Electricity for the Home Shop

I am an avid reader of Robert Heinlein. He has many interesting insights into human nature and socio-politial concepts. By disguising his ideas as science fiction, he conceals those thoughts so that they are ignored by those unworthy of them. The bottom line: good stuff...

One of his extended characters, those that span many stories, is a man named Lazerus Long ne Woody Smith. Long has been quoted on many occasions as saying "Always listen to the experts. They will tell you what cannot be done, and why. Once you have heard them, go on out and do it."

I bring this up because I realise, as an engineer, that there are many things that cannot be done. And can provide detailed explanations of why "it" won't work. Then some experimenter comes along and, since no one told him it couldn't be done, he does it. In the pages that follow, I will give a simplified overview of why electricity does what it does and why certain things should not be attempted. But, if everyone followed expert informed opinion, we would still be throwing spears to put supper on the dinner rock.

When I say it cannot be done, go on and do it anyway. Make me the fool and move mankind another step forward with your invention. I *will* ask that you use this as a starting point and learn more on the subject so you don't burn down your shop. The heat of the fire would ruin the machines. And probably make the spouse a little angry. But, do what I say cannot be done.

I *will* say that I am **not** the expert that I like to appear. I am merely knowledgable of the **current** state of the craft. If you have a better idea, then by all means, do it. Just remember; "There ain't no such thing as a free lunch." There is a price to be paid for everything.

Electricity, since it is such a technical subject, can make for dry reading. I have attempted to present my matter in an informal, even silly, format in an attempt to keep you from getting too bored. And, the sequence is a little unconventional. You are not reading this to become an electrical engineer. Hopefully, you are reading simply to improve your knowledge of machinery.

Bill Hudson

A bibliography

U S Navy Basic Electricity
(Navy Electrician “A” School "Mickey Mouse Book")
Reprinted by Dover Publications (Declassified)
ISBN 0-486-20973-3
The entire contents of the current version is located at:

http://www.tpub.com/content/neets/

(neets= Naval Electrical Engineering Training)
However; having perused the on-line version, I find a number of points that actually I didn’t find. The older print version might be the way to go, after all. But then, I am biased, I prefer print books.

Armature Winding and Motor Repair
Reprinted by Lindsay Publications
ISBN 0-917914-38-4

American Electrician's Handbook
Published by McGraw-Hill
ISBN 07-013929-6
(This book is continuously updated since 1916,
similar to Machinery's Handbook. My copy is a
1970 printing. A more recent version may
not have the same ISBN.)

On the subject of home wiring, I also found what is, I suppose, a DIY site produced by Eaton Corp., the parent company of Cutler Hammer. While I must admit I prefer Sq D products over C-H, this is a very good site and covers almost anything you could want to know about wiring at home. My brand preference has more to do with industrial control elements, not residential wiring.

http://www.eatonelectrical.com/unsecure/html/101basics/Module10/Output/Welcome.html

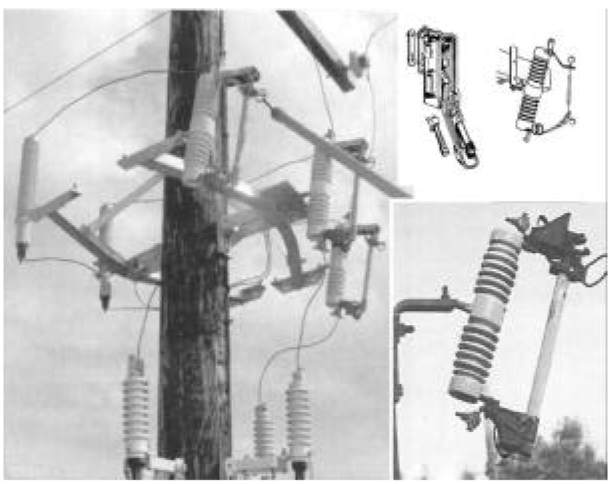
Backtracking up the address may yield even more information.

Electricity for the Home Shop

Let us start with the machine; you have a nice milling machine, just acquired from the junque dealer in the next town. You get it home, cleaned up, tooled and ready to make a pass on a scrap of aluminum. There's nothing matches the feeling of making a mess of the floor with metal shavings.

So you grab the cord and ..... ??What's this s+++?? There's a piece of four conductor rubber cable with the end stripped back and raw copper where it was yanked out of the supply. Now what? Open up the power box in the shop, O.K., let's see; Red and Black to a 220 breaker, ummmm, yeah, we'll use the 50 that runs the welder. Won't need it for a day or two. White with the rest of the whites and, ahhhhh, Green with the bares and greens on the other side.

Awright; "Fire in the Hole!!". Breaker turned on, lights on the panel, lookin' good! Press the "GO" button..... Lights go out with a loud "BANG". Run back in the kitchen to reset the shop feed; ***annddd***, no lights in the house. Step outside, no lights at the neighbors, either. Some coincidence, power goes out just as I hit the switch. Talk about spooky.....



A half hour waiting for the power company, they drive up and down the street, then stop in front of "your" house and start poking at something with a long stick. "BANG!", the lights come on and go right back out. So you *eaassseeee* back into the shop and pop the breaker out, just as the lights come back on, and stay on. This doesn't look good, not good at all.

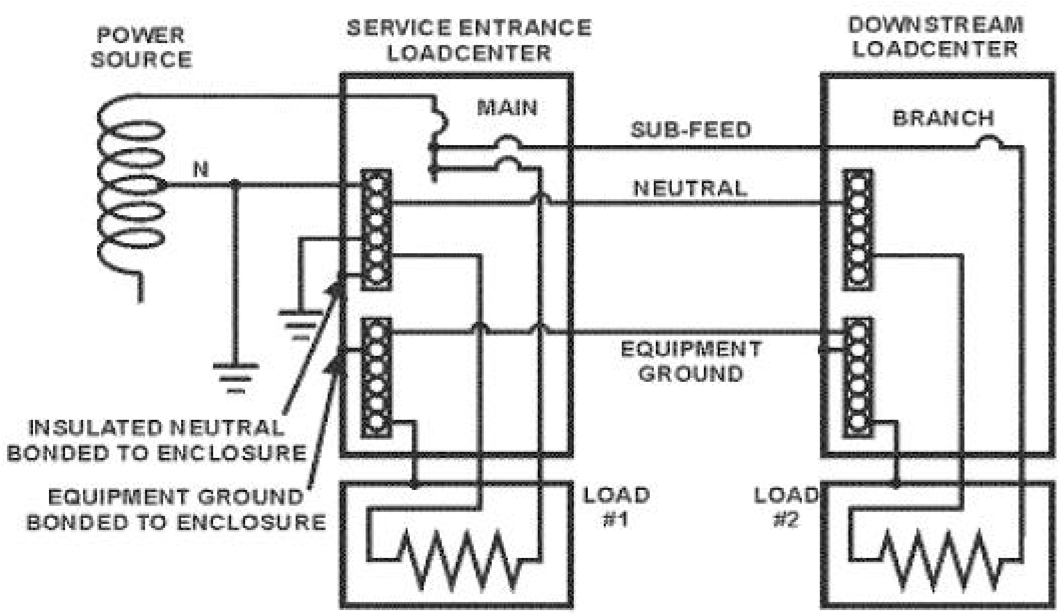
Next morning, have a look at the mill. Funny looking motor, that. So, where do we go from here. Brother-in-law is an Electrician; hell, he wired the shop panel. He'll know. So, B-I-L takes a look at your wiring, says it looks good, although he's not too happy about that 50 Amp breaker feeding a small wire. He seems to think the motor may be shorted; he showed you with an Ohm-Meter where it only read 3-1/2 ohms to ground.

So now starts the search for a motor for this archaic pile of scrap iron that put its' builder out of business 40 years ago. **BULL!**

The “title” *Electrician* covers many different crafts. The “state” places all of them under one heading. Because, like most people, they have no idea what an electrician really does. Most construction wiremen have little or no working knowledge of controls. Just as a motor inspector has little knowledge of the codes covering residential construction. High voltage linemen are in a world of their own. To say a craftsman from one of these crafts should be knowledgable of another would be akin to asking a banker to do architectural design. It just doesn’t work.

The electrical *troubleshooter*, like his kind in any craft, doesn’t build much of anything. But he has a passing good knowledge of most everything. And, can fix almost anything. This is the guy that gets called when changing the fuses doesn’t help. I actually have seen(quite a while back) a company driver sent to the local tavern to bring back such a troubleshooter for a breakdown.

Thankfully, I can say the man was one of many that I learned from over the years. He has forgotten more than I will ever know about mill electrical systems. So, let’s let Mr. Ingle have a look at your machine, and your wiring. Or, at least his protégé’.



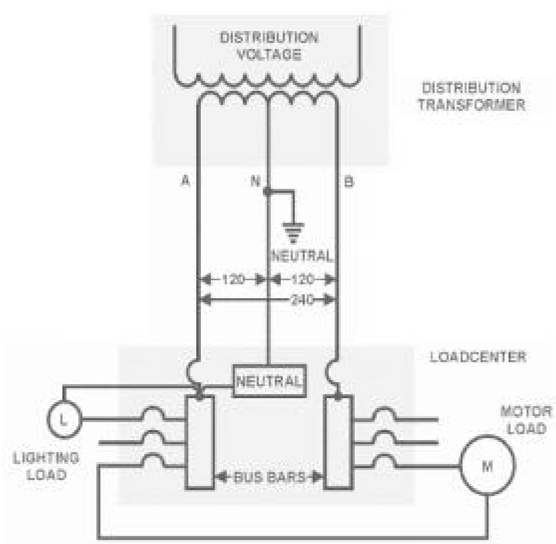
We will start with the shop panel. It is fed from a breaker in the house power box in the kitchen. But the wiring looks different; the green and white wires are on different bars and there isn’t a heavy ground wire or bond strap. A good place to start, this is called a “**Sub-Main**”. It is a distribution panel set up for a number of loads close together, saving running all those circuits back to the main panel in the kitchen. Different, you-betcha ‘tis!

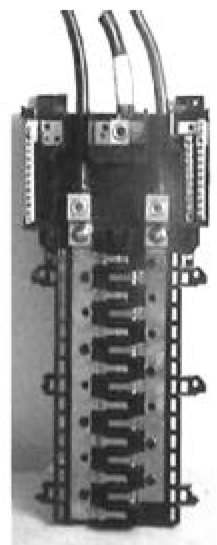
Notice, on the right hand panel, there is a separate wire called “Equipment Ground”. And that it lands on a different bar than the “Neutral”. Following the wires back to the left panel, the ground and neutral are tied together.

What is taking place here is there is one, and **only one**, ground point for the premises. That is at the service entrance, where the power comes in through the meter and is distributed to the loads. Only one line is shown in the drawing, assume the second. It keeps the drawing simple.

This is the arrangement you would use for a “detached” shop. Or a mobile home. Ever notice how mobile home appliances use a different plug, that won’t work at your house. This four circuit plug is to accommodate the isolated neutral.

Although SWMBO probably wouldn’t have it, if you located the laundry in an out-building, the dryer would require such a four wire plug. Just as in a mobile home. The **entire mobile home is a submain**, the main load center is on the pole, right below the meter.





So, let’s look a little closer at this *ground* business. The main load center for the house has either lugs at the top of busbars or a large breaker that spans the width of the box. If the large breaker is there, it is the “Main Disconnect” for the service. No breaker? Then the meter is the disconnect.

So, why is the disconnect so important? It kills **ALL** electrical loads on the premises. In the event of a fire, the Fire Department will pull the meter before any of them step foot in the house.

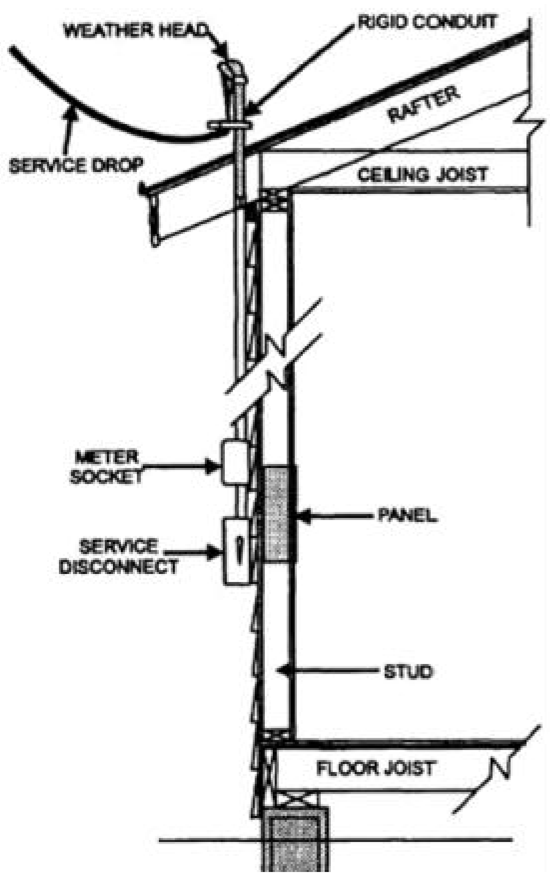
From the top of your panel will be a cable or conduit with wires about the size of your index finger. One will be taped with white tape or a gray stripe and may be a little smaller. This is the neutral.

Notice, in the photograph, the center wire is taped white. It is landed on the neutral lug, with a busbar that passes behind the power leads to the two small bars. On the right is the ground and to the left, neutral. There is a large lug on the top of the right bar.

If this were a sub-main, the two would be separated. With individual neutral and ground conductors returning to the main panel. As it is serving as the main, there is no wire landed there.

An exception would be if there was a main disconnect breaker mounted. The ground is terminated in the same enclosure as the main disconnect.

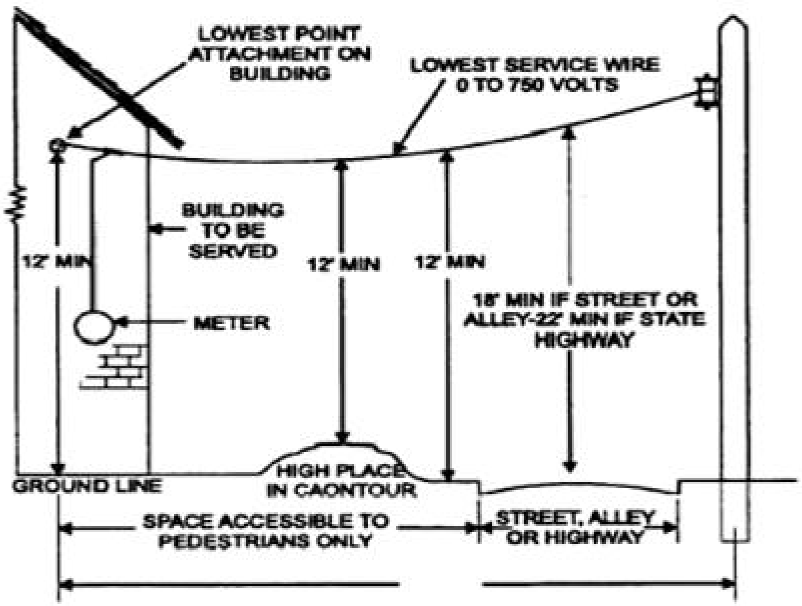
The ground is a copper conductor, probably uninsulated, about the size of a pencil. It is connected either to a metal water pipe, on the street side of the meter. Unless the meter is at the property line. Except, unless, however... Codes, no matter how frustrating, do serve a purpose. Or, to a ground rod, driven in the ground near the power meter. Usually 5/8" diameter, copper or copper clad, with a special "binder" clamp. It is wise to check that clamp from time to time. Loose grounds cause all sorts of problems. Especially if you have computers. Don't bother trying to move it, it's eight feet long.



So, we have the heavy "**Entrance**" cable running from the load center to the meter can. Sorry, I'm not going to tell you how to slow down the meter. In many installations, the meter is the main disconnect. The ground wire will run through a small hole in the bottom of the meter can. Trade secret, here: If you are on good terms with the utility, you can pull the meter, **ONCE**! When the meter reader comes by and finds the seal cut, he will replace it, with one date stamped. If he finds it missing again within a few months, he will install a seal with a different colour. Cut that one and you'll get a lock. I have pulled my meter three or four times in the 30 years I have been here. No repercussions. But, I have always paid on time, even when *they* made the mistake.

There may be another load center at the meter. This is *usually* an upgrade. The original house power box, breakers or fuses, could be anything from a 30 amp, 2 wire, 120 volt to a 100 amp, 3 wire, 240 volt supply.

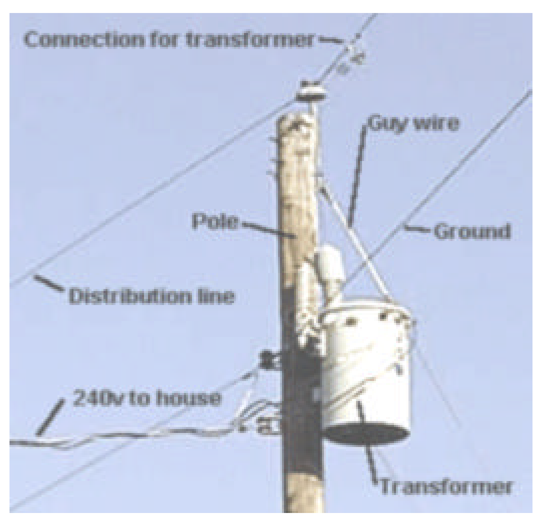
Upgrade boxes allow a service of up to 225 amps, with the original panel fed from a breaker in the upgrade box. Heavy loads like Air Conditioning, Range and Sub-mains are all fed from this location. Some authorities actually allow this arrangement on new services. For my purposes, with three out-buildings(and three sub-mains), it is the ideal installation.



From the top of the meter can is the "**Riser**" cable. Again, this may be in conduit. At the top is a "**Goose neck**" or "**Weather-head**" with a "**Drip Loop**" to prevent water from entering the cable. The riser is spliced to the "**Drop**" cable here. This splice usually looks a little "iffy". Provided the connections are dressed away from the building, it is quite all right. Normally, the splice will be made up with crimped connections. Occasionally, you may find split bolt or "Kearney" clamps. I personally think Kearneys are better, but they do require more time to install properly.

The drop span may be quite long. Mine is over a hundred feet. The cable is rather heavy; the bare (neutral) wire contains a steel strand that provides an integral messenger cable. The insulation on this cable is rated for exposure to the elements. It also may be a size smaller than the riser conductor. Exposed to the cooling of free air, it has a lower temperature rise.

If you have voltage problems, look at that splice. If the drop wire is more than one size smaller than the riser, you may need a larger drop. Most residential services don't have to feed a welder and a range at the same time.



The most interesting call I take is when “the lights work sometimes, and if the dryer is on, several rooms have real dim lights”... et al. Sometimes, I do a “dog and pony show” first, then tell them to crank up the oven to high. If the problem stabilizes, it is a loose neutral. The “sometimes” comes from the water heater. Look at the splice where the drop connects to the riser. There is likely corrosion on the connection in the bare wires. Have the utility come recrimp it.

Let’s digress here for a while and discuss voltages. First off, when I refer to 120/240 volts, it covers the range of standard utility supplies including 105/210, 110/220, 115/230, 117/208, 120/240. The 117/208, you will notice, is the only one not a direct multiple. When we follow the transformer line back, it will become clear. For now, just consider it another service voltage.

There are two arithmetical formulas we need to consider. No math here, not yet, anyway. First is E=IxR. This is the basic “Ohm’s Law”. It means the voltage(E) across a load is equal to the current(I) of that load multiplied by the resistance(R) of the load. The second formula is P=ExI. Power, in watts, equals Voltage(E) multiplied by Current(I) in amps.

A rule of thumb: 750 watts equals one HP. It is a round number, for convenience. Actually it’s 745.7 or some such. There are other considerations, losses in belt drives and so forth. If I am speccing an engine to drive a generator, I expect to get 700 watts per HP. Conversely, the electrical supply is specced for 800 watts per HP. That gives me some wiggle room in either direction.

Now; we have a motor, say 3 HP. Compressor load. Connectable for 120 or 240 with a jumper. 750 x 3 = 2250 watts for this motor. Using P=EI, we find that this motor will pull 19 amps at 120 volts. Or 9.5 amps at 240 volts. The actual current will differ a little by manufacturer, it’s on the name plate.

Sure, it’s on a 20 amp breaker. Along with a shop light, a soldering iron and the radio. Breakers are time rated, a thermal element. When the motor starts, it pulls high current for a few seconds. Then it stabilizes. Three minutes later, the breaker clears. As an aside; breakers are somewhat delicate inside. They do degrade a little every time they are cycled. They should not be used as a switch. And, if you want to run down the code, branch circuits are only permitted 80% load anyway.

So, use the 240 volt connection. It can be on a 15 amp circuit, with plenty reserve. Don’t have an empty 2 slot bay in the shop panel. Rearrange the breakers? Use piggybacks? Two adjacent piggybacks will give 240. Just be sure to install a piece of clothes hanger wire in the toggles so they will common trip. A licensed electrician is not permitted to do this. You, the owner, can.

Remember where I said the service drop could be a size smaller than the riser. Wiring has resistance too. Agreed, you cannot measure it with a Simpson or a Fluke. But, rest assured, it's there. If there is resistance and a current flowing, there is a voltage drop. Where there is a voltage drop, there is heat(watts). Remember, P=EI. I is the current, E is the voltage drop. That's why the drop cable, exposed to air, is acceptable. It is air cooled. But, the wiring in your house isn't.

Further, the smaller the wire, the more resistance. So, there is this feed to an air compressor. The voltage drop is figured as E=IR. With resistance constant, as current goes up, so does the voltage drop.

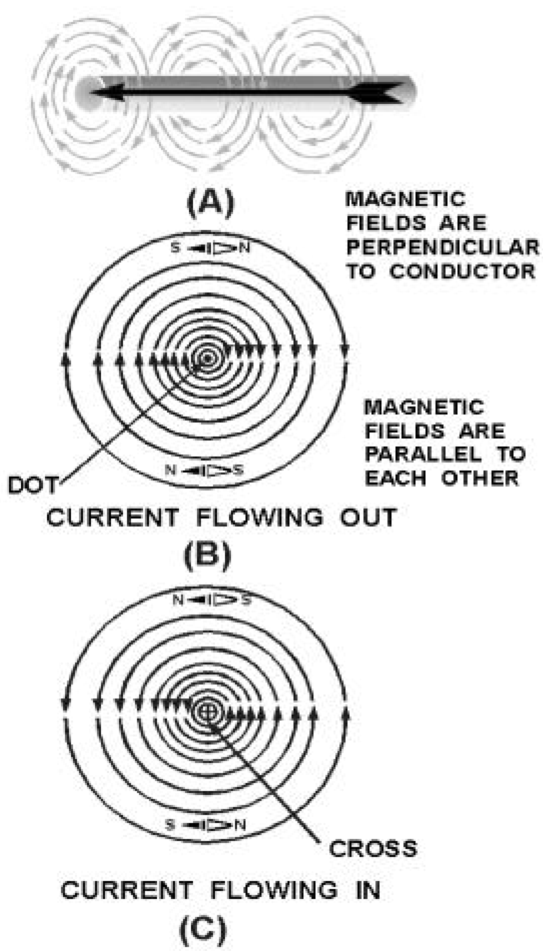
Let us take a hypothetical worst case scenario; You are 12 miles from the substation. The drop is a size too small. The branch circuit to the compressor is too long. The motor is connected for 120 volts. The voltage at the transformer is low, distance from the sub. The voltage at the entrance is lower still, wire size. The branch to the shop is too long, again distance. All told, your 120 branch circuit is 103 volts. Were the motor connected 240, the current would be half. Losses would be half also. Voltage at the motor would be, say, 216. This is an acceptable number, only 2 or 3% low. The 103 is nearly 20% low. Granted, there are many factors not stated and many calculations assumed. But, it demonstrates the principle.

Whatever. A wonderful word. Although young people tend to abuse it these days. It conveys a number of emotions, depending on the topic. There are any number of excellent books on the subject of home wiring. Some are actually accurate dealing with shop installations. I recommend you study a few. I have only scratched the surface here.

So, let us say "What-ev-er!" to house wiring and look at why the motor cleared the jack out on the transformer. Why is it a "Jack"? I have no idea. It is a pole mounted, high voltage fuse. A "jack", huh. Whatever.

To discuss motors, we must have a primitive grasp of magnetism, especially electro-magnetism. The magnetic forces that are associated with electricity. Here is an interesting concept. Your radio receives through the "air ways" from magnetic radiation. Your "microwave" oven heats your coffee through magnetic radiation. The sun heats your back from magnetic radiation. Yes, light is a form of magnetic radiation. A very, very high frequency, yes. But magnetic, none the less. Ever notice how communications go south when sunspots get rowdy?

Back to the subject; If you are in a mechanical craft such as machining, you will likely have a passable knowledge of automobiles. By using the auto electrical system, I can explain the basics of magnetism a little easier. Got that compass you bought last year for the camping trip?



The one where you got lost; it was a cheap compass. And mosquitos the size of pigeons? Pop the hood. Find the battery; and the heavy primary cable that powers the starter. Different makes will have it different places. We want the one the size of a pinkie finger. OK, so I have a big pickup. The size of a pen, then.

Hold the compass over the cable and pull it back until it swings at random. Then turn on the headlights. Notice that the compass "snaps to" and you have to pull back further before it swings free. Try it with a helper turning the starter. If you're *too* close, it may bend the needle of the compass. This is a *strong* field.

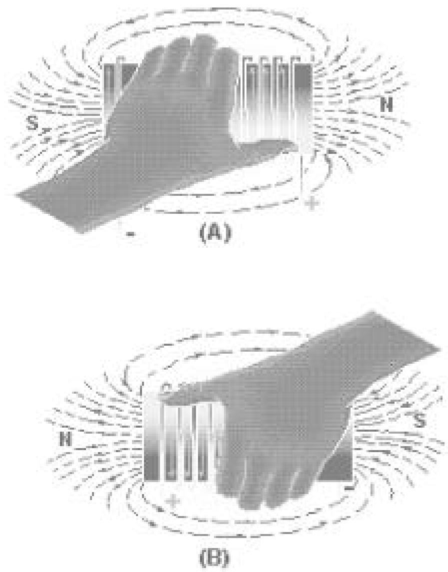
In Fig (A), the current flows from right to left. If you were to wrap your fist around the cable with the thumb extended pointing as the arrow, your fingers will align with the magnetic lines of force.

In Fig (B), the "dot" implies the tip of the arrow, or your thumb. In (C), the "cross" implies the fletching on the arrow.

There are two schools of thought on current flow. Electron, although full of holes, (pun intended) is the theory most often used. Most of this discussion is detailed in the Navy Basic Electricity Manual. They use Electron theory; that electrons, thus current, flow **from** a **Negative** source **to** a **Positive** sink. So, we will here.

Professionally, I prefer the conventional theory. It works better for what I do. But, swapping back and forth would get confusing.

So, current flows from negative to positive. Which means your thumb should be pointing toward the battery. Your fingers, as did the compass needle, will align with the magnetic lines.



Now, here we hit another of those anomalies whose roots are lost in the mists of antiquity. The “South” pole is actually magnetic north. I’ve been to the south pole. Yeah, it was cold. And, no matter where you stood, you faced north. That may be why. Whatever. The point is that the compass needle will indicate opposite of the sketch above.

Now, for my next trick, I will pick up these iron filings from the table, without touching them. Using only this piece of wire, a battery and a nail.

Remember the grammar school science class where you made an electro magnet by wrapping a wire around a nail? The lines of force around the wire above are additive. If the wire is wrapped so that the passes are parallel, the fields will join together into a whole, creating a device such is pictured to the left.

Grasping the winding in your hand, with the thumb pointing to the positive sink, you will see again the “**Left Hand Rule**”, this time pointing the thumb toward the “North” magnetic pole. Notice that your fingers align with the current flow in the turns of the coil.

Here, we have seen that when current is passed through a wire, there is a magnetic field generated that surrounds the conductor. And, that when the conductor is wrapped into a coil, the magnetic field is intensified.

There is an interesting characteristic associated with coils. When current first begins to flow, some effort is required to create the field. The coil opposes the attempt to create and increase the flux. Once this change has been made, the magnetic field will attempt to maintain that current flow. To maintain its’ own strength, so to speak. As the current weakens, the field starts to collapse, generating *some* current flow on its’ own. This is a somewhat dangerous characteristic. As with any such phenomena, if harnessed, it can be useful.

To cause current flow, there must be a voltage. That voltage is often called pressure in old texts is appropriate. Think of electricity as a fluid. The pressure(voltage) causes the fluid(current) to flow, with restrictions in the line(resistance) to direct that flow.

Since the coil is going to cause a given amount of current to flow, it will create the voltage(pressure) necessary to cause that flow. The voltage is not just whipped up out of thin air. The magnetic field is a form of static energy. That energy provides the force to generate the pressure.

When you open the switch feeding the coil, the magnetic field attempts to keep the current flowing in the circuit. It will cause the voltage to increase to whatever level is necessary to cause that flow.

Now, for the horror stories:

An overhead bridge crane with a magnet. Such a magnet is almost six feet in diameter. The case is 72 inches. The actual coil is probably 60. The wire feeding this thing is about the size of what feeds your house. The contact tips are the size of a quarter. The power fails with the magnet energized, so the discharge contactor cannot make up. When the field collapses on a coil that large, there is incredible voltage created. What usually happens is the controller cabinet is destroyed. Doors blown off, contactors blown out onto the catwalk. One very frightened Electronics Tech. I *had* warned him, but I don’t think he truly had a grasp of just how much power was there.

A substation feeding the mill. 13,800 high side. 4160 low side. Distribution switchgear with instrumentation. A coil called a “**Current Transformer**” is used to measure current. It is literally a coil placed around the conductor to repeat the load on the conductor. They can be seen on commercial electrical services. Small “doughnut” shaped devices with leads running down to the meter. This one was 10,000:5, meaning 10,000 amps in the cable generated 5 amps in the instrument loop. A CT is always shipped with a shorting strap, it must never be open circuited. This one was. With the switch out, no current flow; there was no output. When the switch was energized, the CT raised the voltage until there was enough to cause 5 amps to flow. We estimated it hit 150,000 volts before pieces of the CT and the recorder imbedded themselves in the concrete wall across from the switchboard. George said he had never seen a recorder do *that* before.

Televisions have what is called a “fly back” transformer. This device provides the high voltage used by the anode lead on the back of the CRT. Matter of fact, there is one in computer monitors, too. That high voltage is what causes the hair on your arm to stand up when you get close to the screen. Ever seen what happens when the “flyback” fails? Makes a right mess of the insides of the TV.

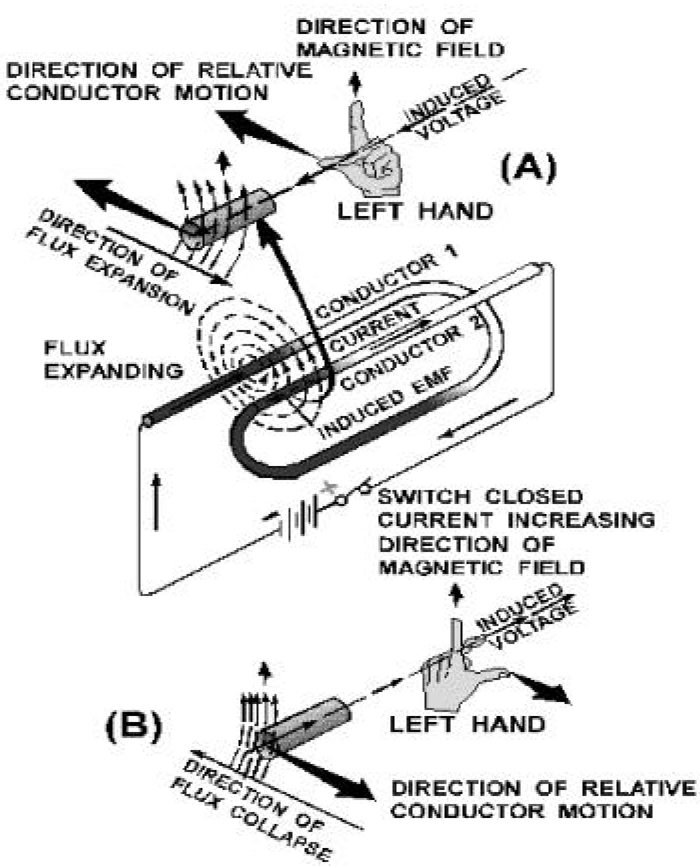
So, with this much power, a coil is a troublesome thing. But, properly harnessed, it can provide useful work. Ever wonder how 14 volts in your car can create enough guts to arc across the tip of a spark plug? Under pressure yet?

That's what the points do. The points are simply contacts that energize the coil. When they open, the field collapses, creating the voltage necessary to spark the plug. A magneto works in a similar fashion, just with a magnet to initially build the field. Then, the points open and the field collapses, creating the spark.

In essence, this coil will create a field whose strength is proportional to the current flowing in that coil. The field "moves" as the current changes. The key to electro-magnetics is that this movement works both ways. If the conductor is placed in a magnetic field, and moved, it will create a current flow. That is what happens when the field collapses. It is "moving" inward, creating the current flow. If the field is static, unchanging, there is no current *generated*. If the field moves one way, the current will flow that way. If the field moves the other way, so does the current. If there is motion, there is current.

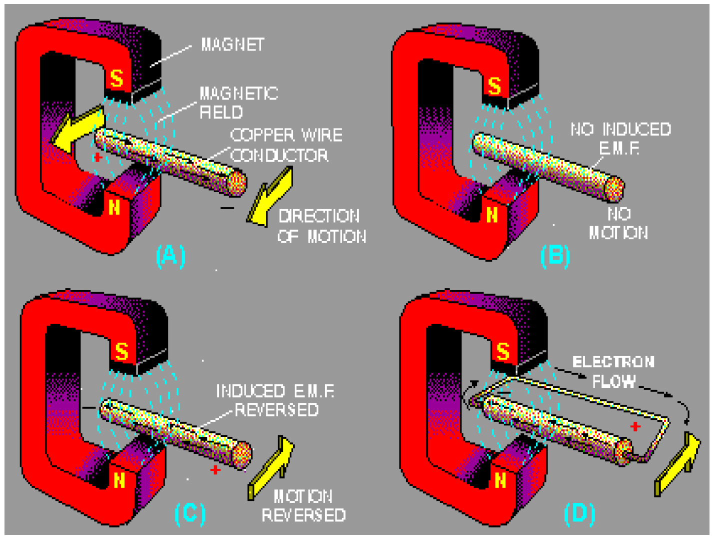
There is actually a grammar school science project that illustrates this effect. It is possible to light a small lamp just by waving a magnet near a coil. Got to be pretty fast, though. Lazy movement won't do it. The experiment needs a closed circuit, though. Ever been fishing with a telephone generator? Neither have I. Heh, heh, heh.

This, then, brings us to the next application of the **Left Hand Rule**. There are three axes, each at right angles to the others. *Motion, Flux, Current.*



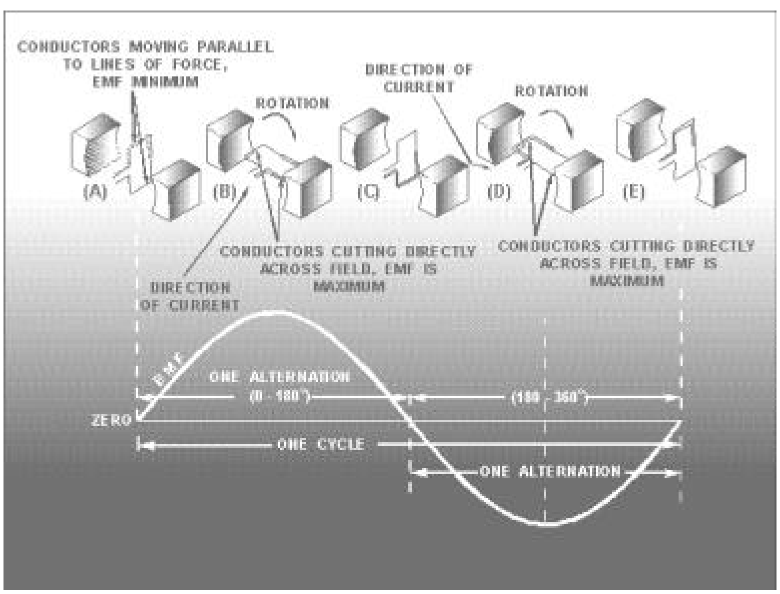
Motion is represented by the thumb. Flux by the index finger. And Current by the middle finger. The acronym MFC associated with the middle finger has gathered many crude descriptions over time. I leave them to your imagination. The association preferred by the Navy book from which I stole this picture is "My Fine Clothes" This association is suitable for mixed company and is easy to remember.

The illustration should be self explanatory. As a conductor is moved through a magnetic field, a current is produced. The relative motion is the key point. Whether the field moves, or the conductor, doesn't matter.



Since the desired end result is understanding of power production and distribution, we will use the moving field. A rotating field is the most common method used for A-C generators.

One of the more difficult concepts in A-C is that every illustration is of an instantaneous event. Thus the drawing to the right, and several that follow will be accurate only at the instant in time that the rotor is positioned as shown.



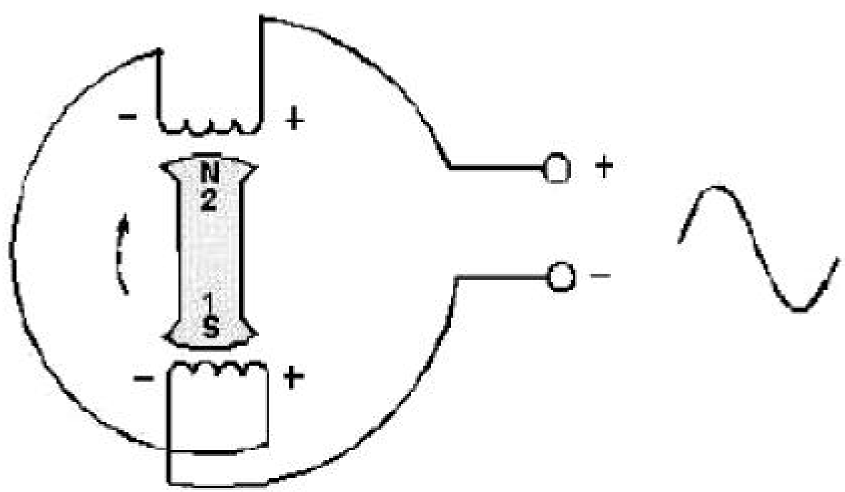
The output waveform shown is for one complete revolution of the rotor. As the conductor passes the face of the magnet, a positive current is produced. Then, as the conductor continues past the opposite face of the magnet, a negative current is produced. The strength of the magnet and its' physical relationship to the coil are what produces the non-linear shape of the waveform.

The amplitude and polarity of the current is directly proportional to the sine of the angle of the rotor during rotation. Thus, a "**sine wave**". Yes, I know, "sine" is properly spelled "Sin". This spelling is common in electrical literature.

As an aside, battery powered standby power supplies do not produce a true sine wave. They produce an approximation. A sine wave can be generated electronicly, but only with a low current capacity. For high power applications, a true sine wave is only available from a magnetic source. The quality, and cost, of a battery back-up supply is directly proportional to the accuracy of the approximation. The cheapest UPS produces a square wave output. Which will work fine for lights and the computer with a “switching” power supply. It is not in the least acceptable for analogue power supplies.

On the previous page, I spoke of a rotating field. Then promptly pictured a rotating coil illustration. Let us now look at a practical application of the same concept. A single phase generator, properly called an “alternator”, such as would be found on a portable “stand-by” gen-set.

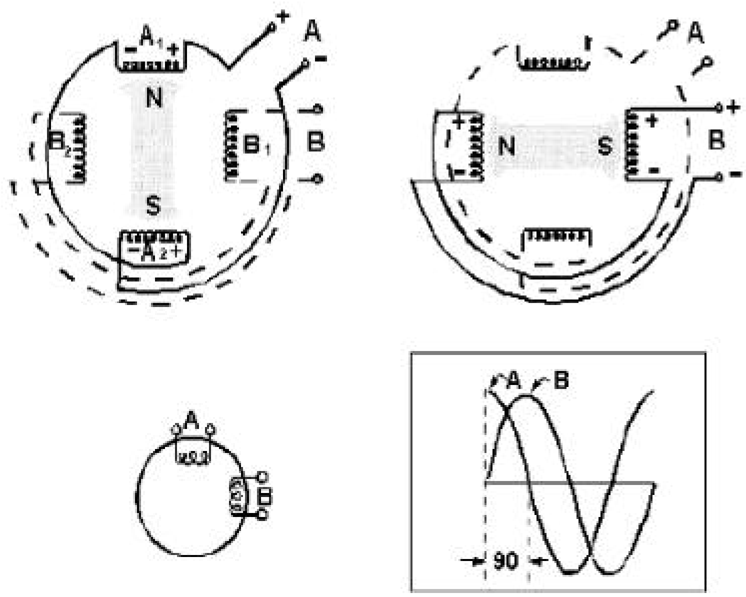
Notice here that the coils are stationary and the field (magnet) rotates. The net result is identical to the previous illustration. The relative motion of the coil and the field produce a current.



The output waveform *is* a bit misleading. Notice that the north pole is at maximum flux density relative to the upper coil. Thus, at this instant, the output is at maximum positive. The waveform is displaying a 90 degree lag. A *minor* point, but it could be confusing. It confused me in ‘68.

There are many factors that affect the output amplitude, the voltage level. The first is the strength of the field. Speed is also a prime factor. However, since speed is the controlling factor for frequency, we must assume it fixed at this time.

The power delivered by a utility is often incorrectly called “two phase”. Mostly because the center tap permits referencing two voltages that are out of phase with each other. Yes, they are out of phase; by 180 degrees. Meaning they are of opposite polarity. A two phase supply, on the other hand, is out of phase by 90 degrees. Such an alternator is shown here.

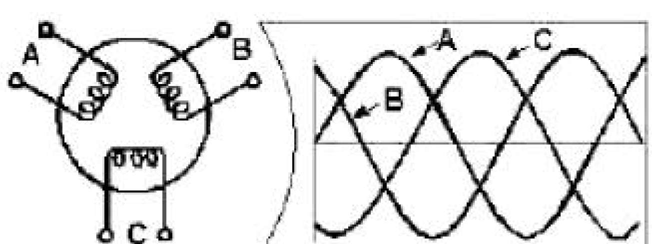


For all intents and purposes, a two phase alternator is identical to two single phase devices with the windings overlaid and offset by 90 degrees. You will notice here that the pictured waveform is “in time” with the magnet as it rotates.

I must assume, at this point, it is obvious why electrical people have such a good knowledge of trigonometry. I had worked in the field for a number of years before I had the opportunity to study it. When I finally did, my grasp of the subject was immediate through relating to rotating magnetics. Between celestial navigation and A-C motors, the fundamentals of trig take about 45 minutes to understand. Should you intend to delve further into the subject of motors and generators, might I suggest you “bone up” on your trig before you do. Rote memorization of formulas *will* get you by, but you would miss out on the fascination of rotating magnetics. And continue to believe Tesla was, indeed, a space alien. Again, I digress.....

A three phase alternator is simply a further expansion of this concept. Take three single phase devices and offset them by 120 degrees.

In this illustration, we have reverted to the “standard” method of picturing the windings. There are still two, on opposite sides.



THREE-PHASE ALTERNATOR

A

Earlier I mentioned that speed was the controlling factor for frequency. Each of the examples presented have been “two pole” machines. Obviously, there can be no “one pole” machine. Sort of like a rope with one end. It simply wouldn’t work.

As the **rotor** moves within the **stator**, it produces one sine wave per revolution. 3600 RPM is 60 revolutions per second. That is where our 60 Hertz line frequency comes from. But, as machines go, 3600 RPM is a “high speed” machine. Suppose we could cut the speed in half? The advantages should be immediately obvious. Slower machine speed leads to less wear and tear. Bearings can be less precise of tolerance. Or high tolerance bearings will last almost forever. And we all know the advantages of less down time. And, many engines are not capable of such speed. I have worked with many marine engines that were “red lined” in the 750 RPM range.

Well, suppose we used *two* magnets, offset by 90 degrees. It *would* work, but with a lope. And, it would still be a two pole machine; 60 Hz at 3600 RPM. Sort of a *chugga, chugga, flop, flop*. Like a Moto Guzzi motorcycle engine. The sine wave wouldn’t be a sine wave any more. Motors would pass this instability into the machines they were driving. Such vibration would cause premature failure of even the stoutest designs.

So, the next best thing would be to double the number of windings. Now, the single magnet makes *two* sine waves per revolution. That would give us a frequency of 120 Hz. Or, we slow the **prime mover** to 1800 RPM. Now we are in the range of a goodly number of very reliable diesel engines.

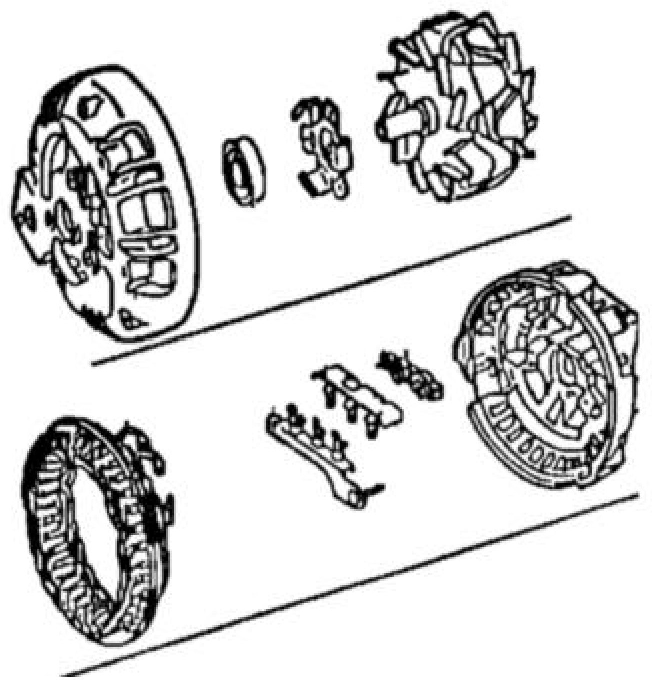
Suppose we double that again, to eight poles. For 60 Hz, the prime mover would run at 900 RPM. Now we are within the range of slide valve steam engines. 15 revolutions per second, not unachievable with locomotive engines. I have worked on motors rated at a synchronous speed of 300 RPM. Twelve poles. A rarity today, but still running. You could *almost* count the pole faces as they came by. 5 per second. Of course, the motor was around 18 feet in diameter. Sunk into a pit, the 16" shaft was about waist high. 900 HP. Torque? Hell, I can’t count that high.

In the real world, both solutions are used. The number of magnet poles and the number of winding poles. But, it is not as simple as gluing two magnets into an X shape.

Look at an automotive alternator. It is a 3 phase machine, with the rectifiers built into the case. You can pull off the 3 phase A-C from insulated studs on the back of the case. Be advised though, it is very high frequency. Upwards of 4000 Hertz with the engine off of idle at cruising speed. But usable.

Ever had an automotive alternator apart? The rotor has two castings that make up the field, each with a number of fingers. When these two pieces are brought together, the fingers interlace, just like clasping your hands.

Mounted on the shaft, with the field coil between the two **pole pieces**, creating a magnetic field of some 12 poles.



The **rotor** is shown in the upper right corner of the illustration. Notice how the two pieces interlace. The field coil is sandwiched between these two pieces.

The **stator** ring is shown in the lower left corner. Notice how slim this piece is relative to the overall size of the casing.

In this case, the field rotates and the **armature** is fixed.

Between the stator ring and the back end bell, lower right, are the diodes. The diodes are what make this a D-C machine. On many alternators, the armature windings are brought out to insulated studs, ahead of the diodes. Most modern alternators use an internal regulator module. Such machines require extensive modification to be used for non-standard applications.

The regulator controls the current in the field windings. The higher the current, the stronger the field. The stronger the field, the higher the voltage, thus current from the armature. Regulators may be as simple as a resistor or as complex as computer control can make them. In its' crudest form, a *carbon pile* regulator can control the output sufficient to run lamps, charge batteries, and other simple loads.

A carbon pile consists of a stack, or pile, of thin carbon disks; about the size of 3.5" floppy disks without the case. This becomes the resistor. A weight is arranged with a bellcrank such that it compresses the pile. The more the pile is compressed, the lower the resistance. More current flows, the voltage increases to the field and the alternator provides more output.

Attached to the bell crank is a voltage sensitive coil with a sliding core. This coil is connected directly across the output of the alternator. The higher the voltage, the stronger the coil. As the coil increases pull, the weight is lifted from the pile by the sliding core. This increases the resistance, decreasing the current to the field and lowering the output voltage.

As I said, this is a crude regulator, but it does work. It is the control used to power the “Sperry Mk. 13 Fire Control Compass”, used to lay the guns of a warship, until *very* recently. Conceded, I am over 50. “*Recently*” covers a lot of territory.

As noted earlier, automotive alternators *are* 3 phase machines. The only difference between such alternators and utility plants is size. The modern automotive alternator can produce 100 plus amps at 120 volts**, if properly regulated**. However, this is a **tremendous** amount of power and must be carefully handled. It also is of fairly high frequency and so cannot be used as an alternative to high energy bills. At home, anyway. If you attempt to run induction motors on this power, the results will be most unpleasant. That means refrigerators, air conditioners, lathes, milling machines and any device with a motor, a transformer on the front end, or most electronic equipment.

Where it *can* be used is with resistance heaters such as ranges with mechanical thermostats, water heaters, space heaters, lighting, and a class of motors known as “series universal”. Motors such as one would find on hand drills, circular saws, sewing machines and the like. A useful possibility if you work in construction.

Well, I keep harping on how magnetic equipment will cause problems if you try to power it with something other than a clean sine wave at the design frequency. Perhaps I should explain what **hysteresis** is all about.

Most magnetism requires iron. There are a few "Rare Earth" materials that exhibit magnetic properties. But, they are the exception. Keep in mind though, that many modern, high efficiency devices depend on these rare earth magnets.

There **is** an electro-magnet that will attract non-ferrous metals such as copper or aluminum. It is not new technology, the patents expired about the time I was born. We will touch on the theory of how the contraption works, but later, much later. I broach the subject mostly to get your interest up on the theory of electro-magnetism. Such a concept is always intriguing.

Magnetism faces the same barriers to flow as electricity does. Resistance to electron flow is called, well, resistance. For magnetism, this property is called reluctance. Different materials have varying degrees of reluctance. Air has medium reluctance, iron has low. Many solid materials, aluminum, paper, wood, have no magnetic properties. Consider them the same as air.

Alright, you say, if aluminum has no magnetic properties, then how can a transformer with aluminum windings work? Just as copper does, also with no magnetic properties. Remember the magnetic field that is created around a conductor with current flowing. This magnetic field will affect any magnetic material. Remember also that a conductor exposed to a *moving* magnet field will have a voltage generated therein. This is the basis for transformers. It is called **mutual induction**. A current flowing in a coil will induce a voltage in another coil that is within the range of the field. Remember a few years back, a farmer in the American Midwest lost a court case over using a roll of wire to "*steal*" electricity from a high voltage line across his pastures. I didn't think it was stealing, but the utility did. That was induction. No, it wasn't me; and the coil was *outside* the easement.

Electro-magnetism also has that other interesting property, the resistance to a *change* in current flow. We touched on the concept earlier. When current is increased in a conductor, the magnetic field requires effort to expand. When current flow is decreased, the collapsing field will tend to generate more current flow in an attempt to maintain the status quo.

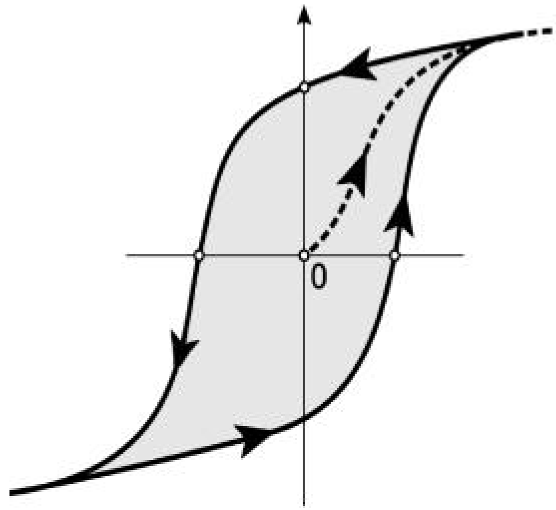
Now we apply these properties to alternating current applications. If you were to use a VOM or "ohm-meter" to measure the resistance of a transformer, you would find the resistance fairly low. So, why then, does the transformer draw little or no current in an open circuit condition. There -is- a minute current called "magnetizing" current and is inversely proportional to the efficiency of the transformer. Usually 2% or less.

Alternating current swings from positive to negative and back, at the rate determined by the frequency. This was illustrated a few pages back, when we first looked at alternators. Reversing the power flow of an alternator, so that the armature or stator is powered from the line, makes the alternator run as a motor.

There have been instances where an off line diesel generator was mistakenly connected to the power grid. It **motorizes** the generator, turning over the prime mover and making any number of engineers most unhappy.

When current is applied to a coil with an iron core, the magnetic lines of force tend to forcibly align the magnetic particles in the iron. As with the field itself, there is a reluctance on the part of the iron to accept this magnetism. Consequently, the magnetic properties of the iron do not directly follow the current. Because of the delay in magnetizing the iron core, the magnetic field "lags" behind the magnetizing current.

Conversely, when the current falls off, the magnetic "decay", in its' attempt to maintain the "status quo", is attempting to maintain the current flow. There is a curve called the "**hysteresis**" of the magnetic field. Just for fun, I have included a sample of the math for calculating hysteresis losses for a particular core. Don't take it too seriously, we aren't designing a power plant here.



The area of a hysteresis loop $B(H)$

$$\int B dH = \frac{E}{V}$$

just corresponds to the energy density loss in remagnetization of the demagnetized material. The enclosed area in the diagram $\Phi(I)$

$$\int \Phi dI = \int N_2 AB \frac{L}{N_1} dH = \frac{N_1}{N_2} V \int B dH = \frac{N_2}{N_1} E$$

gives the precisely energy loss E of the remagnetization for $N_1 = N_2$.

The strength of this hysteresis effect affects the response of the coil to a current flow. These properties combined are referred to as the "reactance" of the coil. The nominal unit of measurement for inductance is in "Henrys". (L)

Reactance is derived by the formula X_L=2Pi **F** L. The actual formula isn't that important to the discussion. What I wanted you to see was the variable "F". That is the frequency of the impressed voltage in Cycles per Second or Hertz. The reactance of a magnetic circuit is directly related to frequency.

Returning to the earlier discussion of measuring the transformer winding with a VOM; that VOM was impressing a D-C voltage on the winding. A frequency of zero. Low resistance. Low voltage. Basic Ohm's law indicates it is a short circuit. (I=E÷R) The VOM uses battery voltage, let us say 3 volts. 3 volts on 10 ohms should draw 300 mAmps, a third of an amp. Connected to 120 volts, reason would tell us the current would be 120÷10 or 12 amps.

Enter reactance... It is the inductive equivalent of ohms in D-C. So, the formula for Ohm's law, I=E ÷ R becomes I=E ÷ Z, where (Z) equals the vector sum of D-C resistance(R) and reactance(X_L). Since X_L is a function of frequency, total **impedance**(Z), hence current, will be directly related to that frequency.

There is a similar element for capacitance, X_C. In calculating impedance, X_L and X_C will cancel each other out. They have opposite vectors. This will become an issue when we get to **Power Factor** and come back around to single phase motors. Beyond that, we will leave the subject alone.

The details of impedance calculations can be further explored through the links in the bibliography. It's plain old Pythagorean trig.

The reactance, on the other hand, is central to the discussion. The core of a magnetic device can be made of soft iron. Carbon bearing iron. The interaction of carbon to the iron creates some strange results. Pure, or nearly pure iron, is soft and crumbly. As I am sure you have found, working it on a lathe. Call it gray iron; it has a silvery, textured surface when it breaks. Iron, as it usually comes from a blast furnace, has a fairly high carbon content. Part of this from the ground, part from the smelting process. This "black iron" is very hard and brittle. Old soil pipe, hit with a hammer, shatters like glass. Plumbers must use a special cutter that scores the surface, just like glass.

An aside here: If you go to a supply house and ask for "black iron" pipe, you will get steel pipe with a black surface and no galvanizing. It will rust, and it will bend. It is called "black" simply because it isn't galvanized. The soil pipe noted above is no longer cast iron, either. It is "ductile" iron and is some *tough* stuff. I have seen a stick of it bent into a circle and hold 5000 PSI in QC testing.

But, take black iron and remove some carbon; you get "wrought" iron. It has a little more "give" than black iron. It becomes useful for structural applications. There are a number of wrought iron bridges still in use around the world.

Remove some more carbon and you get the various grades of steel. At this point, the other alloying agents become an important part of the strength of the steel. As does heat treating.

Remove still more carbon and you get into the "semi-steels". Still more and you get back into the gray irons. Like that cheap vise you bought last month. The one that broke when you put a cheater on the handle.

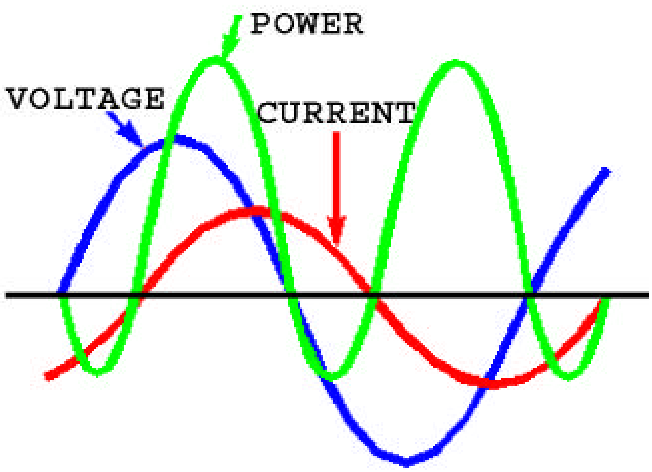
Stay with me, I am not going off to metallurgy. But the various grades of iron do have different magnetic qualities. For our purposes, "soft iron" and "low carbon steel" are very similar. The best magnet steel is a medium carbon, high silicon steel. This is the steel made where I work that is sold to a major motor manufacturer. In house, we call it "Motor Lam." grade. The rest of the metallurgy is proprietary. Sorry; I'm angry with them, but not *that* angry.

The grade of steel and the shape of the core determine the shape of the hysteresis curve illustrated above. The smoother and tighter that curve is, the lower the losses, thus the lower the heating, higher the power factor, and usually stronger the device is.

Lowering the frequency lowers the impedance (X_L=2Pi **F** L). Current, hence heating, increases. Raising the frequency increases the impedance; less current, weaker field. Which brings up Ampere Turns as a rating for magnet field strength.

We will come back and deal with inductive loads some more after while. Especially transformers. But for now, having touched on the reasoning behind *lagging* current in motors and other inductive loads, perhaps we should look at **Power Factor**. Power factor is a multiplier used to describe the efficiency of an electrical load. Ideally, it is 1.0. Incandescent lighting and resistance heaters are perhaps the best examples of non-reactive loads.

As the voltage swings through its' sine wave of positive and negative, so also does the current. But with inductive loads, because of the magnetic characteristics explained above, the current **lags** somewhat behind the voltage.



In the illustration to the left, current(red) lags voltage(blue) by about 60 degrees. This is a radical example, stretched to make it easier to see. You will note the part of the power(green) curve that dips below the baseline. This is the power you have paid for but did not use. Now I have your attention, yes?

With an inductive load, usable power is called **True Power**. (Watts=volts times amps times power factor). Power Factor is the cosine of the phase angle *difference* between voltage and current.

"The instantaneous power in the circuit is equal to the product of the applied voltage and current through the circuit. When the voltage and current are of the same polarity they are acting together and taking power from the source. When the polarities are unlike they are acting in opposition and power is being returned to the source.

Briefly then, in an ac circuit which contains reactance as well as resistance, the apparent power is reduced by the power returned to the source, so that in such a circuit the net power, or true power, is always less than the apparent power."

There are devices advertised that purport to increase the efficiency of appliances through the wonders of solid state technology. I have never used such a device, but others have told me of minor improvements. It seems to me that awareness of testing would make one more conscious of wastage, such as turning off lights when leaving a room. Such a homebrew test is skewed, and therefore invalid on its' face. Beyond that, I have no opinion.

The technique used by such devices is to generate a quasi capacitive load in parallel with the inductive load. You will recall; earlier I stated that reactance was summed vectorially with resistance. And that capacitive reactance was of opposite polarity to inductive reactance. They cancel each other.

In the graph above, inductive loading will shift current(red) to the right. By inserting capacitance into the circuit, one can shift the waveform back to the left. In effect, canceling the lag from the inductive load.

As I mentioned earlier, the ideal power factor is 1.0 or "**Unity**". A motor running at full load will have a power factor on the order of 0.86 or 86%. A motor running with a light load, such as our machines often do, will have the disgusting power factor of 0.20 or 20%. That means 80% of the power paid for is not used. Do I see a rush at the supply house on capacitors.

Power Factor correction is usually accomplished with capacitors made specifically for the purpose. They may be seen at substations, appearing as relatively small boxes, with large insulators, connected across the line.

There is a device called a "synchronous reactor" or "synchronous capacitor". It is, in reality, nothing more than a large synchronous motor, running less than full load and "over-excited". Such a machine does, indeed, correct power factor. And does a better job than static devices like capacitors. Unlike capacitors, it requires constant attention. Usually driving an air compressor, it earns its' keep. But such applications are well outside the scope of this discussion. A synchronous motor rates a goodly sized book on it's own.

Capacitors can be acquired for low(480 or less) voltage applications. Should you opt to add capacitors to your power panel, be sure to use A-C rated capacitors. There is a special class called *non-polarized electrolytic* that are specifically for phase shifting applications. Even a handful of motor starting capacitors will make a difference. The important issue is to enclose them in a metal box and use the same wiring techniques you would use for any line powered control system.

You should also be aware that there are instantaneous currents in such installations that are quite large. Higher than the actual load at times. Do not scrimp on wire size. If the machine is on a 20 amp circuit, use wire and connectors suitable for 20 amps. To be most effective, power factor correction should be located as near the load as practical.

Distorting the sine wave ...... did we touch on light dimmers and router speed controls yet? No? Well, don't use them on anything other than "series universal" motors. Another evil I have stumbled across was specialty lighting, such as photo lighting, disco lights (am I *that* old now?) , a number of similar applications. One would think that a lamp wouldn't be sensitive to a non-linear wave form.

Seems there are a lot of those lights out there that use a low voltage lamp with a transformer in the can. They are rated 120 volts A-C on the line side. Using a distorted waveform leaves the transformer with a life span projected in the tens of hours. Very similar results to what one gets from running an induction motor from such a control. The magic smoke gets out and it doesn't work anymore.

The only safe way to vary the voltage on these devices is with a variable transformer. Lionel, American Flyer, Ives, Marx no longer make A-C toy trains. The old toy train transformers are now highly sought after by collectors, especially the big ones. Look for high prices. They do an excellent job, although limited to the 0-16 volt range. "Variac" is one of a number of trademarks for line voltage variable transformers. Most suppliers are rather proud of them, too.

Ahhh, but there is a way to duplicate some of the functions of those variable transformers. Within a limited range, usually plus or minus 20 percent. It is a common practice with utilities, especially out in the nether regions away from large towns. And something quite useful to know if you are running used, junque, or salvaged motors with odd voltage ratings.

But, to discuss this, we need a little background on transformers. Yeah, I know. That's the way it is in this business. Every little detail depends on some other little detail. And that detail on still another. And the best part? It's all theory. Empirical observations. There is not one shred of documentable proof for any of it. Just a hundred fifty years of observing the results of tests. I love it.

Anyway, transformers. As I have explained, a coil with an alternating current flowing through it generates a "moving" magnetic field. Just as the alternator generated output by physically moving a magnet past a conductor. The only difference is that the transformer is "static". No moving parts. Except for the magnetic field.

Obviously, if one places a second coil of identical characteristics next to the powered coil, on a common core, the **secondary** coil will repeat the conditions of the **primary** coil. There is a little loss, on the order of a couple percent. For our purposes here, we will ignore it. But, a transformer is far and away the most efficient machine in common use. The kicker? The polarity is reversed. Not a big issue here. But, something to be aware of. We'll see it later, talking about motors.

The key to the previous paragraph was the "identical characteristics" business. When we deviate from the identical, we get all sorts of useful characteristics. Consider the term **Ampere Turns**. Turns, of course, is referring to the "turns" of wire around the core. Ampere is simply a base line reference. Ampere Turns is a part of the calculations for the strength of a coil. Transformer, solenoid, motor winding; all of them.

Here we will use it in a looser sense, along with **Turns Ratio**. This is **the** primary factor in dealing with transformers. The transformer referred to in the preceding paragraph is a 1:1 or isolation transformer. What is put in will come out. 180 degrees out of phase, but otherwise the same.

Now, let us add a third coil on the common core. Again, same characteristics. The primary is the coil connected to power. We now have **two** secondaries. Should we connect these two in parallel, the output capacity is doubled. Twice the Ampere Turns. **But**, the primary is unchanged. We can only use half the available current on the secondary because of the capacity of the primary.

However, if we place the two secondaries in **series aiding**, the voltage is doubled. 16 volts in, 32 volts out. Or, we could connect the two in **series opposing**, where we would get an effective nothing. One is out of phase with and canceling the other.

So, you ask, what? Enter turns ratio. Let us take a common doorbell transformer. 120 volt primary, 16 volt secondary. Then, we take a common control transformer, such as is probably on your furnace and/or air conditioner. It will be 120 volt primary and 24 volt secondary.

Connect the two primaries in parallel. Connect the two secondaries in series. Connected one way, you will get 40 volts. Series aiding. Possibly useful. Or, connected the other way, series opposing, the result will be 8 volts. The difference in the two. I can tell you, from *many years* of experience, that 12 volt lamps powered by 8 volts will run about half intensity and last *nearly forever*. This *is* a useful combination.

The turns ratio is the number of secondary turns compared to the number of primary turns. The 24 volt transformer has a ratio of about 5:1. The 16 volt transformer is about 7:1. This ratio indicates current capacity, as well. The door bell transformer has a capacity of 3 amps on the secondary. The line side will draw on the order of 400 milli-amps. 0.4 amps.

Here is where we get the ratings for transformers. The door bell transformer is rated 48 watts. This is the 3 amps at 16 volts. Early on we spoke of watts. Then power factor. Since the transformer *is* reactive, we must consider the impedance rather than resistance. So, the secondary is rated at 3 amps. Multiplied by 16 volts. We get 48 **volt-amps**. In this small package, there is little difference. Many small transformers are rated in watts. But, in the larger sizes, power factor does become an issue.

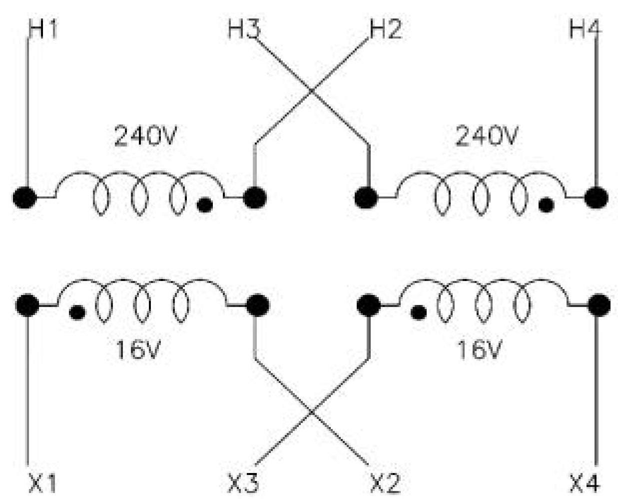
Power transformers may handle *thousands* of volt amps. They are rated as KVA. At 240 volts, 1 KVA is only a little over 4 amps. So, you will see the KVA rating quite often.

I did promise to tell you how to adjust your line voltage. But, it is important to consider whether your line is high or low **consistently**. Else you will be stuck changing taps so often you can get nothing else done. Early on, I mentioned a distribution system of 208/117 volts. This is the most likely application for what I will describe here. At 208 volts, motors are running right at the edge of marginal low voltage. Low torque, overheating, inefficient, disgusting power factor. In the days of $0.04 per KW hour, it wasn't a big deal. But, power today is becoming precious. Power factor *is* important. Not only for your own wallet, but the more efficient a power grid is, overall, the less likely a brownout.

There is a transformer made specifically for the purpose. It is a **Buck-Boost** transformer. Usually available as 12-24 volt or 16-32 volt secondary. With enormous secondary current capacity.

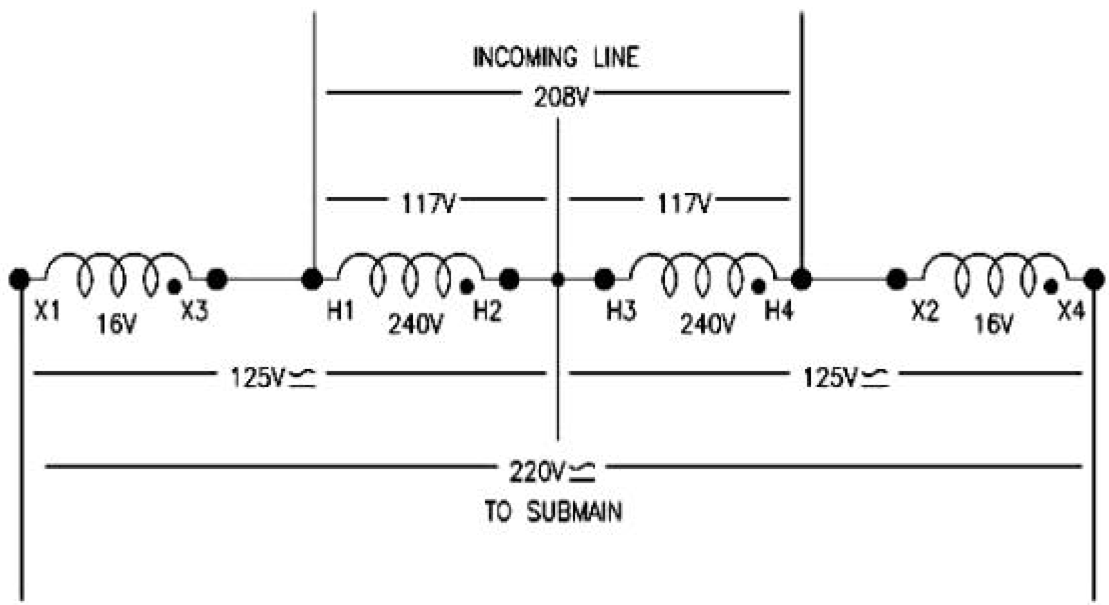
Let us say you have just acquired a machine of some 5 HP rated 220-240 volts. Few motors today will accommodate a 208 volt line. So, you need to bump it up to 220. Adding 12 volts will give you the 220. You could call the utility and raise hell, but likely as not they will tell you that *you* must foot the cost. Just as if you built a home out at the lake, in the middle of 40 acres. The utility will bring power up to the property line; from there you cover the cost.

So, how do you do this yourself, without incurring the cost? There are two possibilities. Large transformers on an existing system, or medium transformers and a sub-main panel. If it were my decision, I would opt for a sub-main. Just the way I do things. As I said earlier, I have a number of outbuildings. Let's use such an approach for our calculations.



To start, you need the buck-boost transformer. Now, there are two lines to consider. And, the 117 is referenced to those lines. So, if we arbitrarily added 12 volts to one line, the 117 would suddenly become 129. A little iffy on the high side. So, we add 8 volts to each line. That will give us 224/125. A usable combination.

The transformer will be rated at 240-480 on the high side. 16-32 on the low side. We will connect the high side in series aiding for 480. The center connection of this series pair is referenced to neutral. That places each 240 volt winding across 117 volts. About half. Consequently, the low side will be 8 volts per winding. Now, the picture of a thousand words.........



Easy, huh? We simply made use of the ratio rather than the voltage ratings. There is a price to pay, though. The current rating in amps will be the same whether we excite it with 240 or 480. So, we must use the higher rating to calculate the current rating.

Assume we want to transform 50 amps per leg. That's 100 total. But, the only part that must be calculated is that portion different from the line. We don't calculate the entire 480 volts. Only the transformed portion. This is 32 volts. Yes, we only used 8 per but the calculation must be at full rating. The total is 3200 volt amps. 3.2 KVA. The next likely standard size is probably 3.5 KVA. Possibly 4.0 KVA.

It has been many years since I have bought one. Surely the price is much higher now. But in 1988, I purchased a 5.0 KVA for a power supply. Price was well under a US$60. Yes, that was then. Even at thrice the price, it makes for an elegant solution to the problem. As it happens, there is a transformer with the exact turns ratios to suit the application. But, they were, even in '88, over twice the price of a *standard* part.

The whole point of this exercise was to illustrate series aiding connections and the concept of transformers. I did not go into great detail. There are many books available that will stuff you full of the formulas for these calculations. I would say don't bother. Study transformers and learn more about them. Then do your own calculations.

I suppose, before we look at poly-phase transformation, we should look at why we even need transformers. In this subject, I hold some very strong opinions and tend to denigrate one of America's technological icons. If you are offended at that, there is nothing more to discuss. Plain and simple, Tommy Edison was not the brilliant genius that history makes him out to be. He had dogged perseverance, yes. Far and away greater than anyone I know of in this generation. And as stubborn as a mule. Maybe mules learned from him. I don't know.

Edison was a D-C man. In the face of overwhelming evidence to the contrary, he persisted with insisting on D-C distribution. Sunk a goodly portion of his own money into it. Good motivation for not admitting your error. But poor judgement, in my book.

And to answer the ubiquitous question, it's his fault we use a split 120-240 volt system. There were a goodly number of urban power plants running at full capacity on D-C before Nicolai Tesla found someone that would listen to his admittedly *radical* ideas.

Conceded, Tesla had the reputation of being a crackpot, of sorts. And he didn't have the good American sounding name of his arch competitor. But, the man was knowledgeable of magnetics. Thomas Edison was experienced from his many experiments, but did not have the vision to follow through with some of the results.

Tesla, at one time, actually was an assistant to Edison. They had a falling out over A-C versus D-C generation and distribution. D-C was inefficient, high maintenance, and somewhat hard to handle. But, it was a known quantity. It was in regular use. And could use storage batteries as backup if a generator went south. Tesla's A-C theories were just that; unproven theories. And he *did* have a number of spectacular failures to his credit.

So, Edison canned Tesla, at about the same time Tesla told him to take his job and shove it. Tesla then spent quite a while finding someone wealthy and adventurous enough to back his crackpot ideas. Fortunately for us, he did.

D-C power generation requires a mechanically complex arrangement of brushes and commutation surface. Take a sewing machine or vacuum cleaner motor apart. The copper bars that carry the brushes are the commutator. Imagine such a motor the size of freight truck. Yeah, they exist. I've worked on them. All 1260 brushes. 5000 HP. But, I digress. The sewing machine motor in your hand is also a generator. Primitive and crude, yes. But, connected to a prime mover, it will generate D-C.

A-C, on the other hand, requires a magnet spinning inside a stationary frame with coils. Two bearings. No other moving parts.

In both cases, the simplicity is overstated. A D-C generator is much more complex than the motor in hand. An alternator has other parts.

When one opens a switch under load, D-C will arc, ionize the air and continue to arc over a significant gap. At 260 volts, on cranes, I have seen arcs maintain over nearly two feet. With A-C, the arc reverses polarity 120 times a second. The reversed polarity extinguishes the arc.

Line losses in a D-C system are not recoverable. One must increase the generating voltage to compensate for these losses. At the limit of distance, one must set a motor and a generator. This M-G set regenerates the voltage at the original level for further transmission. Look to the "power houses" used to power urban street cars away back when. With A-C, one simply adds a "boost" transformer to boost the voltage back up to the desired level. Just as we did with the workshop feed above.

D-C *does* have it's advantages. When the job calls for brute force torque, make the copper big enough and the brushes numerous enough and you can move a battle ship. Literally. Many marine propulsion systems are D-C. Especially those where regular speed changes are necessary. Tug boats, ice breakers, and many of the highly maneuverable warships.

One of the cranes where I work has the capacity to deadlift over 300 tons. And travel with it at something like 60 or 70 feet per minute. We are talking not too small a ship that this thing could move. Railroad propulsion; again, incredible amounts of torque to overcome the static load and start a train of several thousand tons. The sewing machine motor in your hand is but a smaller version of that power.

On the other hand, maintenance costs for such machinery are also enormous. Stop and consider just how many A-C motors are running in the background around you. The line powered clock or clock radio. The ice box, air conditioner, humidifier, a couple fans, your machines, and on and on and on. So seldom do these machines fail that we often forget they are there. And when they do, it's usually something like a dry bearing or a failed contact.

Transformers allow us to shift voltages around as is appropriate to the given situation. And at 98% efficiency with no moving parts, what more could you ask? The most noticeable of these shifts involve transmission lines. To understand why we need high voltage for transmission, we must look at line losses. Just as I said earlier, every detail depends in a pile of other details.

See that smoke? It's eye squared are. Let's go back to basic Ohm's Law. E=IR. And P=EI. Play the algebra game a little. P=EI and E=IR, so P=(IR)I or P=IxIxR. The IxI is I^2 so $P=I^2R$.

I had mentioned that wire does have resistance. With copper, it is rated as ohms per thousand feet. A goodly sized wire, say AWG 4 may have 0.1 ohms per thousand feet. That is 0.5 ohms per mile. 5 ohms in ten miles. Whoopee....... But at the currents called for in distribution, that 5 ohms can be the difference in a solid plant or a very long heater.

Consider a residential neighborhood. My house is the exception here, I have a 225 amp service. Let's say every house has a 150. So, there are 40 houses with 150 amp load. Derated for actual service load there are still 40 houses at 50 amps. That's 2000 amps. Consistently. I^2 then is 4 **million**. Times the 5 ohms for the 10 miles back to the substation. I^2R losses, *wasted heat losses* on the order of 20 mega-watts. That's somewhat more than the full capacity of some power plants I have worked in.

These losses are what was eating Tommy Edison's lunch. Back then, it wasn't residential loads. It was businesses. But, losses all the same. Enter the fellow with the funny name, damn furriner. Take those same 40 houses. Use a transformer to reduce the line potential to a usable level at the load. But instead of 230 volts, let's use 2300 volts for distribution. Now, the same transmission line, 5 ohms for 10 miles, only carries 200 amps. I^2R again. 40,000 watts; 40 KW in line losses.

Still too much? Let's try it with 13.8KV. 13,800 volts is a common local distribution voltage. That 2000 amps is now 33 amps. Need to see the arithmetic? 13800 divided by 230 equals 60. Current is reduced by a factor of 60. So, the 2000 divided by 60 equals 33.3. Now the square of 33.3 is a fuzz over 1100 times the 5 ohms for ten miles gives us 5500 watts in losses. We are feeding power to 40 houses with less loss than a large space heater.

And the best part, the cost of copper. Wire large enough to handle 2000 amps is about the size of my arm. Wire to handle 35 amps is about the size of the clicker on a ball point pen. Tons of weight that doesn't need supporting. And the capital costs? More than enough to pay for the fancy insulators. They are ceramic. They're made out of *mud*, of all things. Just how much cheaper can you get?

Transmission lines serve a much larger load than we saw here with our little neighborhood. And they use a much higher voltage. 115 KV and 230 KV are common levels. But when you compare the cost of the special towers and insulators to the cost of mega-watts of waste heat, I think it's a bargain. The economy of scale.

What our neighborhood did show was a sample of the values involved. It allowed simplified arithmetic, and easy to grasp numbers. And, when considering the size of such a plant, one can begin to see where power factor plays an important part.

With at least a modicum of understanding for the why and how of transformers, let's look at some applications. Most of this will be industrial in nature, but the principles will apply just as well to the home shop. Simply on a smaller scale.

Should you decide to tinker, I do suggest you set up a low voltage A-C supply to test an unknown transformer. Consider what would happen if you hooked up a doorbell transformer backward. 120 volts on the low side. If it didn't blow up in your face, the output would be over 700 volts. Not the sort of potential I would want floating around **my** bench.

By using an old tube type TV power transformer, a 6.3 volt source is convenient to the bench. That 6.3 volts connected to the winding in question would generate about 50 volts on the high side. From that you can determine the turns ratio and take an educated guess at the intended voltages.

And, since I just thought about power supplies, this may save you some effort. Computer power supplies are easily obtained, how many X-Ts and A-Ts have been scrapped out is anyone's guess. I have literally a dozen or more out in the barn. Convenient source of several amps worth of regulated 5 volts.

Because of the world wide market for computers, they mostly contain a *universal* power supply; 90-250 volts, 40-100 hertz. Or there abouts. Just inside the high voltage section, there is a rectifier and filter circuit. This D-C is then chopped up with an oscillator to a fairly high frequency. Xerox used 4000 cycles. I'm not too sure about the rest. But, similar, I'm sure.

Now, harken back to our discussion on hysteresis. The characteristics of the magnetic elements are tuned to the frequency. One of the great advantages of a higher frequency is the smaller physical package. Notice the small transformer that looks just like a power transformer. That's exactly what it is. Were that transformer sized to work at 60 Hertz in linear mode, it would be the size of the entire power supply.

The low side works just as if it were a linear power supply, tapping out the desired voltages, rectifying and filtering, and finally regulation. Power has been generated at many frequencies over the years. I am sure that each was justifiable in the particular circumstances. Just as the rest of the world settled on 50 Hz, the U.S. settled on 60. Because of the enormous existing installed plant. The cost of changing over would have been horrendous and becomes more so every day.

I personally have never worked with any frequencies other than 50 and 60 Hz. I have *seen some* of the other systems in place and operating. But not to work on them. T.C.&I.'s Ensley Works had a 25 Hz plant. It was closed in the early '80s and cut up for scrap. The 25 cycles had to do with the underground equipment in the coal mines. In those days, the mines and the mills worked as a unit. Other oddball frequencies were 120 and 400. I have read of 40 Hz plants.

Remember the old black and white movies with Bogey in the Egyptian desert bars? Or was it Algerian? Or John Wayne in the South Seas, Somebody's Reef. Anyway, the ceiling fans turned incredibly slow. For a long time, I thought it was artifacting in the conversion from film to television. But then, somewhere along the line, I realized it was a low frequency power system. 25 Hz would cause such slow speed. Any opinions out there?

The U.S. Navy experimented a few years ago with 400 Hz designs in an attempt to miniaturize certain types of equipment aboard ships. Imagine a 7-1/2 HP motor no larger than the motor on our 9x20 lathes. That was the advantage. There are several reasons why it didn't work out. I read about them and dismissed the matter. It is obsolete equipment now. And with the miniaturization brought about by solid state and computers, many magnetic applications where 400 Hz had an advantage have been supplanted by solid state technology.

However, the size factor becomes important in aircraft. Many military and civilian airplanes have 400 cycle systems. The tradeoff in favor of size is worth the effort in dealing with the other performance problems.

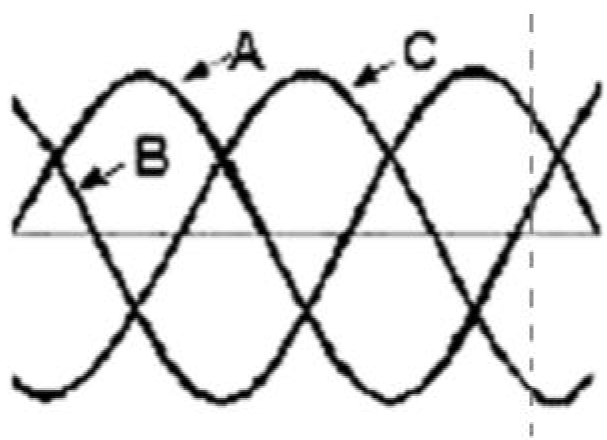
There is really no need to go into the other frequencies and it has no relevance to the discussion. But it is an interesting subject and needed to be introduced. This was as good a place as any.

The generator is usually three phase. I have worked on systems with six phases, but they were limited in the scope of their distribution. Two phase? I have not seen such a plant in many years. Including the time I spent in the" third world". There may be a two phase plant still in operation. I just don't know about it. Six phase has specific industrial applications. Archaic technology still in use. It usually is broken down into two distinct 3 phase systems.

Power plants will vary in size from the gasoline powered stand-by gen-set you have in the garage to the multi-thousand mega-watt nuke plants. The generators will range from 240/120 upward. The highest voltage alternator I personally have worked on was a 13,800 turbine.

Let's start with a 4160 volt generator. An alternator, if you like. Three phase because that has become the "standard". You'll see why later, when we delve into motors. In a power plant, there are usually two or three, or more, generators running in parallel. Synchronization and load sharing is a specialized subject that I won't go into right now.

The combined output might be on the order of 12 mega-watts. No reason, just round numbers to work with. With each generator at 4 Mwatts and 4160 volts that's about 580 amps per machine. If you were following my calculations, you will be squawking at my figures. Yup, it's a test to see if you were paying attention. Try multiplying that number by 1.73. That should bring us up close to 1000 amps.



The 1.73 is a multiplier we will encounter everywhere in three phase systems. Remember this wave form from the conversation on alternators? The "X" axis, horizontal, is time. In this case, 16.6 mSec, 1/60 second, one cycle. The "Y" axis, vertical, is current as it is delivered to the load. Look to the right side, there is a dotted line indicating a time slice. Take the arithmetic sum of the three sine waves. As it is shown, two are positive, one is negative. The sum of these is any one wave multiplied by 1.73. Place this line anywhere along the time axis and make the calculation. The result will be the same.

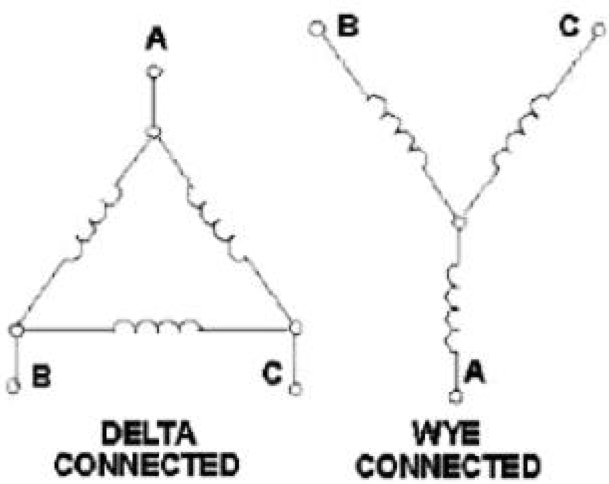
Earlier, I had made a derogatory reference to rote memorization of formulas. This will be an exception. 1.73 is the square root of three. We will also encounter the inverse of this, 0.57, on a regular basis. The phase current, at any instant, is 57% of the total output of a three phase machine. Or, call it phase times 1.73. Or line divided by 1.73. There are many ways to think of it. Just be sure you *do* think of it. It becomes important when converting three phase watts to phase currents.

So, we have a power plant capable of delivering 12 MegaWatts into a distribution system. Roughly 1800 amps phase current. As I said before, the copper capable of carrying this current is the size of my arm.

To get the current down to managable proportions, we will increase the voltage. As you have seen, the turns ratio is inverted for voltage and current. High current low voltage. If you can call 4160 volts low. Although a stretch, it really is. So, let's go to 125KV.

4160 : 125,000 is a ratio of 1:30. Approximately. So, current will be reduced by the same ratio 30:1. Our 1800 amps is now 60 amps. Yes, we need insulators a couple or three feet long. Such transmission lines are readily visible just about anywhere. In the area where the power is to be used, the 125 KV is again transformed down, but to, say, 42KV. About 3:1 ratio. These feeders then feed "sub" substations where it is again reduced to 4160. About 10:1.

The reasoning here has to do with the physical properties of the transmission lines. Imagine trying to build the cross country towers in an urban setting. The logistics would be tremendous. There *is* a trend in this direction, using modern insulations and underground feeders. But the air gaps necessary and the physical size of the transformers place a limit on the practicality of such a move. Anyway, we have now a local distribution network with a phase voltage of 4160.

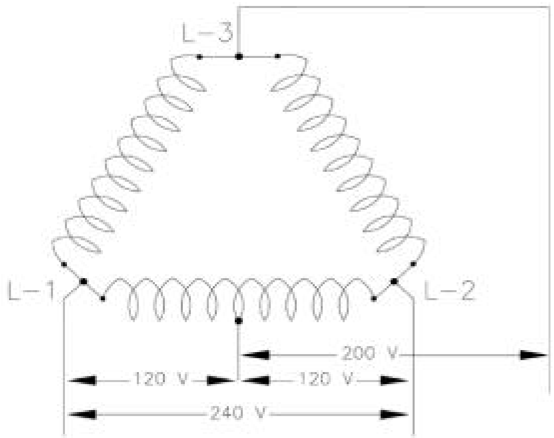


There are two ways to make up poly-phase transformers. **Star**, or **Wye**, has the three windings tied to a common point, and to a phase. **Delta** is connected phase to phase.

This is where we bump into the 1.73 multiplier again. Notice the Delta connections to the left. The voltage across the phase is the same as the line to line voltage. On the Wye connection, however, the phase voltage is line divided by 1.73. Or 57 percent.

So what? Well, let's start with a 10:1 transformer. Connect the primary as Delta. Connect the secondary as delta. Phase voltages are (P)4160, (S)416. Sound familiar? 416 is the predecessor of 440 volt systems. Some old equipment will still show 416 on the motor nameplates.

But, this is a residential and small business neighborhood. 416 is a little like using a howitzer as a flyswatter. Suppose we connect the primary, high voltage side as Wye. Now, the "**Phase**" voltage of the transformer is 57% of the **"Line**" voltage. So, at 10:1, the primary *winding* will have 2400 volts applied. At 10:1, this will give 240 phase voltage on the secondary. A 240 volt, three phase system.



But we still must accomodate the 120 volt lines. So, one phase will have a center tap. 240 / 120 volts. There is a caveat here, though. That 1.73 raises it's ugly head.

Line to neutral for the center tapped winding will yield 120 volts. Line 3 though, because it comes from across a full winding and half of another, divided by 1.73, yields 200 volts to neutral. Not the sort of power you want across your 120 volt electric razor.

Usually referred to as the "Wild Leg" by wiremen, there are two ways of handling this. The first is to rethink our transformation that we explored above. Instead of connecting the primary as Wye and taking out the secondary as Delta, let us use a 20:1 transformer.

Connect the primary as wye, just as we did earlier. But this time, because of the 20:1 ratio, we get 120 volts *phase* voltage on the secondary. Much too low to be of use, so we connect the secondary as Wye as well. Now we take the 120 phase voltage multiplied by 1.73, and get 208. Sound familiar? Many older systems with this configuration are still in service.

Phase to phase provides the 200 plus volts and phase to neutral provides the 120 volts. All three phases can reference to the neutral, thus balancing the phase load.

I mentioned a second solution to the wild leg problem. That is to convert from 4160 through a 20:1 transformer and connect the secondary phases as Delta. This produces a three phase 120 volt system. Harken back to the early discussions on residential load centers. I had stated that there were exceptions to the *grounded neutral* requirement.

This is such a case where the neutral or return wire cannot be tied to ground. Thus requiring a separate ground conductor. From any one wire of a 120 volt appliance to ground should yield about 68 volts. If the system is intact. And no ground faults. And no moisture in the system. And the weather is clear.

Such installations are common in hospitals and large office buildings with extensive 120 volt circuits. They are handled just as any other three phase system for distribution.

There is a 480 volt delta system that has been outlawed in the States for a number of years. I bring it up because the code alows such installations to continue in operation under a “Grandfather” clause. I have come face to face with my mortality on several occasions with “Grounded Delta” systems. If you are not working as an electrician or a wireman, you will be unlikely to encounter it. And if you are, you likely already know what I speak of.

One phase of the line is intentionally grounded. This makes the other two phases 480 to ground. I have taken phase to phase across the chest and lived to tell about it. Somebody up there likes me.

The premise is valid. In an ungrounded system, the ground reference will move around in a random manner. Ask any marine electrician about the misery this causes. If a phase picks up a ground, it becomes a short and clears a fuse. No fiddle faddle leakage that comes and goes with the weather. It clears the fuse and it gets fixed. Hopefully, you will never have to deal with one.

There are many combinations of transformation used to solve specific problems. Consider the insulation classes. In the U.S., they are 150, 300, 600, and the high voltage stuff. In most cases, 600 and up is considered beyond the scope of the average electrician. There are exceptions. I have worked with motors of 2300, 4160, 6900, and 7200 volts rating. I’ll be telling some tales later about some of these. For now, let’s solve some low voltage problems.

Continental Europe uses 360 volts for three phase motors. I do not know how widespread this voltage is, but I have encountered it on many occasions with French built equipment. So, we have a French built machine and want to run it from 480 volts. The simplist, brute force solution would be to use three buck-boost transformers, just as we did earlier to increase your 208 to 240. But this time, we use 120 volt windings and connect series opposing. 480-120=360. This would work the other way, as well. 240+120=360 with a series aiding connection to a 240 volt supply.

There is a type of “Control” transformer in a sand filled enclosure used for general purpose applications. The high side is two 240 volt windings, the low side has two 120 volt windings. They become 480-240 X 240-120 transformers. Basically a transformer with 2:1 turns ratio. Such transformers are available from 500 VA to 50 KVA or more. 50 KVA is a *lot* of transformer.

As we saw earlier, one need not connect a winding to it's rated voltage. Never above, but lower is not a problem. So, we connect the primary side as 480 but connect three of them them as Wye. This is a phase voltage of 277 from a 480 volt system. The secondary voltages then are 135 volts phase. With this connected as series opposing to the line supply, the derived voltage is about 350 volts. A little low, but well within tolerance.

When we calculated the size of the transformer, the less wattage we must transform translates into the smaller the transformer. In this case, either option produces the same approximate voltage. But the second option does not require we transform the entire line. Only the 130 odd volts bucking. Smaller transformers, less copper, lower cost.

The 277 volts may have rung a bell with some folks. It is common practice to bring out 480 volts from the substation in a Wye configuration. With the center tap grounded, each leg is 277 volts to ground / neutral. Large area lighting is available and in common use at 277 volts. In an area with only a few 120 volt requirements, 480-277 is quite common. Higher voltage means lower current. Less copper, lower cost. Run the machines at 480, the lighting at 277.

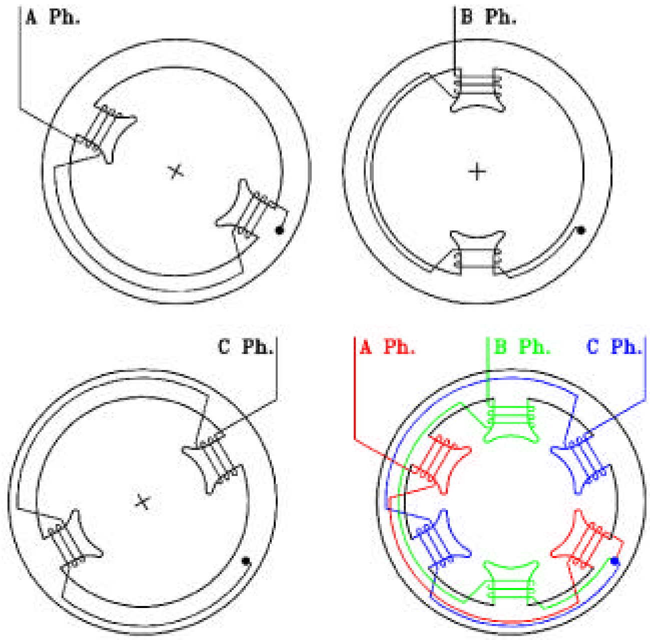
Anybody over the age of 25 should remember the little "Kissy Face dogs". Toys that looked like Scotties or Yorkies, with magnets in the base. If they were pushed face to face, they would attract, seemingly kissing. Any other position they would push apart. Probably the most effective demonstration of magnetism ever made. Simply because it was cute and would attract kids of any age.

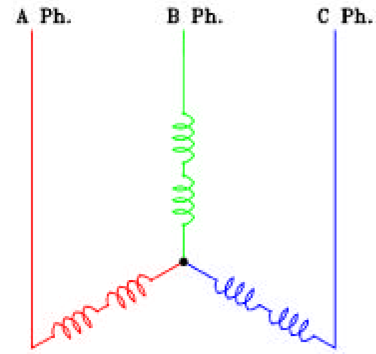
All the hub-bub in the last 2/3 of this article has been to show how electricity creates that same magnetic attraction and repulsion. With a few side trips into interesting applications. I like to talk, what can I say.

So, now that you have weathered nearly forty pages, let's get into motors and how they work. And yes, all the foregoing, except the sea stories, really was necessary.

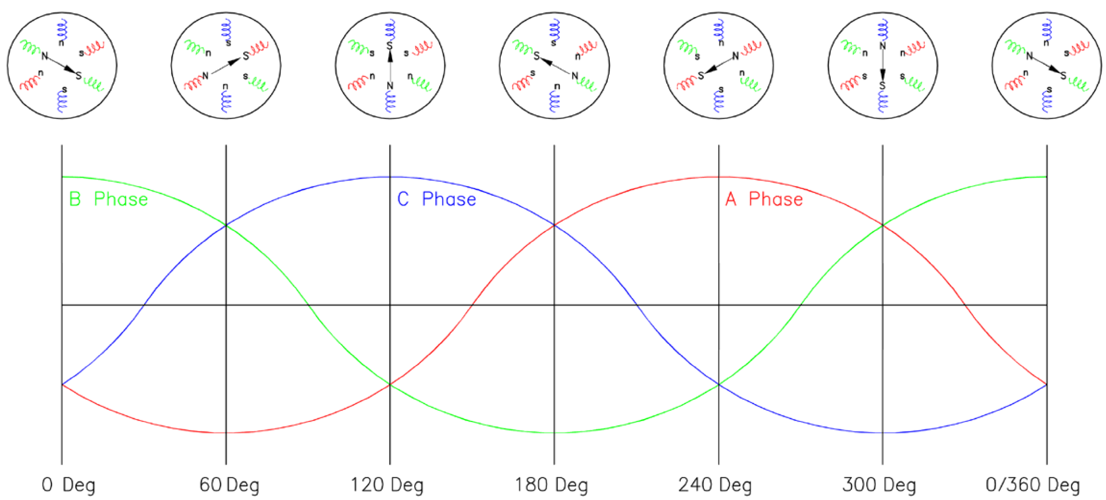
Most texts introduce the subject with repulsion motors. D-C and series universal. I prefer to start with three phase, lots fewer parts to keep track of. Once you have a grasp of the induction motor, the rest just sort of fall into place.

The illustration shows, both schematically and in "elementary" form, the connections to a three phase line. It represents a two pole motor, so the rotating field will be 3600 RPM at 60 Hz. (3000 for 50 Hz) Notice the pole faces displaced 60 degrees. If you think of the lines of force across the center opening, as indicated by the (X), each pair is 120 degrees from the others.

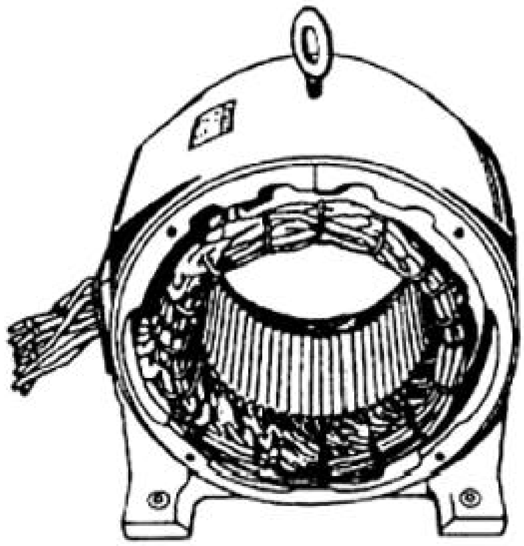




As the alternator produces three sine waves from a rotating magnet, we now are looking at reproducing that magnet inside the motor. Essentially reversing the process. You will note that the times shown in the illustration are indicative of the position of the rotating magnet in the alternator.

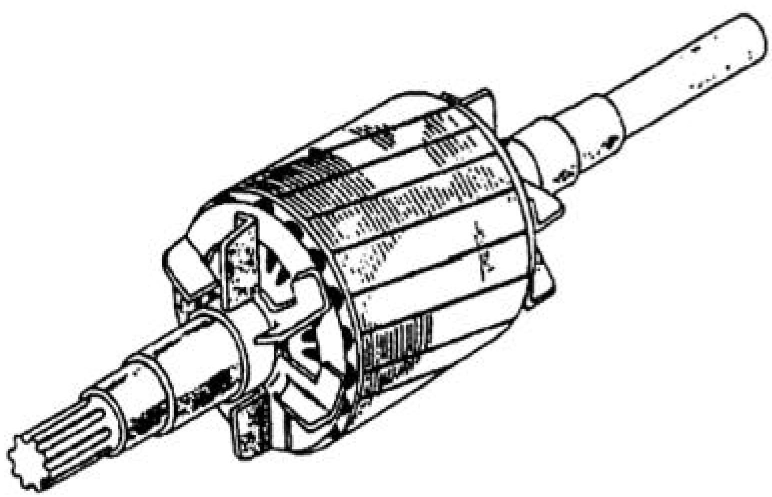


At time “**0**" **Phase B** has maximum current sinking to positive and creating a magnetic south as indicated by the arrow head. At time “**120**", the south pole has moved to align with the **Phase C** coil. Then again at time “**240**", the south pole has moved to align with **Phase A**. You will note that as each phase swings negative, current is sourcing through the second half of each coil. As at time “**60, 180**, and **300**".



The net result is an electro-magnet that literally rotates inside the frame of the motor. The speed of this rotating field is called the "Synchronous Speed". Many times I have connected a motor without the "guts' and spun a steel ball inside the stator frame to illustrate this field. The ball is actually pulled to the center of the frame as it spins.

Inside this rotating field is a "cage" made up of conducting bars. The cage can be of copper or other conductor. Many newer motors have the conducting bars imbedded into an aluminum casting. At each end is a ring, shorting the bars into the squirrel cage form.



Yes, this is a conductor buried in another conductor. As will be discussed shortly, while the currents are high, voltages tend to be very small. The current will follow the path of least resistance, seldom straying outside the cage proper.

The rotor illustrated here is of "skew" construction. This helps reduce "poling" or "cogging", smoothing out the vibration that occurs as the currents move around the cage.

Back around page 20, or thereabouts, we touched on magnetic coupling as it occurs in transformer windings. This mutual induction is the basis of operation in an "**induction" motor**. As illustrated on the preceding page, Phase B (green) is conducting at time "0", creating a field that increases as the current peaks, then collapses as the current falls off, approximately time "100".

Remember that the building and collapsing field is "moving". The lines of force travel further out from the coil as voltage (current) builds, then "fall" back as current decreases. Placing a conductor in that moving field creates a current flow within the conductor in the cage. This current passes through the end rings and another conductor of opposing polarity.

Since there is current flowing through the bar of the cage, there is a magnetic field that surrounds it. Now remember that the polarity of the induced field is opposite that of the “primary” that created it. At approximately time “100", the rotating field has advanced counter-clockwise. The field created in the cage bar is in opposition the this magnet, therefore attracted to it. So that bar, for the short life of the field before it collapses, is attracted to the rotating field. This attraction is the source of the torque in the rotor. Each iteration of this attraction is quite small, but combined as each bar is “cut” by lines of force from three pairs of coils a sizeable torque is produced.

With zero speed or stalled rotor, the torque is somewhat limited. The field merely sweeps by as it rotates. As the rotor begins to turn, the cage bars are cut by the building or collapsing lines of force, as well as the sweep, creating much higher currents. These currents, of course, translate directly into torque.

As the rotor approaches “synchronous” speed, the bars in the rotor are again being cut by fewer lines of force, hence a reduction in torque. The rotor slows until the bars are again cut by sufficient lines of force to balance the torque to the load. Thus, induction motors tend to be self regulating, variable torque, constant speed devices.

Looking at this concept, it becomes obvious the rotor can never achieve synchronous speed. Were it to do so, there would be no lines of force cutting the bars and no torque developed. The difference in the synchronous speed of the rotating magnetic field and the speed of the rotor is referred to as **slip**. I will often refer to a motor by it’s synchronous speed. Thus, a two pole, three phase motor is a 3600 RPM device. The actual speed as output is this value less the slip. For most motors, this speed will be on the order of 3450 RPM, a slip value of 150 RPM, approximately 5%. This value will vary some small amount by load, winding impedence, conductivity of the cage bars, and other factors.

A synchronous motor, on the other hand, *does* reach synchronous speed, hence the name. A synchronous motor is not self starting, however. It must be brought up to speed by other means. Sometimes by a kicker motor, more often as an induction motor. Once up to speed, less a nominal slip, a wound field on the rotor is energized, creating a magnet that directly follows the rotating magnet produced by the stator. It then “*locks*” into synchronization with that rotating field.

In both cases, there is the phenomena of “back EMF” or counter EMF. The rotor, with it’s magnetic fields created by induction or excitation, becomes a generator, creating it’s own output. This back EMF opposes the applied line voltage, reducing currents to nominal levels. As the load increases beyond the available torque, the rotor slows, this back EMF decreases, allowing higher currents to flow from the line. Should this continue, the magic smoke gets out and the motor doesn’t work any more.

The back EMF can be used to advantage with a synchronous motor. By over-exciting the rotor field, the motor can be caused to generate. The power generated feeds back into the line, with a **leading** power factor. This leading power factor will balance, or cancel, the usual lagging power factor seen with inductive loads.

Many older industrial operations will use a synchronous motor, coupled to a fairly constant load, specifically for this purpose. In every instance I have worked with such installations, they were driving large air compressors. The excitation is coupled to a power factor meter so that the field will self regulate within certain limits. Recalling back over the last 35 years or so, it seems like most, if not all, were in the 900 HP range.

Looking back to our calculations for power transmission losses, it is obvious that 900 HP at 480 volts would be terribly lossy. 2300 and 4160 are those I remember most. One was 6900, and I seem to recall having heard of one at 7200 volts.

The switchgear for such motors is how I came to be involved with high voltage transmission equipment. I have never worked as a high line electrician per se. But one cannot work that close to such equipment without some of it rubbing off.

Now, that sort of motor is a little esoteric for a discussion like this. Here, we are interested more in small, fractional horsepower equipment. The theory of operation applies to any three phase squirrel cage motor. Two phase motors work in a similar fashion. The primary difference is the rotating field has only four pole faces as compared to six for three phase. For a given winding, there will be less torque developed.

Two phase usually is four wire distribution, minimum is three. Three phase also requires four wires, minimum three. Three phase equipment is generally smaller for given power, so there is no practical gain in using two phase.

The important issue is to simulate the rotating field with single phase power. Obviously, if we use two pole faces, one winding with two coils, the field will simply toggle back and forth. If the motor is up to speed, this will work, but there is zero starting torque. We must artificially create the second phase to get starting torque.

Recall, from the discussion of magnetism and power factor, the delay between voltage rise and current flow. Lagging power factor. Also, the delay between current flow and rise of the magnetic field. Hysteresis. The formula was X_L=2 Pi F **L**. At the time, we were looking at the effects of (F), frequency. Let us now consider (L), the **Inductance** of the coil. Inductance, in this formula, has the same effect as frequency. Altering the reactance, through inductance, directly affects the rise time of the magnetic field. If we physically offset the altered windings within the frame of the motor, we can simulate the operation of a two phase motor.

Although 90 degrees offset is ideal from the standpoint of torque, there are practical limitations involving complexity. Such complexity translates into both cost and reliability. So, we consider the intended application and use one of several methods to accomplish the ***phase shift***.

In the simplest form, there is the **Shaded Pole**. A portion of the pole face is physically separated with a shading coil consisting of a conductive band encircling a portion of the pole face. The small fan that circulates air in a refrigerator is a common example of such a motor. Line powered clocks is another. These motors have fairly low torque, both starting and running, but are well suited to the intended application. Both simple and reliable, they are inexpensive to construct and last nearly forever. The usual failure is dry bearings or a stalled load. Their high impedence limits current to a safe value so, even stalled, they *normally* don't overheat and self destruct. Often, you will find such motors protected by a thermal link that opens on high temp. Usually about the size of a half watt resistor, they can be replaced or bypassed.

The next method up the "food chain" is **permanant split phase**. Here, there is actually a second winding that has slightly higher or lower reactance. Whether the secondary field leads or lags the primary is moot. So long as there is an offset to simulate the second phase. Permanant split phase motors are common with larger fans as would be used for ventilation. Ceiling fans and floor fans are a common form of such motors. They are also often seen as condensor fans on air conditioners and blowers of forced air heating systems.

More common today is the **permanant split capacitor** type motor. They are used in larger fans and similar loads. They will be distinguishable by the small capacitor package and no start switch. (Centrifugal switch)

Of most interest to us here is the **capacitor start** motor. This motor will be evidenced by the large external capacitor can, a centrifugal switch and the general appearance of a serious work horse motor.

Most times, the motor will be reversable. This is accomplished by reversing the magnetic relationship of the start and run windings. Simply reverse the start winding leads and the motor will start backwards.

Such motors cannot be used in **plugging** service. Plugging a motor is a form of braking wherein the motor is reversed for a short time. Capacitor start motors run with the start winding open at normal speed and depend on the inertia of the rotor to generate the coupling to the run winding. Quickly reversing the motor simply re-energizes the run winding. Only when the motor slows sufficiently for the centrifugal switch to drop out can the motor be reversed.

Dynamic braking can be achieved by applying a D-C current to both sets of windings after the switch is opened. However, the nature of dynamic braking is such that it cannot stop the motor, only slow it. The D-C must be applied only long enough to slow the motor. More than a few seconds can damage the motor.

If you want to try dynamics, use a transformer to cut the line voltage to about half. 120 to 60, 240 to 120, etc. Rectify this and use a relay to apply it to the motor leads for a couple seconds. Be sure to interlock to the power switch. Polarity is unimportant.

Common maintenance problems with these motors are:

1> High temperature. Be sure the vents are open.

2> Bearings. Many of them have sleeve bearings and must be wet lubricated. Some of the Asian made motors will have a well made of low grade cotton waste that will dry and harden over time. I usually disassemble such wells and use a piece of old "Tee" shirt to repack the resevoir. "Tee" shirts are mostly cotton.

3> Start switch. Welded contacts keep the start winding powered on all the time. Resulting in lots of torque but high temperatures. Usually, we don't find this until the smoke gets out and it won't start any more.

Open contacts mean the start winding never comes on. No starting torque and the same general result as above. Well made motors from known manufacturers often have a repair kit available for the switch.

4> Capacitor aging and/or wearing. Yes, capacitors *will* "wear out" with time. The size of the capacitor is determined by the inductive reactance of the windings. Just arbitrarily changing capacitors may or **may not** work. Make a note of the capacitance when it is new and write it down inside the switch box or cover.

There are numerous methods of connecting the start winding. The form used will depend on other functions of the motor. For example: the motor may have the start winding tapped into the center of the windings so that the motor may be reversed simply by moving a single lead from one side of the line to the other. Another common method involves moving two leads, swapping them to reverse direction.

The most reliable source of this information is, of course, the nameplate. Should the name plate be damaged, a brand name manufacturer may have their terminations printed or posted on a web site.

Worst case is to "*ring out*" the motor with an ohm-meter. Make a sketch as you go and pay close attention to the resistance readings. They will be fairly low, from two to ten ohms. The lower resistance windings are probably the start windings, although this is not a hard and fast rule.

Remember, too, that the start winding will have a capacitor in series. Measurements must be taken below the capacitor, but then if there is a capacitor, it is the start winding and maybe doesn't need measuring.

A compass is useful here to determine the polarity of a particular winding. As the ohm-meter power is on the coil, hold the compass near the frame. It should indicate the polarity of the field. It may be necessary to use a stronger battery, such as a six volt lantern battery.

In the last resort, I have connected the leads in a logical manner and powered on the motor for a few seconds. Growling or vibration is an obvious indication that the connections are not correct. So also is smoke or a tripped breaker. So, try another combination. I apologize, this particular technique cannot be readily imparted verbally. The "scientific wild ass guess" is based on many years experience and cannot be easily quantified.

There is a great deal more I would like to discuss about motors; how to use them as generators, running three phase motors from single phase power, using an automotive alternator to generate 120 volts...... Such topics involve details beyond the scope of this document; perhaps I will write an addendum when time permits.

There isn't a lot I can tell about transmission lines. If you have ever watched a T-V show on the subject, you would know about as much as I do. For the most part, what I speak of here relates to local distribution systems, 13800, 6900, 4160, and 2300. Switchboards and transformers aren't much different from their low voltage equivalent, just larger.

High line cable is often made of aluminum. It has higher resistance than copper, so line losses are somewhat higher. But, it is much lighter. Looking at a transmission line, the spans seem like they are a half mile between towers. That's a lot of weight to support. In most cases it is simply bare wire.

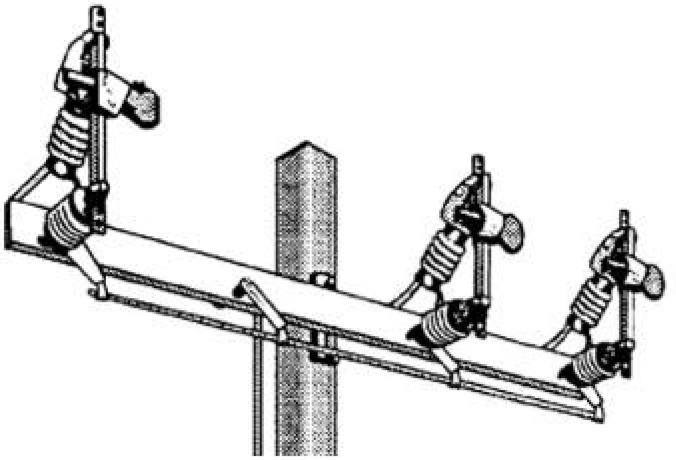
Another common wire is "CopperWeld", where a steel core has a copper conductor bonded to the outside. Not really plated, it is much thicker. Imagine copper tubing with a steel core. The steel core, of course, provides the strength that permits long spans.

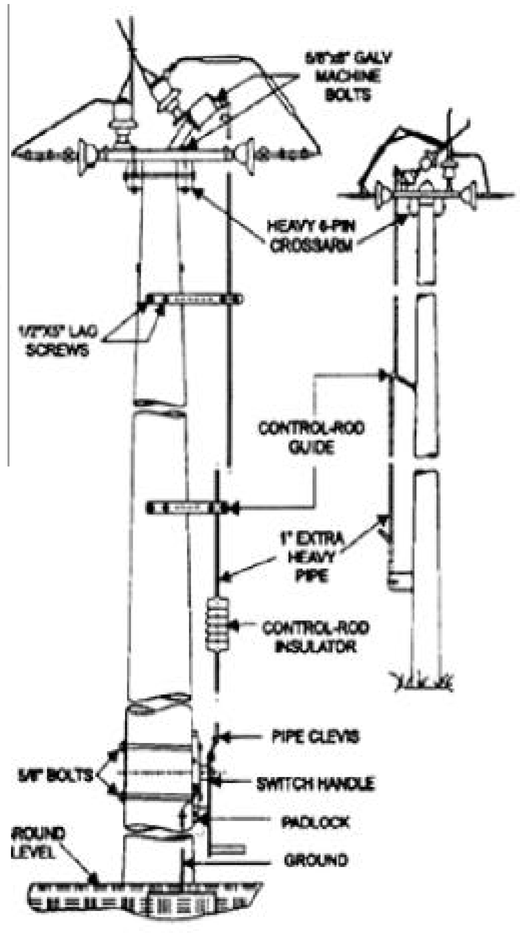
There is a rule of thumb for ceramic insulators. One inch per thousand volts. Possibly useful if you are scouting out lines and circuits. Otherwise, just more esoteric information.

At the "lower" voltages, 13-8 and 4160, pole lines will often carry multiple circuits of different voltages. As a rule, the highest voltage will be the upper conductors. There are exceptions, although rare. I recall, specifically, a system in the Caroline Islands where a 240 volt drop was taken off of a 13-8 transformer, with both low and high voltage fed between 4160 phase conductors. All I can say is that, thankfully, I was there for computer work and didn't have to deal with it.

I had mentioned earlier that A-C is *not as prone* to arcing as D-C. This applies more to the low voltage lines. At high voltage, moisture in the air can be all that's needed to sustain an arc. The air won't stay ionized, but the current is running the moisture.

There were some specific background details that I won't bore you with; it was **my error**. The blame cannot be shifted. I opened a 44KV air break switch under full load. The blades *were* some five feet long. When the arc finally gave out, there was about a foot of the blades left. Took two days to get it back in service. That story has followed me around for twenty years. And my reaction always gets a good laugh, from me *and* from the listeners. In my book, a man that can't laugh at himself isn't much of a man.

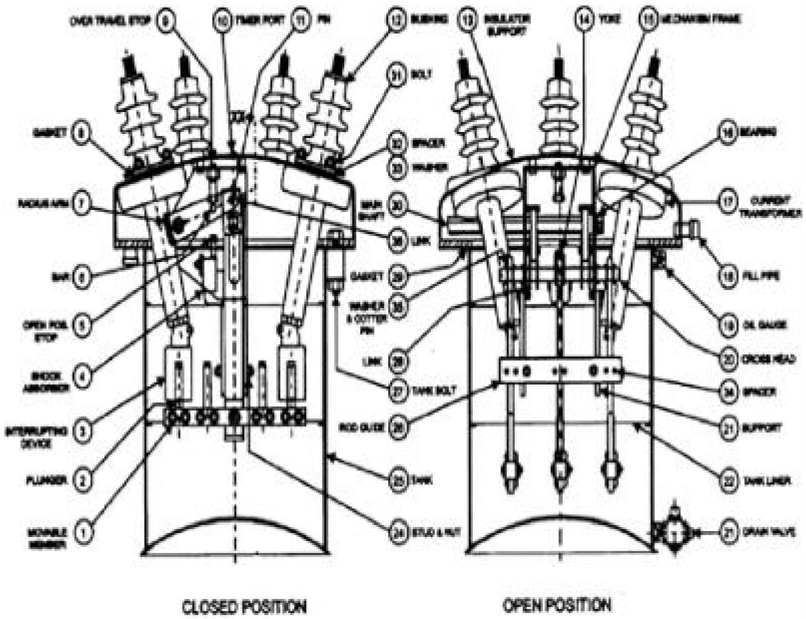




There are three types of high voltage switches. **Air break, Vacuum break**, and **Oil break**. As noted above, opening an air break switch under load is not a good thing. They are used mostly for isolation. Sure is nice to walk up and see the knife arms out and grounded before starting work. There is no question it is safe to work. They may be manually operated or motorized. Or both, as appropriate.

Vacuum break switches are normally used for remote control. They are solenoid operated, which lends many avenues of control. They *can* operate under load, but it degrades the switch contacts. Obviously, with no air, there is no arc. But there are minuscule bits of copper vaporized with each operation. Over time, this pitting will ruin the contact. Sometimes, they will fail closed, from welding. That is the most hazardous condition. Vacuum switches usually are solenoid operated in both conditions. One to close, another to open.

Oil break switches are the high voltage equivilant of contactors. They are the component that can handle opening under load. The oil is very similar to transformer oil. Very high dielectric strength, carefully monitored for water. Anything over a couple parts per million is considered contaminated.

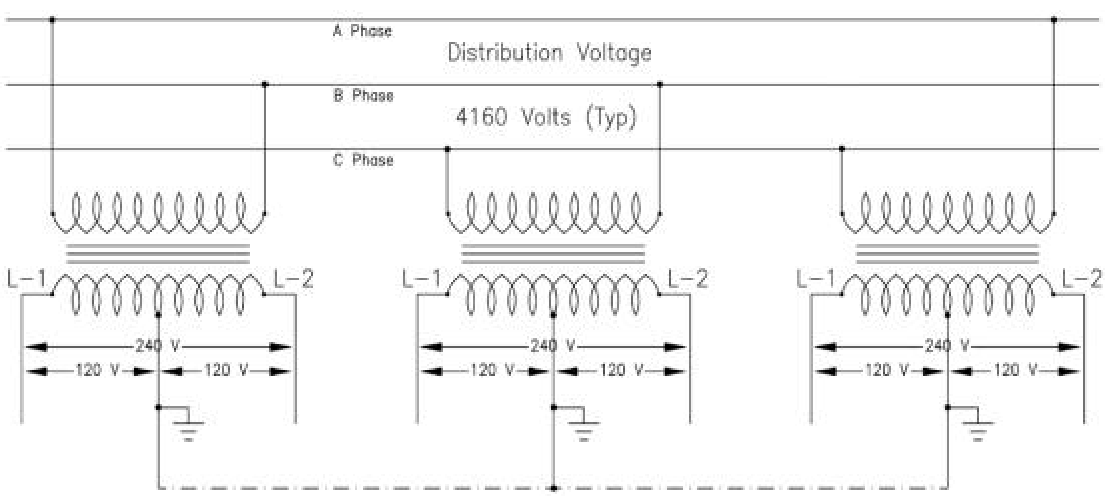


Oil break switches are usually spring operated in both conditions. Then motors rewind the springs, “charging” them for the next operation. The reasoning here is that the faster the contact closes or opens, the less damage from melting off tiny pieces of copper.

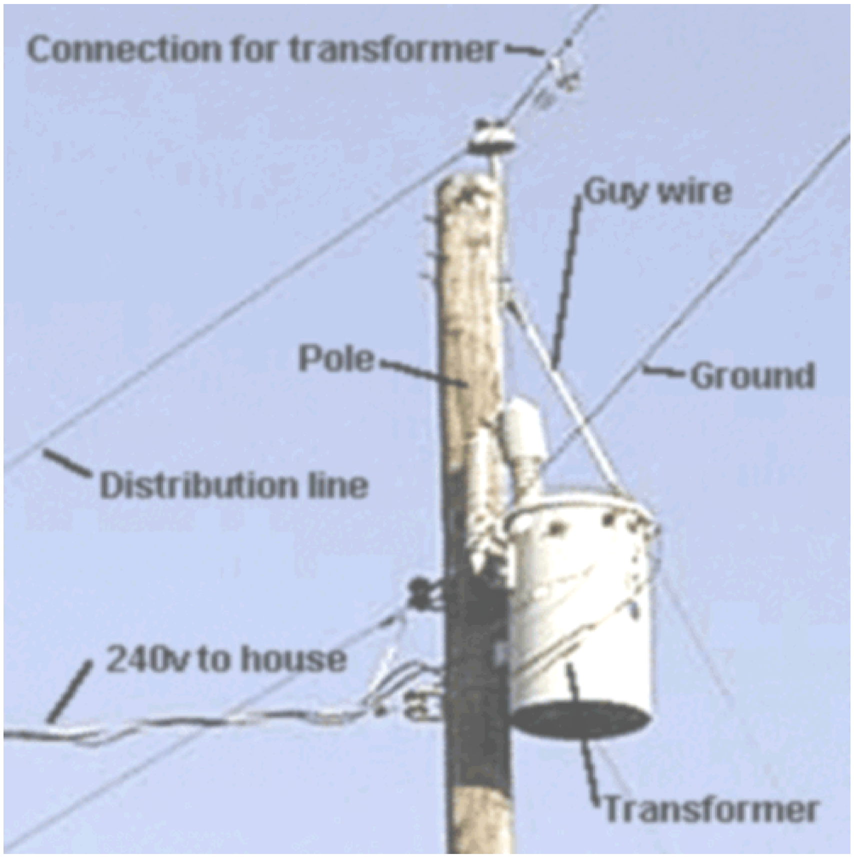
Spring loaded switches are often used in line voltage distribution, as well. Because of the high currents involved.

The portions of a transmission system that you are likely to be involved with will be the pole line, or possibly underground, feeders to a neighborhood. The three phase is transformed to distribution voltages and **magnetically isolated**.

Magnetic, or transformer, isolation is how they manage to balance the phase load with each phase having a grounded center tap. There is no *electrical* connection between the center taps and the distribution phases.



The dashed line on the bottom does not exist as a specific conductor. Through bonding and the natural conductivity of the ground, there is a low impedence path between neutrals from the various transformers. The bars in each transformer indicate “magnetic isolation”.



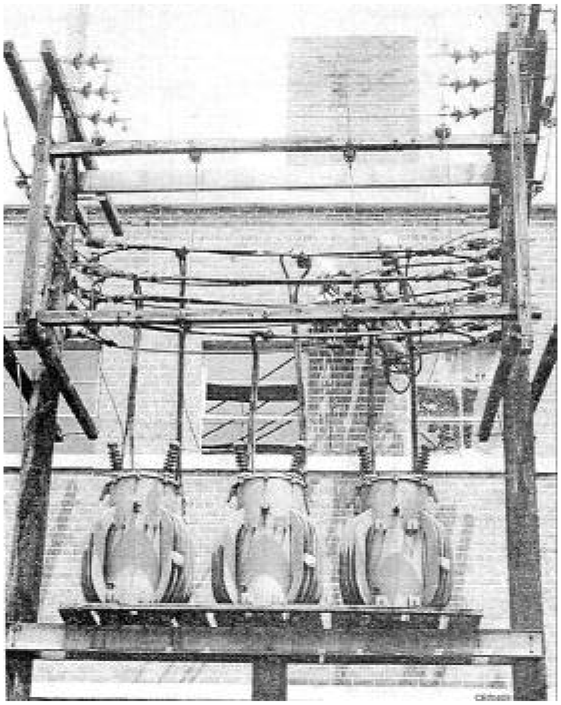
As shown earlier in a schematic form, this photo illustrates the typical service to a residential customer.

The fuse we were discussing early on is the gizmo just above the transformer can and to the right of the word “Distribution Line”. There is a connector on the top line that is fabricated similar to a “C” clamp so the tap can be connected or opened with the distribution line hot. A bucket and rubber gloves are the only requirement.

This fuse is to protect the tansformer and the high voltage lines. It does not protect the load, the drop to the residence. So, why did the new machine clear the jack. It should not have; probably just a fluke in timing. It is not unusual to clear a new fuse when it is installed, especially if the line is at or near capacity. But I got you to read this whole article looking for the answer.

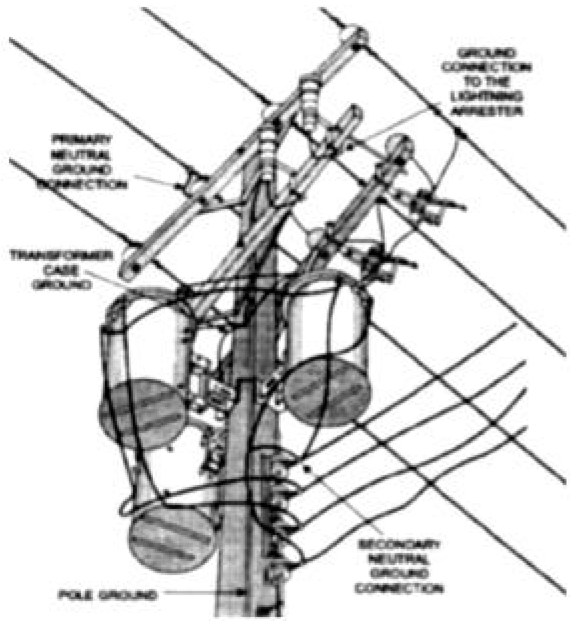
My bet would be that the machine was a three phase machine. Red, Black and White as the phases with Green as a ground. Likely a high voltage machine, as well. 240 or 480 line.

Look in the control cabinet at the incoming line. There should be a disconnect or main switch. Also, the motor starter; two leads is a single phase motor, three means a two or three phase motor. Look at the connections on the control transformer. That will indicate the voltage the machine is designed to run on.



Three phase, as it is delivered to a light industrial load, is shown in the photo left.

Small substations such as this are commonly raised above the ground to limit access. Much simpler than a fenced compound.



Very small three phase drops simply have the transformers mounted on a service pole. Such an installation is similar to a residential single phase service, just with the additional transformers.

This brings up another point; when I was expounding on three phase transformers, I neglected to discuss “Open Delta” configuration. This is a method whereby three phase may be transformed using only two transformers. I personaly have never seen it used outside of an emergency situation. I am told, however, that it is sometimes used when the cost of three transformers outweighs the larger sizes required.