion among students new to electric switching circuits is the use of the word *normal* to refer to an electrical switch's default state. Switches, of course, are discrete devices capably only of two definite states: *open* (i.e. no electrical continuity) and *closed* (i.e. electrical continuity). *Toggle* switches are constructed in such a way that they may latch in either of these two states, which means they have no default condition. A great many switch types, however, are designed with a spring-return mechanism or equivalent functionality to make the switch return to a certain default state in the absence of any external stimulus. **This is called the "normal" state of the switch: its electrical state when at rest.**

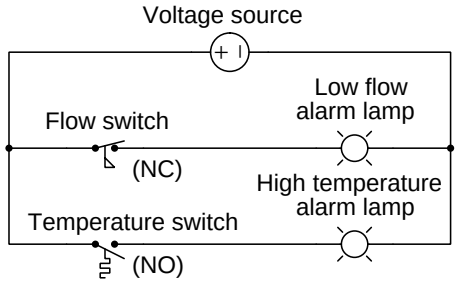
Where this becomes confusing is in applications where such a switch is *typically* found in an actuated state, such that ordinary operating conditions for the circuit maintain that switch in its *non-normal* state. Colloquial use of the word "normal" is synonymous with "typical" which makes it possible for someone to see a switch's "normal" status and mistakenly think this refers to its state in the circuit's normal operation rather than meaning its "normal" status as defined by its manufacturer.

A brief illustration is helpful here. Consider a *flow switch* used to detect the presence of liquid coolant flow through a pipe, carrying coolant to an operating engine. Engines, of course, dissipate heat as they run, and so a continuous flow of coolant to the engine is critical for maintaining safe operating temperature. A simple diagram shows how this flow switch would be connected to a warning lamp to alert personnel of any interruption in coolant flow to the engine:



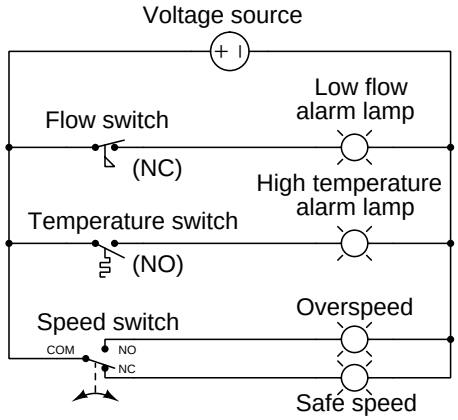
Since the purpose of this circuit is to energize the warning lamp in the event of *no coolant flow*, the flow switch's spring-return mechanism must be configured in such a way to *close* the switch contact in the absence of flow. In other words, this flow switch's contact will be closed when at rest – i.e. it will be a *normally-closed* flow switch. However, during typical operation when adequate coolant flow is present in the pipe, this switch will be held in its open state and the alarm lamp will be de-energized. Even though the flow switch is *normally-closed* (NC), in this application it will be *typically open* – the "normal" and "typical" states for this switch in this application are opposite.

Now consider the addition of a different type of switch and alarm lamp to the circuit, with the new switch installed on the same heat-dissipating engine serving to warn personnel if the engine becomes too hot:



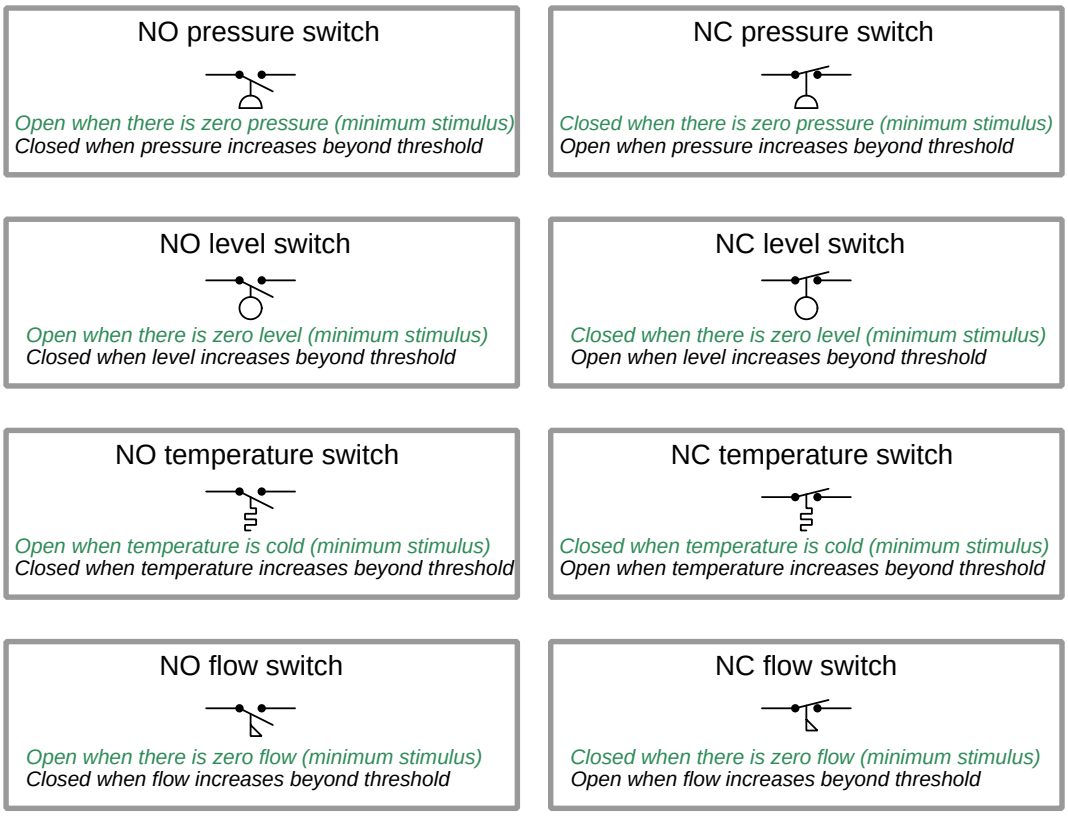
This new switch's purpose is to energize its warning lamp in the event the engine overheats, and its mechanism must be configured to *close* the switch in the presence of high temperature. This means the temperature switch's spring-return will force it open at rest, making it a *normally-open* temperature switch. During typical operation when the engine's temperature is within reasonable bounds, this switch will still be in its resting state, and so this *normally-open* (NO) temperature switch will also be *typically open* – a case where "normal" and "typical" states happen to be identical.

Let us consider one more switch application for this hypothetical engine, this time using a *single-pole, double-throw* (*SPDT*) speed switch to monitor the engine's shaft speed and trigger energization of two indicator lamps, one for "safe speed" and another for "overspeed":



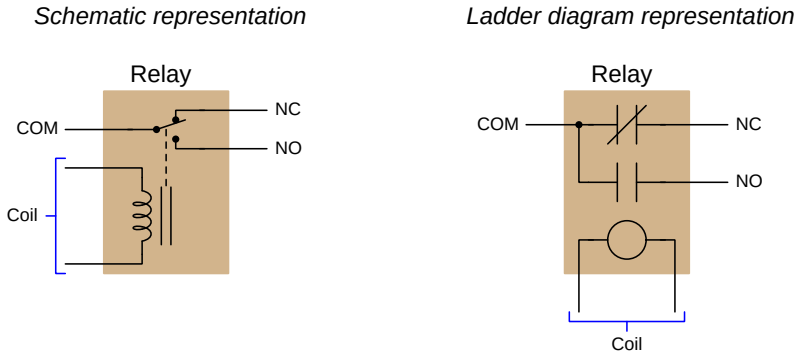
Note the COM, NO, and NC labeling of this switch's three terminals, denoting "Common", "Normally-Open", and "Normally-Closed", respectively. As with the other two switches, these contact labels as well as the switch symbol itself as drawn in the diagram represent the switch's state *when at rest*. This is strict convention in electrical switching circuits: the "normal" state of any switch is defined by a condition of minimal stimulus, and this is always how it is drawn.

A helpful tip to remember about sensing switches and their respective symbols is that the symbols are conventionally drawn in such a way that an *upward* motion of the movable switch element represents *increasing stimulus*. Here are some examples of this, showing various switch types and NO/NC contact configurations, comparing their states with no stimulus versus when the stimulus exceeds the each switch's threshold or "trip" setting. The *normal* status of each switch as defined by the manufacturer is labeled in green text:



Interestingly, the convention of upward motion representing the direction of stimulus is not maintained for hand-operated switches.

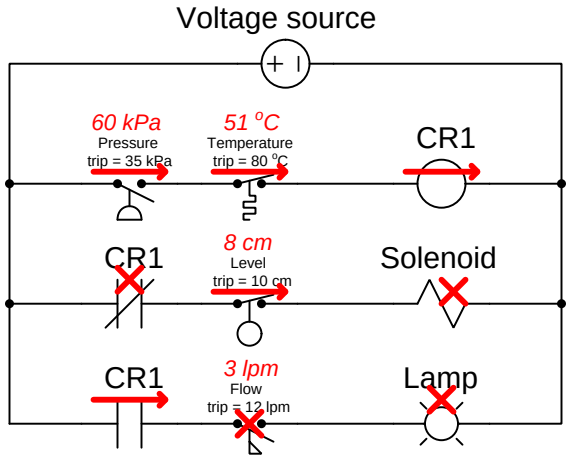
Switch contacts within electromechanical relays are also characterized as being either normally-open (NO) or normally-closed (NC), and in this case the stimulus in question is the energization of the relay's electromagnet coil. When the coil is de-energized, the contacts will all be in their resting (i.e. "normal") states which is also how the relay's contacts are drawn in diagrams. When the coil is energized, though, all contacts within the relay flip to their opposite states: all NO contacts *close* and all NC contacts *open*. The specific symbols used to represent relay coils and contacts differ according to the type of diagram, but their meaning is the same:



A normally-closed (NC) relay contact is one which will be in its closed state when the coil is de-energized, represented in diagram form by touching lines or by a slash mark between the two contact plates. A normally-open (NO) relay contact is one which will be in its open state when the coil is de-energized, represented in diagram form by an air gap between the contacting surfaces. Upon energization of the relay coil, all the contacts within that relay change state, *but their written symbols remain the same*[1] in order to represent their *resting* states.

[1] A bad habit some people adopt is to draw a slash mark through a relay contact symbol in order to annotate that relay contact's *closure* when analyzing the diagram for a relay-based circuit. This habit should avoided, as the symbols used to represent *normal* status should never be used to represent *present* status. There is enough confusion as it is surrounding the term "normal" without any more being added, so please do not contribute to the chaos!

When analyzing electrical switching circuits, a helpful problem-solving strategy is to annotate the diagram with symbols denoting the *actual* status of each switch contact in any given circuit condition, and not the *normal* status. Such annotations make it easier to determine which loads in a circuit will be energized, and which will not, for any given circuit condition. For this I recommend sketching an arrow or a line nearby a contact to show a closed state, and an "X" nearby a contact to show an open state. These annotations demonstrate real contact status without obscuring normal status. Consider these annotations used in the following example diagram:

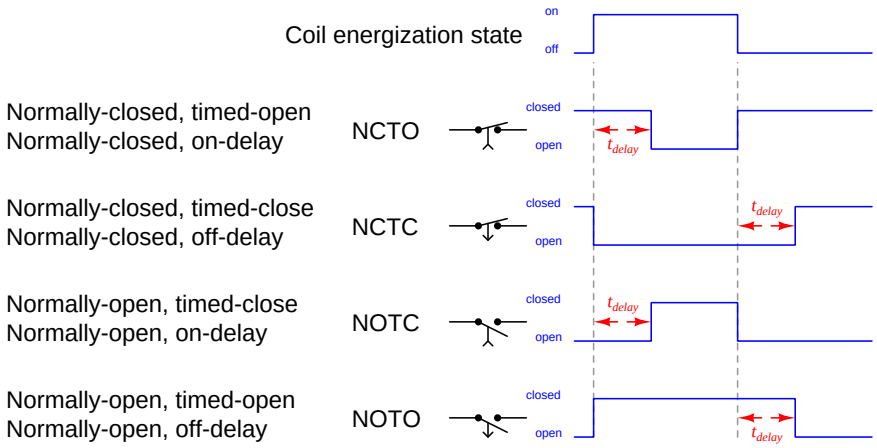


In the upper "rung" of this ladder-style diagram we see the normally-open pressure switch is actuated (i.e. closed) because the applied pressure of 60 kPa exceeds the switch's trip setting of 35 kPa. The normally-closed temperature switch is unactuated (i.e. closed) because the applied temperature of 51 ^{o}C is less than the trip threshold of 80 ^{o}C. The red arrows annotating both switches show their closed statuses. Wired in series, these two closed switch contacts permit energizing current to the coil of relay CR1, and so another red arrow drawn there indicates that coil's energized status.

In the second and third rungs we see the present status of each CR1 contact. Since the CR1 relay coil is energized it places each CR1 relay contact into a state opposite of its "resting" or "normal" condition, therefore the normally-closed CR1 contact in rung 2 is open (shown with a red "X" annotation) and the normally-open CR1 contact in rung 3 is closed (shown with a red arrow annotation). The level switch's stimulus is less than its trip setting, and so that normally-closed contact remains closed and gets a red arrow. The flow switch's stimulus is also less than its trip setting, and so that normally-open switch remains open and gets a red "X" annotation. Neither rung 2 nor rung 3 is completed because one of the series-connected contacts in each rung is open thus preventing energization of its load. Therefore, both the solenoid coil and the lamp are de-energized, shown with red "X" annotations.

4.2 Time-delay relays

Specially-constructed relays exist to perform *time-delay functions* where the actuation or de-actuation of the armature is intentionally delayed. Four variations on this theme are shown in the following illustration of an SPST time-delay relay contact:



The "normal" (i.e. *resting*) state of each contact is represented the same as for any other switch contact: the switch is always drawn in that "normal" state: NO contacts are always drawn as though open and NC contacts are always drawn as though closed. What is new with time-delay relay contact symbols is the addition of a small arrowhead representing the direction of delayed armature motion: if the arrowhead points away from the contact it means the contact is delayed returning to its "normal" (resting) state; if pointing toward the contact it means the time delay occurs upon energization. Another way of thinking about this is to say if the arrowhead points away from the contact then it is an *off-delay* contact (i.e. the delay occurs when the coil turns off), and if the arrowhead points toward the contact it is an *on-delay* contact (i.e. delay occurs when coil turns on).

4.3 Electrical safety

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

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

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

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

Table II of Dalziel's' report (shown on page 24) is partially[3] reproduced in the following table. The headings "M" and "F" refer to male and female subjects, respectively. Tests conducted using direct current[4] are labeled "DC" while tests conducted using alternating current[5] are labeled with

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

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

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

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

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

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

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

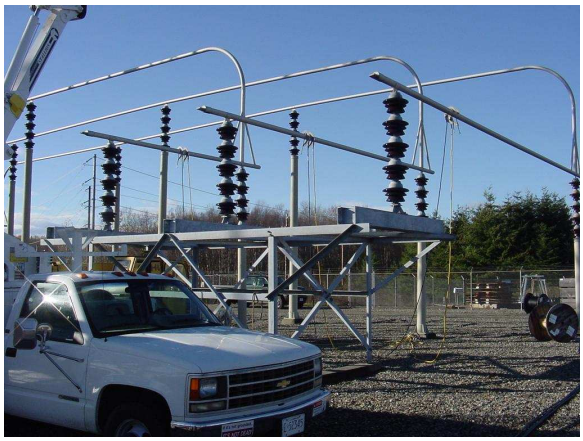
All gruesome details aside, the lesson to be learned here is very plain: *very little electric current is necessary to induce painful and even life-threatening effects on the human body!* These danger thresholds are all substantially less than the amount of current most power conductors are rated to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

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

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

Once all electrical energy sources have been disconnected from the circuit you intend to work on, an additional safety measure is to *bond* that circuit's power conductors to Earth ground. This step forces the power conductors to be *electrically common* with Earth, and therefore guarantees a condition of equipotentiality with the Earth. Line workers who install and maintain electric power line conductors do this as a standard part of their operating procedure: attaching temporary grounding cables between the power conductors and Earth after opening all disconnect switches normally connecting those lines to electrical sources. This extra step of bonding the power conductors ensures no stray sources[6] of electrical energy may pose a threat.

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



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

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

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

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

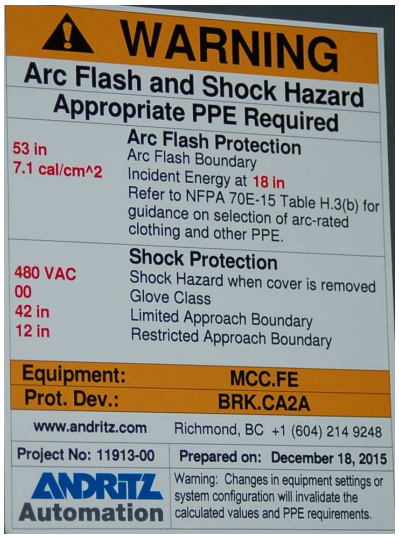
Burns produced by electricity passing through the body may manifest on the skin, at the point of contact with an electrical conductor (such as a wire), or in severe cases may extend to internal organs. Comparing internal flesh with skin, dry human skin tends to exhibit much greater levels of electrical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

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

The amount of resistance exhibited by a high-temperature arc is surprisingly low, typically less than one Ohm across the entire length of the arc. With such low resistance, Ohm's Law predicts relatively high current values for even modest voltages ($I = \frac{V}{R}$), resulting in high power levels. Even if the amount of energy released by each charge carrier moving through the arc is small, the fact that a great many charge carriers are moving through the arc each second means that the total amount of energy dissipated may be phenomenally large. This is why arcs forming in high-voltage electric power systems may reach temperatures of tens of thousands of degrees[7]!

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

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



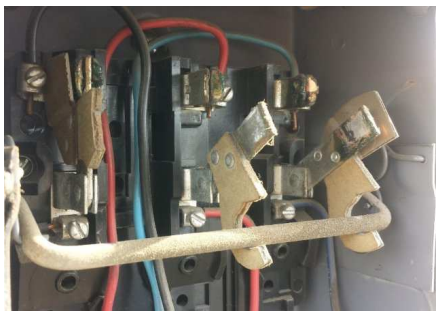
The first line of defense against arc flash is the same as for electric shock: *de-energize the circuit* so there will be no electrical energy present to harm you. The procedure for de-energizing includes placing a warning *tag* as well as a secure *lock* on any main disconnecting switches or circuit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

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

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

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

Such a lengthy procedure may seem paranoid, but there is good reason for all these steps. Remember that *all safety standards and procedures are written in blood:* in other words, every one of them exists because either someone got hurt or came close to getting hurt by not taking appropriate precautions. One example of the latter is the following photograph generously shared by Jim Lyon[8] who discovered a failed three-phase disconnect switch during a routine LOTO procedure:



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

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

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

In cases where de-energization is not possible or not practical, special "arc-flash rated" clothing may be worn to protect your skin against the high temperatures of arc flash should an arc flash occur. Arc flash suits cover all skin surfaces, and are rated according to the number of calories[9] of heat the fabric may sustain without disintegrating. The following photograph shows a pair of arc flash suits hanging on a wall ready for electricians to use while working on circuit breakers at an electric power generating station:

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

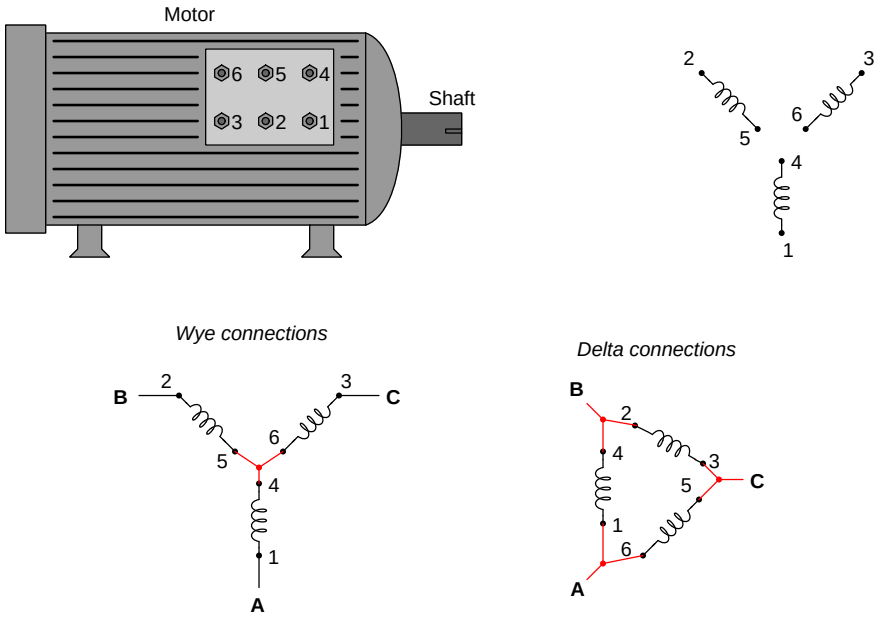
[9] A *calorie* is simply another unit of energy measurement. The unit-conversion equivalence is 4.187 Joules per calorie.

The hazards of electrical arcs are not limited to bodily burns. Given sufficient arc power, the explosive expansion of hot air and the shrapnel created by disintegrating hardware represents its own unique hazard, known as *arc blast*. As an *electrically-driven* explosion[10], arc blast is limited only by the available power of the fault, and can in fact be more violent than a chemical explosion. No suit can ensure safety against arc blast, and so the only reasonable precaution is maintaining a safe distance beyond the blast radius.

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

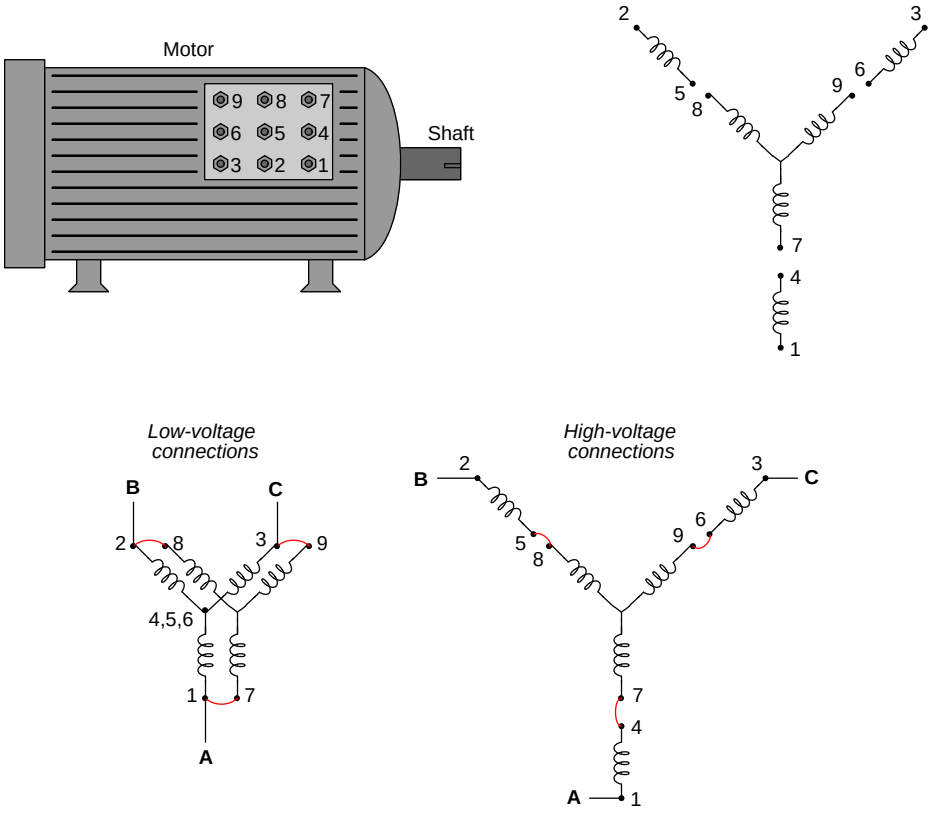
4.4 6-lead AC induction motors

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:



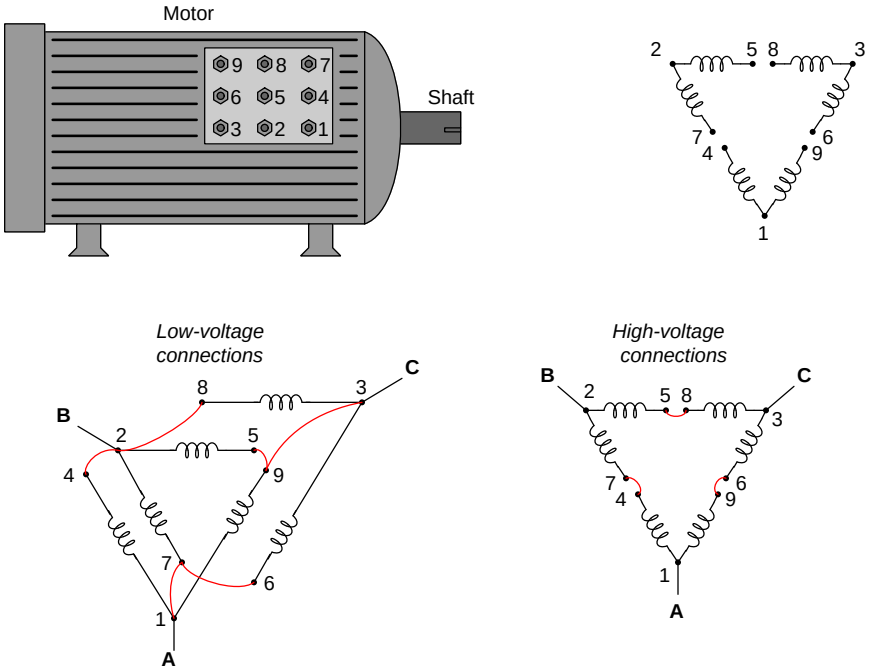
4.5 9-lead AC induction motors

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.

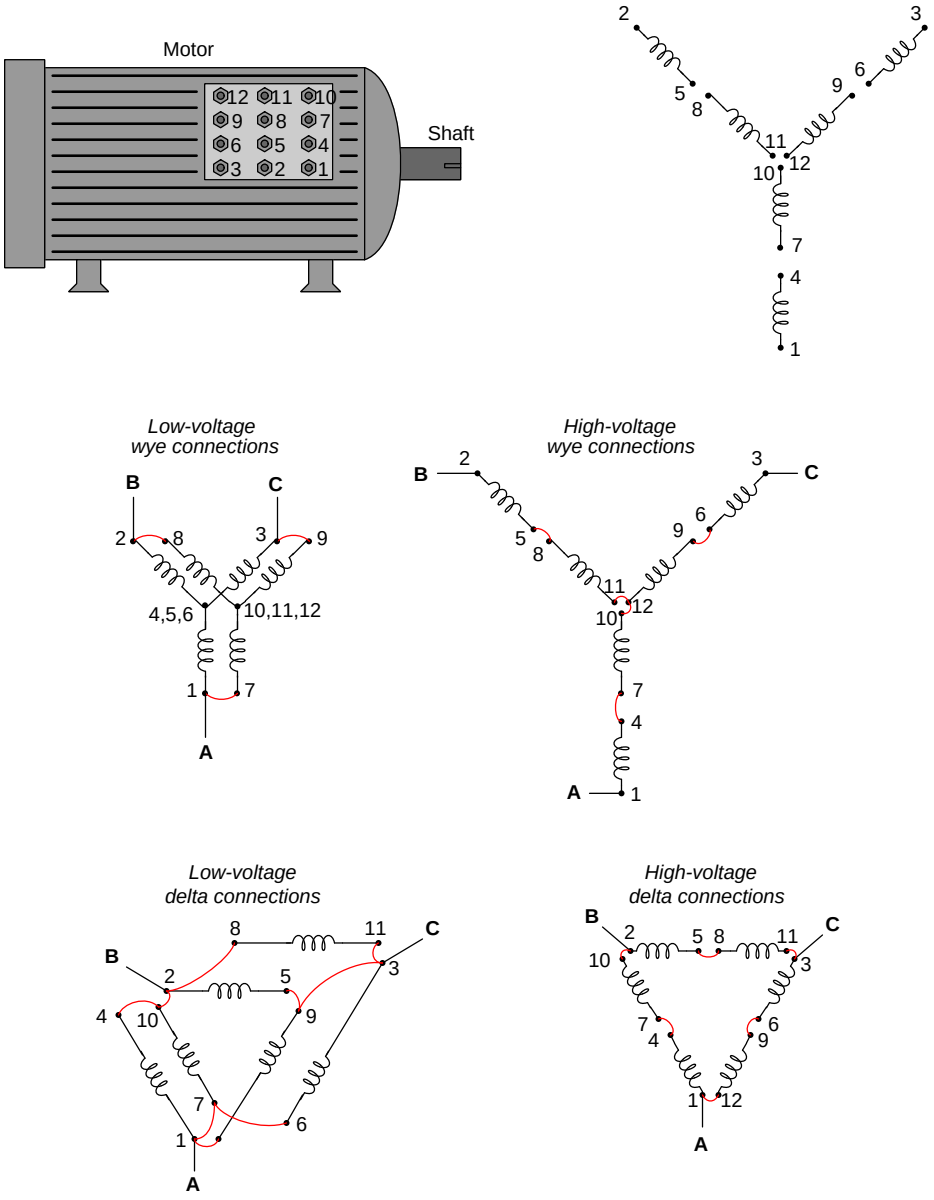
The following illustrations show a 9-lead delta-wound AC induction motor. Six winding pairs exist in this motor's stator, which may be connected either in series or in parallel for different operating voltages:



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

4.6 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

Questions

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

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

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

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

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

General challenges following tutorial reading

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

General follow-up challenges for assigned problems

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

General follow-up challenges for experiments or projects

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

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

5.1 Conceptual reasoning

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

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

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

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

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

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

5.1.1 Reading outline and reflections

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

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

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

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

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

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

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

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

5.1.2 Foundational concepts

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

Electrical source

Electrical load

Ohm's Law

Kirchhoff's Voltage Law

Discrete

Contactor

Arc flash

Arc blast

Arc shield

Fuses and circuit breakers

Overload heater

Trip curve

Starter

Current transformer

Control power transformer

Bucket

Latching circuit

Seal-in contact

Relay ladder diagram

Reversing a three-phase motor

Interlock

Digital motor control

Process switch

Hand-Off-Auto switch

Inrush current

Electromagnetism

Electromagnetic induction

Counter-EMF

Joule's Law

Inrush-limited motor starting

On-delay relay

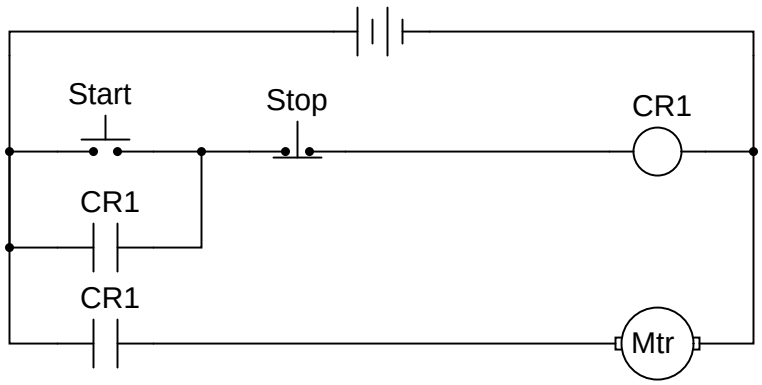
Off-delay relay

Autotransformer

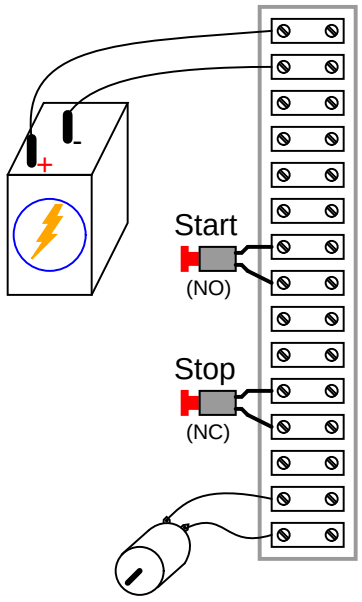
Silicon-Controlled Rectifier (SCR)

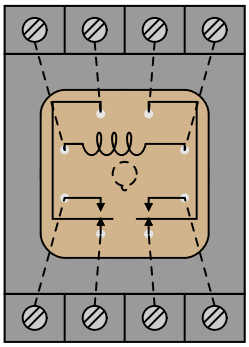
5.1.3 Sketching connections for a relay motor control

A *very* common application of electromechanical relay logic is motor control circuitry. Here is a ladder diagram for a simple DC motor control, where a momentary pushbutton switch starts the motor, and another pushbutton switch stops the motor:



Translate this ladder diagram into point-to-point connections between the following components (shown in the following illustration):





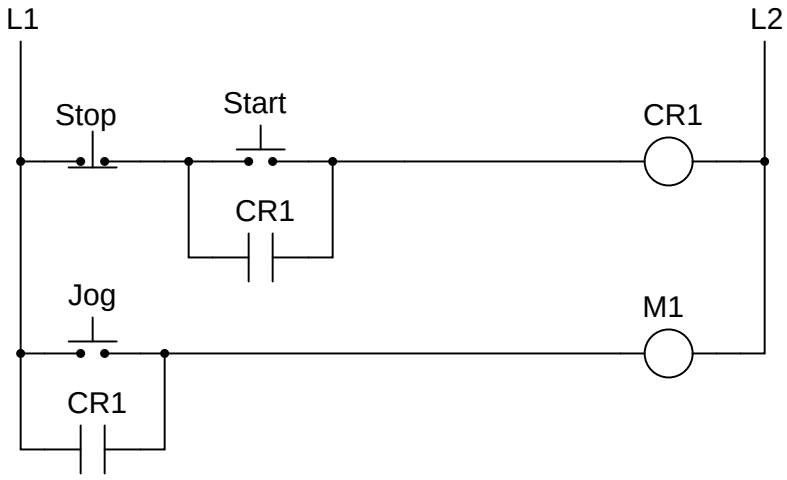
(Dashed lines represent connections between relay terminals and socket screw lugs, hidden from sight)

Challenges

- Explain how this circuit "latches" the motor so that the manual switches may use momentary contacts.

5.1.4 Start/Jog control

Examine this motor control circuit for a *start/stop/jog* control:



Identify the electrical status of this circuit when each of the pushbuttons is pressed (one at a time).

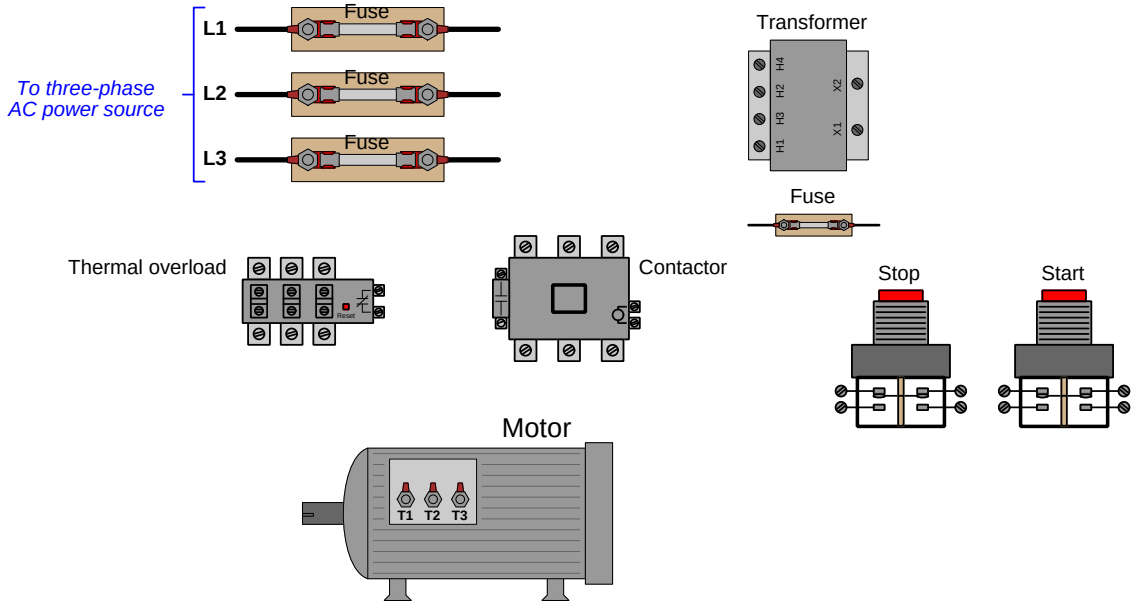
Explain in your own words what distinguishes the "Start" function from the "Jog" function, and think of a practical application where this might be useful.

Challenges

- Suppose one day the "Start" pushbutton began behaving exactly like the "Jog" pushbutton. Identify one fault that could cause this effect.
- What happens if someone presses all three buttons simultaneously?

5.1.5 Sketching connections for a three-phase starter

Three-phase motor *starter* circuits are extremely common in industry. Sketch wire connections between the following components necessary to form a complete starter circuit:

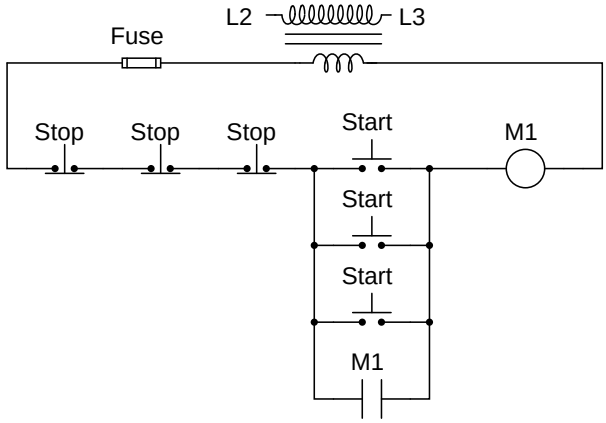


Challenges

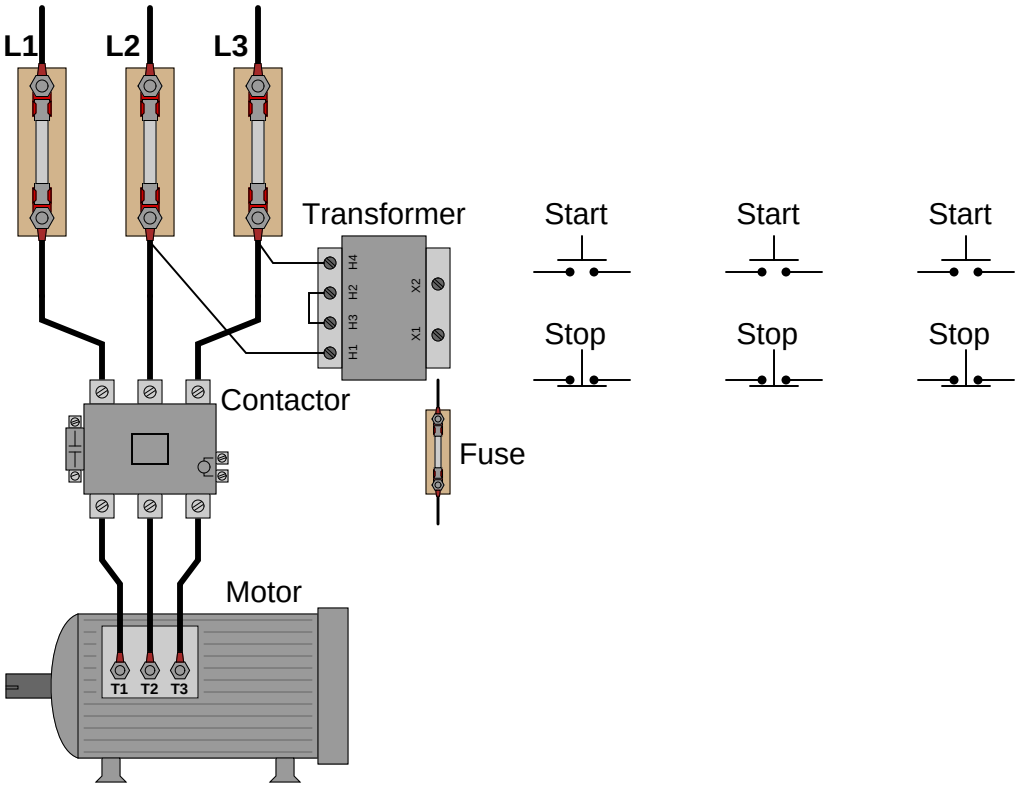
- Explain how this circuit "latches" the motor so that the manual switches may use momentary contacts.

5.1.6 Sketching connections for a three-station motor starter

Suppose we wish to have three separate pushbutton start/stop stations for operators to use in controlling a single three-phase electric motor. The control circuit wiring schematic shows how this will work:



Sketch the necessary connecting wires to build this control circuit:

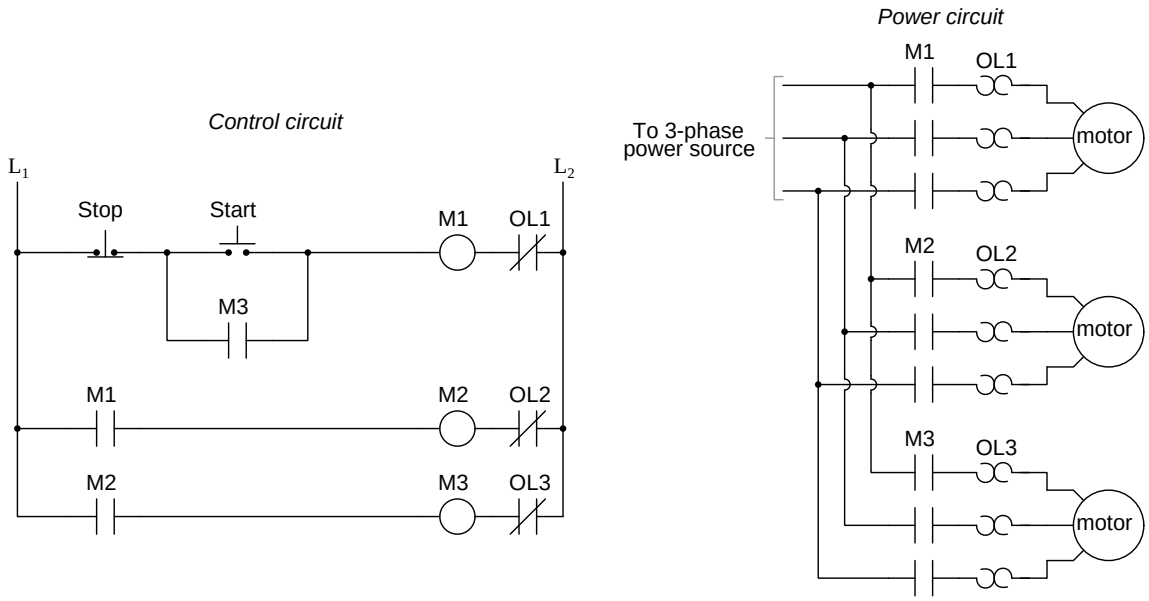


Challenges

- Give a practical example where multiple start/stop stations might be desired or needed for a single motor.
- Identify an electrical fault in any one of the switches which would effectively disable the others.

5.1.7 Three-motor starter circuit

This motor control circuit commands three motors to start and stop together:



Examine the control circuit and then explain how starting one motor starts up the others.

Determine what will happen if motor #3 suffers an overload (i.e. OL3 warms up enough to trip).

Challenges

- Explain why *inrush current* could be a problem in this three-motor control system, and identify at least one practical solution for it.
- If motor #2 were to become overloaded, would the system react any differently from an overloaded motor #3?

5.1.8 Thermal overload misconceptions

Each of these statements is incorrect in some way. Correct the misconceptions in each:

"Thermal overloads protect against overcurrent conditions in case there is a short-circuit in the power conductors feeding a motor bucket."

"Thermal overloads protect against motor overheating by sensing the temperature of the motor. They operate on temperature, rather than on motor current like a circuit breaker."

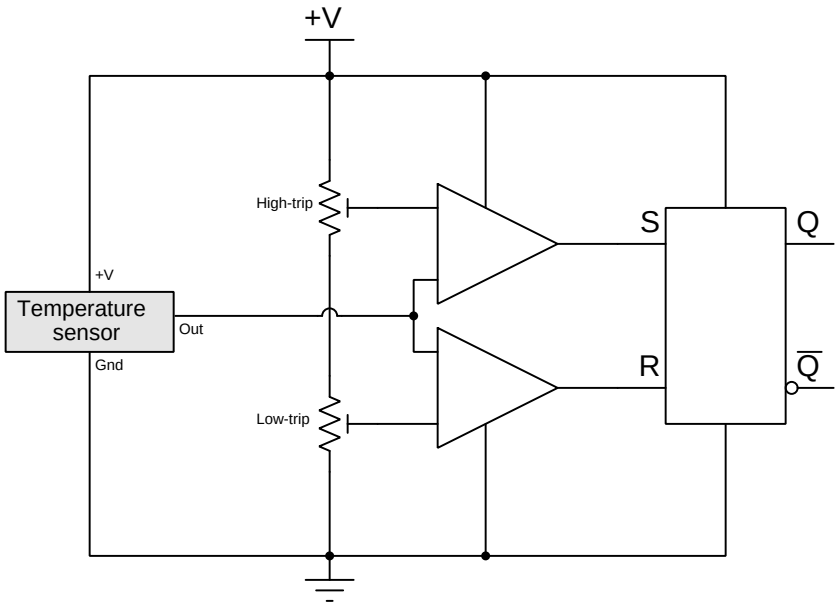
"When an overload heater senses an over-loaded condition, it opens up like a fuse to directly interrupt power to the motor."

Challenges

- Misconceptions regarding thermal overloads are very common among both students and working electricians. Why do you think this is?
- Identify at least one way in which a thermal overload unit can fail to protect the motor.

5.1.9 Digital cooling fan control

An analog temperature sensor sends a voltage signal to a pair of comparators, which change state if the temperature exceeds a high-trip threshold or goes below a low-trip threshold. Their outputs connect to the Set and Reset inputs of an SR latch:



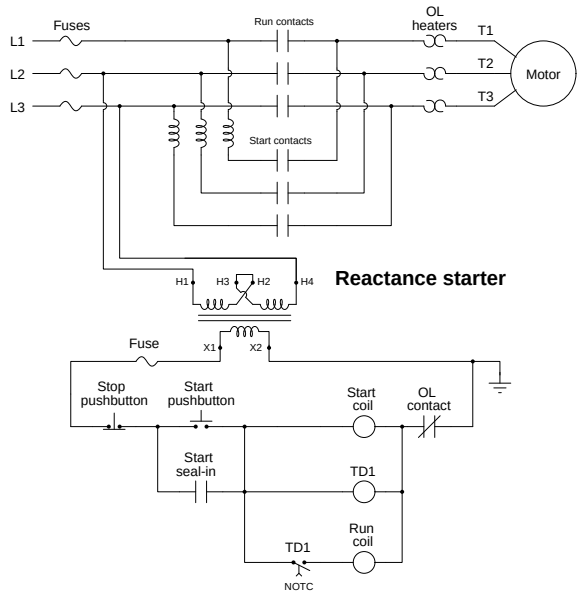
Complete this schematic diagram to show how this circuit could be used to control the starting and stopping of a 2 horsepower three-phase cooling fan motor. Note that you will need to specify the + and − input assignments for both comparators as part of your design.

Challenges

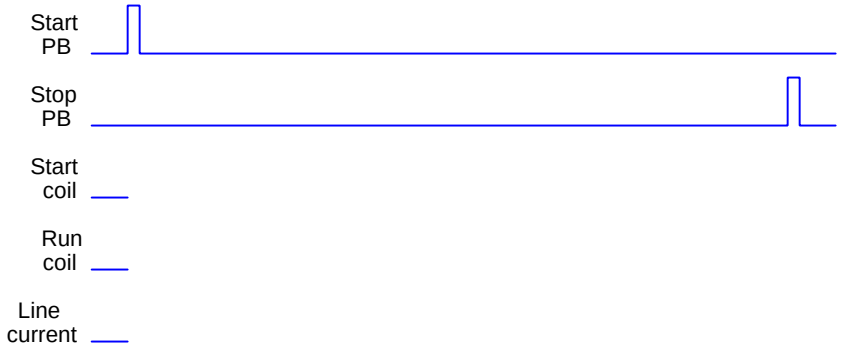
- Design a version of a motor starter circuit using no moving parts.
- Suppose the load were a three-phase electric heater rather than a cooling fan? What would need to be different about the circuit to make it function properly with this new load?

5.1.10 Inrush current for a reactance starter

Suppose we were to attach a clamp-on ammeter to one of the lines on this motor, sending the output signal to a graphing recorder that plots current magnitude over time:



Complete the following timing diagram showing coil statuses (discrete) and current (as a qualitative graph of absolute magnitude):

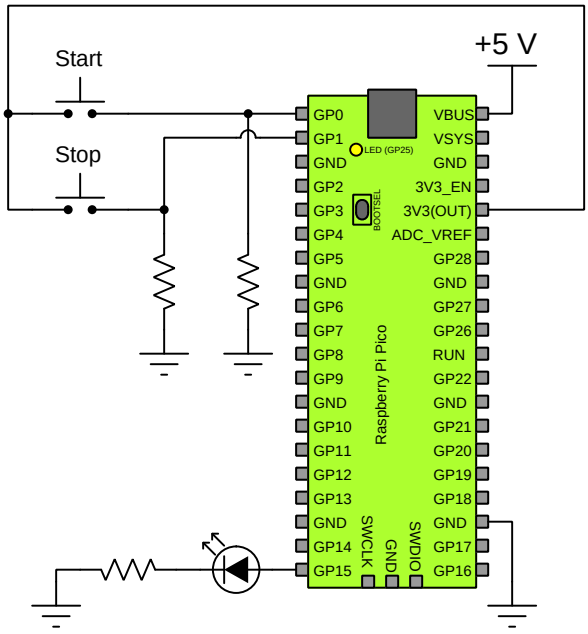


Challenges

- How would the timing diagram be altered if we gave TD1 a shorter delay time?
- How would the timing diagram be altered if the line reactor values were decreased?
- What would be the effects of coil TD1 failing open?

5.1.11 Microcontroller program for a simple motor starter

The following Raspberry Pi Pico microcontroller has been programmed in the Sketch language to provide start-stop latching control for an electric motor:




```
// For the Raspberry Pi Pico (2020 design)
// using the Sketch programming language

void setup()
{
  pinMode(15, OUTPUT); // LED on GP 15
  pinMode(0, INPUT);   // Start PBNO on GP 0 with pulldown R
  pinMode(1, INPUT);   // Stop PBNO on GP 1 with pulldown R
}

void loop()
{
  if (digitalRead(0))     // If Start button pressed
    digitalWrite(15, 1);

  if (digitalRead(1))     // If Stop button pressed
    digitalWrite(15, 0);
}
```

First, explain how the Sketch code forms a latching start-stop function suitable for controlling a motor.

Second, modify the circuit so that the Raspberry Pi Pico microcontroller actually controls a 5 Horsepower, single-phase AC electric motor with a 240 Volt rating.

Challenges

- How much motor current would the motor-controlling circuit have to handle if the 240 VAC motor were three-phase rather than single-phase?

5.2 Quantitative reasoning

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

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

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

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

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

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

5.2.1 Miscellaneous physical constants

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5.2.2 Introduction to spreadsheets

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

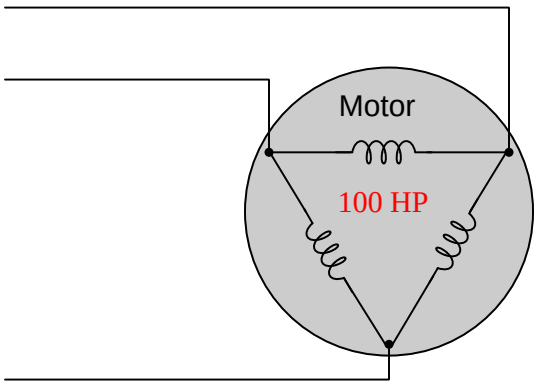
Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference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

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

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

5.2.3 Motor current calculations

Calculate the amount of current through each of the line conductors, as well as through each of the phase windings of this 100 horsepower electric motor while operating at full load, assuming a line voltage of 460 Volts, 91% motor efficiency, and a power factor of 1:

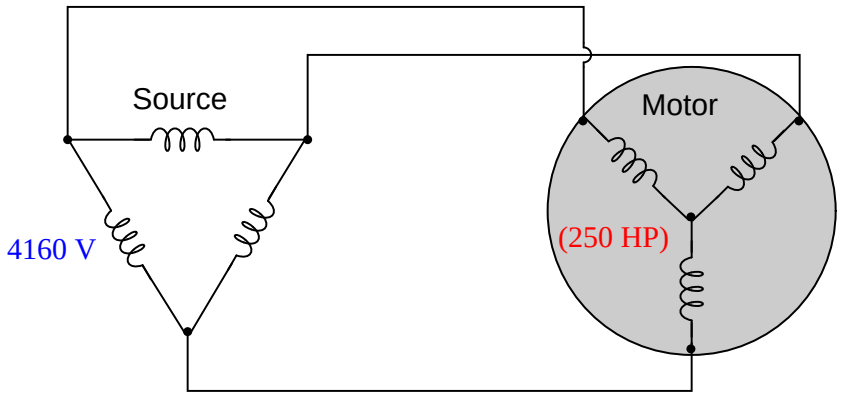


Challenges

- What happens to line current as the mechanical loading on the motor decreases?
- What happens to motor efficiency as the mechanical loading on the motor decreases?

5.2.4 Wye motor fed by Delta source

Calculate all voltages, currents, and total power in this balanced three-phase system where a Delta-connected source provides electrical power to a 250 horsepower Wye-connected motor. Assume the motor operates at full load (100% power) with perfect power factor and perfect efficiency:



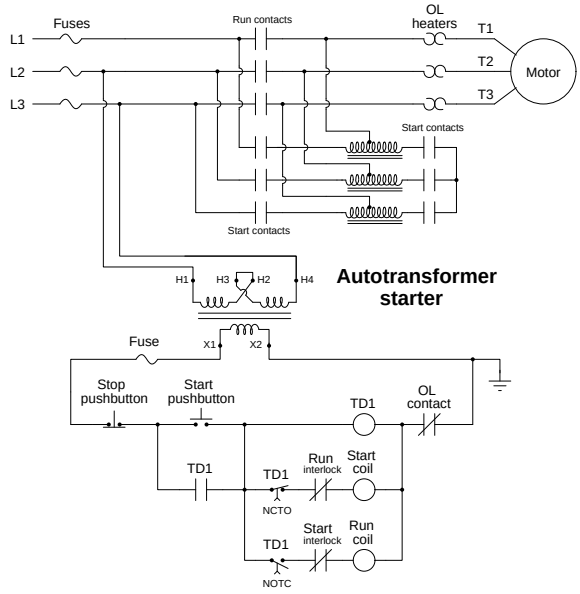
- V_{line} =
- I_{line} =
- $V_{phase(source)}$ =
- $I_{phase(source)}$ =
- $V_{phase(load)}$ =
- $I_{phase(load)}$ =
- P_{total} =

Challenges

- How will these figures change if the motor operates at 90% efficiency instead of 100% efficiency?
- How should we re-wire this motor to make it spin the other direction?

5.2.5 Autotransformer starter calculations

Calculate the following parameters during start-up before TD1 has timed out, assuming a 575 VAC source line voltage, an autotransformer tap ratio[11] of 70%, and a motor terminal current of 238 AAC at that particular moment in time.



- Voltage between motor terminals T1 and T2 =
- Current through fuse on line L3 =
- Voltage across full span of autotransformer winding =
- Voltage from autotransformer tap to left-hand end of winding =
- Voltage from autotransformer tap to right-hand end of winding =

Challenges

- Identify how to modify this circuit to provide a gentler start-up to the motor.
- What would happen if one of the Start contacts located to the left of the autotransformers were to fail open?
- What would happen if one of the Start contacts located to the right of the autotransformers were to fail open?

[11] i.e. the motor taps are located at the 70% location on each autotransformer winding. 100% would provide full voltage to the motor, and 0% would provide no voltage to the motor.

5.2.6 Motor current simulation program

Write a computer program in a text-based language such as C, C++, or Python calculating the line current for a three-phase AC induction motor given line voltage, mechanical power output by the motor (in Horsepower), motor efficiency, and power factor.

Challenges

- What happens to line current as the mechanical loading on the motor decreases?

5.3 Diagnostic reasoning

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

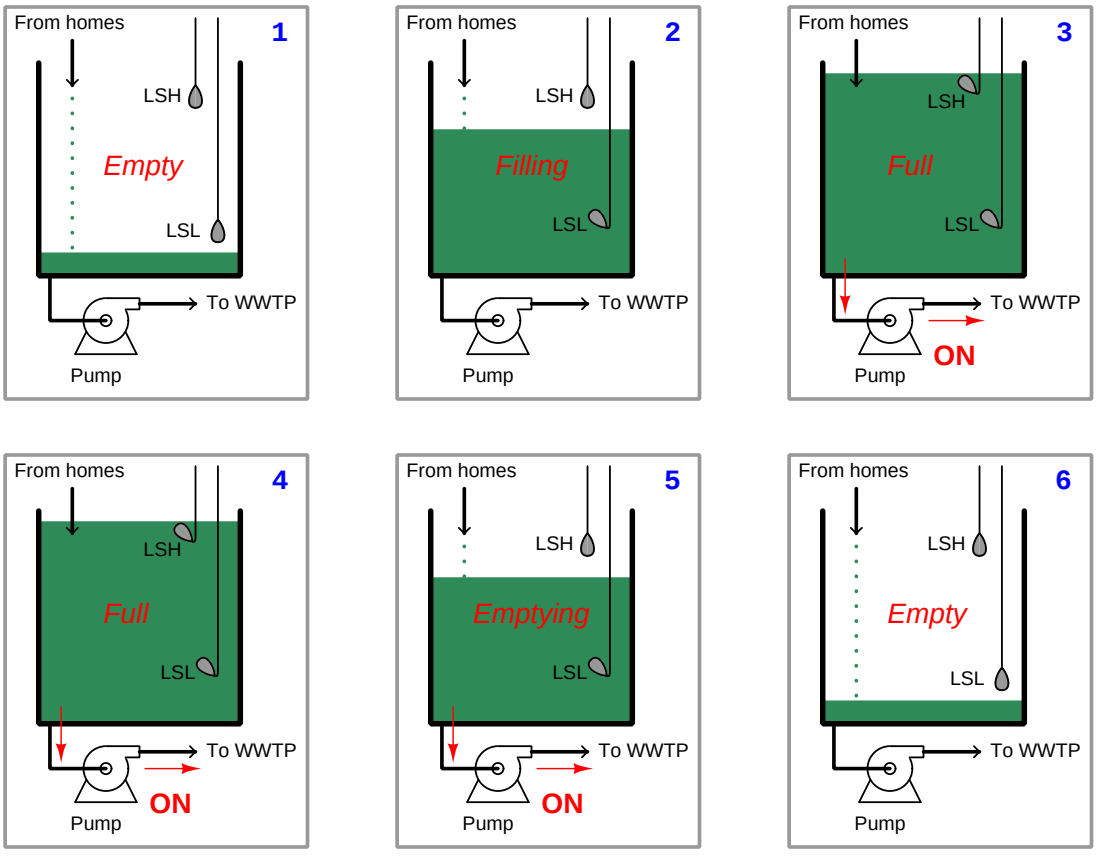
As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of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

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

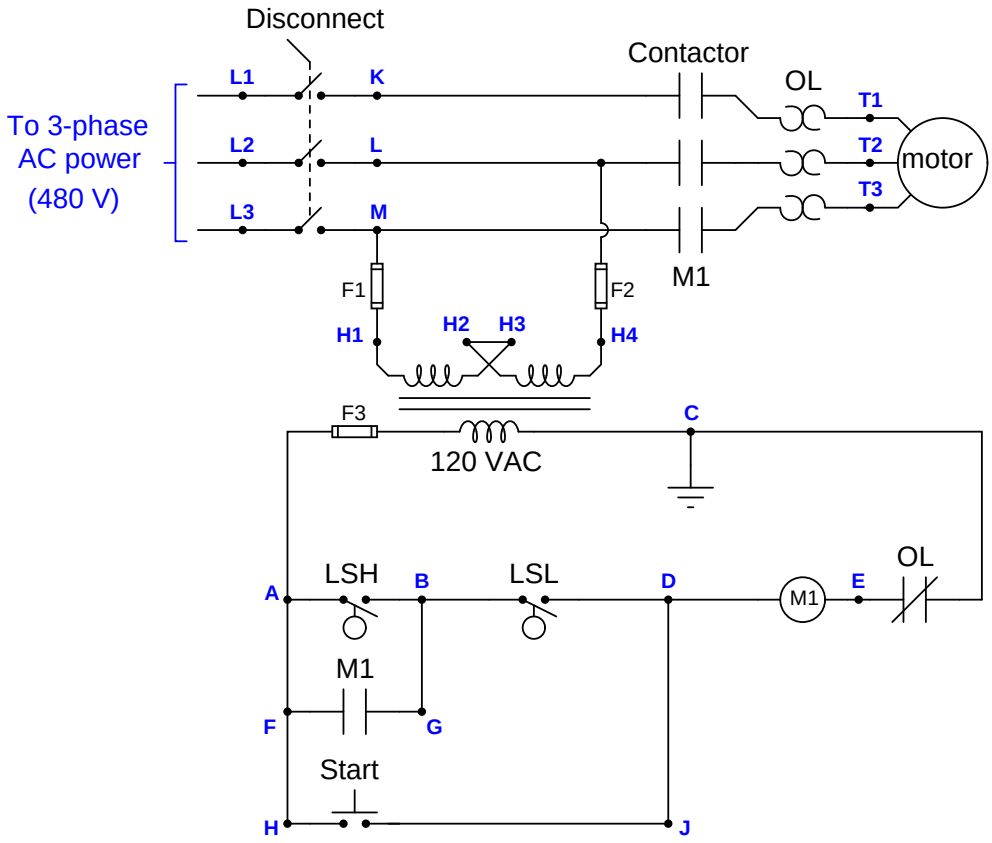
Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the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

5.3.1 Routine motor testing

A *lift station* is an underground reservoir with an automatically-controlled electric pump that collects and transports sewage from neighborhoods to a centralized wastewater treatment plant (usually located miles away):



The wiring diagram for a simple lift station pump control circuit is shown here:



An electrician needs to perform some routine "megger" measurements on the electric pump motor. "Megger" is the brand name of a high-voltage ohmmeter used to check the integrity of electrical insulation in electric motors, transformers, and other devices with wire coils subject to faults due to corrosion, vibration, or overheating. Here, the electrician will check resistance between each of the motor's terminals (T1, T2, T3) and the metal frame of the motor, ensuring there are many millions of Ohms (open) as the wire insulation should provide.

Like all ohmmeter tests, a "megger" check must be performed on a device that is unpowered. For this reason, and also for personal safety, the electrician must ensure no power will get to the motor during his test.

Before commencing the test, the electrician follows this procedure to ensure the motor is in a *zero energy state*:

1. Turn off the disconnect switch
2. Place a padlock and a danger tag on the switch's handle to ensure it cannot turn on
3. Push the "Start" pushbutton switch to check that the pump does *not* start up
4. Use an AC voltmeter to verify 120 Volts at a known source (e.g. wall receptacle)
5. Use an AC voltmeter to verify 0 Volts between the following test points:

   Voltage between terminals K and L

   Voltage between terminals K and M

   Voltage between terminals L and M

   Voltage between terminals K and earth ground

   Voltage between terminals L and earth ground

   Voltage between terminals M and earth ground
6. Use an AC voltmeter to verify 120 Volts at a known source (e.g. wall receptacle)

Explain the rationale behind each step in this sequence. Although this many steps may appear to be a bit paranoid, there is actually logical justification for each one.

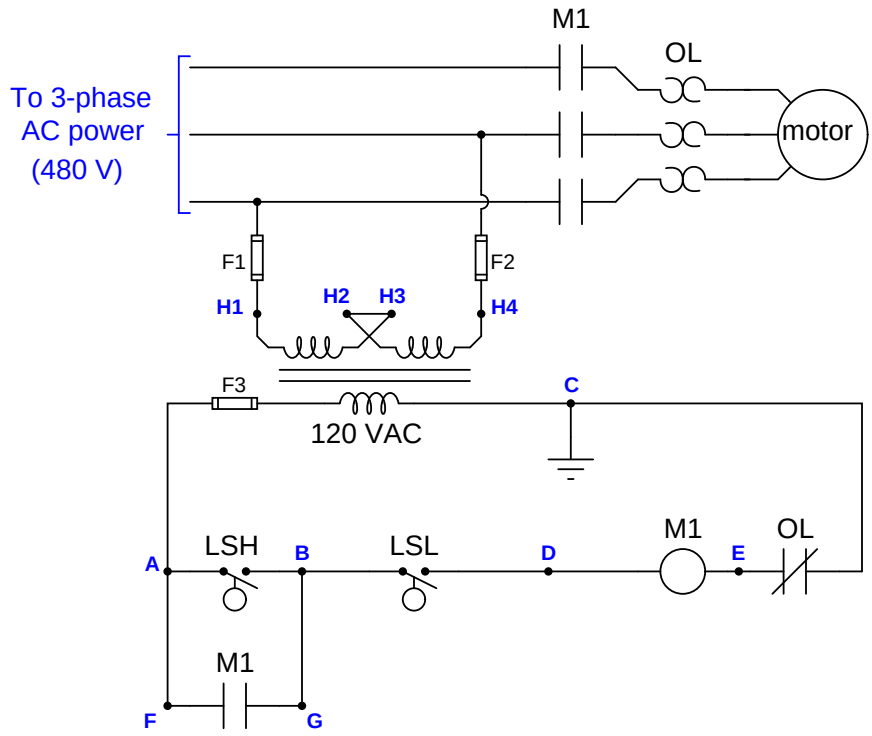
Suppose another electrician looked at this diagram and declared, *"We don't actually have to turn the disconnect switch off – we can prevent power from getting to the motor's terminals just by just pulling any one of the fuses in this circuit! If the M1 coil can't energize with 120 Volts, then the M1 contactor relay cannot close, which effectively locks out 480 Volt power from getting to the motor."*
What would be your response to this electrician's suggestion, and why?

Challenges

- What sort of information do you think the electrician should write on the danger tag?
- Why do you suppose it is necessary to use high voltage to test the insulation integrity of an electric motor? Why not just use a regular ohmmeter that only uses a few Volts between the test probes?

5.3.2 Faulted lift station pump control

This "lift station" pump control circuit has a problem. The sump pump is supposed to come on when the high level is reached, and turn off when the water pumps down to the low level point. Instead, however, the motor "cycles" on and off at the high-level point.



Using an AC voltmeter, you measure a voltage from point **D** to point **E** that switches back and forth between 120 Volts and 0 Volts.

Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

- High level switch failed open
- Low level switch failed open
- Broken wire between **D** and M1 coil
- Contactor auxiliary contact failed open
- Contactor auxiliary contact failed shorted
- 480 Volt fuse(s) blown

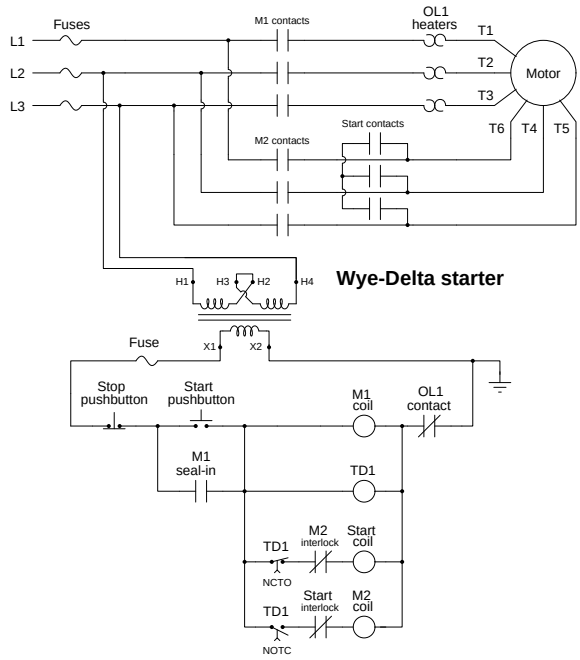
- Contactor main contact(s) failed open
- Broken wire between **B** and **G**
- Thermal overload unit tripped
- Low level switch failed shorted
- Transformer secondary winding failed open

Challenges

- Identify any possible faults not shown in the list.
- For each fault you identified as "possible", explain why.
- For each fault you identified as "impossible", explain how the symptoms would differ.
- Identify what your next diagnostic step might be to pinpoint the fault.

5.3.3 Faulted wye/delta starter

This Wye-Delta motor starter has developed a problem. It used to work just fine, but now when the Start pushbutton is momentarily pressed nothing happens at all, and then after a few seconds the motor jumps up to full speed.



Identify the likelihood of each specified fault for this circuit. Consider each fault one at a time (i.e. no coincidental faults), determining whether or not each fault is compatible with *all* measurements and symptoms in this circuit.

- Stop pushbutton failed open
- Start pushbutton failed open
- M1 coil failed open
- OL1 contact failed open
- M1 seal-in contact failed open
- TD1 coil failed open
- Start coil failed open
- M2 coil failed open
- TD1 NCTO contact failed open

- M2 interlock contact failed open
- TD1 NOTC contact failed open
- Start interlock contact failed open

Challenges

- Identify a good diagnostic test you could do to help pinpoint the fault.

Chapter 6

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!*

6.1 Recommended practices

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

6.1.1 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.

6.1.2 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.

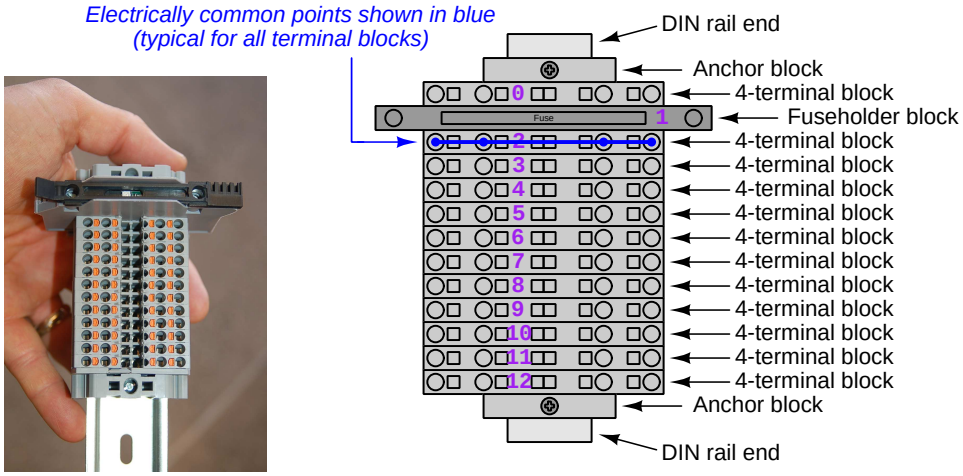
[4] An example of a necessary resistor value much less than 1 kΩ is a *shunt resistor* used to produce a small voltage drop for the purpose of sensing current in a circuit. Such shunt resistors must be low-value in order not to impose an undue load on the rest of the circuit. An example of a necessary 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.

6.1.3 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.

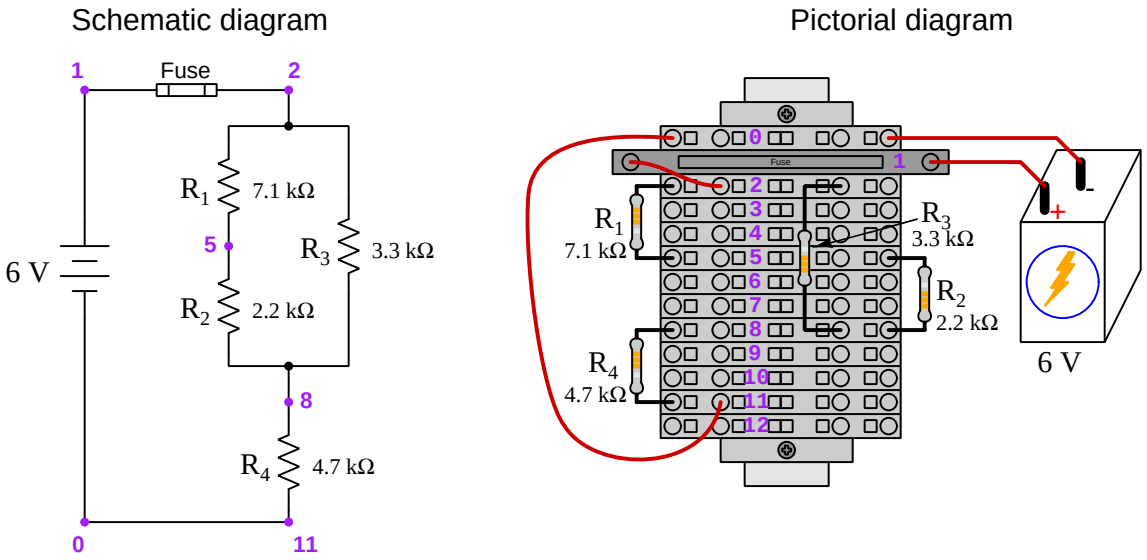
[6] Solderless breadboard are preferable for complicated electronic circuits with multiple integrated "chip" components, but for simpler circuits I find terminal blocks much more practical. An alternative to solderless breadboards for "chip" circuits is to solder chip sockets onto a PCB and then use 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
```

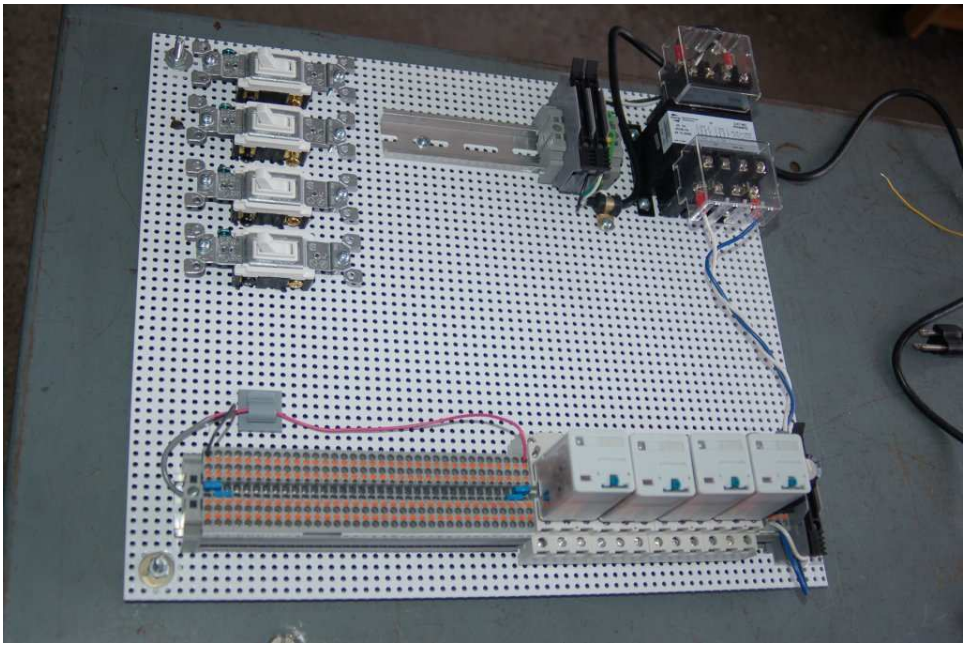
Note the use of two resistances `rfuse` and `rwire` to describe fuse resistance between terminals 1 and 2 and "jumper" wire resistance between terminals 0 and 11, respectively. Being resistances, SPICE requires a resistance value for each, and here we see they have both been set to an arbitrarily low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

6.1.4 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.

6.1.5 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.

6.2 Experiment: Demonstrate DC motor starter circuit

Motor starters are very common circuits in a range of applications, especially industrial. The basic concept is the same regardless of motor type, and so a valuable learning experience is to experiment with a motor starter for a very small ("hobby") DC motor. Devise and execute an experiment whereby such a motor may be started and stopped by momentary-contact switches.

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!

6.3 Experiment: Demonstrate inrush-limited DC motor starter

Inrush-limited motor starters are very common for large industrial-scale electric motors, but the basic concept may be demonstrated on any size or type of motor, and so a valuable learning experience is to experiment with inrush-limited starting of a very small ("hobby") DC motor. Devise and execute an experiment whereby such a motor may be started gradually in automatically-timed stages. The circuit should utilize momentary-contact switches for Start and Stop just like a regular motor starter.

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

- Certain techniques for limiting the inrush current of an AC motor simply do not apply for DC motors. Identify some of them, and explain why they will not work the same for DC as for AC.

- 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.

7 August 2026 – edited image_1438 to include three more frames showing the lift station reservoir's status through one complete pump on/off cycle.

12-13 November 2025 – deleted some placeholder "Challenge" questions that were not populated yet. Also capitalized two instances of the word "Volt" that were previously uncapitalized.

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

17-18 April 2024 – corrected a minor typographical error and also added more comments about "across the line" starting. Also edited image_5222 to show the OL contact as normally-closed.

13 April 2024 – divided up the Tutorial to have one more section, focusing on digital motor controls.

25 July 2023 – added a Quantitative Reasoning question challenging students to write a computer program predicting motor current.

19 June 2023 – added questions based on the use of a Raspberry Pi Pico microcontroller for motor start-stop control.

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.

22 April 2021 – added time-delay relay section to the Technical Reference chapter.

19 April 2021 – added questions.

13-14 April 2021 – significantly edited the Introduction chapter to make it more suitable as a pre-study guide and to provide cues useful to instructors leading "inverted" teaching sessions. Also added more comments in the Tutorial about overload heaters not acting as fuses.

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

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

25 May 2020 – deleted a Challenge question on one of the projects, because the scenario implied a non-standard way of building a motor starter circuit. This edit courtesy of Ron Felix.

17 May 2020 – fixed omission of two meter-checking steps in the "Routine motor testing" diagnostic reasoning question. This error was reported by Ron Felix.

8 May 2019 – added iron core symbols to all autotransformers.

3 May 2019 – added comment in inrush-limited DC starter experiment that it should use momentary-contact switches like a regular motor starter.

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

30 April 2019 – minor edits to numerical values on "Wye motor fed by Delta source" question, using 745.7 Watts per HP instead of 746 Watts per HP.

27 April 2019 – updated graphic image for latching motor starter to include industrial-style pushbutton switches with form-C contacts.

14 April 2019 – clarified the meaning of *process*-type switches. For example, level switches, pressure switches, temperature switches. Also added entry for process switches to Foundational Concepts section.

30 March 2019 – added more questions. Also corrected error on Wye-Delta starter schematic diagram (Start seal-in should be M1 seal-in).

28 March 2019 – since there is no Simplified Tutorial yet, I renamed "Full Tutorial" to just "Tutorial".

10 March 2019 – completed the Foundational Concepts list.

5 January 2019 – added explanations of motor overload protection to the Historical References chapter, from the Westinghouse protective relay manual *Silent Sentinels*. Also added a section in the Tutorial on the use of current transformers to energize overload heaters as opposed to direct energization of overload heaters by motor line current.

1 January 2019 – added 12-lead motor diagram to Technical Reference chapter, as well as a Technical Reference section on electrical safety.

29 December 2018 – added inrush-limiting starter techniques to the Full Tutorial. Also added "Normal status of a switch" section to the Derivations and Technical References chapter.

24 November 2018 – added to the Full Tutorial, as well as to the Historical References chapter.

23 November 2018 – wrote Introduction and about half of the Full Tutorial.

12 November 2018 – document first created.

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