Troubleshooting Motors and Controls

Troubleshooting Motors and Controls

KEN DICKSON-SELF

Contents

Introduction and Disclaimer

KEN DICKSON-SELF

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PART I

LESSON 1

Lesson one includes the following topics:

- Safety
- Refresher
    - Current, voltage, resistance
    - Ohm's law
    - Scientific Notation
    - How to use a Digital Multimeter (DMM)
    - Series and parallel circuits
    - Testing coils (solenoids, relays and transformers)
    - Operation of relays
    - Ladder diagrams and wiring
- Usage of a Digital Multimeter (DMM)
- Worksheet1-Parallel and Series Circuits
- Worksheet2-LadderDiagram
- Homework 1

1. Safety

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Nothing should be more important to you than your own safety.

Think about Charlie Morecraft.

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He had an industrial accident that left him in the hospital for about five years. Think about that. A shortcut in safety procedures left him in the hospital for five. Long. Years.Charlie had to open a valve on a petroleum line. It was a routine task he'd done "a thousand times" before. It was messy and difficult. The valves leaked and were sticky, but management had planned to replace the valves, and they put a safe procedure in place to ensure the valves could be operated without danger to the operator. Spoiler alert: Charlie didn't follow the procedure.

Charlie worked on the valve without his safety glasses, and the valve leaked. Charlie didn't bother trying to control the petroleum leak ("this will just take a minute"), and it got worse. When Charlie completely actuated the valve, it sprayed material into his face and soaked his clothes. Now blinded, he ran past his truck toward a nearby safety shower. Unfortunately, Charlie left the truck running (against procedure), and it ignited the vapors, engulfing Charlie in a ball of fire. When you think about taking shortcuts at work, remember Charlie.

The work we do is dangerous, and while I can never watch Mehdi Sadaghar (an electrical engineer who does unsafe things with electricity) without laughing, we have to remember that electricity can be fatal, and you never want to be involved in an arc flash incident.

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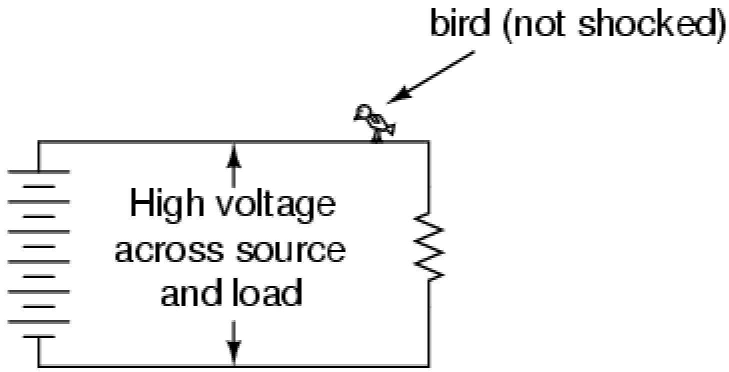
Shock Current Path

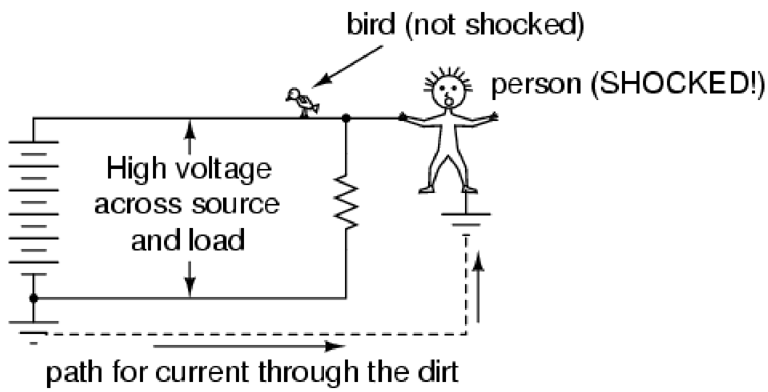
As we've already learned, electricity requires a complete path (circuit) to continuously flow. This is why the shock received from static electricity is only a momentary jolt: the flow of electrons is necessarily brief when static charges are equalized between two objects. Shocks of self-limited duration like this are rarely hazardous.

Without two contact points on the body for current to enter and exit, respectively, there is no hazard of shock. This is why birds can safely rest on high-voltage power lines without getting shocked: they make contact with the circuit at only one point.



In order for electrons to flow through a conductor, there must be a voltage present to motivate them. Voltage, as you should recall, is *always relative between two points*. There is no such thing as voltage "on" or "at" a single point in the circuit, and so the bird contacting a single point in the above circuit has no voltage applied across its body to establish a current through it. Yes, even though they rest on *two* feet, both feet are touching the same wire, making them *electrically common*. Electrically speaking, both of the bird's feet touch the same point, hence there is no voltage between them to motivate current through the bird's body.

This might lend one to believe that its impossible to be shocked by electricity by only touching a single wire. Like the birds, if we're sure to touch only one wire at a time, we'll be safe, right? Unfortunately, this is not correct. Unlike birds, people are usually standing on the ground when they contact a "live" wire. Many times, one side of a power system will be intentionally connected to earth ground, and so the person touching a single wire is actually making contact between two points in the circuit (the wire and earth ground):



The ground symbol is that set of three horizontal bars of decreasing width located at the lower-left of the circuit shown, and also at the foot of the person being shocked. In real life the power system ground consists of some kind of metallic conductor buried deep in the ground for making maximum contact with the earth. That conductor is electrically connected to an appropriate connection point on the circuit with thick wire. The victim's ground connection is through their feet, which are touching the earth.

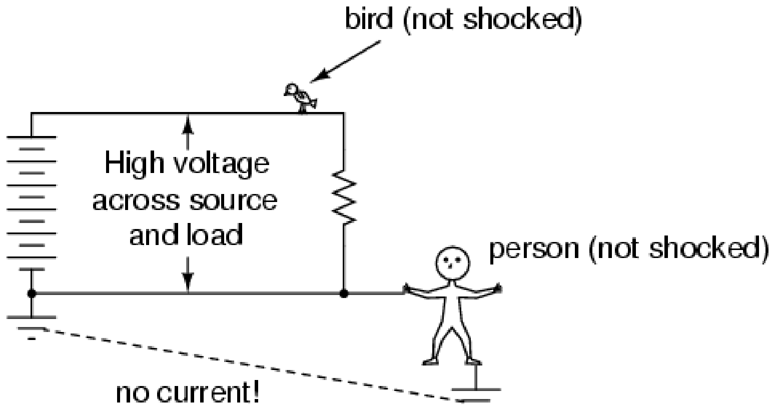
A few questions usually arise at this point in the mind of the student:

- If the presence of a ground point in the circuit provides an easy point of contact for someone to get shocked, why have it in the circuit at all? Wouldn't a ground-less circuit be safer?
- The person getting shocked probably isn't bare-footed. If rubber and fabric are insulating materials, then why

aren't their shoes protecting them by preventing a circuit from forming?

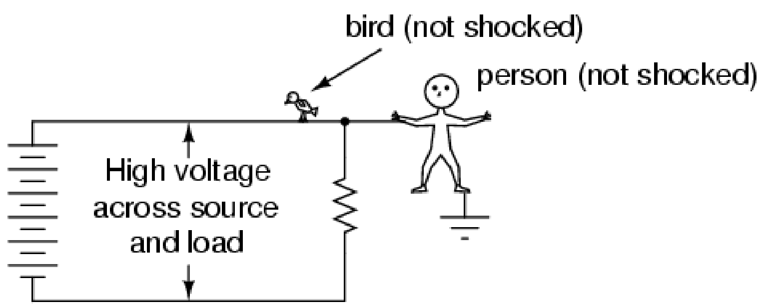
- How good of a conductor can *dirt* be? If you can get shocked by current through the earth, why not use the earth as a conductor in our power circuits?

In answer to the first question, the presence of an intentional "grounding" point in an electric circuit is intended to ensure that one side of it *is* safe to come in contact with. Note that if our victim in the above diagram were to touch the bottom side of the resistor, nothing would happen even though their feet would still be contacting ground:

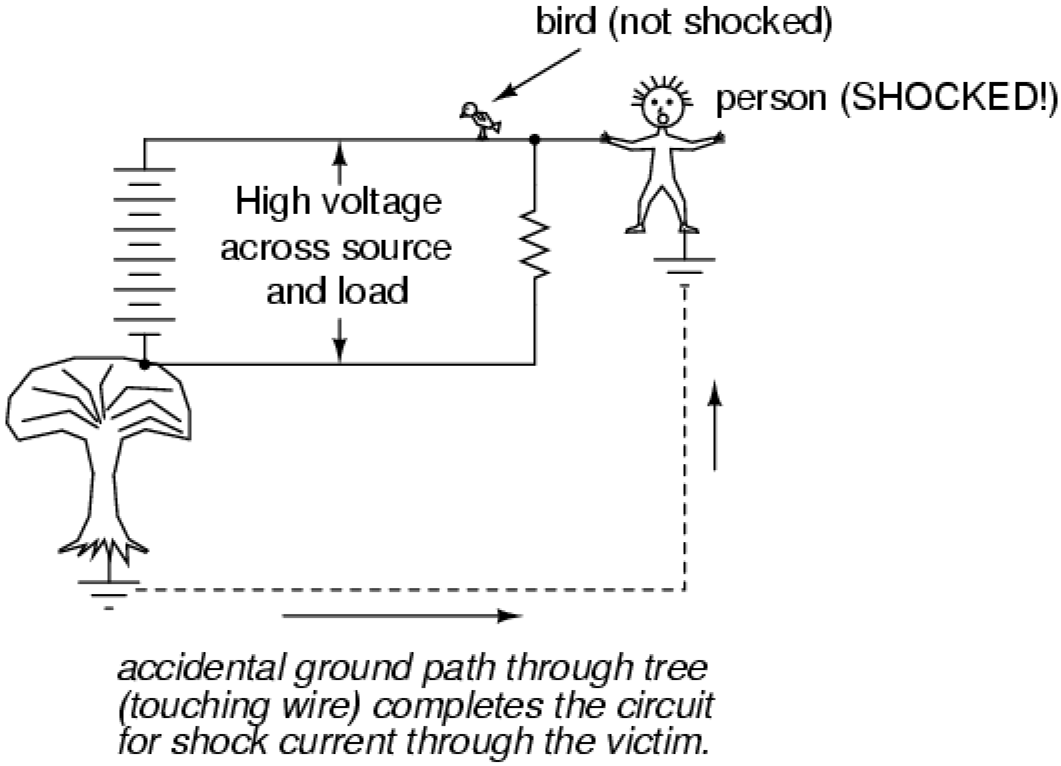


Because the bottom side of the circuit is firmly connected to ground through the grounding point on the lower-left of the circuit, the lower conductor of the circuit is made *electrically common* with earth ground. Since there can be no voltage between electrically common points, there will be no voltage applied across the person contacting the lower wire, and they will not receive a shock. For the same reason, the wire connecting the circuit to the grounding rod/plates is usually left bare (no insulation), so that any metal object it brushes up against will similarly be electrically common with the earth.

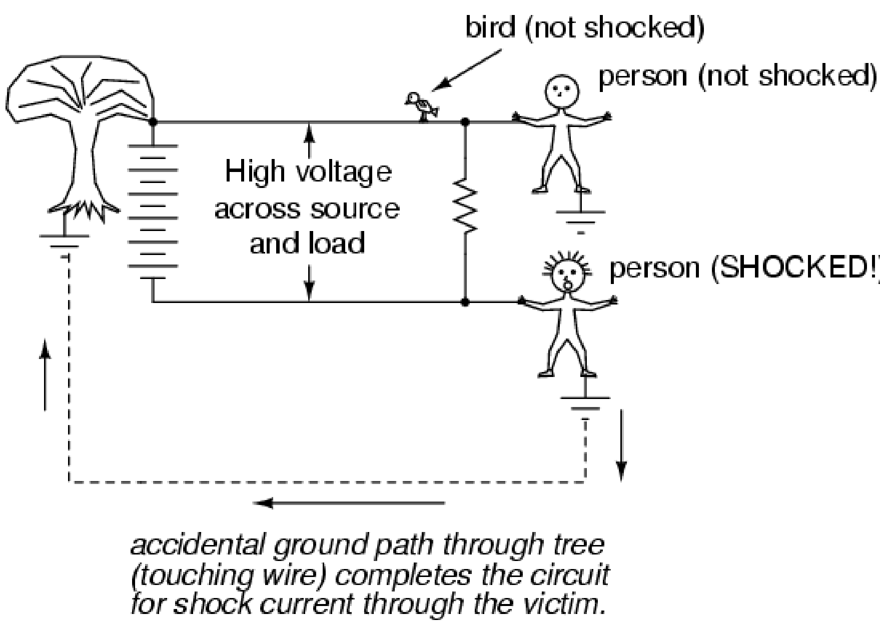
Circuit grounding ensures that at least one point in the circuit will be safe to touch. But what about leaving a circuit completely ungrounded? Wouldn't that make any person touching just a single wire as safe as the bird sitting on just one? Ideally, yes. Practically, no. Observe what happens with no ground at all:



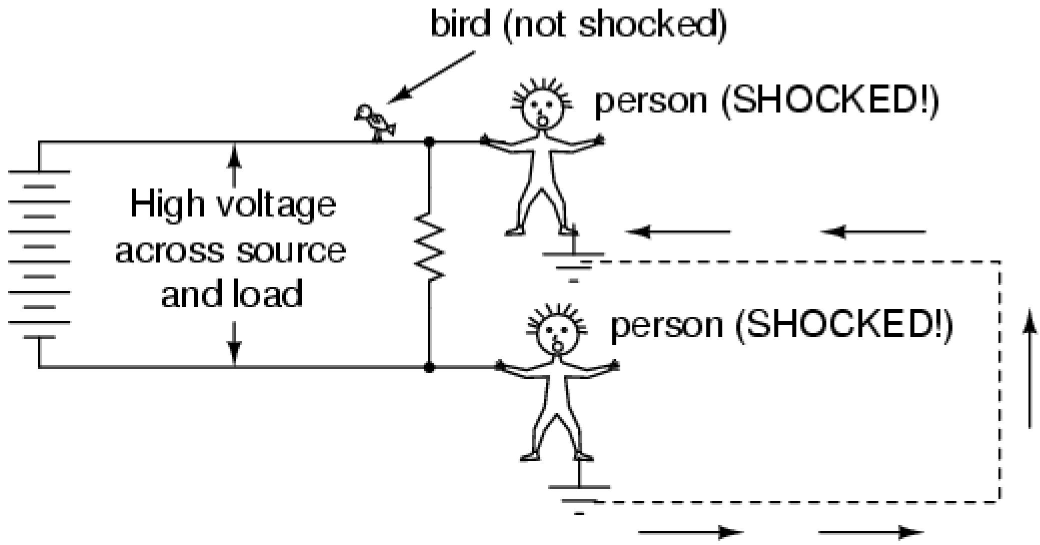
Despite the fact that the person's feet are still contacting ground, any single point in the circuit should be safe to touch. Since there is no complete path (circuit) formed through the person's body from the bottom side of the voltage source to the top, there is no way for a current to be established through the person. However, this could all change with an accidental ground, such as a tree branch touching a power line and providing connection to earth ground:



Such an accidental connection between a power system conductor and the earth (ground) is called a *ground fault*. Ground faults may be caused by many things, including dirt buildup on power line insulators (creating a dirty-water path for current from the conductor to the pole, and to the ground, when it rains), ground water infiltration in buried power line conductors, and birds landing on power lines, bridging the line to the pole with their wings. Given the many causes of ground faults, they tend to be unpredictable. In the case of trees, no one can guarantee *which wire* their branches might touch. If a tree were to brush up against the top wire in the circuit, it would make the top wire safe to touch and the bottom one dangerous—just the opposite of the previous scenario where the tree contacts the bottom wire:



With a tree branch contacting the top wire, that wire becomes the grounded conductor in the circuit, electrically common with earth ground. Therefore, there is no voltage between that wire and ground, but full (high) voltage between the bottom wire and ground. As mentioned previously, tree branches are only one potential source of ground faults in a power system. Consider an ungrounded power system with no trees in contact, but this time with *two* people touching single wires:



With each person standing on the ground, contacting different points in the circuit, a path for shock current is made through one person, through the earth, and through the other person. Even though each person thinks they're safe in only touching a single point in the circuit, their combined actions create a deadly scenario. In effect, one person acts as the ground fault which makes it unsafe for the other person. This is exactly why ungrounded power systems are dangerous: the voltage between any point in the circuit and ground (earth) is unpredictable, because a ground fault could appear at any point in the circuit at any time. The only character guaranteed to be safe in these scenarios is the bird, who has no connection to earth ground at all! By firmly connecting a designated point in the circuit to earth ground ("grounding" the circuit), at least safety can be assured at that one point. This is more assurance of safety than having no ground connection at all.

In answer to the second question, rubber-soled shoes *do* indeed provide some electrical insulation to help protect someone from conducting shock current through their feet. However, most common shoe designs are not intended to be electrically "safe," their soles being too thin and not of the right substance. Also, any moisture, dirt, or conductive salts from body sweat on the surface of or permeated through the soles of shoes will compromise what little insulating value the shoe had to begin with. There are shoes specifically made for dangerous electrical work, as well as thick rubber mats made to stand on while working on live circuits, but these special pieces of gear must be in absolutely clean, dry condition in order to be effective. Suffice it to say, normal footwear is not enough to guarantee protection against electric shock from a power system.

Research conducted on contact resistance between parts of the human body and points of contact (such as the ground) shows a wide range of figures (see end of chapter for information on the source of this data):

- Hand or foot contact, insulated with rubber: 20 MΩ typical.
- Foot contact through leather shoe sole (dry): 100 kΩ to 500 kΩ
- Foot contact through leather shoe sole (wet): 5 kΩ to 20 kΩ

As you can see, not only is rubber a far better insulating material than leather, but the presence of water in a porous substance such as leather *greatly* reduces electrical resistance.

In answer to the third question, dirt is not a very good conductor (at least not when its dry!). It is too poor of a conductor to support continuous current for powering a load. However, as we will see in the next section, it takes very little current to injure or kill a human being, so even the poor conductivity of dirt is enough to provide a path for deadly current when there is sufficient voltage available, as there usually is in power systems.

Some ground surfaces are better insulators than others. Asphalt, for instance, being oil-based, has a much greater resistance than most forms of dirt or rock. Concrete, on the other hand, tends to have fairly low resistance due to its intrinsic water and electrolyte (conductive chemical) content.

Safe Practices

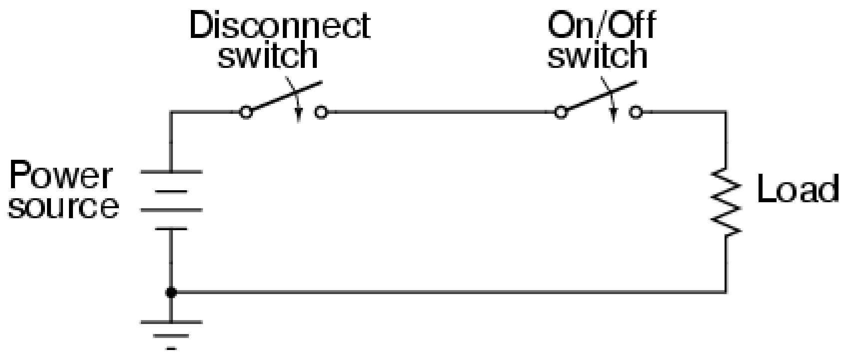
If at all possible, shut off the power to a circuit before performing any work on it. You must secure all sources of harmful energy before a system may be considered safe to work on. In industry, securing a circuit, device, or system in this condition is commonly known as placing it in a *Zero Energy State*. The focus of this lesson is, of course, electrical safety. However, many of these principles apply to non-electrical systems as well.

Securing something in a Zero Energy State means ridding it of any sort of potential or stored energy, including but not limited to:

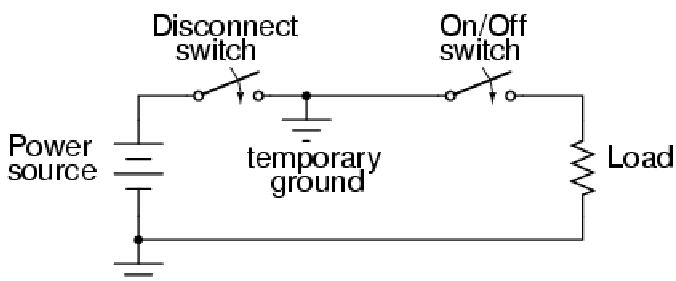
- Dangerous voltage
- Spring pressure
- Hydraulic (liquid) pressure
- Pneumatic (air) pressure
- Suspended weight
- Chemical energy (flammable or otherwise reactive substances)
- Nuclear energy (radioactive or fissile substances)

Voltage by its very nature is a manifestation of potential energy. In the first chapter I even used elevated liquid as an analogy for the potential energy of voltage, having the capacity (potential) to produce current (flow), but not necessarily realizing that potential until a suitable path for flow has been established, and resistance to flow is overcome. A pair of wires with high voltage between them do not look or sound dangerous even though they harbor enough potential energy between them to push deadly amounts of current through your body. Even though that voltage isn't presently doing anything, it has the potential to, and that potential must be neutralized before it is safe to physically contact those wires.

All properly designed circuits have "disconnect" switch mechanisms for securing voltage from a circuit. Sometimes these "disconnects" serve a dual purpose of automatically opening under excessive current conditions, in which case we call them "circuit breakers." Other times, the disconnecting switches are strictly manually-operated devices with no automatic function. In either case, they are there for your protection and must be used properly. Please note that the disconnect device should be separate from the regular switch used to turn the device on and off. It is a safety switch, to be used only for securing the system in a Zero Energy State:

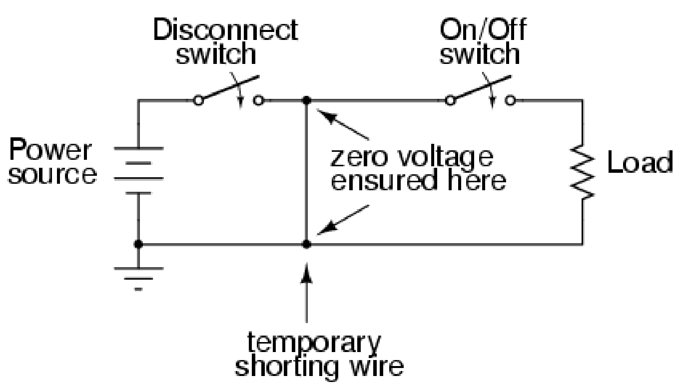


With the disconnect switch in the “open” position as shown (no continuity), the circuit is broken and no current will exist. There will be zero voltage across the load, and the full voltage of the source will be dropped across the open contacts of the disconnect switch. Note how there is no need for a disconnect switch in the lower conductor of the circuit. Because that side of the circuit is firmly connected to the earth (ground), it is electrically common with the earth and is best left that way. For maximum safety of personnel working on the load of this circuit, a temporary ground connection could be established on the top side of the load, to ensure that no voltage could ever be dropped across the load:



With the temporary ground connection in place, both sides of the load wiring are connected to ground, securing a Zero Energy State at the load.

Since a ground connection made on both sides of the load is electrically equivalent to short-circuiting across the load with a wire, that is another way of accomplishing the same goal of maximum safety:



Either way, both sides of the load will be electrically common to the earth, allowing for no voltage (potential energy) between either side of the load and the ground people stand on. This technique of temporarily grounding conductors in a de-energized power system is very common in maintenance work performed on high voltage power distribution systems.

A further benefit of this precaution is protection against the possibility of the disconnect switch being closed (turned "on" so that circuit continuity is established) while people are still contacting the load. The temporary wire connected across the load would create a short-circuit when the disconnect switch was closed, immediately tripping any overcurrent protection devices (circuit breakers or fuses) in the circuit, which would shut the power off again. Damage may very well be sustained by the disconnect switch if this were to happen, but the workers at the load are kept safe.

It would be good to mention at this point that overcurrent devices are not intended to provide protection against electric shock. Rather, they exist solely to protect conductors from overheating due to excessive currents. The temporary shorting wires just described would indeed cause any overcurrent devices in the circuit to "trip" if the disconnect switch were to be closed, but realize that electric shock protection is not the intended function of those devices. Their primary function would merely be leveraged for the purpose of worker protection with the shorting wire in place.

Since it is obviously important to be able to secure any disconnecting devices in the open (off) position and make sure they stay that way while work is being done on the circuit, there is need for a structured safety system to be put into place. Such a system is commonly used in industry and it is called *Lock-out/Tag-out*.

A lock-out/tag-out procedure works like this: all individuals working on a secured circuit have their own personal padlock or combination lock which they set on the control lever of a disconnect device prior to working on the system. Additionally, they must fill out and sign a tag which they hang from their lock describing the nature and duration of the work they intend to perform on the system. If there are multiple sources of energy to be "locked out" (multiple disconnects, both electrical and mechanical energy sources to be secured, etc.), the worker must use as many of his or her locks as necessary to secure power from the system before work begins. This way, the system is maintained in a Zero Energy State until every last lock is removed from all the disconnect and shutoff devices, and that means every last worker gives consent by removing their own personal locks. If the decision is made to re-energize the system and one person's lock(s) still remain in place after everyone present removes theirs, the tag(s) will show who that person is and what it is they're doing.

Even with a good lock-out/tag-out safety program in place, there is still need for diligence and common-sense precaution. This is especially true in industrial settings where a multitude of people may be working on a device or system at once. Some of those people might not know about proper lock-out/tag-out procedure, or might know about it but are too complacent to follow it. Don't assume that everyone has followed the safety rules!

After an electrical system has been locked out and tagged with your own personal lock, you must then double-check to see if the voltage really has been secured in a zero state. One way to check is to see if the machine (or whatever it is that's being worked on) will start up if the *Start* switch or button is actuated. If it starts, then you know you haven't successfully secured the electrical power from it.

Additionally, you should *always* check for the presence of dangerous voltage with a measuring device before actually touching any conductors in the circuit. To be safest, you should follow this procedure of checking, using, and then checking your meter:

- Check to see that your meter indicates properly on a known source of voltage.
- Use your meter to test the locked-out circuit for any dangerous voltage.
- Check your meter once more on a known source of voltage to see that it still indicates as it should.

While this may seem excessive or even paranoid, it is a proven technique for preventing electrical shock. I once had a meter fail to indicate voltage when it should have while checking a circuit to see if it was "dead." Had I not used other means to check for the presence of voltage, I might not be alive today to write this. There's always the chance that your voltage meter will be defective just when you need it to check for a dangerous condition. Following these steps will help ensure that you're never misled into a deadly situation by a broken meter.

Finally, the electrical worker will arrive at a point in the safety check procedure where it is deemed safe to actually touch the conductor(s). Bear in mind that after all of the precautionary steps have taken, it is still possible (although very unlikely) that a dangerous voltage may be present. One final precautionary measure to take at this point is to make momentary contact with the conductor(s) *with the back of the hand* before grasping it or a metal tool in contact with it. Why? If, for some reason there is still voltage present between that conductor and earth ground, finger motion from the shock reaction (clenching into a fist) will *break* contact with the conductor. Please note that this is absolutely the *last* step that any electrical worker should ever take before beginning work on a power system, and should *never* be used as an alternative method of checking for dangerous voltage. If you ever have reason to doubt the trustworthiness of your meter, use another meter to obtain a "second opinion."

2. Electrical Fundamentals

KEN DICKSON-SELF

Hopefully by the time you're considering wiring up motors and their controls, you already have a knowledge of electricity and how it behaves. The following is just a brief refresher, but any technician considering the wiring of three-phase motors should have a solid understanding of electrical fundamentals. If you do not have this understanding, please use your favorite education resource to complete training.

Electrons moving around in a never-ended loop is considered a **circuit**. Circuits that are **closed** allow for electron flow. Circuits that are **open** (broken) do not allow for electron flow.

Electricity has three main components. Voltage is the amount of potential electrical energy between two points, and it is usually represented by the letter E (for electromotive force) and is measured in volts, abbreviated with V. Current is the flow of electrons from negatively-charge atoms toward atoms with a positive charge. We measure current in Amperes or Amps (abbreviated A), and the symbol for current is I. Current that travels in only one direction we call direct current (DC). Current that changes direction at regular intervals we call alternating current (AC). The final component is resistance. Resistance (abbreviated R) is the opposition to current flow, and it is measured in ohms (abbreviated with the Greek letter Omega, Ω).

These three terms are related to one another in the following way: $E = I * R$. Knowing this, if we ever know any two of these variables in a circuit, we can always calculate the third. Two other ways to express the same equation are: $I = E / R$ and $R = E / I$.

In electricity, we often use scientific notation and prefixes with the units we measure. If you're unfamiliar with these concepts, you may want to study them a bit more. With electricity, some multiples and prefixes are used more often than others. These are in bold in the table below.

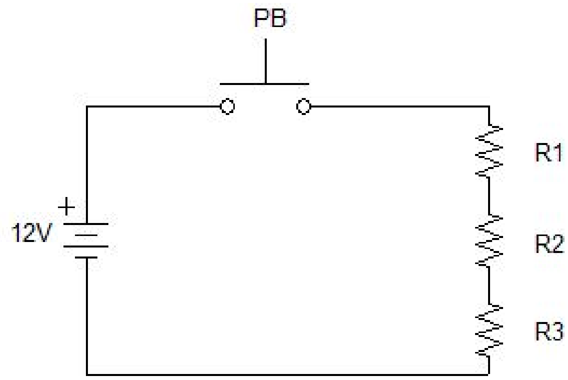
Multiple	Prefix	Symbol		Multiple	Prefix	Symbol
10^{24}	yotta	Y		10^{-1}	deci	d
10^{21}	zetta	Z		10^{-2}	centi	c
10^{18}	exa	E		**10^{-3}**	**milli**	**m**
10^{15}	peta	P		**10^{-6}**	**micro**	**µ**
10^{12}	**tera**	**T**		**10^{-9}**	**nano**	**n**
10^{9}	**giga**	**G**		**10^{-12}**	**pico**	**p**
10^{6}	**mega**	**M**		10^{-15}	femto	f
10^{3}	**kilo**	**k**		10^{-18}	atto	a
10^{2}	hecto	h		10^{-21}	zepto	z
10^{1}	deka	d		10^{-24}	yocto	y

Abbreviations and Prefixes

When building electrical circuits, components can be connected in two basic ways: either in series with one another or in parallel.

Series

When there is only one path for current flow, the components are said to be in series. Look at this example of a series circuit.



Series circuit with three resistors

The circuit has three resistors (labeled R1, R2, and R3), and these resistors are in series with each other. Notice too that the push button (labeled PB) is also in series with the resistors, as is the 9-volt battery. There is only one path for electrons to take, and all electrons must follow the same path through the circuit when the push button is pushed.

Because the electrons only have one path, the current flow is the same throughout the entire circuit, and all resistances are cumulative. Let's say that R1 has a resistance of 10Ω, R2 has a resistance of 20Ω, and R3 has a resistance of 30Ω. Because all resistances are cumulative and current is the same through, voltage at any particular component is determined by that component's resistance. The formula look like this:

Series

$$R_{Total} = R_1 + R_2 + R_3 + \ldots$$

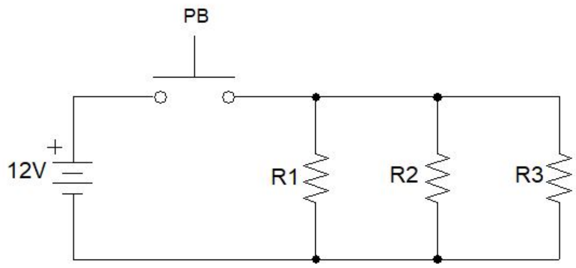
$$I_{Total} = I_1 = I_2 = I_3 = \ldots$$

$$E_{Total} = E_{R1} + E_{R2} + E_{R3} + \ldots$$

In our example, total resistance is 60 ohms (10Ω + 20Ω + 30Ω). Since the total resistance is 60Ω in a 12-volt system, the total current must be 0.2A, or 200mA (12V/60Ω). Now that total current is known, voltage at each load can be calculated. For instance, the voltage at R1 (E=IR) is going to be 0.2A * 10Ω, or 2V. Voltage at R2 is 4V and voltage at R3 is 6V. Notice that all of our voltages (2V, 4V, 6V) add up to the source voltage of 12V. This rule applies to all series circuits.

Parallel

In parallel circuits, current flow has more than one path. This changes the behavior of the electrons in the circuit. First, the voltage across parallel components is no longer split among them. Since they are in parallel with one another (electrically common), they each get full voltage. Notice on the diagram below where the black connecting dots are located. Each of those represent two (or more) locations where voltage is going to be available equally in either direction.



Parallel Circuit with Three resistors

So, in this example, when the push button is pushed, 12 volts becomes available to every resistor in the circuit, since they are each parallel with each other (the push button, however, is still in series with all resistors). So, if every resistor has the full source voltage available, how much current will be flowing through the circuit? This depends on the resistance of each "branch" or "rung" of our circuit. We simply calculate the current through each resistor, then add them together to get the total current (see below).

Parallel

$$E_{Total} = E_{R1} = E_{R2} = E_{R3} = \ldots$$

$$I_{Total} = I_1 + I_2 + I_3 + \ldots$$

$$R_{Total} = 1 / (1/R_1 + 1/R_2 + 1/R_3 + \ldots]$$

Total resistance, however, is now a little more difficult, because as resistors are added in parallel to our circuit, we're providing more paths for electrons to flow. Each new path that's added *decreases* the total resistance of the whole circuit. In fact, the total resistance of our parallel circuit MUST be lower than the resistance of the lowest resistor.

Let's use the same resistance values as the series circuit (R1 has a resistance of 10Ω, R2 is 20Ω, and R3 is 30Ω). Knowing that our total resistance is now going to be less than 10Ω, let's do the math.

$$R_{Total} = 1 / (1/10 + 1/20 + 1/30)$$

$R_{Total} = 1 / (0.1 + 0.05 + 0.0333)$

$R_{Total} = 1 / 0.1833$

$R_{Total} = 5.45\Omega$

Clever technicians always look for ways to verify results. In this case, we could calculate current for our circuit at each resistor.

$I_{R1} = 12/10$ $I_{R2} = 12/20$ $I_{R3} = 12/30$

$I_{R1} = 1.2A$ $I_{R2} = 0.6A$ $I_{R3} = 0.4A$

$I_{Total} = 1.2A + 0.6A + 0.4A = 2.2A$ of total current

Using Ohm's Law, our total resistance should be equal to total voltage divided by total current, and indeed, if we divide 12V by 2.2A, we get a total resistance of 5.45Ω. matching our previous result. Nice.

Testing Components

Switches/Contacts

Switches and contacts are designed to allow and stop the flow of current. When a switch or set of contacts are closed, the resistance should be very low (near zero), meaning that very little voltage is dropped (near zero). When a switch or set of contacts are open, the resistance should be infinite (OL on many meters), meaning that all potential voltage is available across those open contacts (assuming there aren't other opens in series with the one being measured).

Protection Devices

Testing fuses, circuit breakers, or overloads is similar to testing switches, except they are designed to always allow current flow. It's only when a protection device has experienced current higher than its specified amount that the device opens the circuit, stopping current. When testing resistance, these devices should have very low resistance. Since they are placed in series with the circuit they are designed to protect, we don't want them using up available voltage. A protection device with infinite resistance is "blown" or in its "tripped" state. When measuring voltage across one of these devices, when good there should be very little voltage dropped. If source voltage is present, the device is "blown" or in its "tripped" state.

Loads

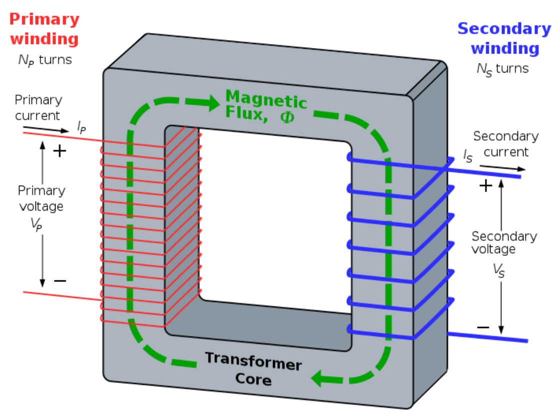
Loads are designed to use applied voltage to do the work of the circuit. This could be running a motor, lighting a bulb, or actuating a relay. Loads need to have some amount of resistance (this amount will vary by load and can be found by checking the manufacturer's specifications or measuring similar "known good" parts). Loads that measure either no resistance or an infinite amount of resistance are not good. Because loads are designed to use the available voltage, measuring voltage at a load may not always tell you if the load is good or bad. If the load has an internal open, source voltage will be read at the load. If the load is working properly, source voltage will also be found at the load. If the load is shorted, most likely, any protection devices in the circuit (fuses, circuit breakers, overloads) will be tripped, due to the increased current.

Relays

Because relays operate like an electrically-controlled switch, you have two components to test. First is the coil of the relay, which acts as a load. Next are the contacts within the relay, which act as switches. The contacts of the relay are often in a different circuit than the coil, but all of these components are tested as described above.

Transformers

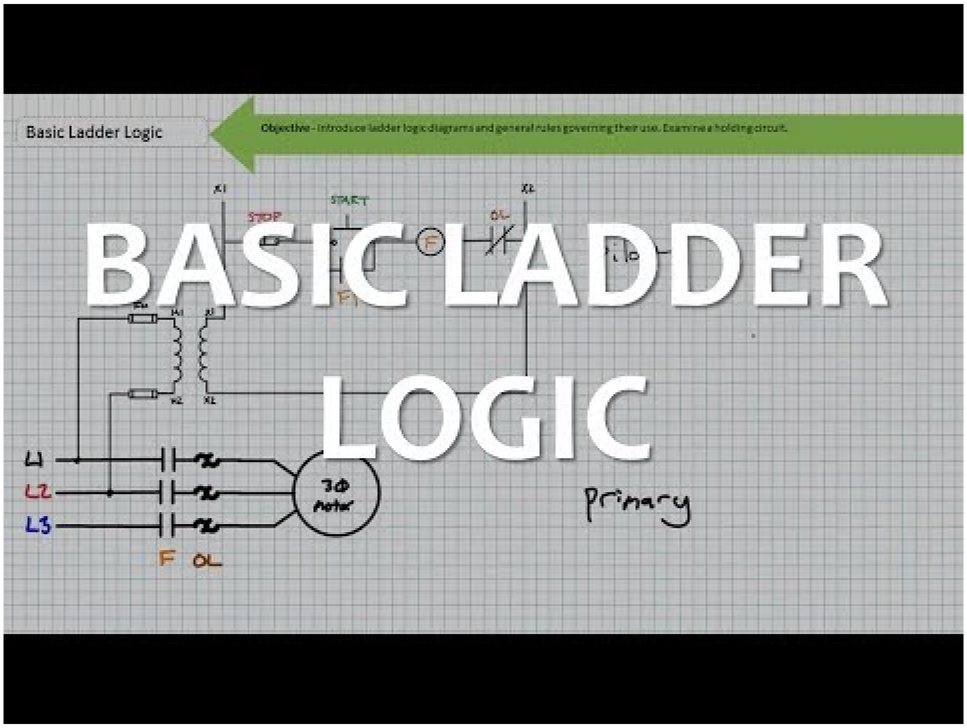
Lastly are transformers. Transformers are typically used to change AC voltage by either stepping it up or stepping it down. Transformers consist of two coils of wire wrapped around an iron core. The coils of wire behave like a typical load and can be tested similarly, as described above.



Step-down Transformer

1. Test primary coil
2. Test secondary coil
3. Measure Resistance (Rs) from primary to secondary coil (should be no continuity)
4. Measure Rs from Primary coil to transformer housing (should be no continuity)
5. Measure Rs from Secondary coil to transformer housing (should be no continuity)

Ladder Diagrams



A YouTube element has been excluded from this version of the text. You can view it online here: https://openoregon.pressbooks.pub/motorcontrols/?p=44

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3. Meter Usage

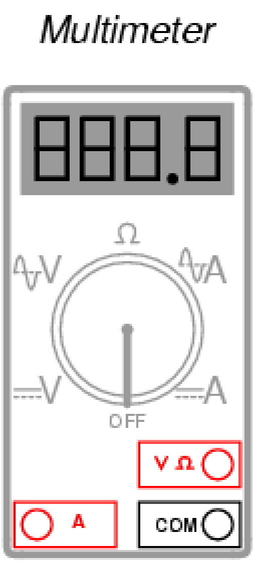
KEN DICKSON-SELF

Safe Meter Usage

Using an electrical meter safely and efficiently is perhaps the most valuable skill an electronics technician can master, both for the sake of their own personal safety and for proficiency at their trade. It can be daunting at first to use a meter, knowing that you are connecting it to live circuits which may harbor life-threatening levels of voltage and current. This concern is not unfounded, and it is always best to proceed cautiously when using meters. Carelessness more than any other factor is what causes experienced technicians to have electrical accidents.

The most common piece of electrical test equipment is a meter called the *multimeter*. Multimeters are so named because they have the ability to measure a multiple of variables: voltage, current, resistance, and often many others, some of which cannot be explained here due to their complexity. In the hands of a trained technician, the multimeter is both an efficient work tool and a safety device. In the hands of someone ignorant and/or careless, however, the multimeter may become a source of danger when connected to a "live" circuit.

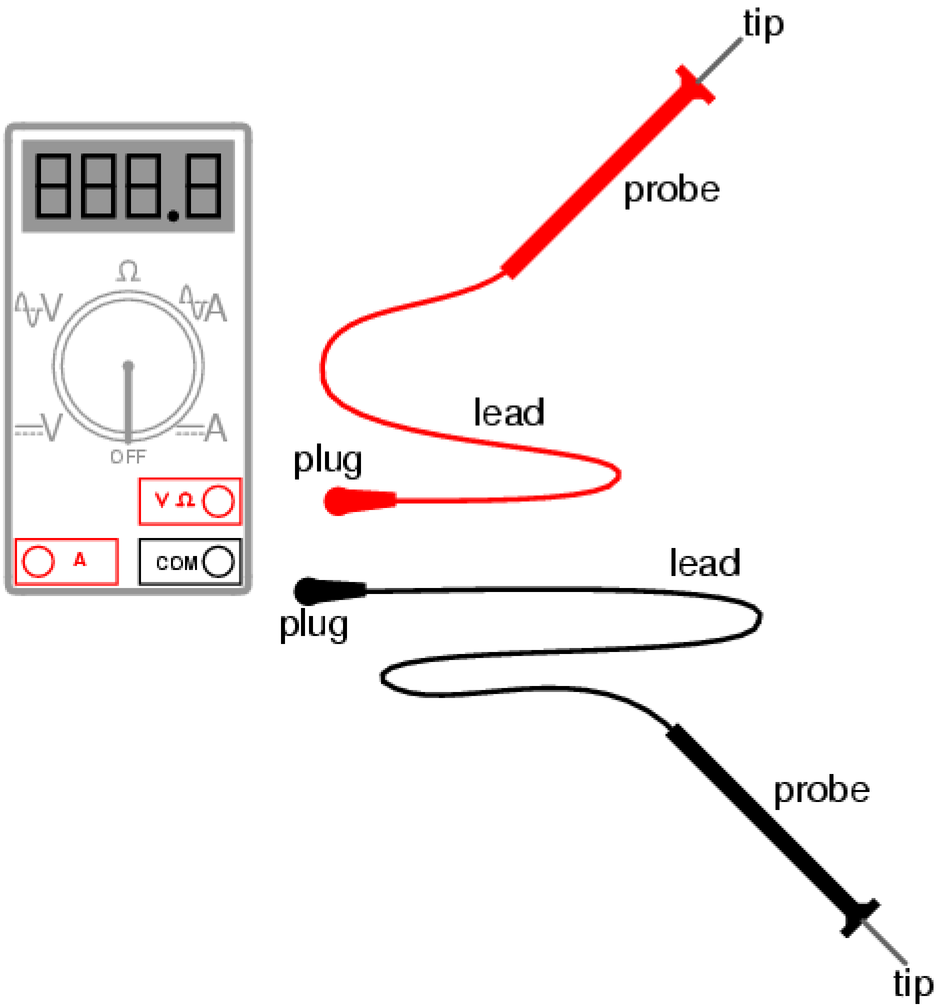
There are many different brands of multimeters, with multiple models made by each manufacturer sporting different sets of features. Most meters used in industry today have digital displays, rather than a needle style. These Digital Multimeters (DMMs) allow us to measure voltage, current and resistance. The multimeter shown here in the following illustrations is a "generic" design, not specific to any manufacturer, but general enough to teach the basic principles of use:



The rotary selector switch (now set in the *Off* position) has five different measurement positions it can be set in: two "V" settings, two "A" settings, and one setting in the middle with a funny-looking "horseshoe" symbol on it representing "resistance." The "horseshoe" symbol is the Greek letter "Omega" (Ω), which is the common symbol for the electrical unit of ohms.

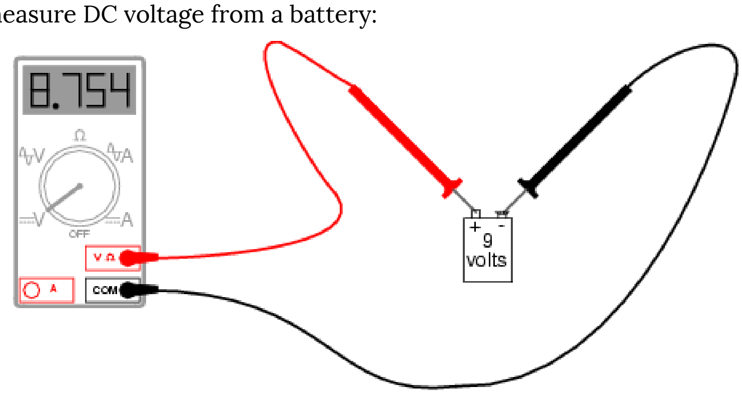
Of the two "V" settings and two "A" settings, you will notice that each pair is divided into unique markers with either a pair of horizontal lines (one solid, one dashed), or a dashed line with a squiggly curve over it. The parallel lines represent "DC" while the squiggly curve represents "AC." The "V" of course stands for "voltage" while the "A" stands for "amperage" (current). The meter uses different techniques, internally, to measure DC than it uses to measure AC, and so it requires the user to select which type of voltage (V) or current (A) is to be measured. Although we haven't discussed alternating current (AC) in any technical detail, this distinction in meter settings is an important one to bear in mind.

There are three different sockets on the multimeter face into which we can plug our *test leads*. Test leads are nothing more than specially-prepared wires used to connect the meter to the circuit under test. The wires are coated in a color-coded (either black or red) flexible insulation to prevent the user's hands from contacting the bare conductors, and the tips of the probes are sharp, stiff pieces of wire:

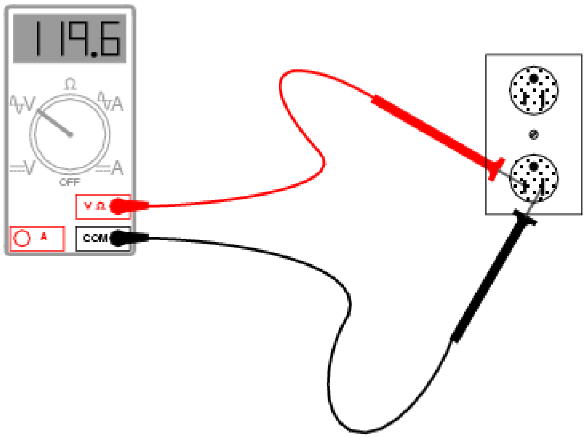


The black test lead *always* plugs into the black socket on the multimeter: the one marked "COM" for "common." The red test lead plugs into either the red socket marked for voltage and resistance, or the red socket marked for current, depending on which quantity you intend to measure with the multimeter.

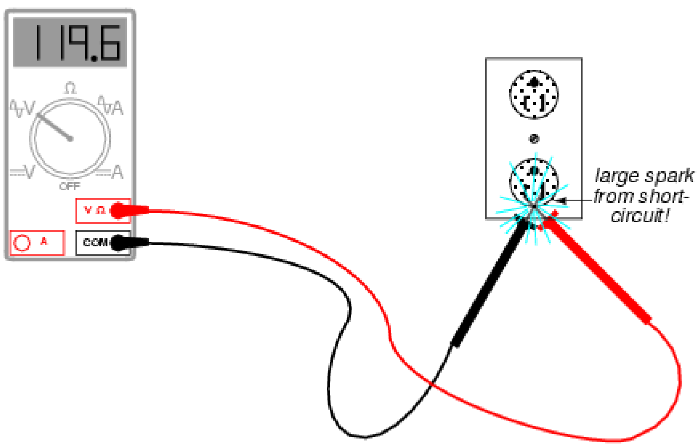
To see how this works, let's look at a couple of examples showing the meter in use. First, we'll set up the meter to measure DC voltage from a battery:



Note that the two test leads are plugged into the appropriate sockets on the meter for voltage, and the selector switch has been set for DC “V”. Now, we’ll take a look at an example of using the multimeter to measure AC voltage from a household electrical power receptacle (wall socket):



The only difference in the setup of the meter is the placement of the selector switch: it is now turned to AC “V”. Since we’re still measuring voltage, the test leads will remain plugged in the same sockets. In both of these examples, it is *imperative* that you not let the probe tips come in contact with one another while they are both in contact with their respective points on the circuit. If this happens, a short-circuit will be formed, creating a spark and perhaps even a ball of flame if the voltage source is capable of supplying enough current! The following image illustrates the potential for hazard:



This is just one of the ways that a meter can become a source of hazard if used improperly.

Voltage measurement is perhaps the most common function a multimeter is used for. It is certainly the primary measurement taken for safety purposes (part of the lock-out/tag-out procedure), and it should be well understood by the operator of the meter. Being that voltage is always relative between two points, the meter *must* be firmly connected to two points in a circuit before it will provide a reliable measurement. That usually means both probes must be grasped by the user’s hands and held against the proper contact points of a voltage source or circuit while measuring.

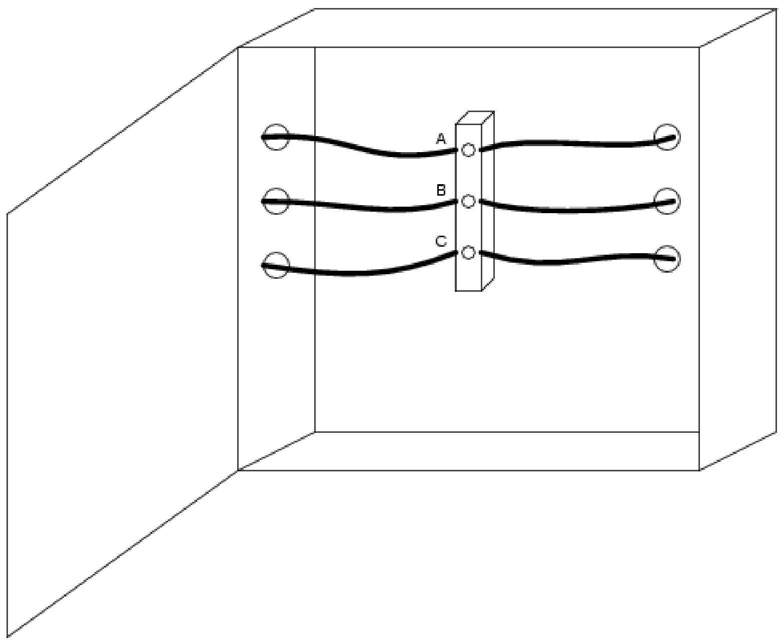
Because a hand-to-hand shock current path is the most dangerous, holding the meter probes on two points in a high-voltage circuit in this manner is always a *potential* hazard. If the protective insulation on the probes is worn or cracked, it is possible for the user’s fingers to come into contact with the probe conductors during the time of test, causing a bad shock to occur. If it is possible to use only one hand to grasp the probes, that is a safer option. Sometimes it is possible to “latch” one probe tip onto the circuit test point so that it can be let go of and the other probe set in place, using only one hand. Special probe tip accessories such as spring clips can be attached to help facilitate this.

Remember that meter test leads are part of the whole equipment package, and that they should be treated with the same care and respect that the meter itself is. If you need a special accessory for your test leads, such as a spring clip or other special probe tip, consult the product catalog of the meter manufacturer or other test equipment manufacturer. *Do not* try to be creative and make your own test probes, as you may end up placing yourself in danger the next time you use them on a live circuit.

Also, it must be remembered that digital multimeters usually do a good job of discriminating between AC and DC measurements, as they are set for one or the other when checking for voltage or current. As we have seen earlier, both AC and DC voltages and currents can be deadly, so when using a multimeter as a safety check device you should always check for the presence of both AC and DC, even if you're not expecting to find both! Also, when checking for the presence of hazardous voltage, you should be sure to check *all* pairs of points in question.

For example, suppose that you opened up an electrical wiring cabinet to find three large conductors supplying AC power to a load. The circuit breaker feeding these wires (supposedly) has been shut off, locked, and tagged. You double-checked the absence of power by pressing the *Start*button for the load. Nothing happened, so now you move on to the third phase of your safety check: the meter test for voltage.

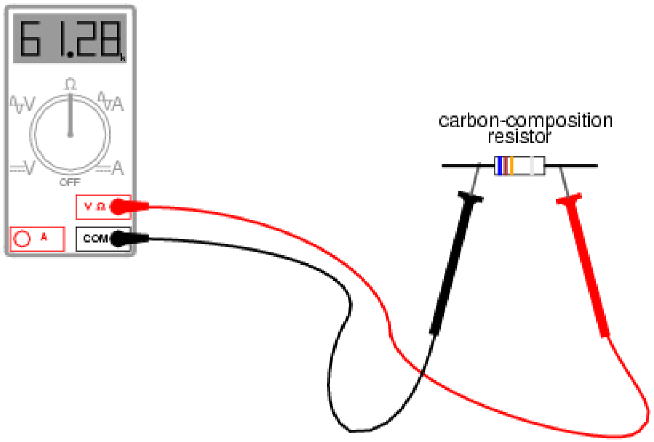
First, you check your meter on a known source of voltage to see that its working properly. Any nearby power receptacle should provide a convenient source of AC voltage for a test. You do so and find that the meter indicates as it should. Next, you need to check for voltage among these three wires in the cabinet. But voltage is measured between *two* points, so where do you check?



The answer is to check between all combinations of those three points. As you can see, the points are labeled "A", "B", and "C" in the illustration, so you would need to take your multimeter (set in the voltmeter mode) and check between points A & B, B & C, and A & C. If you find voltage between any of those pairs, the circuit is not in a Zero Energy State. But wait! Remember that a multimeter will not register DC voltage when its in the AC voltage mode and vice versa, so you need to check those three pairs of points in *each mode* for a total of six voltage checks in order to be complete!

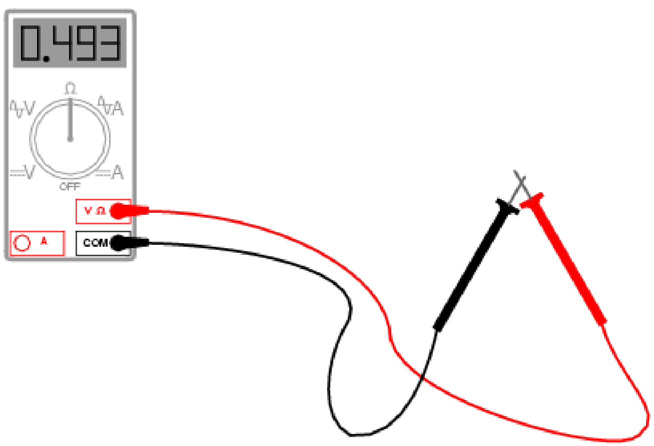
However, even with all that checking, we still haven't covered all possibilities yet. Remember that hazardous voltage can appear between a single wire and ground (in this case, the metal frame of the cabinet would be a good ground reference point) in a power system. So, to be perfectly safe, we not only have to check between A & B, B & C, and A & C (in both AC and DC modes), but we also have to check between A & ground, B & ground, and C & ground (in both AC and DC modes)! This makes for a grand total of twelve voltage checks for this seemingly simple scenario of only three wires. Then, of course, after we've completed all these checks, we need to take our multimeter and re-test it against a known source of voltage such as a power receptacle to ensure that its still in good working order.

Using a multimeter to check for resistance is a much simpler task. The test leads will be kept plugged in the same sockets as for the voltage checks, but the selector switch will need to be turned until it points to the "horseshoe" resistance symbol. Touching the probes across the device whose resistance is to be measured, the meter should properly display the resistance in ohms:

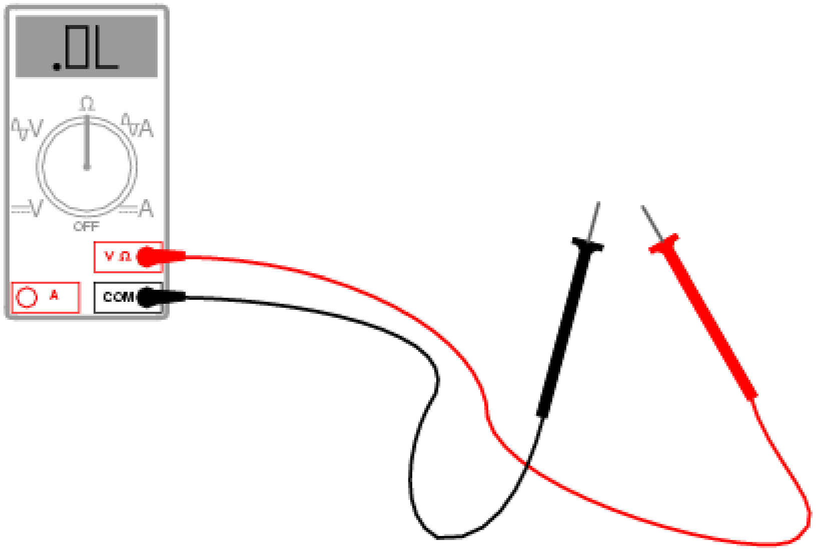


One very important thing to remember about measuring resistance is that it must only be done on *de-energized* components! When the meter is in "resistance" mode, it uses a small internal battery to generate a tiny current through the component to be measured. By sensing how difficult it is to move this current through the component, the resistance of that component can be determined and displayed. If there is any additional source of voltage in the meter-lead-component-lead-meter loop to either aid or oppose the resistance-measuring current produced by the meter, faulty readings will result. In a worse-case situation, the meter may even be damaged by the external voltage.

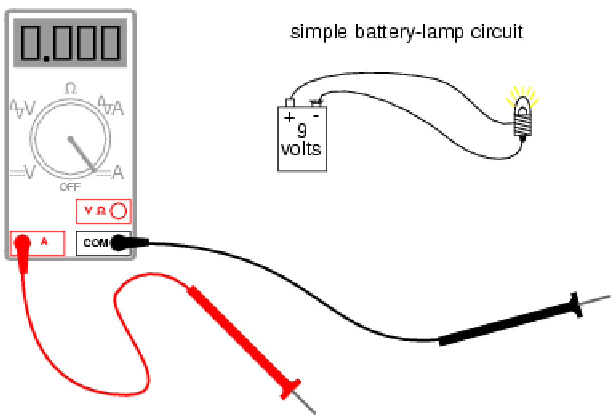
The "resistance" mode of a multimeter is very useful in determining wire continuity as well as making precise measurements of resistance. When there is a good, solid connection between the probe tips (simulated by touching them together), the meter shows almost zero Ω. If the test leads had no resistance in them, it would read exactly zero:



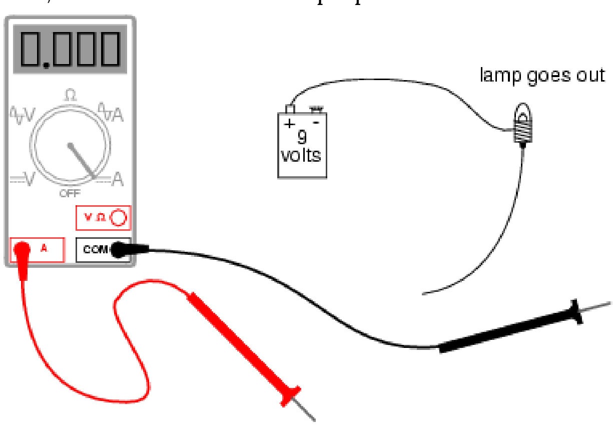
If the leads are not in contact with each other, or touching opposite ends of a broken wire, the meter will indicate infinite resistance (usually by displaying dashed lines or the abbreviation "O.L." which stands for "open loop"):



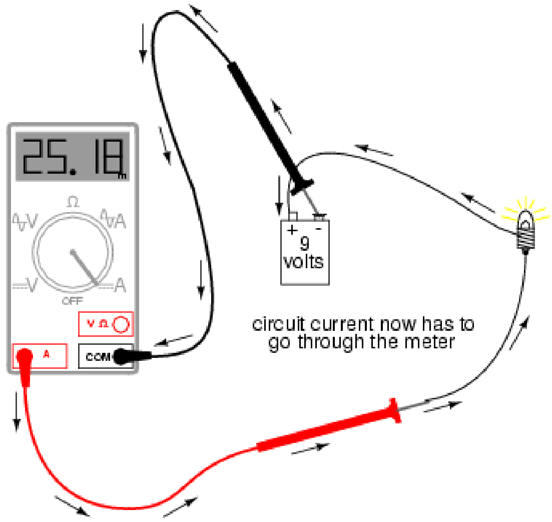
By far the most hazardous and complex application of the multimeter is in the measurement of current. The reason for this is quite simple: in order for the meter to measure current, the current to be measured must be forced to go *through* the meter. This means that the meter must be made part of the current path of the circuit rather than just be connected off to the side somewhere as is the case when measuring voltage. In order to make the meter part of the current path of the circuit, the original circuit must be “broken” and the meter connected across the two points of the open break. To set the meter up for this, the selector switch must point to either AC or DC “A” and the red test lead must be plugged in the red socket marked “A”. The following illustration shows a meter all ready to measure current and a circuit to be tested:



Now, the circuit is broken in preparation for the meter to be connected:



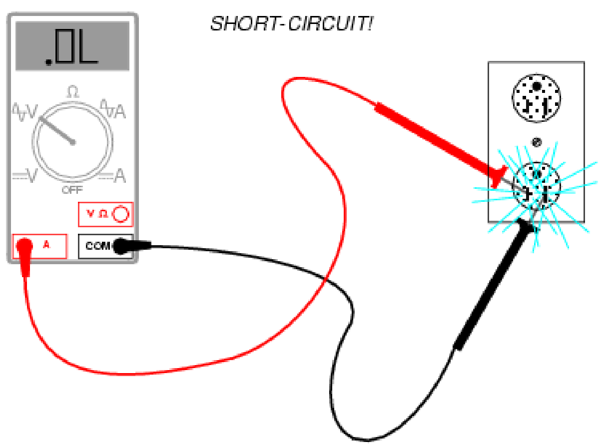
The next step is to insert the meter in-line with the circuit by connecting the two probe tips to the broken ends of the circuit, the black probe to the negative (-) terminal of the 9-volt battery and the red probe to the loose wire end leading to the lamp:



This example shows a very safe circuit to work with. 9 volts hardly constitutes a shock hazard, and so there is little to fear in breaking this circuit open (bare handed, no less!) and connecting the meter in-line with the flow of electrons. However, with higher power circuits, this could be a hazardous endeavor indeed. Even if the circuit voltage was low, the normal current could be high enough that an injurious spark would result the moment the last meter probe connection was established.

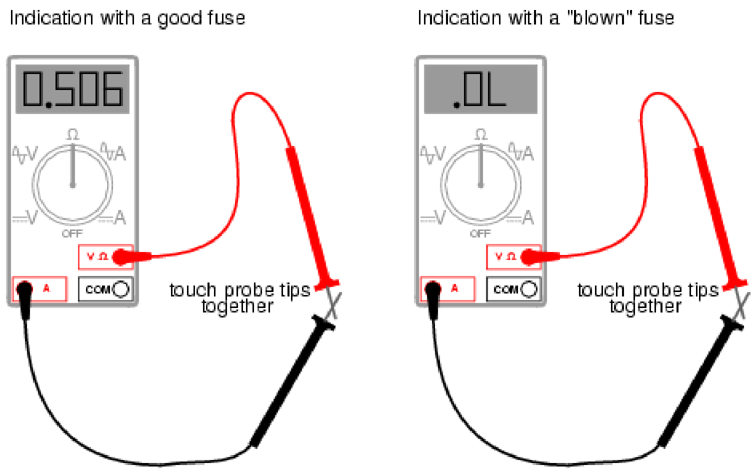
Another potential hazard of using a multimeter in its current-measuring ("ammeter") mode is failure to properly put it back into a voltage-measuring configuration before measuring voltage with it. The reasons for this are specific to ammeter design and operation. When measuring circuit current by placing the meter directly in the path of current, it is best to have the meter offer little or no resistance against the flow of electrons. Otherwise, any additional resistance offered by the meter would impede the electron flow and alter the circuits operation. Thus, the multimeter is designed to have practically zero ohms of resistance between the test probe tips when the red probe has been plugged into the red "A" (current-measuring) socket. In the voltage-measuring mode (red lead plugged into the red "V" socket), there are many mega-ohms of resistance between the test probe tips, because voltmeters are designed to have close to infinite resistance (so that they *don't* draw any appreciable current from the circuit under test).

When switching a multimeter from current- to voltage-measuring mode, its easy to spin the selector switch from the "A" to the "V" position and forget to correspondingly switch the position of the red test lead plug from "A" to "V". The result—if the meter is then connected across a source of substantial voltage—will be a short-circuit through the meter!



To help prevent this, most multimeters have a warning feature by which they beep if ever there's a lead plugged in the “A” socket and the selector switch is set to “V”. As convenient as features like these are, though, they are still no substitute for clear thinking and caution when using a multimeter.

All good-quality multimeters contain fuses inside that are engineered to “blow” in the event of excessive current through them, such as in the case illustrated in the last image. Like all overcurrent protection devices, these fuses are primarily designed to *protect the equipment* (in this case, the meter itself) from excessive damage, and only secondarily to protect the user from harm. A multimeter can be used to check its own current fuse by setting the selector switch to the resistance position and creating a connection between the two red sockets like this:



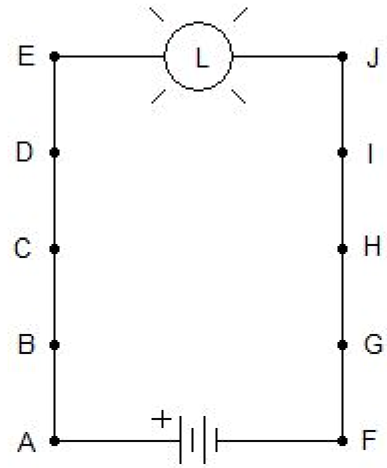
A good fuse will indicate very little resistance while a blown fuse will always show “O.L.” (or whatever indication that model of multimeter uses to indicate no continuity). The actual number of ohms displayed for a good fuse is of little consequence, so long as its an arbitrarily low figure.

So now that we’ve seen how to use a multimeter to measure voltage, resistance, and current, what more is there to know? Plenty! The value and capabilities of this versatile test instrument will become more evident as you gain skill and familiarity using it. There is no substitute for regular practice with complex instruments such as these, so feel free to experiment on safe, battery-powered circuits.

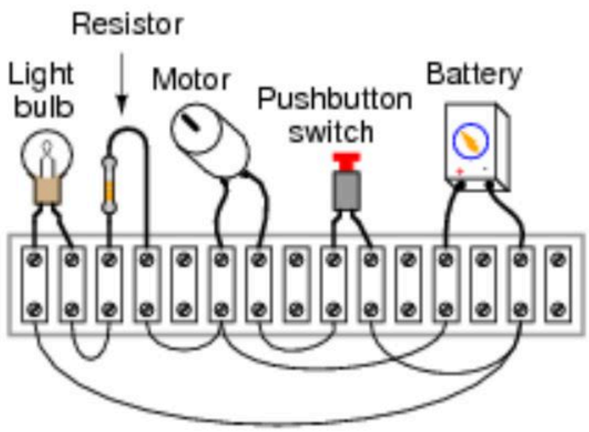
4. Homework 1

KEN DICKSON-SELF

Use the following schematic for questions 1, 2 and 3.

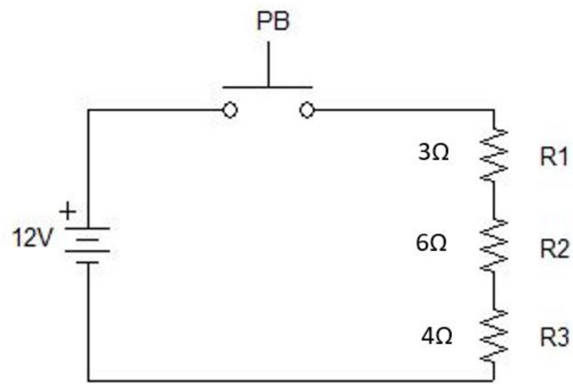


1. Between which points would you expect to measure no voltage?
2. Between which points would you expect to measure source voltage?
3. The light bulb stops working. Using your meter, you read zero volts between points F and H and between E and J. You measure source voltage from I and B and from G and J. Where is the problem located?
4. Draw a ladder diagram of the following circuit:



Wired Circuit

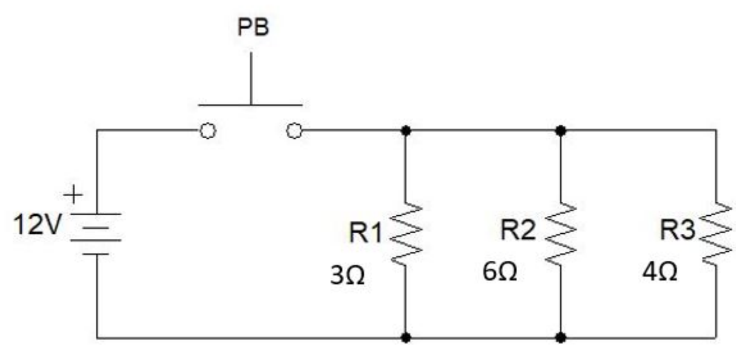
5. Using Ohm's Law, fill in the missing values for the following circuit:



Series Circuit

	R1	R2	R3	Total
E				12V
I				
R	3Ω	6Ω	4Ω	

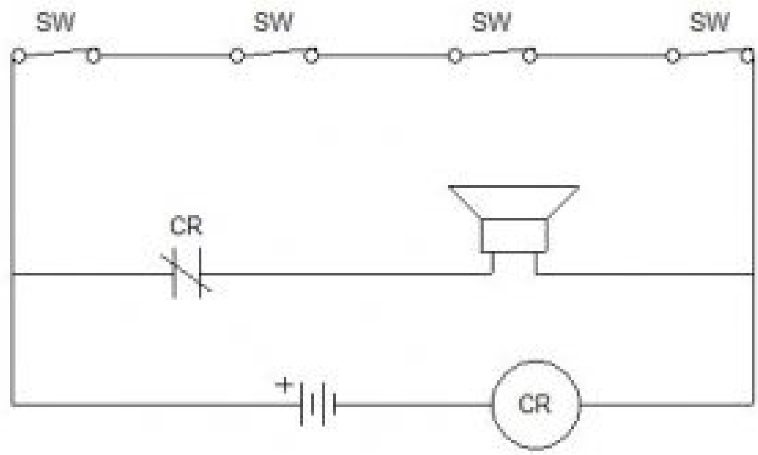
6. Using Ohm's Law, fill in the missing values for the following circuit:



Parallel circuit

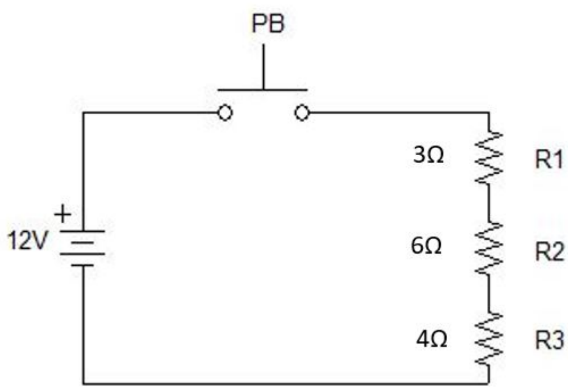
	R1	R2	R3	Total
E				12V
I				
R	3Ω	6Ω	4Ω	

7. Given the following schematic diagram with a control relay, siren and four switches, describe the behavior of this circuit in words.



Speaker Circuit

8. How much current is in a 12V circuit that has 24kΩ of resistance?
9. How much voltage is present in a circuit with 30mA of current and 800Ω of resistance?
10. What resistance is present in a circuit with 120V and 80µA of current?
11. How would you write 2.4MΩ in scientific notation?
12. How would you write 2.4µA in scientific notation?
13. How might you write 3.45 x 10^{8}A?
14. How might you write 8.34 x 10^{-6}Ω?
15. In the circuit below, draw in your meter to measure the following properties:
    1. Resistance of R1
    2. Voltage across R2
    3. Current through R1, R2, and R3



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PART II

LESSON 2

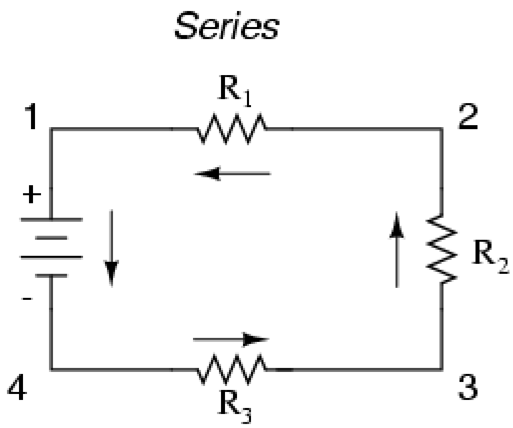
Lesson 2 consists of:

- Series and Parallel Combination Circuits
- Redrawing Complex Circuits
- Introduction to Logic
- Homework 2

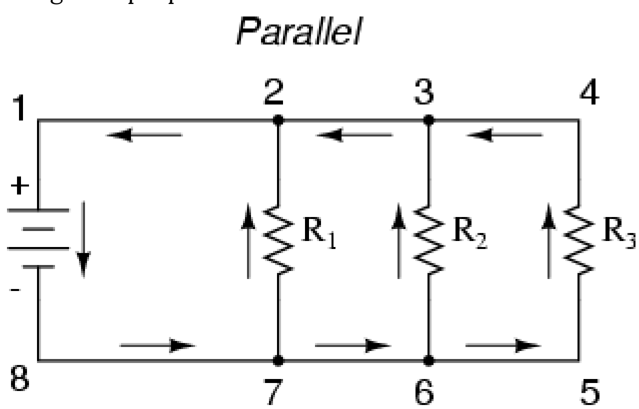
5. Combination Series/Parallel Circuits

KEN DICKSON-SELF

With simple series circuits, all components are connected end-to-end to form only one path for electrons to flow through the circuit:



With simple parallel circuits, all components are connected between the same two sets of electrically common points, creating multiple paths for electrons to flow from one end of the battery to the other:

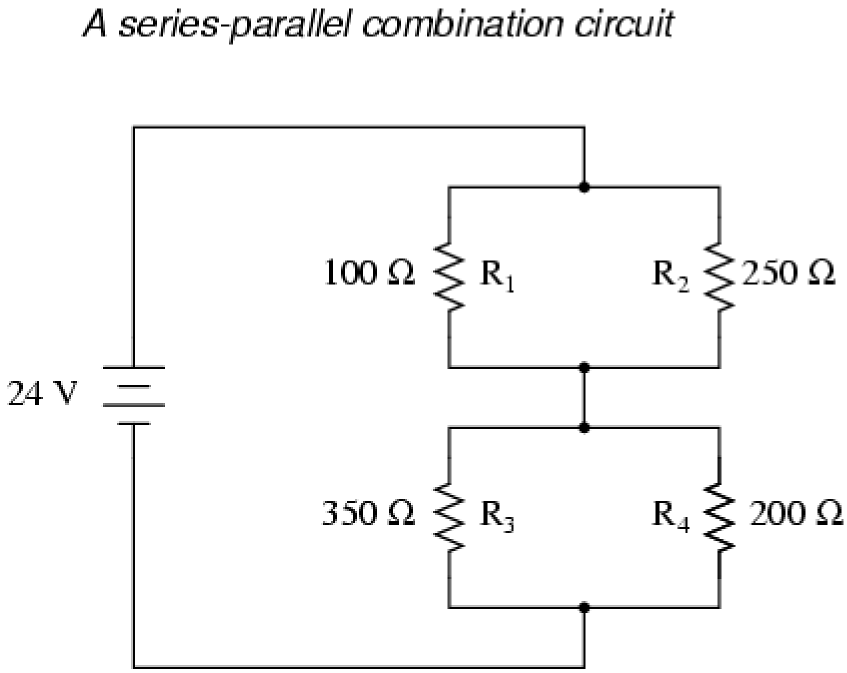


With each of these two basic circuit configurations, we have specific sets of rules describing voltage, current, and resistance relationships.

- **Series Circuits:**
- Voltage drops add to equal total voltage.
- All components share the same (equal) current.
- Resistances add to equal total resistance.

- **Parallel Circuits:**
- All components share the same (equal) voltage.
- Branch currents add to equal total current.
- Resistances diminish to equal total resistance.

However, if circuit components are series-connected in some parts and parallel in others, we won't be able to apply a *single* set of rules to every part of that circuit. Instead, we will have to identify which parts of that circuit are series and which parts are parallel, then selectively apply series and parallel rules as necessary to determine what is happening. Take the following circuit, for instance:



This circuit is neither simple series nor simple parallel. Rather, it contains elements of both. The current exits the bottom of the battery, splits up to travel through R_3 and R_4, rejoins, then splits up again to travel through $R_1$and R_2, then rejoins again to return to the top of the battery. There exists more than one path for current to travel (not series), yet there are more than two sets of electrically common points in the circuit (not parallel).

Because the circuit is a combination of both series and parallel, we cannot apply the rules for voltage, current, and resistance "across the table" to begin analysis like we could when the circuits were one way or the other. For instance, if the above circuit were simple series, we could just add up R_1 through R_4 to arrive at a total resistance, solve for total current, and then solve for all voltage drops. Likewise, if the above circuit were simple parallel, we could just solve for branch currents, add up branch currents to figure the total current, and then calculate total resistance from total voltage and total current. However, this circuit's solution will be more complex.

The table will still help us manage the different values for series-parallel combination circuits, but we'll have to be careful how and where we apply the different rules for series and parallel. Ohm's Law, of course, still works just the same for determining values within a vertical column in the table.

If we are able to identify which parts of the circuit are series and which parts are parallel, we can analyze it in stages, approaching each part one at a time, using the appropriate rules to determine the relationships of voltage, current, and resistance. The rest of this chapter will be devoted to showing you techniques for doing this.

Process of Series-Parallel Resistor Circuit Analysis

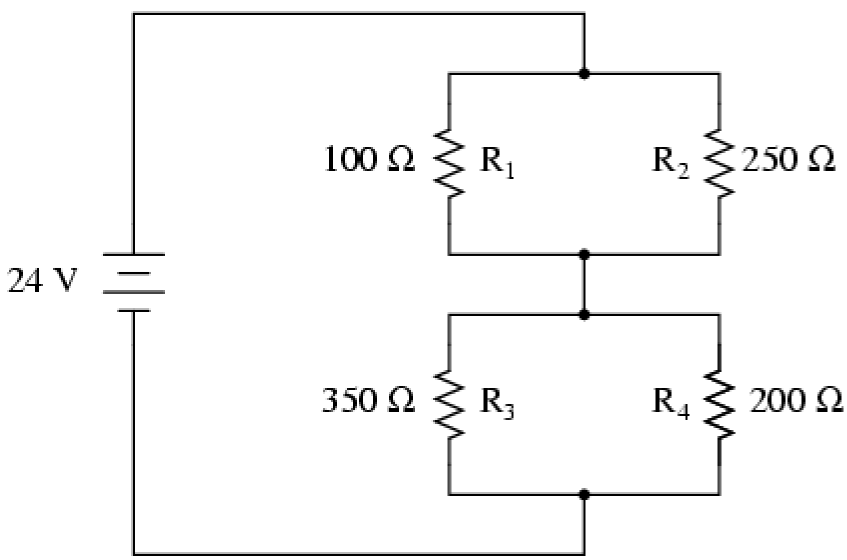
The goal of series-parallel resistor circuit analysis is to be able to determine all voltage drops, currents, and power dissipations in a circuit. The general strategy to accomplish this goal is as follows:

- Step 1: Assess which resistors in a circuit are connected together in simple series or simple parallel.
- Step 2: Re-draw the circuit, replacing each of those series or parallel resistor combinations identified in step 1 with a single, equivalent-value resistor. If using a table to manage variables, make a new table column for each resistance equivalent.

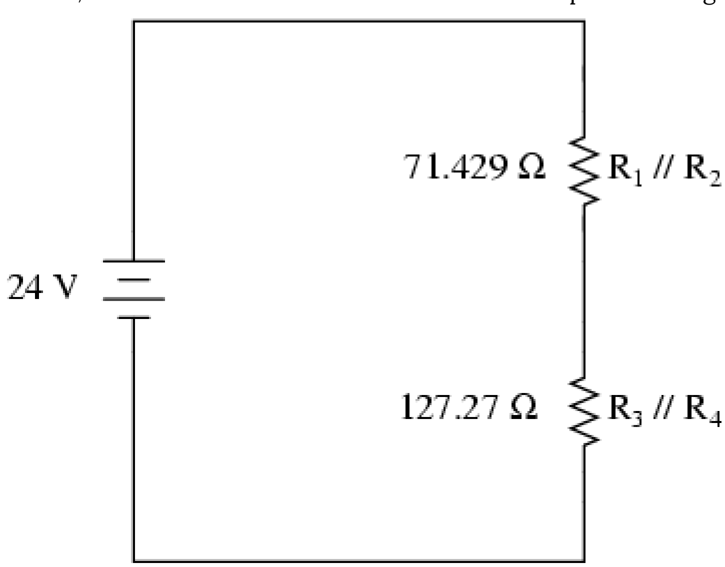
- Step 3: Repeat steps 1 and 2 until the entire circuit is reduced to one equivalent resistor.
- Step 4: Calculate total current from total voltage and total resistance (I=E/R).
- Step 5: Taking total voltage and total current values, go back to last step in the circuit reduction process and insert those values where applicable.
- Step 6: From known resistances and total voltage / total current values from step 5, use Ohm's Law to calculate unknown values (voltage or current) (E=IR or I=E/R).
- Step 7: Repeat steps 5 and 6 until all values for voltage and current are known in the original circuit configuration. Essentially, you will proceed step-by-step from the simplified version of the circuit back into its original, complex form, plugging in values of voltage and current where appropriate until all values of voltage and current are known.
- Step 8: Calculate power dissipations from known voltage, current, and/or resistance values.

This may sound like an intimidating process, but its much easier understood through example than through description.

A series-parallel combination circuit



In the example circuit above, R_1 and R_2 are connected in a simple parallel arrangement, as are R_3 and R_4. Having been identified, these sections need to be converted into equivalent single resistors, and the circuit re-drawn:

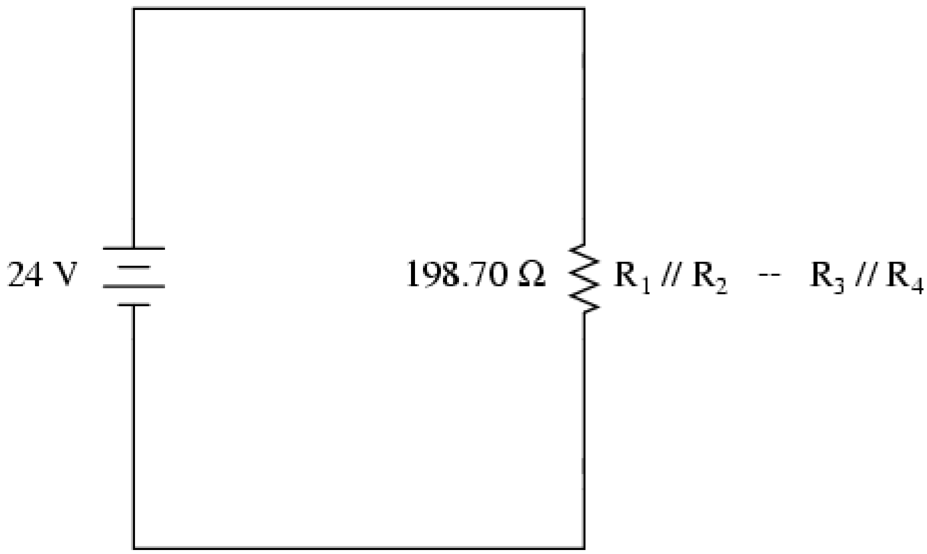


The double slash (//) symbols represent "parallel" to show that the equivalent resistor values were calculated using the 1/(1/R) formula. The 71.429 Ω resistor at the top of the circuit is the equivalent of R_1 and R_2 in parallel with each other. The 127.27 Ω resistor at the bottom is the equivalent of R_3 and R_4 in parallel with each other.

Our table can be expanded to include these resistor equivalents in their own columns:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	Total	
E							24	Volts
I								Amps
R	100	250	350	200	**71.429**	**127.27**		Ohms

It should be apparent now that the circuit has been reduced to a simple series configuration with only two (equivalent) resistances. The final step in reduction is to add these two resistances to come up with a total circuit resistance. When we add those two equivalent resistances, we get a resistance of 198.70 Ω. Now, we can re-draw the circuit as a single equivalent resistance and add the total resistance figure to the rightmost column of our table. Note that the "Total" column has been relabeled (R_1//R_2−R_3//R_4) to indicate how it relates electrically to the other columns of figures. The "−" symbol is used here to represent "series," just as the "//" symbol is used to represent "parallel."

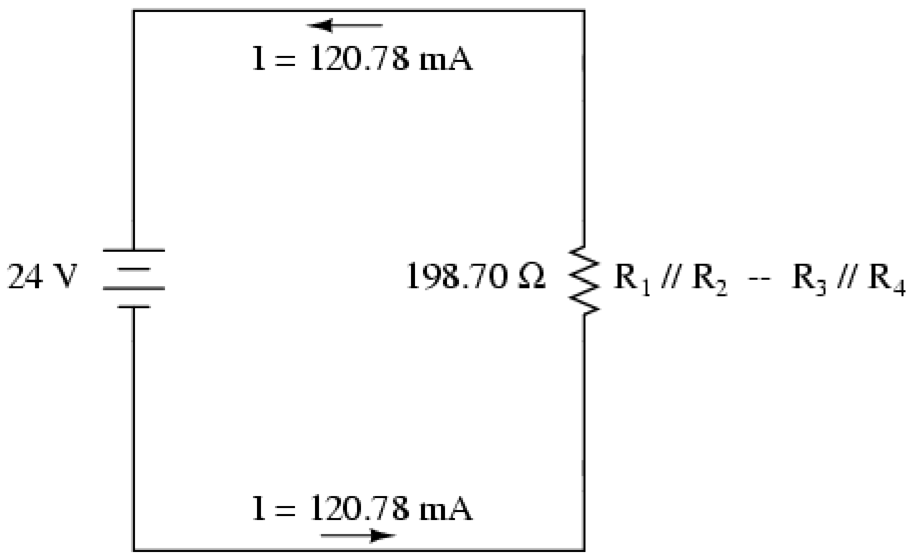


	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	R_1 // R_2 -- R_3 // R_4 Total	
E							24	Volts
I								Amps
R	100	250	350	200	71.429	127.27	**198.70**	Ohms

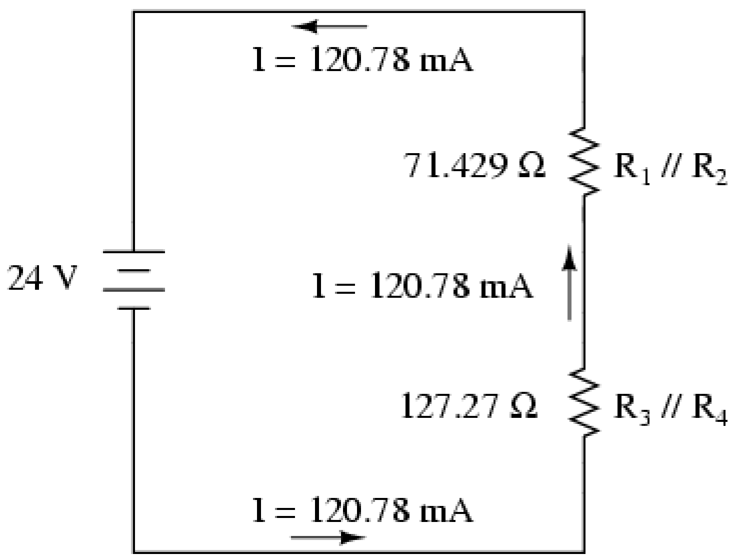
Now, total circuit current can be determined by applying Ohm's Law (I=E/R) to the "Total" column in the table:

	R_1	R_2	R_3	R_4	R_1 // R_2	R_3 // R_4	R_1 // R_2 -- R_3 // R_4 Total	
E							24	Volts
I							**120.78m**	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Back to our equivalent circuit drawing, our total current value of 120.78 milliamps is shown as the only current here:



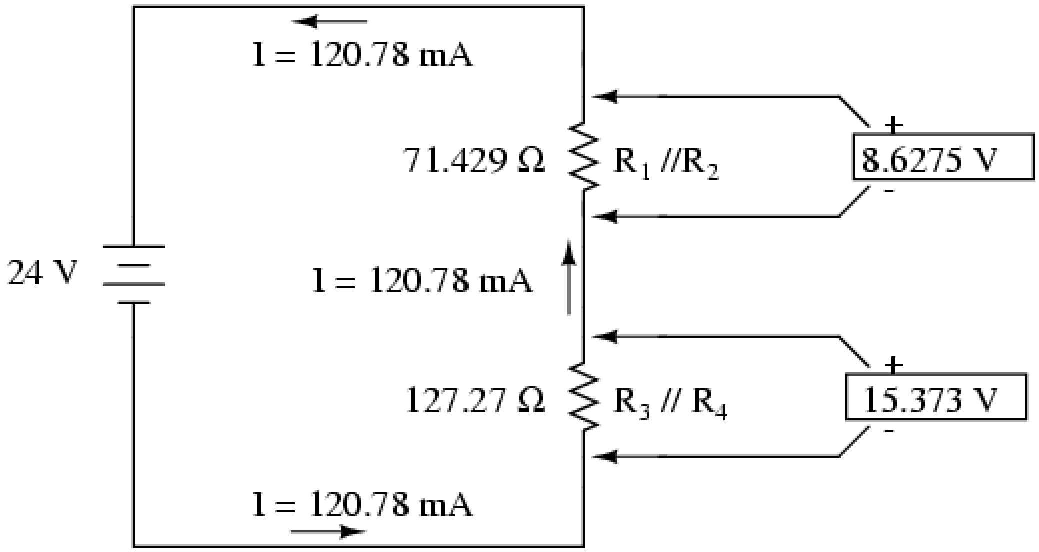
Now we start to work backwards in our progression of circuit re-drawings to the original configuration. The next step is to go to the circuit where $R_1//R_2$and $R_3//R_4$ are in series:



Since $R_1//R_2$ and $R_3//R_4$ are in series with each other, the current through those two sets of equivalent resistances must be the same. Furthermore, the current through them must be the same as the total current, so we can fill in our table with the appropriate current values, simply copying the current figure from the Total column to the $R_1//R_2$ and $R_3//R_4$ columns:

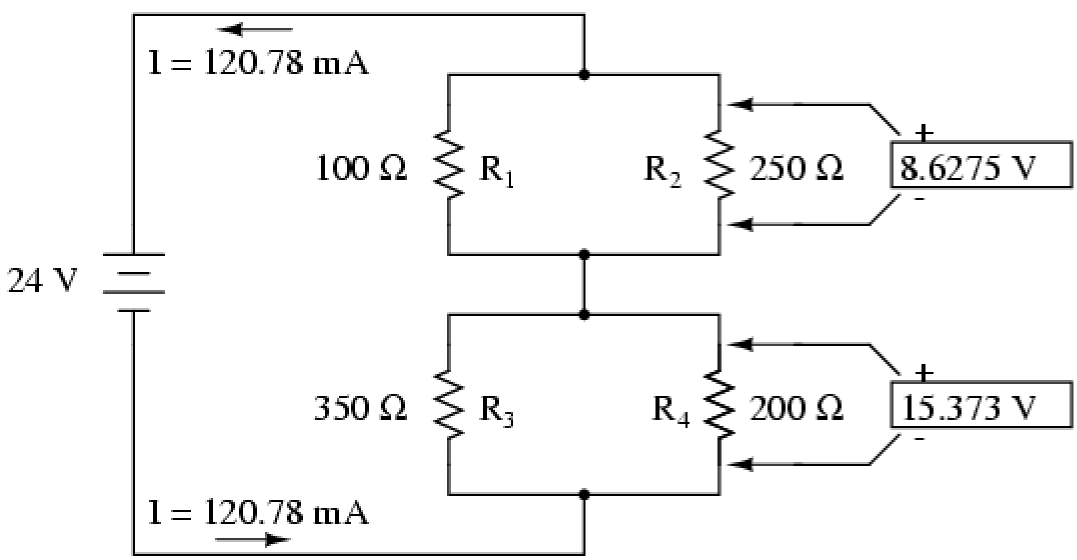
	R_1	R_2	R_3	R_4	$R_1 // R_2$	$R_3 // R_4$	$R_1 // R_2$ -- $R_3 // R_4$ Total	
E							24	Volts
I					**120.78m**	**120.78m**	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Now, knowing the current through the equivalent resistors $R_1//R_2$ and $R_3//R_4$, we can apply Ohm's Law (E=IR) to the two right vertical columns to find voltage drops across them:



	R_1	R_2	R_3	R_4	$R_1 // R_2$	$R_3 // R_4$	$R_1 // R_2$ -- $R_3 // R_4$ Total	
E					**8.6275**	**15.373**	24	Volts
I					120.78m	120.78m	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Because we know $R_1//R_2$ and $R_3//R_4$ are parallel resistor equivalents, and we know that voltage drops in parallel circuits are the same, we can transfer the respective voltage drops to the appropriate columns on the table for those individual resistors. In other words, we take another step backwards in our drawing sequence to the original configuration, and complete the table accordingly:



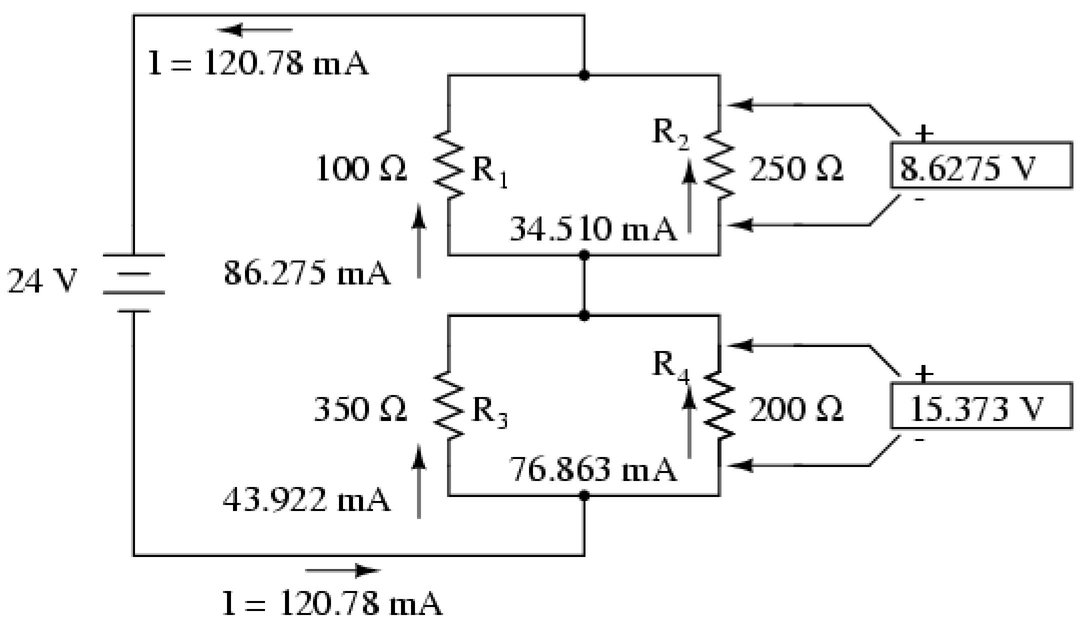
	R_1	R_2	R_3	R_4	$R_1 // R_2$	$R_3 // R_4$	$R_1 // R_2$ -- $R_3 // R_4$ Total	
E	**8.6275**	**8.6275**	**15.373**	**15.373**	8.6275	15.373	24	Volts
I					120.78m	120.78m	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Finally, the original section of the table (columns R1 through R4) is complete with enough values to finish. Applying Ohm's Law to the remaining vertical columns (I=E/R), we can determine the currents through R1, R2, R3, and R4individually:

	R_1	R_2	R_3	R_4	$R_1 // R_2$	$R_3 // R_4$	$R_1 // R_2$ -- $R_3 // R_4$ Total	
E	8.6275	8.6275	15.373	15.373	8.6275	15.373	24	Volts
I	**86.275m**	**34.510m**	**43.922m**	**76.863m**	120.78m	120.78m	120.78m	Amps
R	100	250	350	200	71.429	127.27	198.70	Ohms

Placing Voltage and Current Values into Diagrams

Having found all voltage and current values for this circuit, we can show those values in the schematic diagram as such:



As a final check of our work, we can see if the calculated current values add up as they should to the total. Since R1 and R2 are in parallel, their combined currents should add up to the total of 120.78 mA. Likewise, since R3 and R4 are in parallel, their combined currents should also add up to the total of 120.78 mA. You can check for yourself to verify that these figures do add up as expected.

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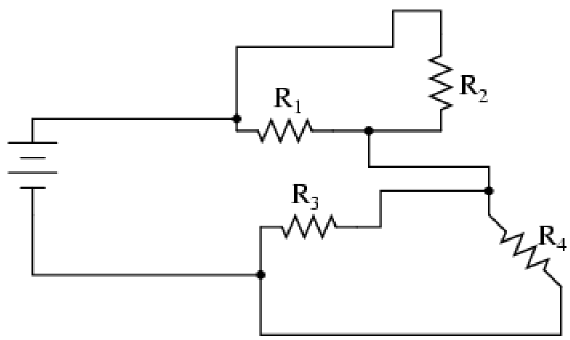
6. Redrawing Complex Circuits

KEN DICKSON-SELF

Typically, complex circuits are not arranged in nice, neat, clean schematic diagrams for us to follow. They are often drawn in such a way that makes it difficult to follow which components are in series and which are in parallelwith each other. The purpose of this section is to show you a method useful for re-drawing circuit schematics in a neat and orderly fashion. Like the stage-reduction strategy for solving series-parallel combination circuits, it is a method easier demonstrated than described.

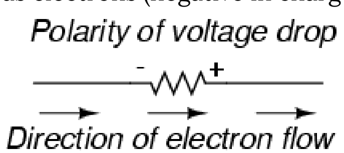
Let's start with the following (convoluted) circuit diagram. Perhaps this diagram was originally drawn this way by a technician or engineer. Perhaps it was sketched as someone traced the wires and connections of a real circuit. In any case, here it is in all its ugliness:

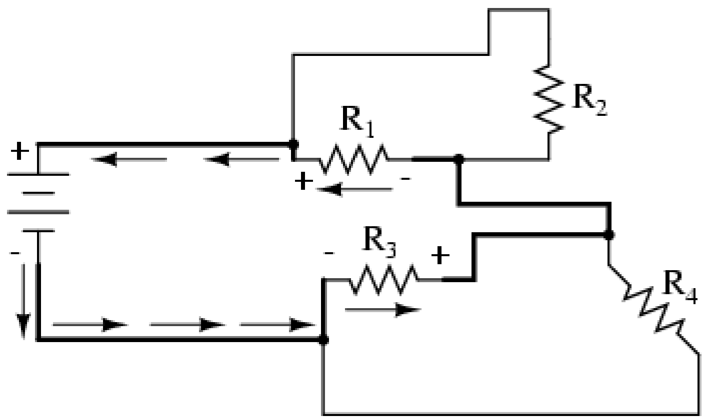


With electric circuits and circuit diagrams, the length and routing of wire connecting components in a circuit matters little. (Actually, in some AC circuits it becomes critical, and very long wire lengths can contribute unwanted resistance to both AC and DC circuits, but in most cases wire length is irrelevant.) What this means for us is that we can lengthen, shrink, and/or bend connecting wires without affecting the operation of our circuit.

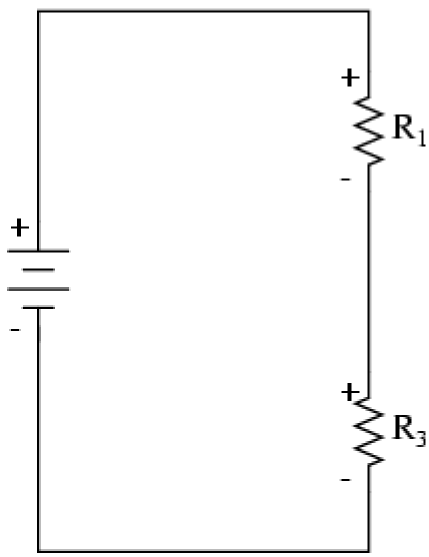
The strategy I have found easiest to apply is to start by tracing the current from one terminal of the battery around to the other terminal, following the loop of components closest to the battery and ignoring all other wires and components for the time being. While tracing the path of the loop, mark each resistor with the appropriate polarity for voltage drop.

In this case, I'll begin my tracing of this circuit at the negative terminal of the battery and finish at the positive terminal, in the same general direction as the electrons would flow. When tracing this direction, I will mark each resistor with the polarity of negative on the entering side and positive on the exiting side, for that is how the actual polarity will be as electrons (negative in charge) enter and exit a resistor:

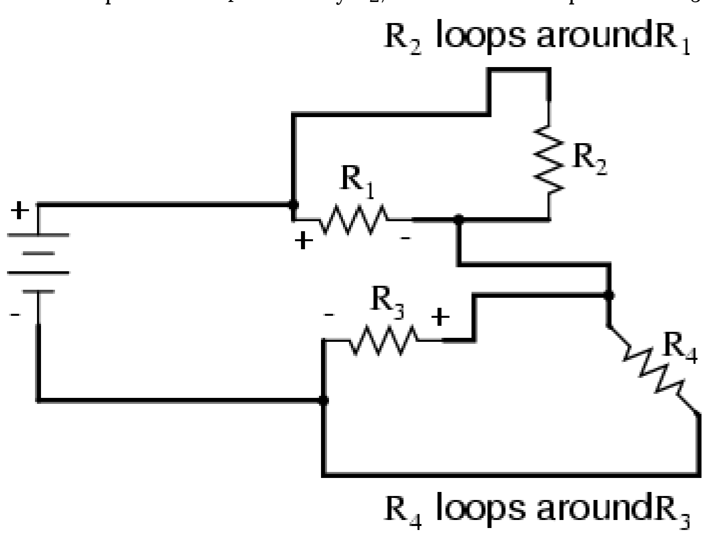




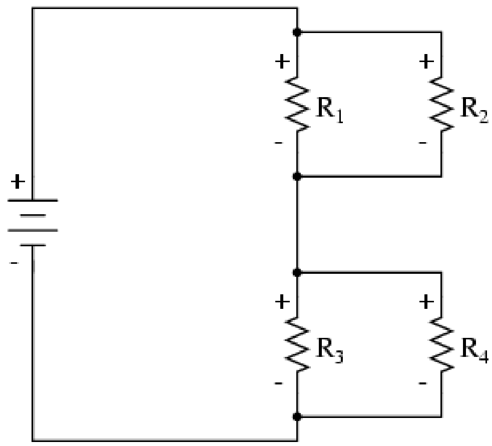
Any components encountered along this short loop are drawn vertically in order:



Now, proceed to trace any loops of components connected around components that were just traced. In this case, there's a loop around R_1formed by R_2, and another loop around R_3 formed by R_4:

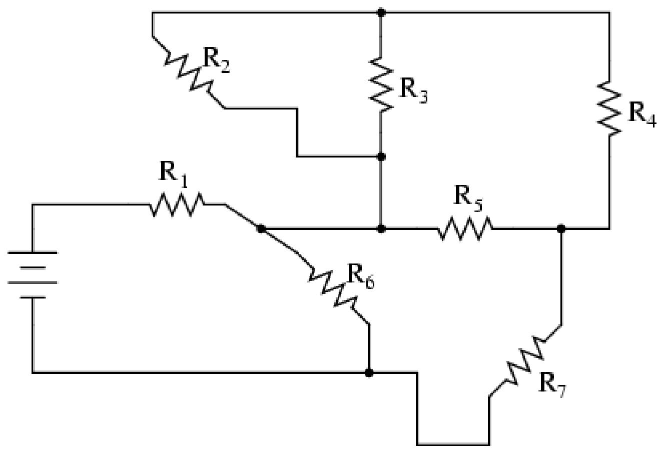


Tracing those loops, I draw R_2 and R_4 in parallel with R_1 and R_3(respectively) on the vertical diagram. Noting the polarity of voltage drops across R_3 and R_1, I mark R_4 and R_2 likewise:

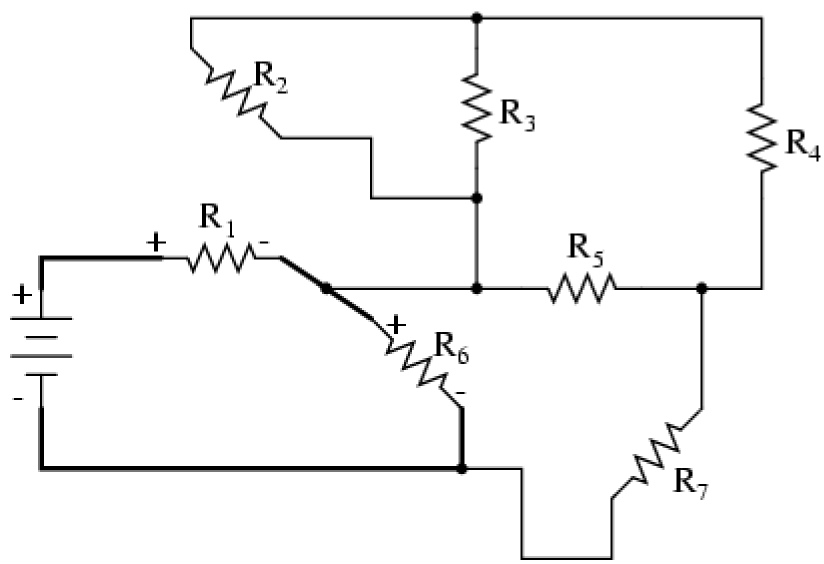


Now we have a circuit that is very easily understood and analyzed. In this case, it is identical to the four-resistor series-parallel configuration we examined earlier in the chapter.

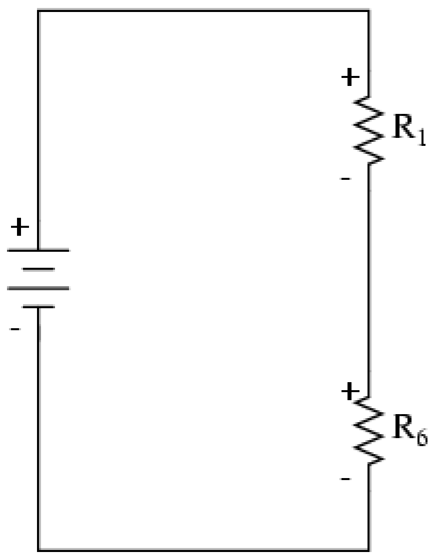
Let's look at another example, even uglier than the one before:



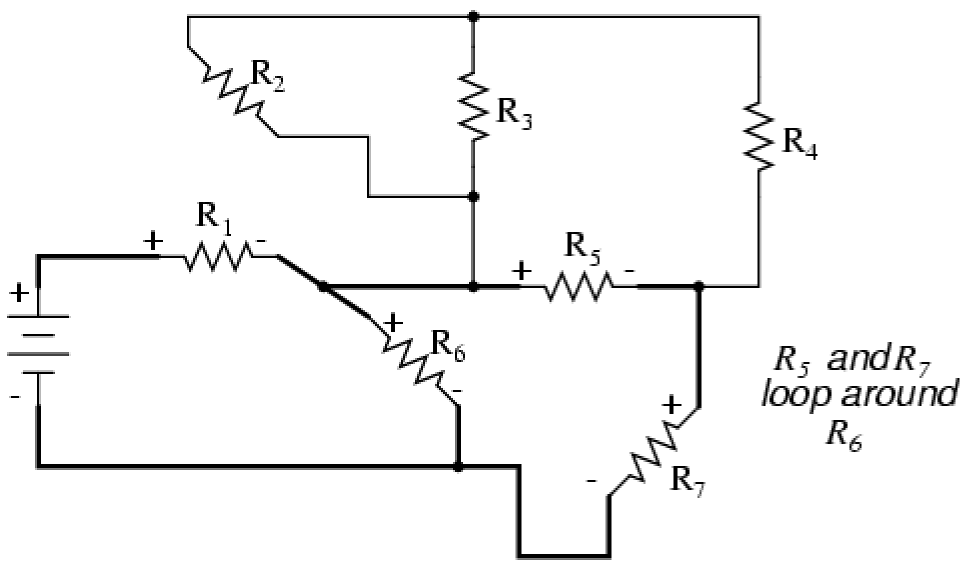
The first loop I'll trace is from the negative (-) side of the battery, through R_6, through R_1, and back to the positive (+) end of the battery:



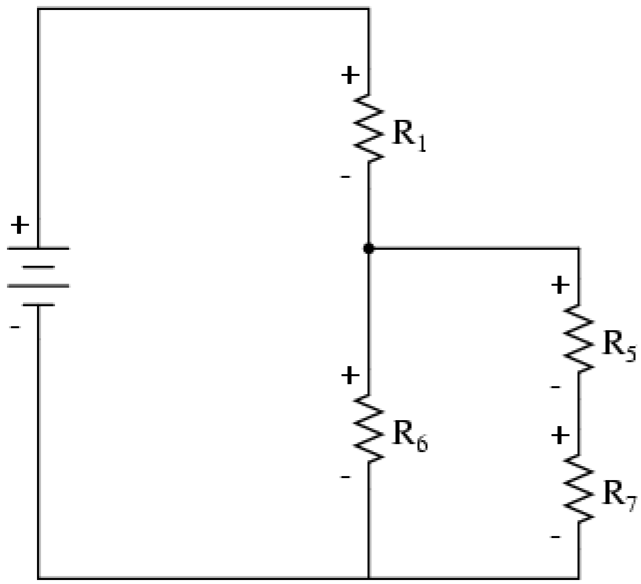
Re-drawing vertically and keeping track of voltage drop polarities along the way, our equivalent circuit starts out looking like this:



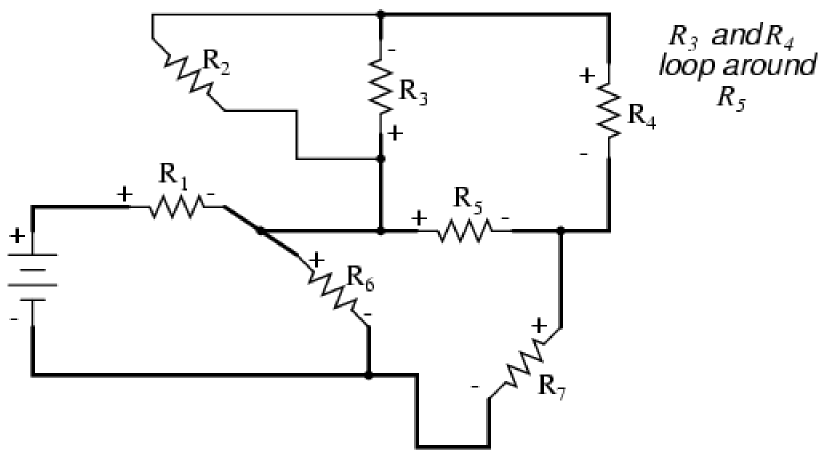
Next, we can proceed to follow the next loop around one of the traced resistors (R_6), in this case, the loop formed by R_5 and R_7. As before, we start at the negative end of R_6 and proceed to the positive end of R_6, marking voltage drop polarities across R_7 and R_5 as we go:



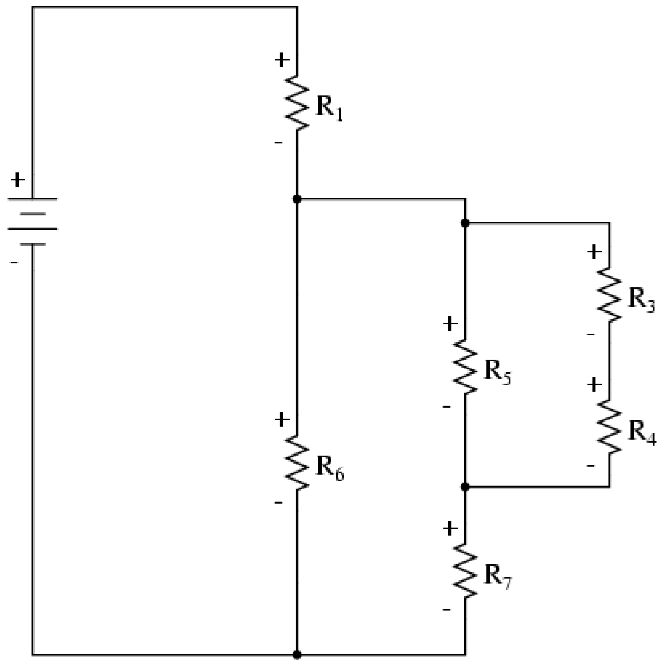
Now we add the R_5—R_7 loop to the vertical drawing. Notice how the voltage drop polarities across R_7 and R_5 correspond with that of R_6, and how this is the same as what we found tracing R_7 and R_5 in the original circuit:



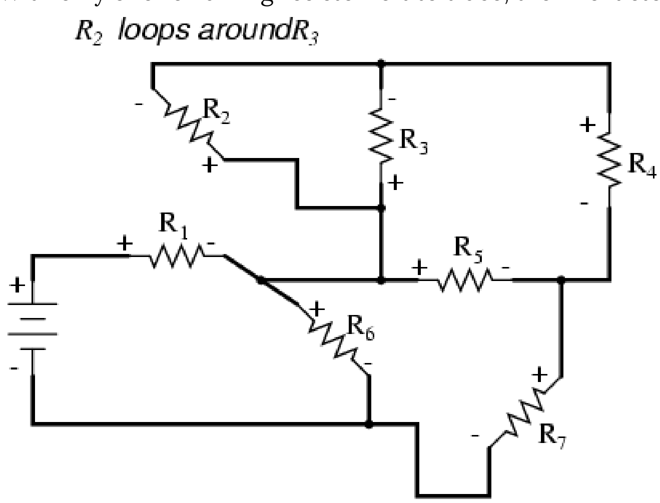
We repeat the process again, identifying and tracing another loop around an already-traced resistor. In this case, the R_3–R_4 loop around R_5 looks like a good loop to trace next:



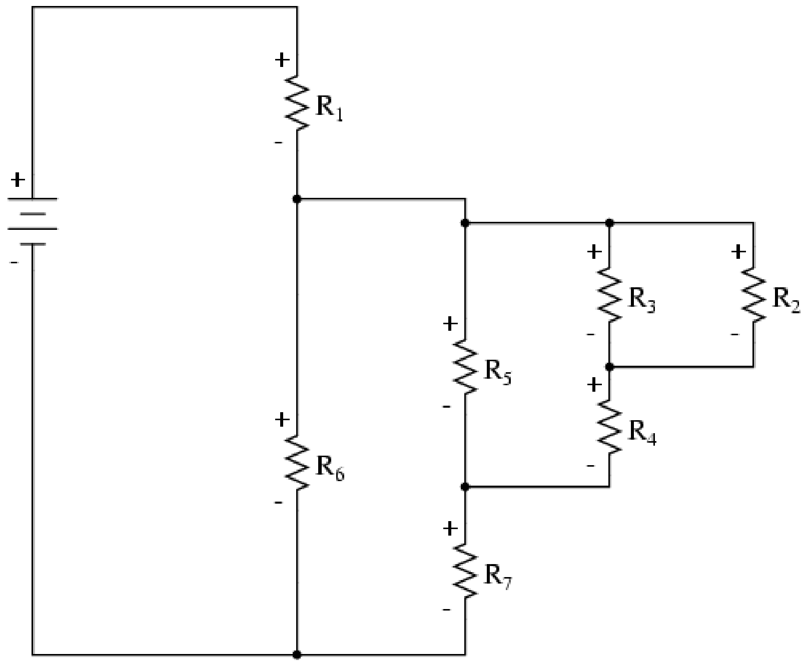
Adding the R_3–R_4 loop to the vertical drawing, marking the correct polarities as well:



With only one remaining resistor left to trace, then next step is obvious: trace the loop formed by R_2 around R_3:



Adding R_2 to the vertical drawing, and we're finished! The result is a diagram that's very easy to understand compared to the original:



This simplified layout greatly eases the task of determining where to start and how to proceed in reducing the circuit down to a single equivalent (total) resistance. Notice how the circuit has been re-drawn, all we have to do is start from the right-hand side and work our way left, reducing simple-series and simple-parallel resistor combinations one group at a time until we're done.

In this particular case, we would start with the simple parallel combination of R_2 and R_3, reducing it to a single resistance. Then, we would take that equivalent resistance ($R_2//R_3$) and the one in series with it (R_4), reducing them to another equivalent resistance ($R_2//R_3$—R_4). Next, we would proceed to calculate the parallel equivalent of that resistance ($R_2//R_3$—R_4) with R_5, then in series with R_7, then in parallel with R_6, then in series with R_1 to give us a grand total resistance for the circuit as a whole.

From there we could calculate total current from total voltage and total resistance (I=E/R), then "expand" the circuit back into its original form one stage at a time, distributing the appropriate values of voltage and current to the resistances as we go.

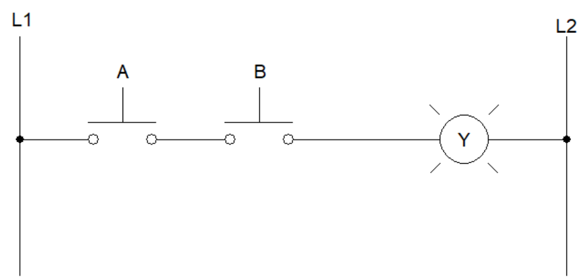
7. Introduction to Logic

KEN DICKSON-SELF

Logic in Electronics

While this lesson is a brief introduction to logic, understand that almost no part of our modern society can function without the touch of digital electronics. Everything from our TVs to phones, cars to gaming consoles, and computers to even the cash registers at the local grocery store would not be possible without these electronic devices. In this lesson, you'll learn how to hard-wire these types of logical functions. Later, when you learn to use Programmable Logic Controllers (PLCs), you'll also learn about the small electronic devices that perform the following functions.

AND



Logical AND

In words, the logical AND sounds something like this, "If A **AND** B are pressed, then Y is energized."

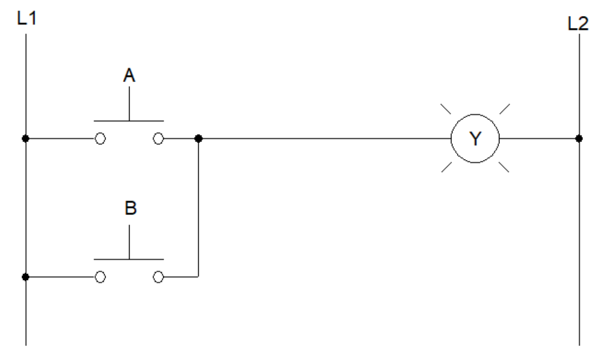
Considering A and B as our *inputs*, we can determine when Y (our *output*) is energized. Folks sometimes use a truth table to help analyze these functions. We use binary (using only the numerals 0 and 1) to help represent the state of our circuit. Binary can be used any time something only has two states (true/false, high/low, yes/no, open/closed, etc.). If "0" is the normal state, and "1" denotes an activated or energized state, let's look a truth table for the AND function.

AND

A	**B**	**Y**
0	0	0
0	1	0
1	0	0
1	1	1

The table is read row-by-row. In the first case, neither A or B is pressed, and Y is not activate. In the second row, A is not pressed, B is pressed, and Y is not energized. Notice that Y is only energized when both A and B are pressed. In any other case, lamp Y is not lit.

OR



Logical OR

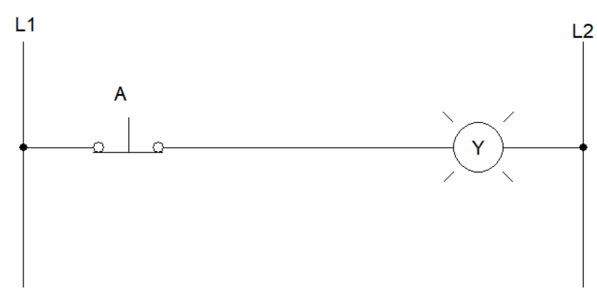
In words, the logical OR description might be, “If button A **OR** B are pressed, then Y is energized.”

The truth table for OR logic looks like the following. Notice that in this case, the only time lamp Y is not lit is in the first row when neither button is pressed. In all other cases, Y is energized.

OR

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

NOT

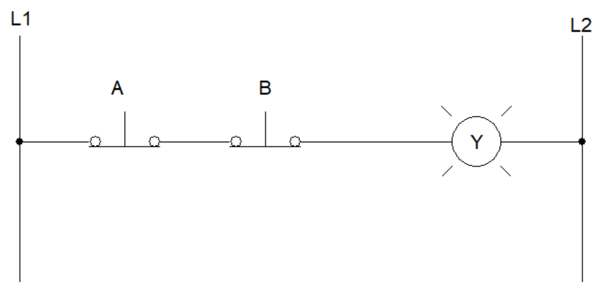


Logical NOT

Not is the simplest logical operation. It simply takes the input and inverts it. In our case, if button A is **NOT** pressed, then Y is energized (you could also say that if A is pressed, then Y is **NOT** energized). The truth table is shorter, since there’s only one input, and it looks like this:

OR	
A	**Y**
0	1
1	0

NOR

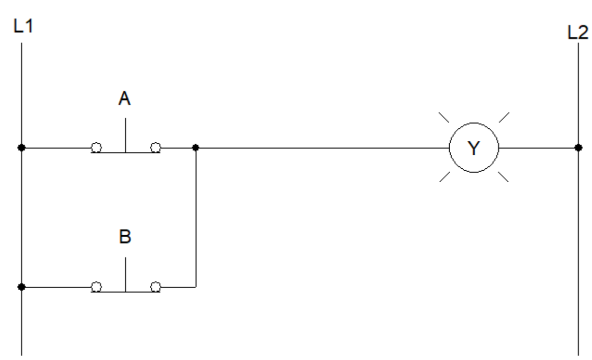


Logical NOR

In the case of NOR, Y is energized as long as neither A **NOR** B is pushed. Notice that the truth table is an exact inverse of OR. In the case of OR, Y was energized if either button was pressed. With NOR, Y is de-energized if either button is pushed.

NOR		
A	**B**	**Y**
0	0	1
0	1	0
1	0	0
1	1	0

NAND

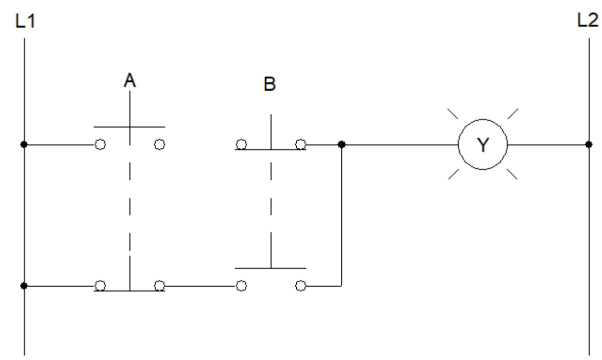


Logical NAND

With NAND, if both A and B are not pressed, then Y is energized. Notice the wording **NOT AND**. Looking at the truth table might confirm your suspicions. The output column for NAND is an inverse of the AND truth table.

	NAND	
A	**B**	**Y**
0	0	1
0	1	1
1	0	1
1	1	0

XOR



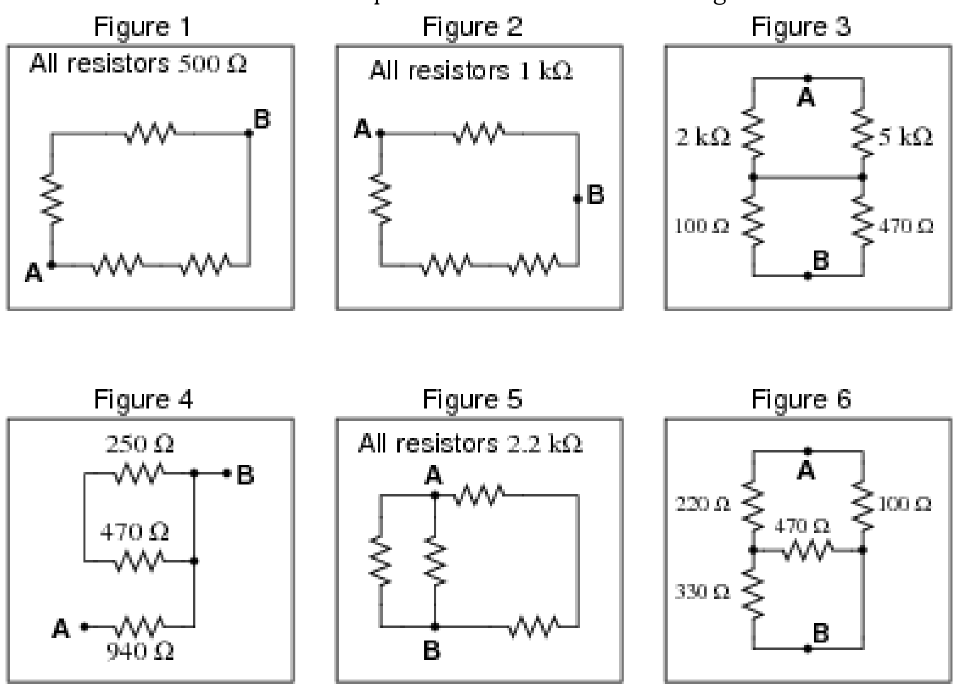
Logical XOR

XOR (pronounced "ex-or" or "exclusive or") allows us to energize Y if either A or B is pressed, but not if both are pressed. So, it's function is like OR logic, but the load is not energized if both buttons are pressed.

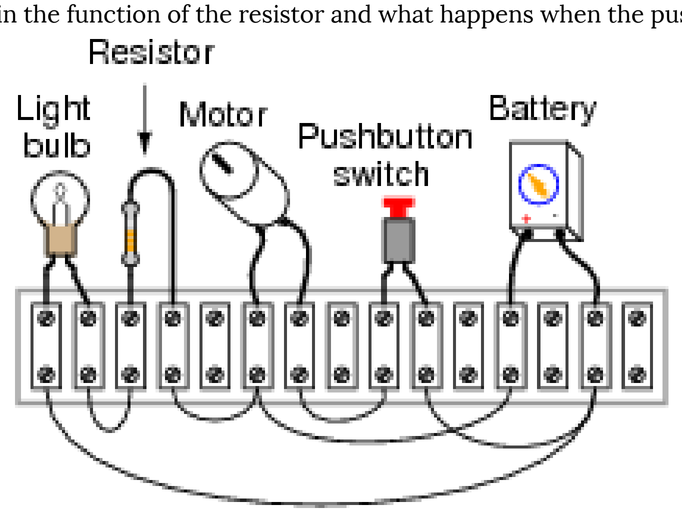
8. Homework 2

KEN DICKSON-SELF

1. Calculate the resistance between points **A** and **B** for the following resistor networks:

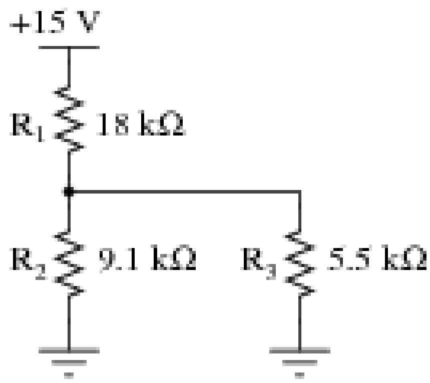


2. From this circuit (with components attached to a "terminal strip"), draw an appropriate schematic diagram. Then explain the function of the resistor and what happens when the pushbutton is pressed (assuming it is normally

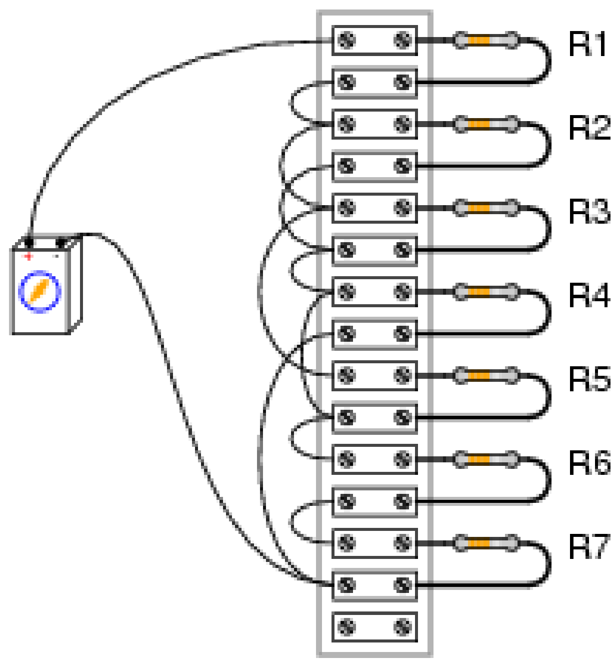


open).

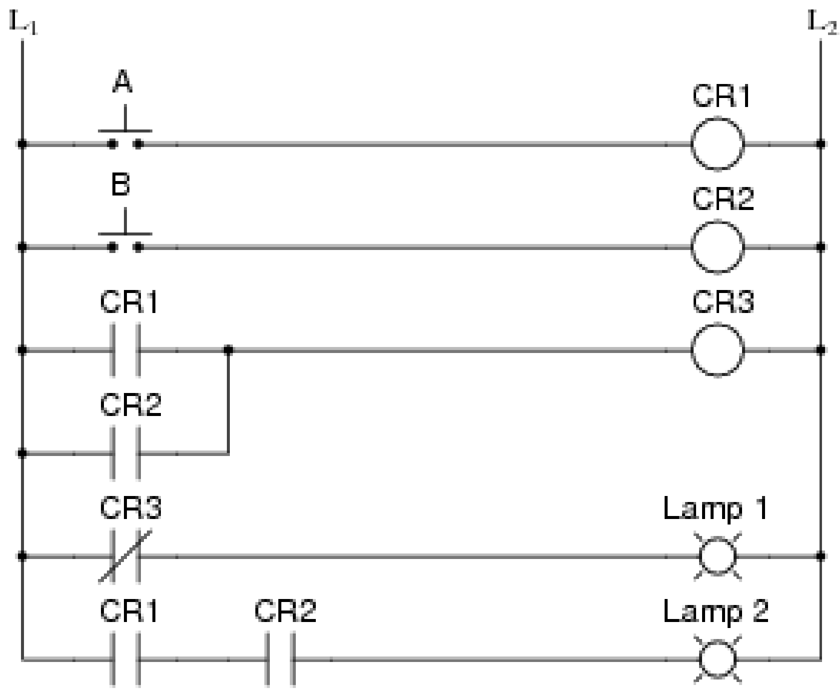
3. Complete the table of values for this circuit:

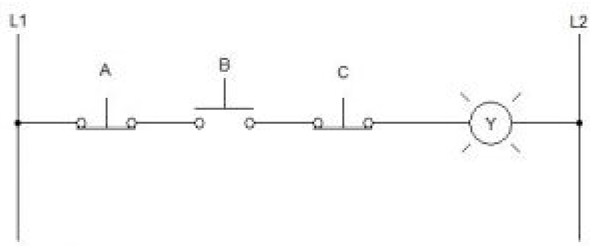


	R_1	R_2	R_3	Total
V				
I				
R	18 kΩ	9.1 kΩ	5.5 kΩ	
P				

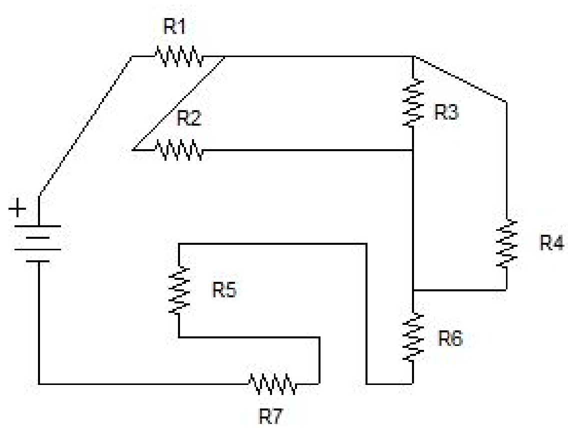


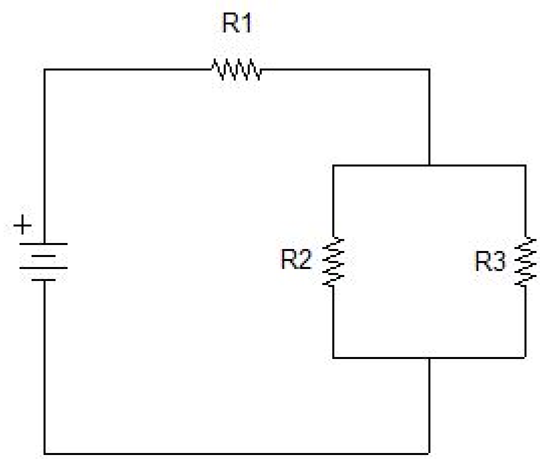
4. Draw a schematic for the following:
5. Considering your two inputs (A and B) in the image below, what type of logic is used to actuate the coil of CR3? Lamp 1? Lamp 2? If Lamp 2 never turns on, what components of the circuit could be causing the problem?



6. Create a truth table for the following diagram: 

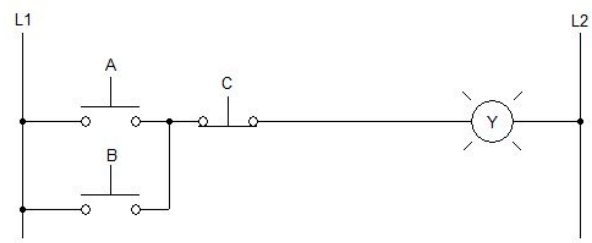
What conditions must exist in order for the light to energize?
7. Create a simplified schematic for the following complex circuit:





8. Complete the table for the following schematic: Express all current in milliamps.

	R1	R2	R3	R2 // R3	Total
E					48 V
I					
R	120 Ω	120 Ω	200 Ω		



9. Create a truth table for the following diagram: What conditions must exist in order for the light to energize?

This chapter is an adaptation of *Lessons in Electric Circuits* by Tony R. Kuphaldt (on allaboutcircuits.com), and is used under a Design Science License.

Media Attributions

- Logic Problem
- Complex Circuit
- Combination Circuit
- Logic Problem 2

PART III

LESSON 3

Lesson 3 consists of:

- Motor Controls – Introduction
- Homework 3

9. Motor Controls - Introduction

KEN DICKSON-SELF

In order to understand how motors are controlled, it is first necessary to understand the basics.

To help with this, we'll be using several videos from Jim Pytel's Big Bad Tech YouTube channel. The playlist we'll be using is titled Electrically Controlled Systems. There are over 50 videos in this playlist, and while we won't be using all of them, you'd be well-served to watch as many of them as you can throughout the term. The information there is clear, concise, and entertaining. Much of the hardware described in labs for this course may not match the components used in the video, but this actually helps you to learn about the many varieties of hardware you'll find in industry.

The following videos are REQUIRED for this lesson before starting Lab 3. Give yourself a couple hours to watch the videos and digest the material. Remember, this isn't like that History of Architecture class you took in high school, wondering if you were ever going to use the information you were being tested on. If you're taking this course, you've chosen a profession that requires you to know how to wire, maintain and repair systems very similar to this. Do not short-change yourself, thinking you'll be able to skim material and still be an effective technician. You won't. What you'll become, if you're ever hired into the field, is a liability to yourself, your company, and your co-workers. Taking time now will prevent potentially disastrous mistakes later.

Contactors

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Control Relays

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Overload Relays

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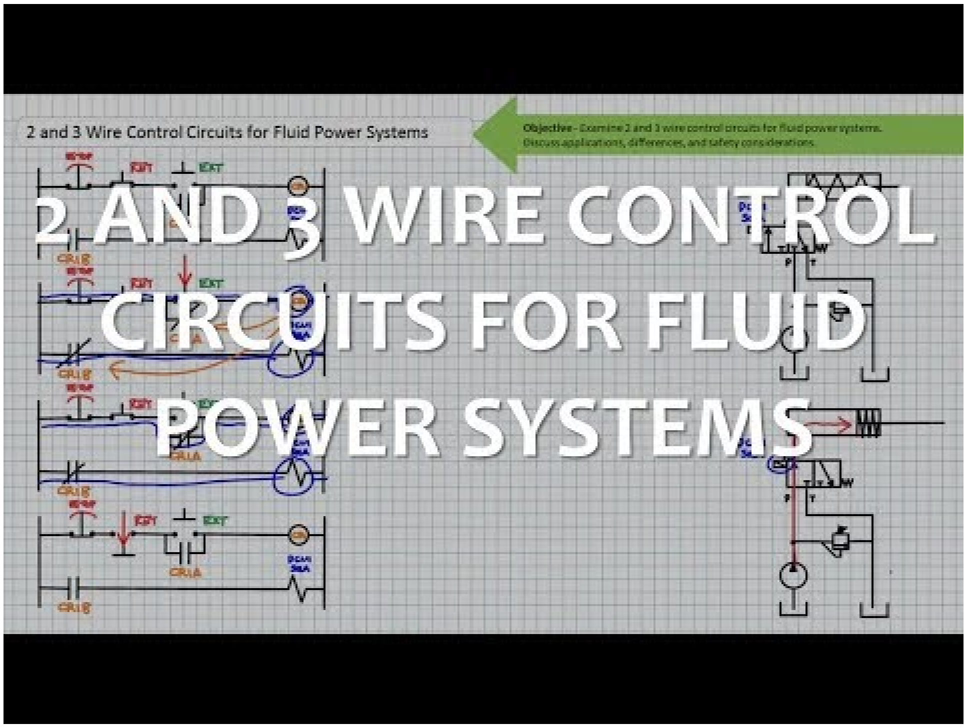
2- and 3-Wire Magnetic Motor Starters



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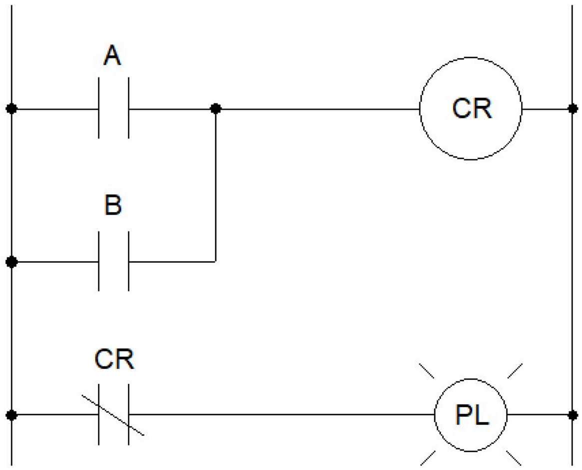
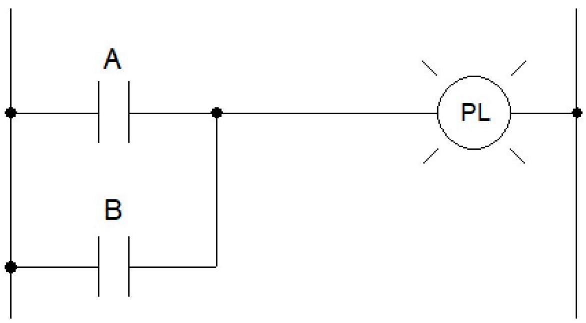
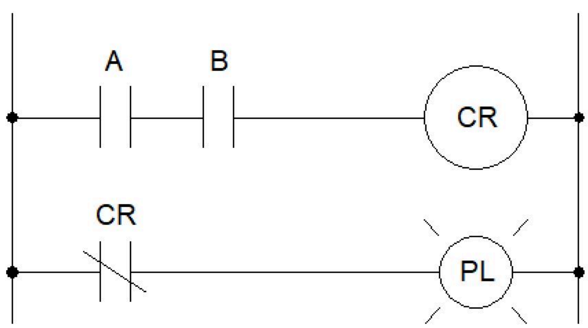
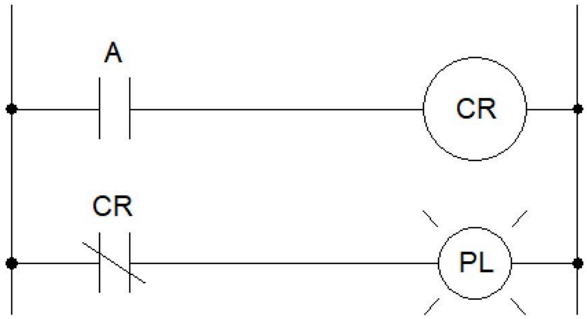
10. Homework 3

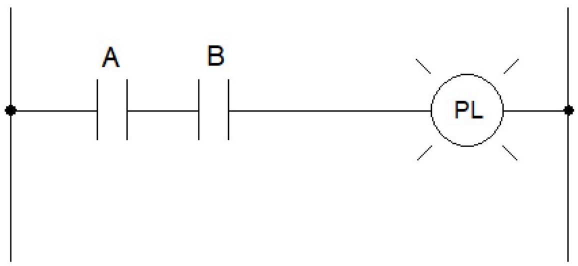
KEN DICKSON-SELF

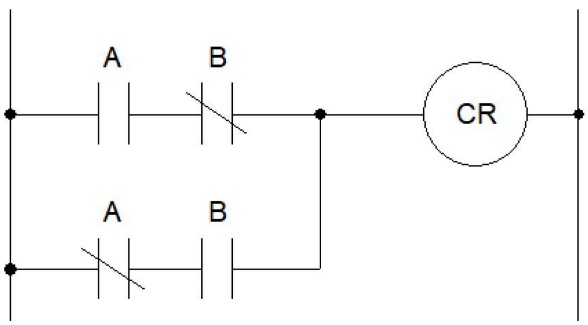
1. Create a truth table for each of the following circuits and identify the logical function of each (what's it take for the pilot light to energize?).
    1. 

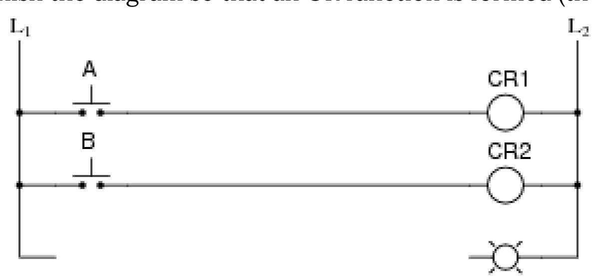
    2. 

    3. 

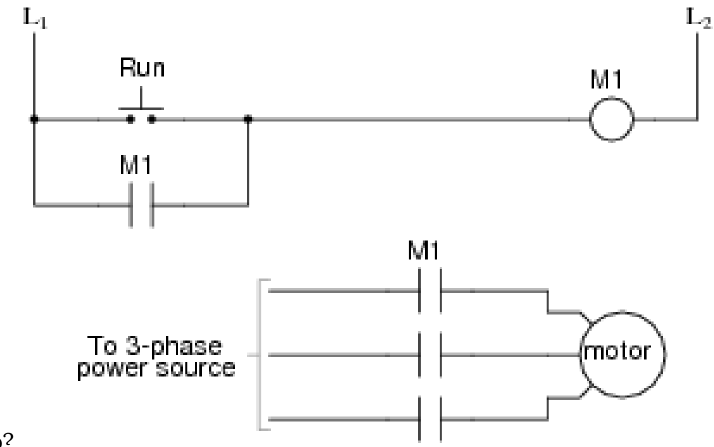
4. 

5. 

6. 

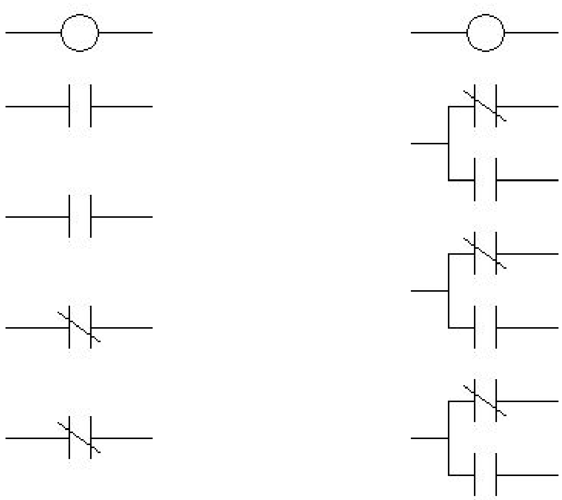
2. You’ve been given a partial ladder diagram. Finish the diagram so that an OR function is formed (the indicator lamp 

energizes if either button A OR B is actuated).
3. Analyze this AC motor control circuit diagram, explaining the meaning of each symbol. Also, explain the operation of this motor control circuit. What happens when someone pushes the “Run” button? What happens when they let



go of the “Run” button? When does the motor stop?

4. The L-side of the contactor is often known as the _______ side, while the T-side of the contactor is often known as the _______ side.
5. What do the auxiliary contacts of a contactor do?
6. Describe, in your own words, the difference between pick-up, hold-in, and dropout voltage.
7. According to the video, how much greater is inrush current than full load current?
8. Use IEC numbering to label the following two schematics (you can re-draw these on separate paper, if necessary):



9. List 5 possible causes of overload in an industrial setting.
10. What are the two components of a motor starter?
11. What’s the difference between a manual and automatic reset on an overload relay?
12. Name three types of overloads discussed in the video.
13. Draw the NEMA schematic symbol for an overload and show how overloads are represented in a ladder diagram.
14. Draw a diagram (not one used in the video) of a 2-wire circuit.
15. Draw a diagram (not one used in the video) of a 3-wire circuit.

Media Attributions

- Relay Schematics

PART IV

LESSON 4

Lesson 4 consists of:

- Multiple Push Button Stations
- Homework 4

11. Multiple Push Button Stations

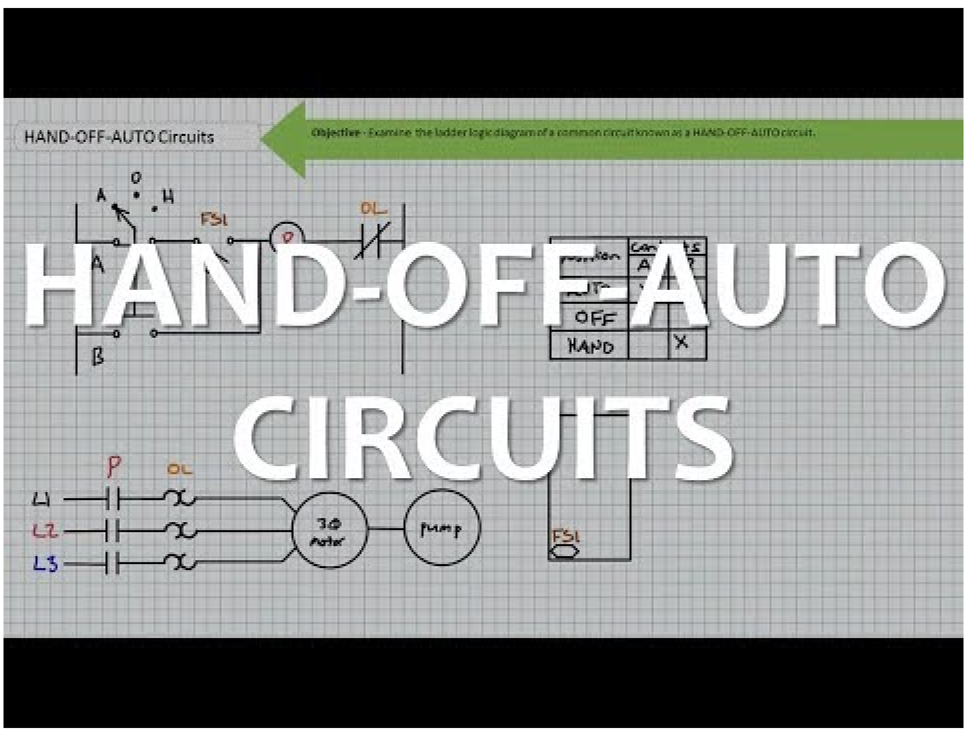
KEN DICKSON-SELF

In this lesson, we'll learn how to wire and draw multiple push buttons into our motor control station. It is often convenient to be able to control industrial machinery or equipment from more than one location. In this lesson, we'll combine videos, schematics, and lab activities to deepen our understanding of the best way of adding multiple inputs to control motors.

Again, we'll be using several videos from Jim Pytel's Big Bad Tech YouTube channel.

The following videos are REQUIRED for this lesson before starting Lab 4. Remember to give yourself ample time to watch the videos and digest the material BEFORE coming in to do the labs.

HAND-OFF-AUTO Circuits



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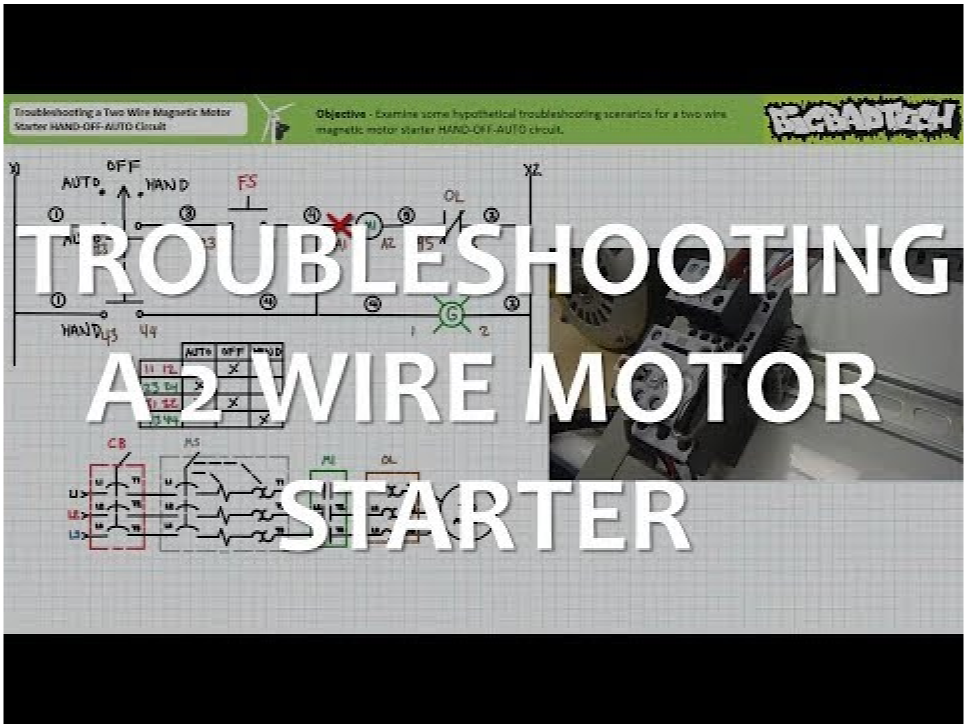
Troubleshooting HAND-OFF-AUTO Circuits



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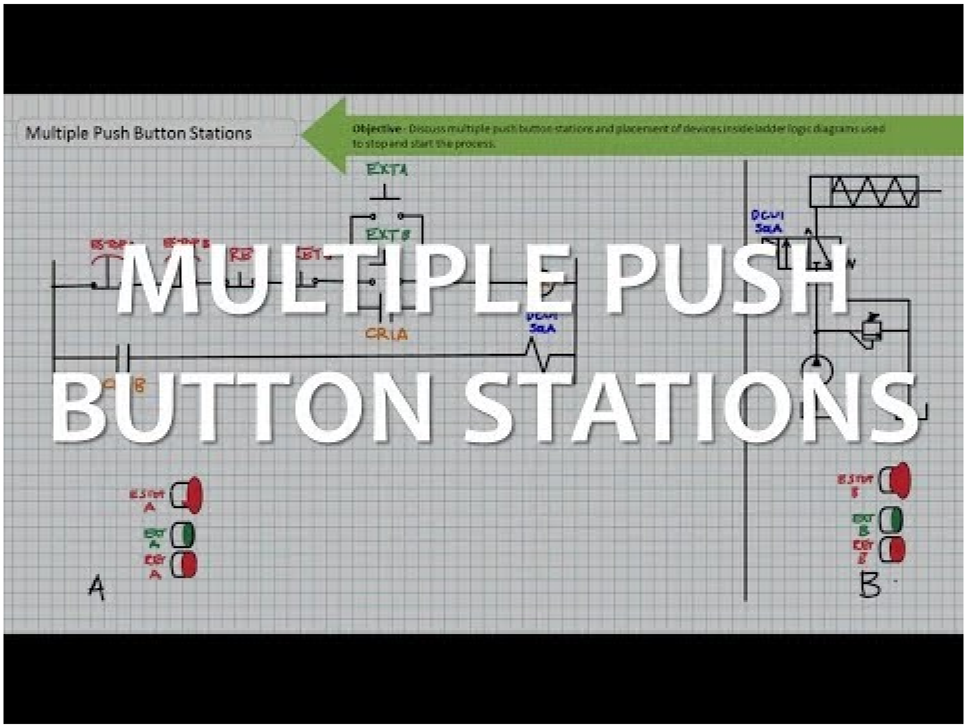
Multiple Push Button Stations



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12. Homework 4

JOSH HANSON

1. Give 3 examples of different types of automatic switches typically used in 2-wire control circuits.
2. Name 2 things that the "Hand" position allows us to do in an HOA control circuit.
3. Design, draw and describe (with words) your own HOA circuit. Make sure to label your schematic and that your description indicates how it operates.
4. Is there, or why should there be, a testing/commissioning period of all new motor control circuit installs? You should give at least 2 reasons.
5. What is a pushbutton station?
6. What is a benefit of having multiple pushbutton stations? What is a disadvantage of having multiple pushbutton stations?
7. If I wanted to add an additional stop function to a motor control station, should I wire the new stop in series or parallel with the other stop pushbuttons?
8. If I wanted to add an additional start function to a motor control station, should I wire the new start in series or parallel with the other start pushbuttons?
9. Design, draw and label a motor control circuit that uses 4 pushbutton stations and 4 E-Stops.
10. Explain why it's best to think of all of the additional push button stations needed before the installation takes place.

PART V

LESSON 5

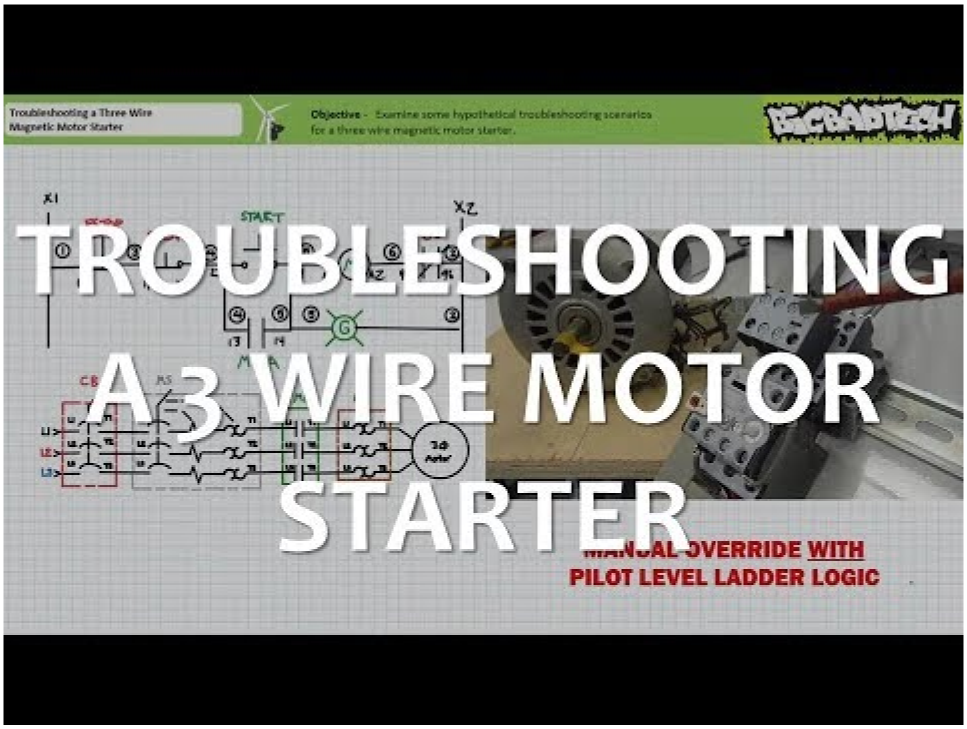
Lesson 5 consists of:

- Troubleshooting
- Forward/Reversing
- Jogging
- Homework 5

13. Intermediate Motor Controls

KEN DICKSON-SELF

As our circuits get more complex and we're able to control more systems from various inputs, we'll need to learn ways to systematically troubleshoot our motors and controls.



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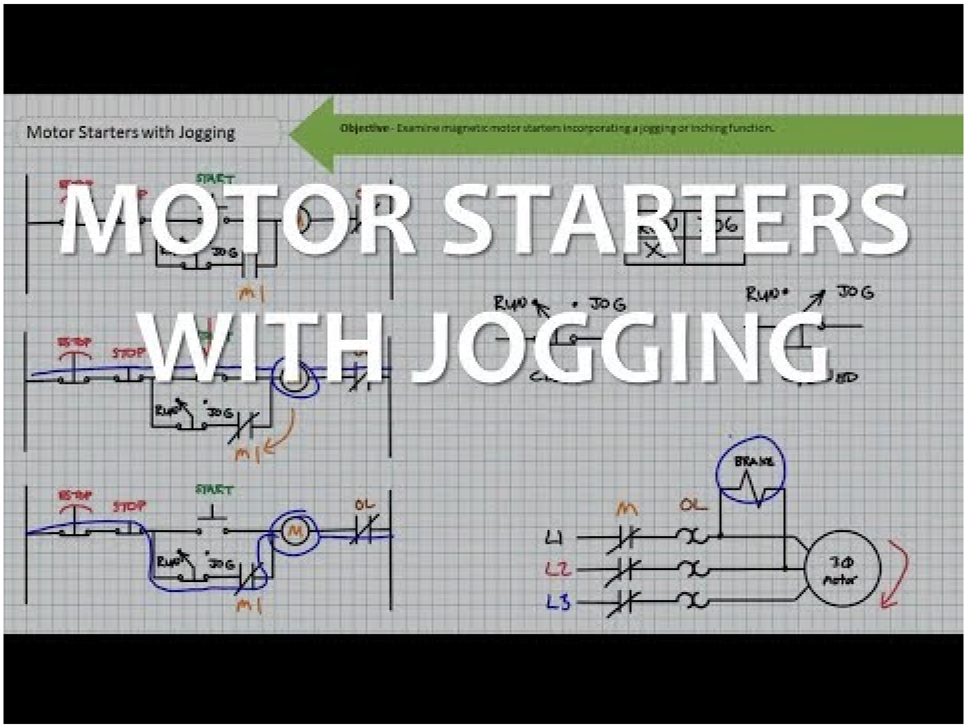
Once we can troubleshoot basic 3-wire controls, we can easily see how to implement jogging and reversing motor controls.



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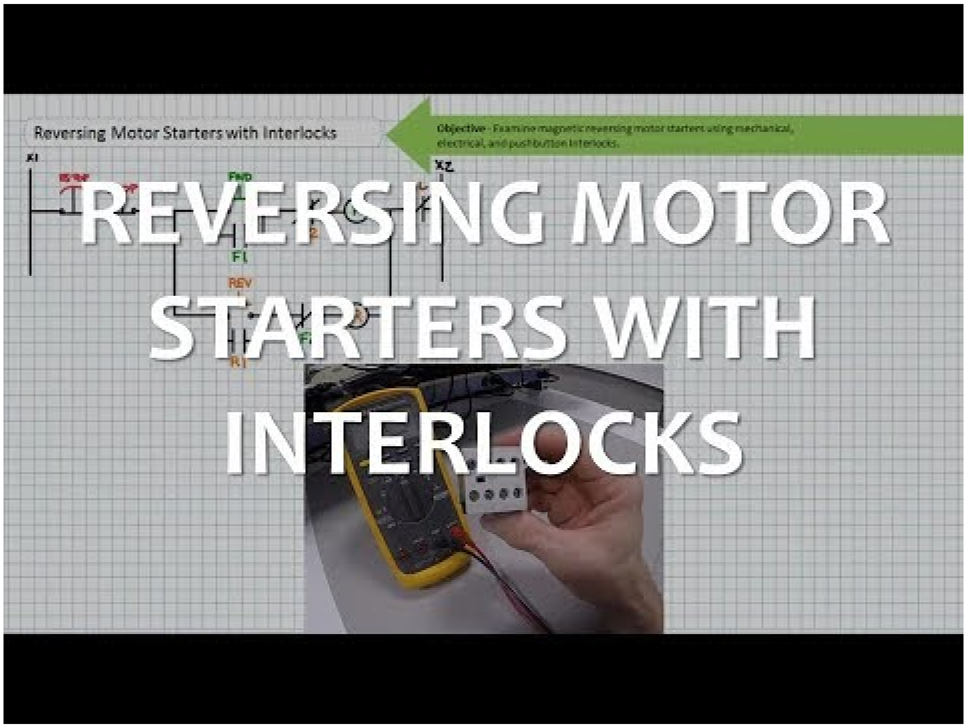

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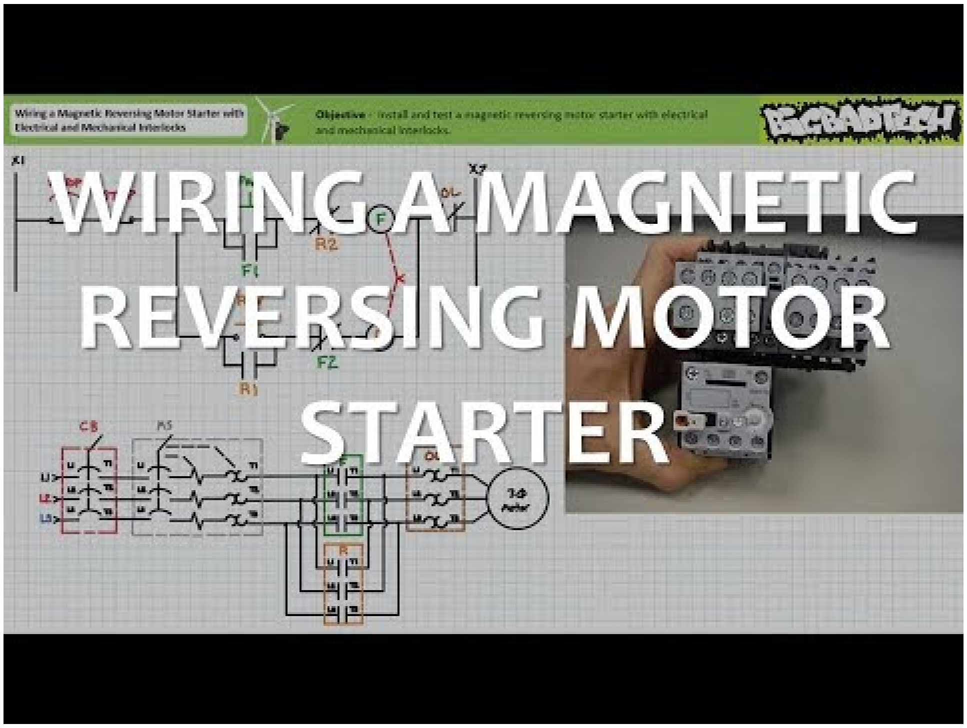

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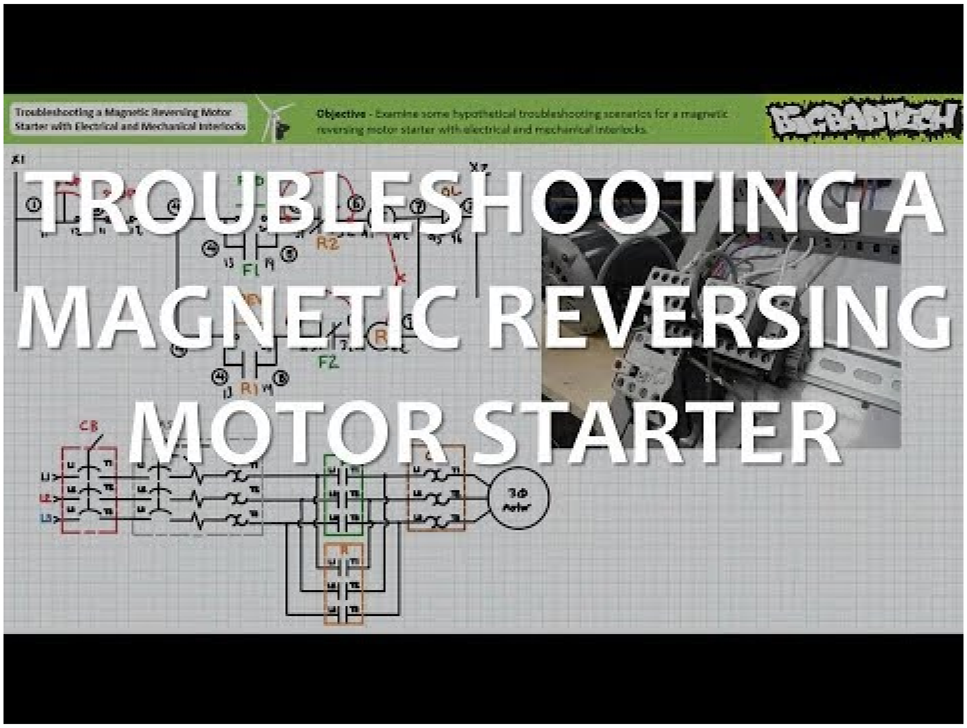

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14. Homework 5

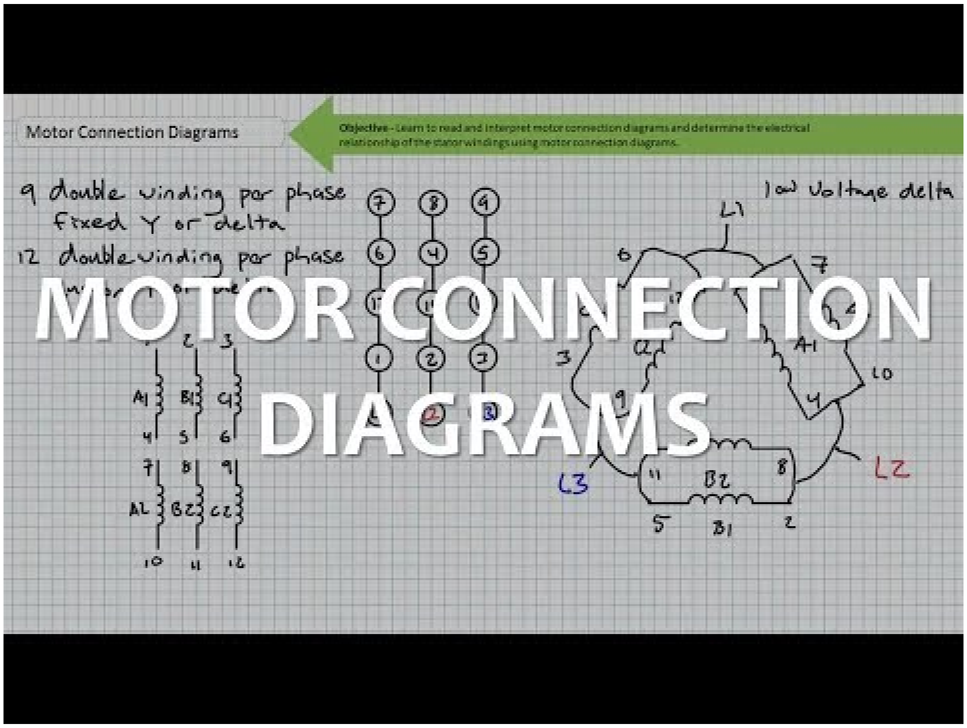
KEN DICKSON-SELF

1. What is the first step in troubleshooting any system?
2. What would happen in a scenario where only the primary power to the motor is lost, while pilot-level ladder logic remains functional)?
3. Describe the difference between overloads in manual reset mode and automatic reset mode.
4. What is "jogging" or "inching"
5. When is jogging used?
6. What is in-rush current and what is its proportion compared to normal full-load current?
7. Describe the purpose of a magnetic reversing motor starter and how it functions.
8. What is an interlock and what are the three different types?
9. Why must magnetic reversing motor starters contain an interlock?
10. What types of events may cause an overload?
11. If a motor is running in reverse mode when the overloads are tripped, can the motor be run in forward mode? Also, what is required in order to start the motor in reverse mode again?
12. What happens when the electrical interlocks are removed form a circuit and the reverse button is pressed while the motor is running in the forward direction (mechanical interlocks are in place)?

PART VI
LESSON 6

15. Testing Motor Components

KEN DICKSON-SELF



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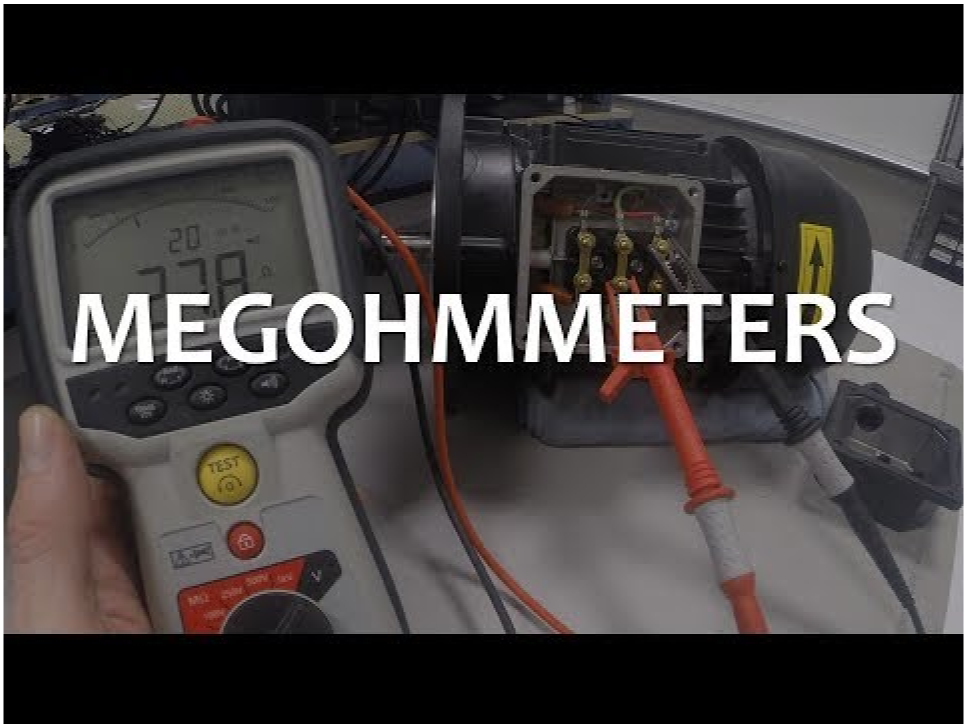

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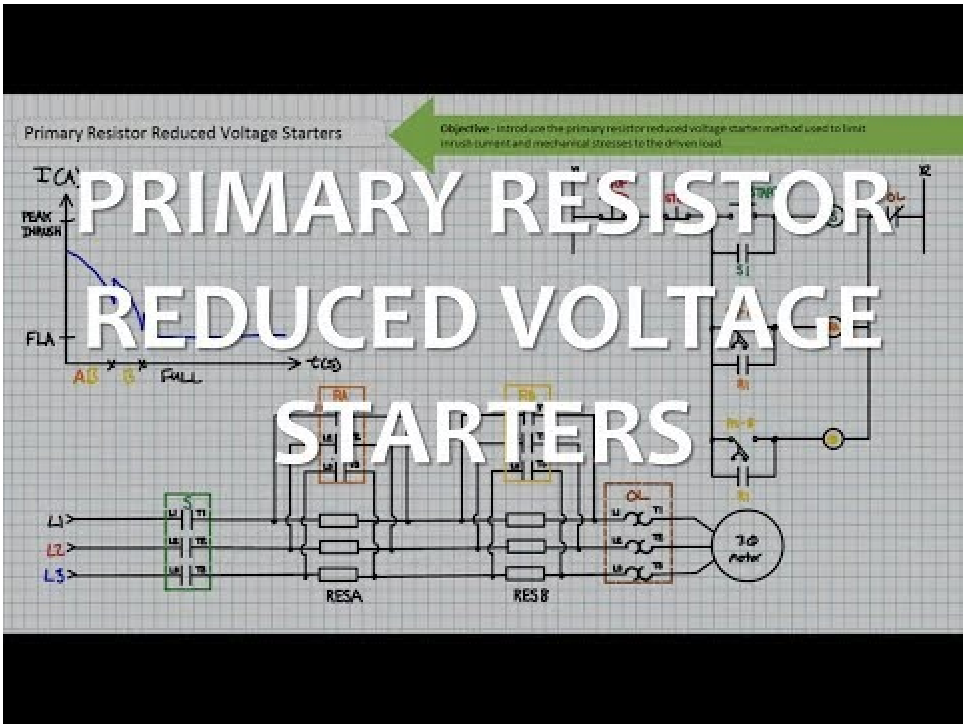

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Testing capacitors

Warning: A good capacitor stores an electrical charge and may remain energized after power is removed. Before touching it or taking a measurement:

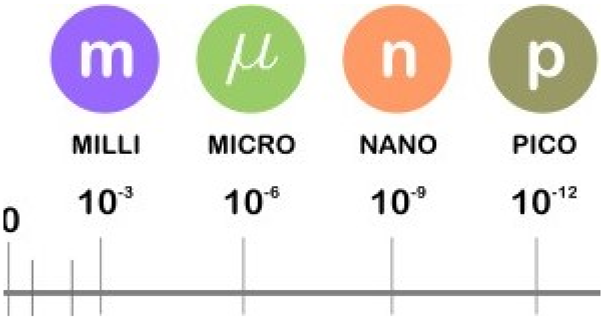
1. Turn all power OFF
2. Use your multimeter to confirm that power is OFF
3. Carefully discharge the capacitor by connecting a resistor across the leads. Be sure to wear appropriate personal protective equipment.

To safely discharge a capacitor: After power is removed, connect a 20,000 Ω, 2-5 watt resistor across the capacitor terminals for 20 – 40 seconds. (You can use your multimeter set to volts to confirm the capacitor is fully discharged.)

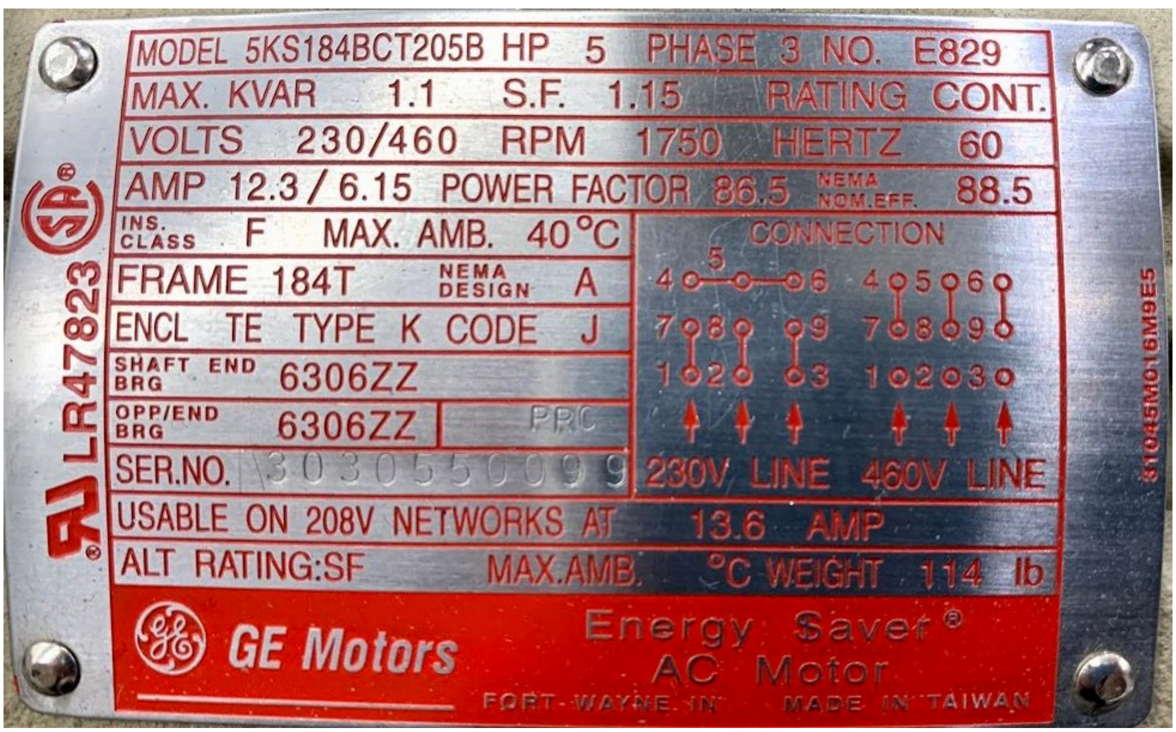
1. Visually inspect the capacitor. If leaks, cracks, bulges or other signs of deterioration are evident, replace the capacitor.
2. Turn the dial to the Capacitance Measurement mode (⊣⊢).
3. For a correct measurement, the capacitor will need to be removed from the circuit and properly discharged.
4. Connect the test leads to the capacitor terminals. Keep test leads connected for a few seconds to allow the multimeter to automatically select the proper range.
5. Read the measurement displayed. Value should fall within specified range (or +/- 10% of stated value). DMM will display OL if a) the capacitance value is higher than the measurement range or b) the capacitor is faulty.

Troubleshooting single-phase motors is one of the most practical uses of a digital multimeter's Capacitance Function. A capacitor-start, single-phase motor that fails to start is a symptom of a faulty capacitor. Such motors will continue to run once operating, making troubleshooting tricky. Failure of the hard-start capacitor for HVAC compressors is a good example of this problem. The compressor motor may start, but soon overheat resulting in a breaker trip.

Three-phase power factor correction capacitors are typically fuse protected. Should one or more of these capacitors fail, system inefficiencies will result, utility bills will most likely increase and inadvertent equipment trips of may occur. Should a capacitor fuse blow, the suspected faulty capacitor farad value must be measured and verified it falls within the range marked on the capacitor.



Motor Nameplates



There are many different types of electric motors, and they all have unique parameters, requirements and specifications. Motor nameplates contain information concerning motor performance and mounting parameters, defined by the National Electrical Manufacturers Association (NEMA). These parameters include:

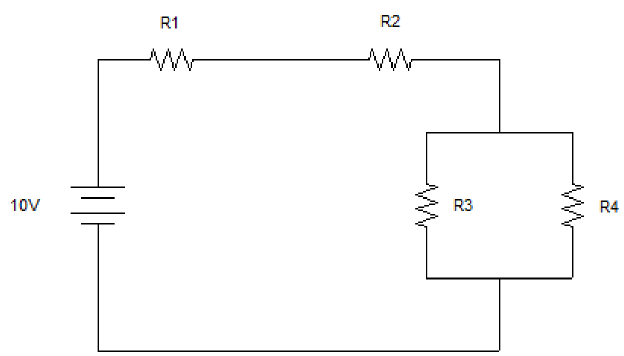
- **Manufacturer's type and frame designation** – This can include information such as the frame mounting pattern, shaft diameter and shaft height

- **Horsepower** – Measure of motor's mechanical output. This is based on the motor's full-load torque and speed. Horsepower = Motor Speed x Torque / 5250. If your application's requirement falls between two horsepower ratings, generally pick the larger-sized motor.
- **RPM** – Sometimes called "slip speed" (as opposed to synchronous speed). Determined by winding pattern and power frequency.
- **Locked-rotor Code Letter** – Uses letters A to V to define the locked rotor kVA per HP. Typically, A is the lowest. B is greater than A. C is greater than B, etc. A higher code may require replacing other equipment, such as motor starters to handle greater current.
- **Maximum ambient temperature and time rating or duty cycle-** Standard motors are rated for continuous duty (24/7) at their rated load and maximum ambient temperature. Specialized motors can be designed for "short-time" requirements where intermittent duty is all that's needed. These motors can carry a short-time rating from 5 minutes to 60 minutes.
- **Voltage** – 230V motor running at 208V will be less efficient, but a 480V motor works at 460V because voltage drop is assumed (if motors are designed to handle a 10% voltage difference, then a 480V motor should be able to handle any voltage from 432-528V.
- **Frequency** – Input frequency (60 Hz in the US, 50 Hz in many other countries)
- **Phase** – The number of AC power lines supplying the motor
- **Current draw** – When motor is fully loaded. Unbalanced phases and under voltage can cause current deviation.
- **Power factor** – Ratio of the active power to the apparent power (at full load).
- **Efficiency** – Power calculation = (Output / Input) x 100
- **Service factor** – This will only by on the nameplate if it is higher than one. Service factor (SF) is an indication of how much overload a motor can withstand when operating normally within the correct voltage tolerances. For example, the standard SF for open drip-proof (ODP) motors is 1.15. This means that a 10-hp motor with a 1.15 SF could provide 11.5 hp when required for short-term use. n general, it's not a good practice to size motors to operate continuously above rated load in the service factor area.
- **Wiring diagrams**
- **Bearing** – Drive-end (sometimes called shaft-end) and non-drive-end bearing identification.

16. Homework 6

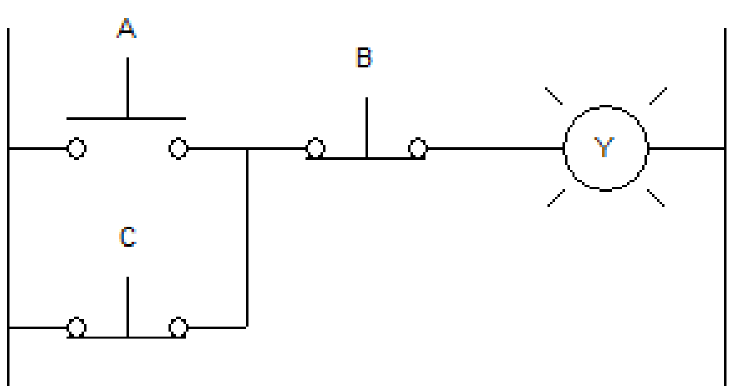
JOSH HANSON

1. Complete the table below

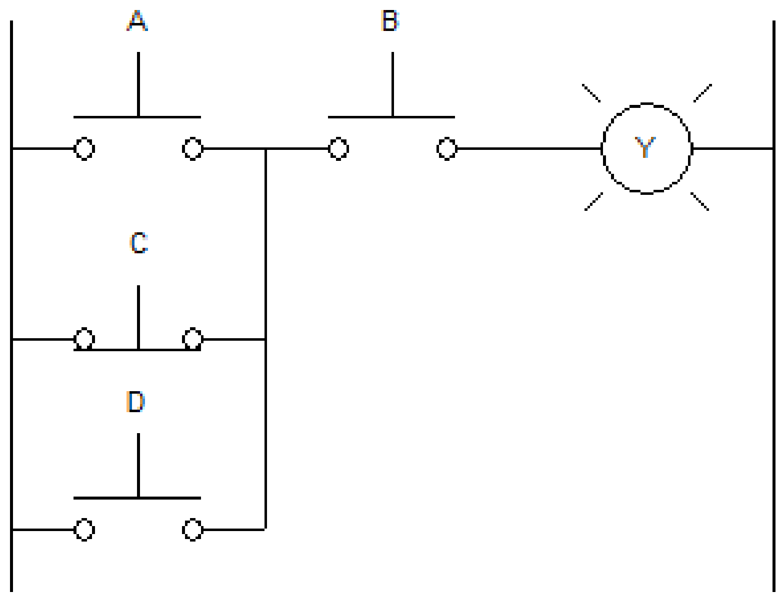


	R1	R2	R3	R4	R3//R4	Total
E						10V
I						
R	200Ω	300Ω	400Ω	400Ω		

2. Create a truth table based upon the ladder diagram below:



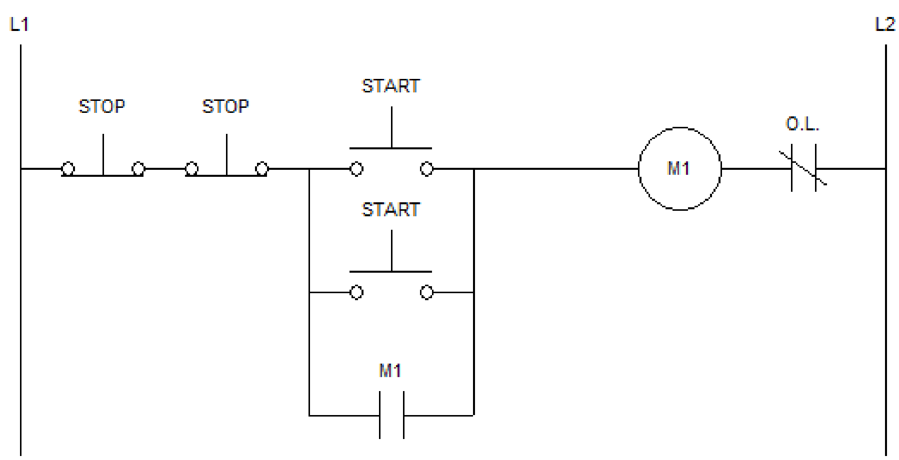
3. Create a truth table based upon the ladder diagram below



4. Draw a ladder diagram of a 2-wire circuit using a temperature switch.

5. Draw a ladder diagram of a 3-wire circuit using 2 E-Stops

6. I thought that I wired up the circuit shown below. As soon as I plugged the circuit in, the motor starter coil immediately energized and pulled-in. When I push either STOP button, the coil will de-energize. Give at least two things that could be wrong.



7. I wired up another motor starter, identical to the circuit shown in problem #6. I am 100% sure that all of the wiring is correct. When I plug my circuit in, nothing happens (which is how it should be, right?), but when I press either START button, the coil will not energize. What could be causing this problem? Give at least two things that could be wrong.

8. Using the same circuit that's shown in problem #6, what voltage should I measure across the coil when it is energized? (Zero, Ghost, or Source)

9. Using the same circuit that's shown in problem #6, what voltage should I measure across any of the START pushbuttons when the coil is energized? (Zero, Ghost, or Source)

10. How can using a 2-wire circuit be dangerous?

PART VII

LESSON 7

17. Timers

KEN DICKSON-SELF

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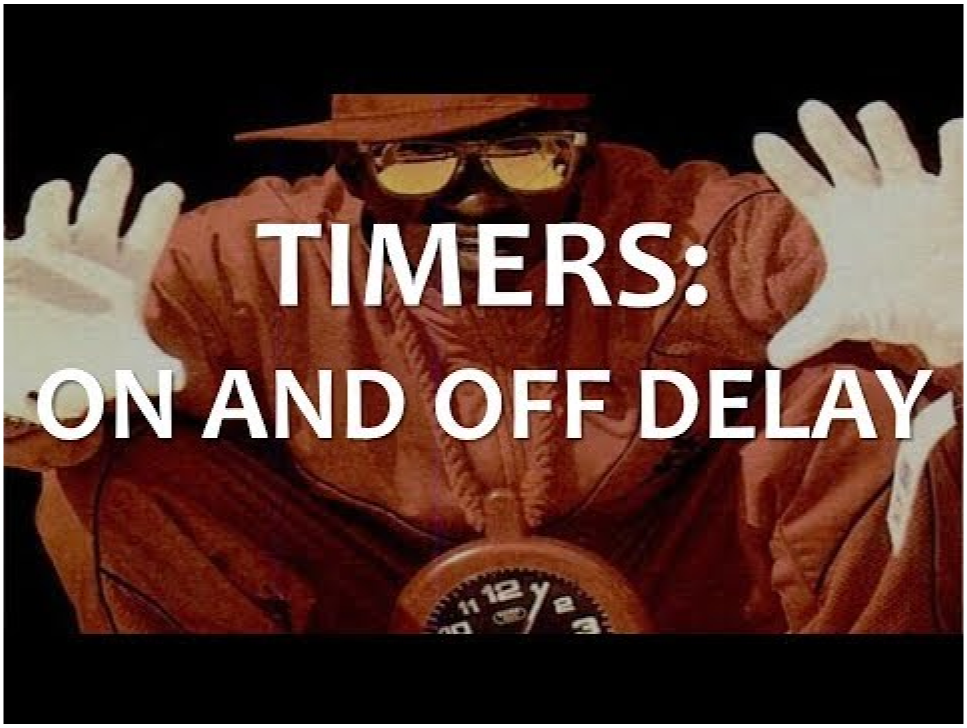

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18. Homework 7

KEN DICKSON-SELF

1. What is another name for an on-delay timer?
2. Draw a timing diagram for the on-delay timer (including signal/control, NO and NC contacts)
3. What's the difference between a single-function and multi-function timer?
4. Draw the schematic symbol for both the NO and NC contacts of an on-delay timer.
5. Describe a situation in industry where you might want to use a cumulative on-delay timer.
6. Describe the example Jim uses in the first video where an on-delay timer is used to control two conveyor belts. What's the function of the timer in this case?
7. What is another name for an off-delay timer?
8. Draw a timing diagram for the off-delay timer (including signal/control, NO and NC contacts).
9. Draw the schematic symbol for both the NO and NC contacts of an off-delay timer.
10. Describe the performance of a flash/repeat/recycle timer.
11. Describe the difference between symmetric and asymmetric timers.
12. Describe the function of a positive/rising edge triggered one-shot timer.
13. Draw the timing diagram for a negative/falling edge triggered one-shot timer.

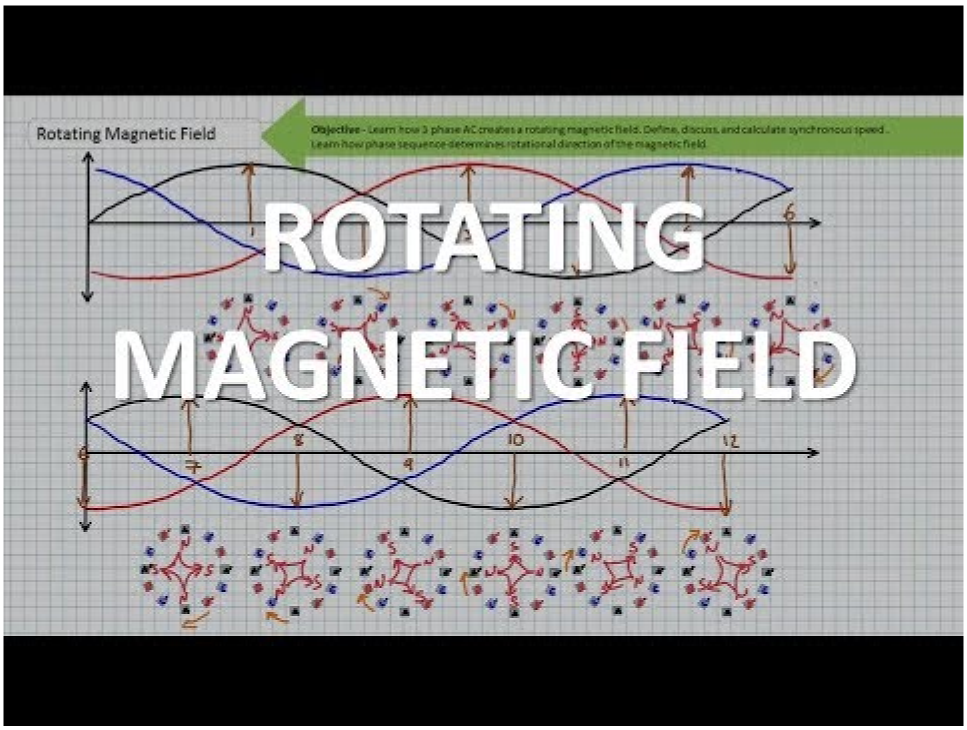
PART VIII

LESSON 8

19. Motor Drives

KEN DICKSON-SELF

A frequently-used component in any modern industry are motor drives, sometimes called variable frequency drives or VFDs. In order to understand how VFDs control the speed of a motor, you must first understand what happens inside an AC induction motor.



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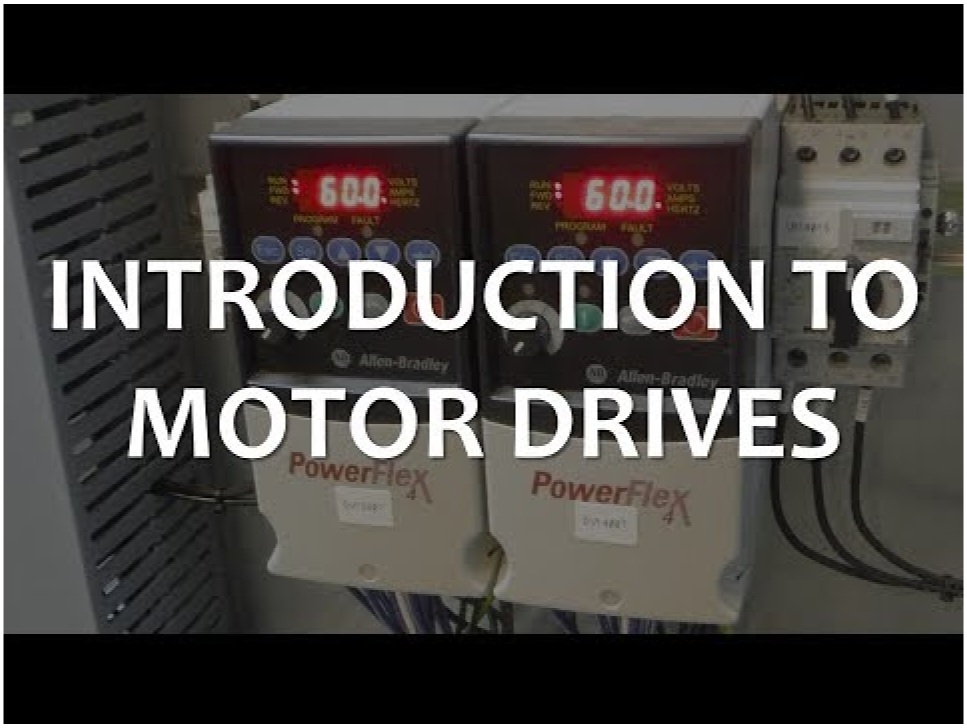

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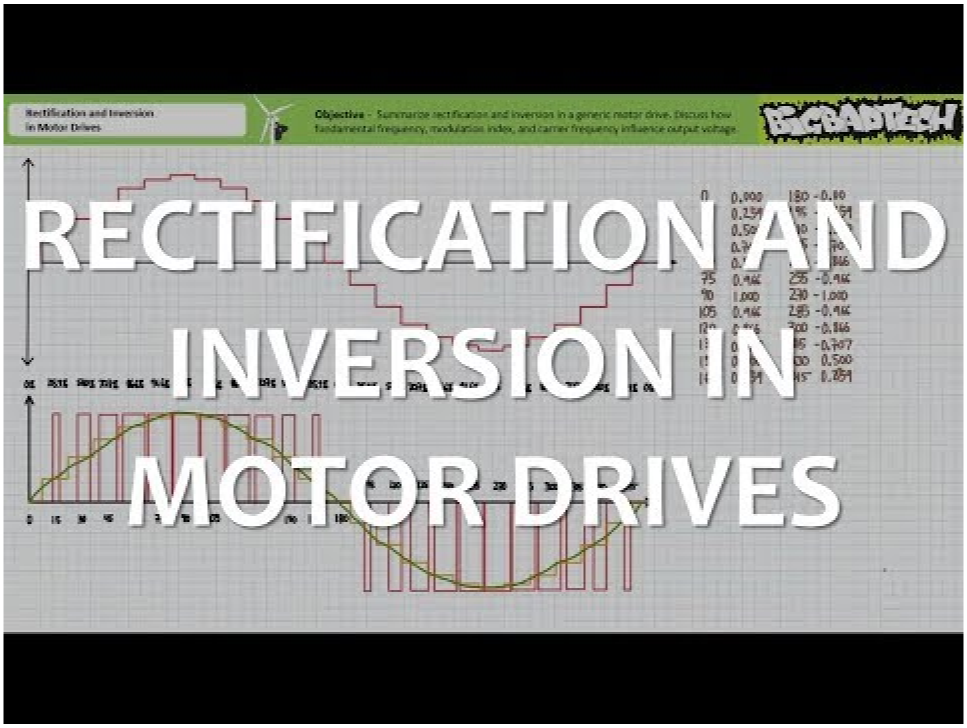

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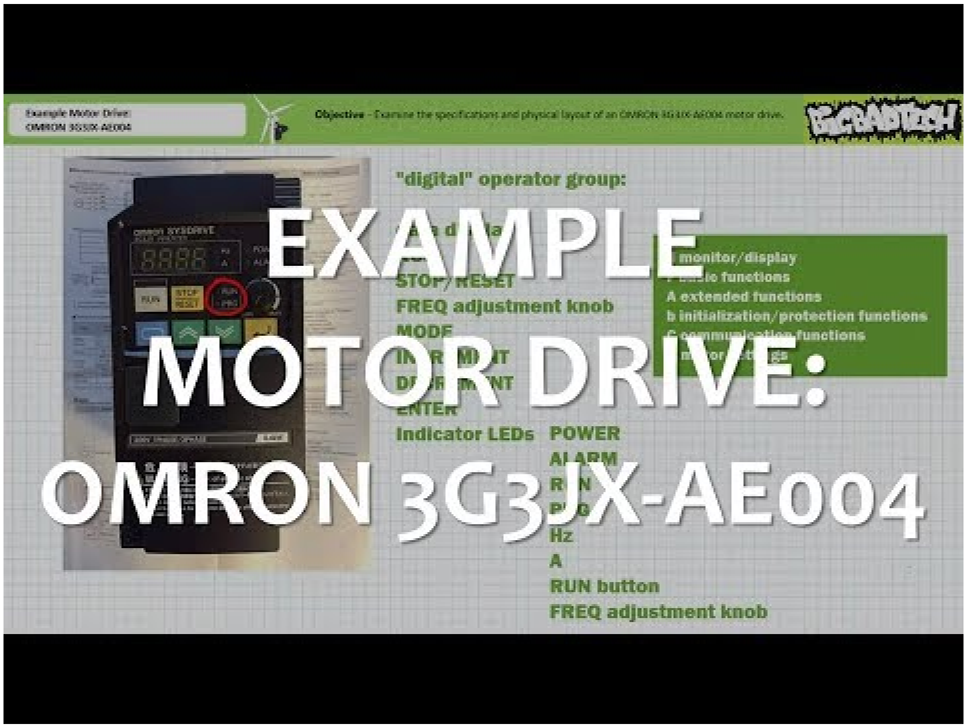
Below, Jim Pytel explains an example motor drive by Omron. Use this information as an introduction to the topic. There are MANY different types of motor drives, and they all have their own little idiosyncrasies. Even VFDs made by the same manufacturer may have very different programming steps. **READ THE MANUAL** for the drive you're working with. As you become more familiar with these, you'll be able to quickly find the information you need to set-up your particular drive.



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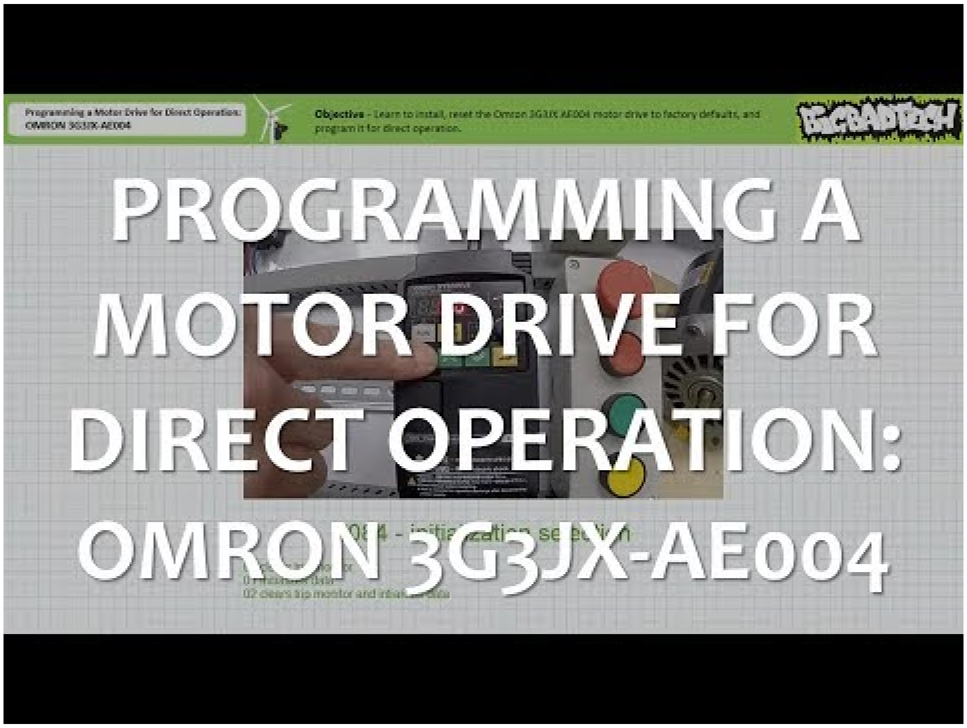

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20. Homework 8

JOSH HANSON

1. How can you change the direction of rotation on a three-phase AC motor?
2. The rotating part of a three-phase AC motor is called a ___________.
3. The stationary part of a three-phase AC motor is called a ____________.
4. Which three-phase AC motor has a higher RPM, one with 2 poles, or one with 4 poles?
5. When the supplied frequency for a three-phase AC motor increases, does the motor RPM's increase or decrease?
6. Name one **mechanical** method to step-up or step-down a motor's output speed (note: changing the number of poles, while technically correct, is not a method typically used in an industrial environments to change the speed of rotating equipment).
7. In a motor drive, what does the rectifier portion of the drive do?
8. Name three characteristics of an inverter rated motor.
9. Name three of the broad categories that motor drives need to have programmed by the user.
10. What is the purpose of the communication port on a motor drive?

Instructor Support

KEN DICKSON-SELF

Documents on this page are designed to help the instructor with worksheets and lab exercises that could be used to make the course more interesting and reinforce key course concepts.

Lesson1-Series Parallel Worksheet
Lesson 1-Lab 0
Lesson 2-Worksheet-Series Parallel Combo
Lesson 2-Worksheet-Logical Operations
Lesson 2-Logical Operations-Answers
Lesson 3-Lab 2
Lesson 3-Lab 3
Lesson 4-Lab 4
Lesson 5-Lab 5
Lesson 6-Lab 6
Lesson 7-Lab 7
Lesson 8-Lab 8