ELECTRONOTES

WEBNOTE 13 8/27/2013

ENWN-13

FUN WITH GROUNDS AND NEUTRALS

As reported in the last Webnote, we recently had an adventure with a failed AC supply line, Very interesting. Many people who have heard this story have remarked that we were lucky we did not lose the “neutral”. I know a fair amount about electricity and a bit about electrical wiring. But I did not really understand this, or at least thought that a good number of important and specific details were missing. If one runs to the Internet you find questions and answers about lost neutrals. This would be more reassuring if it were not usually the case that one person answers and another says that the first guy’s reply was nonsense, etc. Here I have no final answers because I do not know well enough how power lines are installed, or supposed to be installed, in my area, in other areas of the country, and certainly not around the world. So here I discuss things that help us to ask the right questions, based on the common experienced I think most of the readers here share. But I will begin with what are probably some less familiar examples.

CRYSTAL SETS DAYS – INTRO TO GROUNDS

I don’t know if guys (or now gals) interested in electronics and gadgets in general still build “crystal sets”. Likely not, but most everyone has heard the term. Originally the “crystal” was galena (PbS) and using the crystal was a vast improvement over the variously contrived “coherer” as a rectifying devices prior. What you did was mount the crystal in metal (or pour molten lead around it leaving some surface exposed. Then the crystal radio was constructed and the user probed the crystal surface with a “cat’s whisker”, a spring lever with a wire probe (or just a bent safety pin), to find a sweet spot, determined to have been located when the station was received. It was a basic semiconductor rectifier. I tried to build a crystal set, but lacked some parts! There were lots of plans in books like ***The Cub Scout Handbook*** and ***The Boy Electrician*** (originally published about 1940 I believe, but seems to be still in print). The “crystal” I had was actually quartz (it was a crystal) and critically, I lacked an earphone! Soon enough I got a kit from a hobby shop which had all the parts. The “crystal” was now a 1N34 diode. The circuit is seen in Fig. 1. The instructions all said I needed a good “ground”. This was the first time I heard of such a thing. You could drive a metal pipe in the earth, or you could attach a wire to water pipes. The project worked well.

I did not know that the tuner (parallel L-C here) worked by bypassing all but the desired station to ground. I did not understand that the earphone was a mechanical low-pass filter converting half-wave rectified RF to audio. (Today I think of it like an oversampled D/A converter!) To this day I do not understand how the real diode worked here. Clearly it does not actually turn on, but just preferentially passes current in one direction, reminiscent of the coherers of old. I did learn some things about grounds**:** (1) the circuit worked without any ground, though at a much lower volume, and (2) you could reverse the antenna and ground, and it worked just as well. The second of these things I think I understand fully.

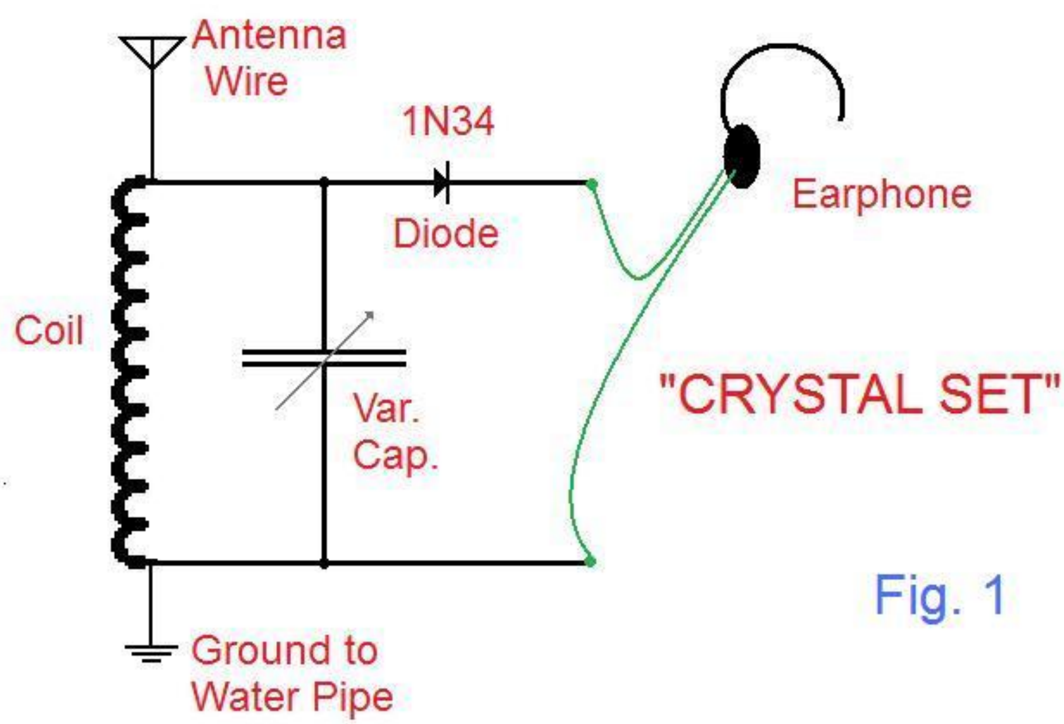


Fig. 1

FARM DAYS

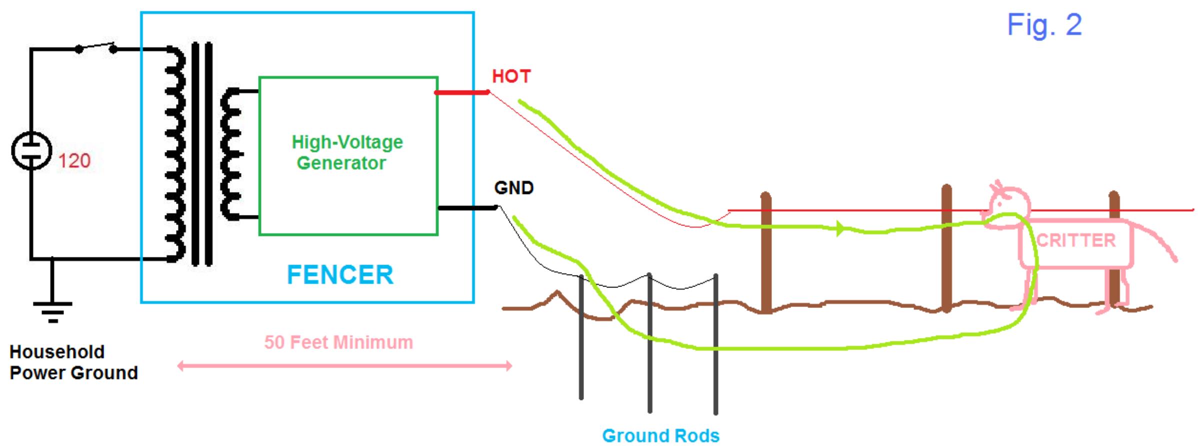
Electric Fences

Electric fences are ubiquitous on farms or course, quite often used only for temporary installations. The critters never seemed to understand the temporary nature of the fence. Even when removed, they didn't seem to recognize that they could now cross a line that was forbidden. Less the reader think the fences were cruel, it was always the case that farmers tested the shock on themselves, and found them not only survivable, but more of a surprise than a pain. (These "tests" were "unscheduled" event by the way!). Currently I use electric fencing for deer control, although there is no such thing as deer control as it turns out. I still do "unscheduled" tests on myself. The full "wet feet" spark resembles a bee sting, with one important exception – the spark stops "hurting" in a small fraction of a second while the bee sting hurts more after a few seconds, and for many minutes.

In fact, most of these tests are mostly capacitive. An electric fence features a train of narrow high voltage pulse (about 40/minute at 10,000 volts) on a single wire relative to ground. If your shoes are wet and on damp soil, you can be a resistive load. But if you have dry shoes on dry soil, you are mostly a floating capacitor to ground. You get a very mild tickle, and it was common for farmers to intentionally test a fence this way.

Farm electric "fencers" (a better term than the alternative "controllers", "chargers" or "energizers") were often powered by batteries, being some distance from AC power. A fencer today is usually AC (or solar) powered. You connect up the hot wire, a ground, and plug it in. The AC fencer has no third prong on its plug. Further you are cautioned NOT to use the household AC ground (or a water pipe) for the ground to the fencer. Why not? I'm not entirely sure.

What the instructions tell you to do is establish a robust system of ground rods away from the household ground (by something like 50 feet). Fig. 2 shows the full idea. Here we see the desired spark pulse, through the red output, inconveniencing the critter down through its legs to the earth, and back to the ground rods and up to the black terminal (yellow-green path). Variously the instructions advise not to use the household ground (with associated water pipes, etc) for a variety of reasons, usually relating to "ground currents". For one thing, note that no matter what we do, household ground is inside the charger box as the "return" or "neutral" of the power supply (the



transformer primary), and the secondary (and associated circuitry driving an induction coil) are also only a spark jump away from being connected. The instructions advise against sparking inside the fencer if the fence wire is grounded for a long period of time by a tree limb or weed. I don't entirely understand this. Secondly, and more convincingly, a second issue is that of lightning damage. A lightning strike on the fence (not uncommon) would want to arc to the fencer ground. You don't need your household ground volunteering to take up part of the chore. Thirdly, and quite convincingly, without a good dedicated ground, anything connected to the water supply (like a poor animal taking a drink, or a farmer touching the faucet) may become a better return path to household ground than the earth.

So – do it right, and what do we learn. It is true that in a very general sense a ground is a ground. In fact, if you measure the resistance between household ground and a separate ground rod it may be as low as 50 ohms. Many of us have also done the calculus study which shows that a ground resistance persists, with little increase with distance, as the "shells" added have more and more surface area. But at the same time (this view of "shells") we recognize that the nearest ground is the most influential, and will collect up a vast majority of the current it needs to return, as long as there is good earth contact. Hence in Fig. 2, the ground rods will collect most of the return current.

Magneto Phones on a Single Wire

At some point in time, our hand-cranked (magneto) phones were replaced with dial phones. In the magneto phones, the crank operated an AC generator of about 100 volts to cause neighbor's phones, or "Central", to ring. [This is all they did. You have all seen movies – you didn't have to keep cranking. They had 6 volt batteries for the actual sound] At that point we gave our phone back. Remember in those days the telephone company owned all the phones. Ours, installed in a then new house, looked like a slightly bulky dial phone, since it had a magneto inside. But most of the neighbors had the separate cradle, a wooden box with the magneto, and a metal can with four #6 dry cells. These older style versions were collected by the phone company and taken to a warehouse. It became known that these were available for $1 each. I ended up with 6 of them. Two were wired with surplus WWII field-phone cable from my room to my brother's room. Fun, but not too useful. I really wanted to run to the barn, some 650 feet further away. I needed more cable. I found a 1000 foot roll of 300 ohm twin lead (the kind that we formerly used to connect a TV antenna to a TV set) that I could afford. Putting up some poles and rigging the wire, we got a third phone in the barn. But the wire was two cheap. After a few bad wind storms, it was torn to shreds.

Perhaps I was looking with envy at the long stretches of multi-conductor "Figure 8" cable the phone company was installing, replacing our former two wire "party-line". That was out of the question, but one of the installers who had taken an interest in what I was up to must have taken pity. Somehow a huge coil of used, but very nice two-conductor cable appeared – more than the 650 feet I needed. Bless his heart. So we were back in service. This was very useful.

But there was then the possibility of going further. Why not another half mile to the back pastures. We often needed to come back to the house to summon the vet, request a part, something like that. One type of wire was cheap – galvanized steel un-insulated electric fence wire. The insulators to install it were also cheap, and we knew how to install it (maintain it frequently) so that it did not break or short out. And the posts were already there for the fence. But two wires were at least twice the problem. Could it be done with one wire, using a ground return (Fig. 3)? After all, the electric fence itself worked with a ground return.

It was a simple matter to test this with one wire and a big spike stuck in the soil from the house to the barn (650 feet) and that worked just fine. Soon enough we had four phones. Hardly foolproof, as tree limbs and wild animals could put it down temporarily. But it worked.

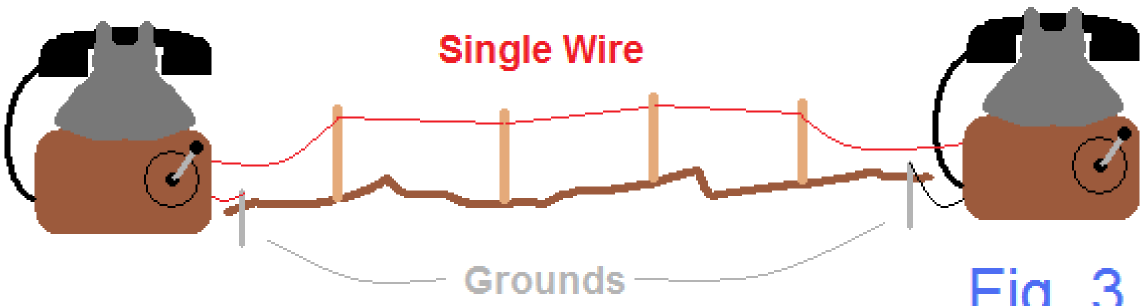


Fig. 3

Code Through The Ground

Somewhat later I became interested in using the ground to transmit audio. The idea came from an article in ***Popular Electronics*** which had been written by John Fry and was an account of the adventures of what I am sure was a fictitious “Carl and Jerry”. In order to do Morse code practice, without resorting to the airwaves, they drove audio signals between two grounds that were physically separated. I had to try this! I used our house ground, and the other was driven to an antenna wire with the far end grounded by a buried metal can. The audio was from a power amplifier with a 500 ohm output (the 16 ohm output would probably have worked as well). The receiver was an ordinary set of 2000 ohm earphones connected between nails stuck in the ground about 6 feet apart. Astoundingly this worked. It worked around the house. It worked quite well 3/4 of a mile back on the farm. It is, to this day, not obvious to me why this worked so well.

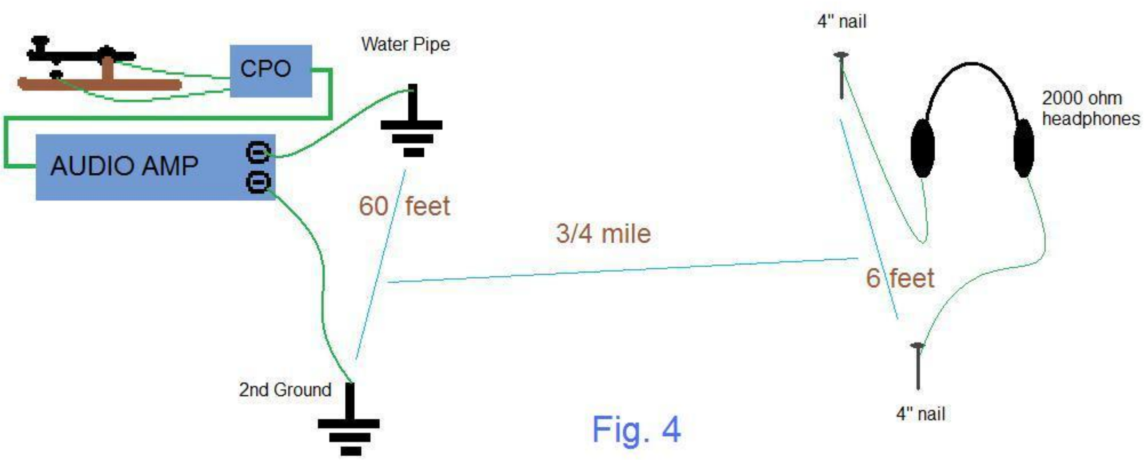


Fig. 4

What do we learn from this? Well, it seems that two separated grounds driven 180° out of phase produce voltages in the earth that retain a differential component. I wish I had done more tests. Yes, I did put the nails in a line back toward the house, instead of parallel to the two grounds back there, and it still worked. I can't help think however that this was, after all, a farm and many areas might be more electrically noisy (AC hum), at least today. We are also reminded how sensitive the ears are, and how a very tiny power can transmit information reliably.

ELECTRONIC MUSIC DAYS

Center Tapped Power Supplies

Readers of this note are mostly electronic music folks and likely are very familiar with power supplies based on a center-tapped transformer, full-wave rectifiers, "filter capacitors", and (finally as needed) regulators. Fig. 5 shows the general idea of the circuit that comes before the regulators (type 320 and 340 IC's regulators typically). [All this is before the current era switching power supplies.]

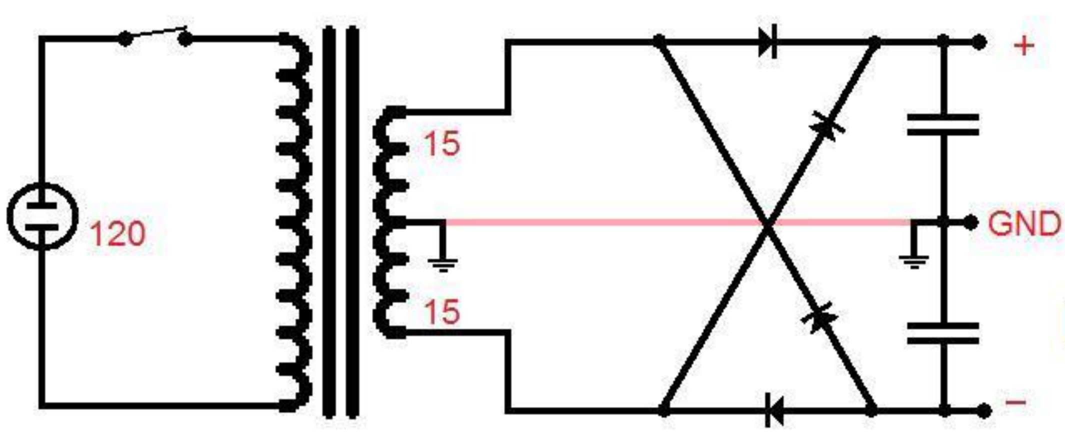


Fig. 5

Here the need was for a “bipolar” supply, both positive and a negative supply rails, for use with common op-amps handling bipolar audio signals.   Note that we anticipate the actual voltages of the points (+) and (-) would be larger than 15 volts in magnitude. The transformer secondary is likely rated RMS and the circuit shown is unloaded and unregulated, so the magnitudes are probably 21 volts ($\sqrt{2}$ times RMS). No big deal. We just note here how we achieve a split supply using a grounded center tap and grounded filter capacitors. That is, we have two points shown grounded, so they are connected. We might have an actual wire connecting these (shown in pink) but more usually, both are just connected to the metal chassis box on which the supply is built. In addition, commonly the 120 volt primary cord would have a third wire (not shown) that would be the safety ground (round pin on the plug) of the household wiring, and this too would be grounded (it too would be connected to the metal box). This is standard and familiar. We review this here to compare to the two-phase household wiring.

Battery Supplies

No kidding – the need for a power supply is a pain. The old crystal sets were powered by the distant radio transmitter (only a tiny, tiny amount of power was recovered by the earphone).   Today electric power out of the wall is reliable and relatively cheap.   Somewhere between the crystal set and the household AC we had batteries. Batteries still are attractive in some instances.

Something portable kind of had to have batteries, and as long as they are not going to require large currents, they would last fairly well. Our synthesizer circuits, especially as we experimented and tinkered with them (not to mention tried to make actual music) were not candidates for batteries. Hence the plug-in supplies. Occasionally however we had something for which batteries were still a good choice. If the device used op-amps, we might have looked for two 15 volt batteries. However, what was available off the (grocery store) shelf was probably 9 volt batteries. You can usually run op-amps on ±9 volts – two ordinary rectangular 9-volt batteries back to back, tapping the center (Fig. 6).   Performance of the op-amp did degrade some by using supply rails much below ±12, and of course, all internal and output voltages had to stay between ±9, perhaps ±6 in practice, and you only wanted to try this with a few ICs in your project.

Here we also discuss a way of using two 9-volt batteries that is wrong. Most people only do this once. Note in Fig. 6 that the correct way switches off both voltages with individual switches, generally one physical switch that is DPST. Here we have two

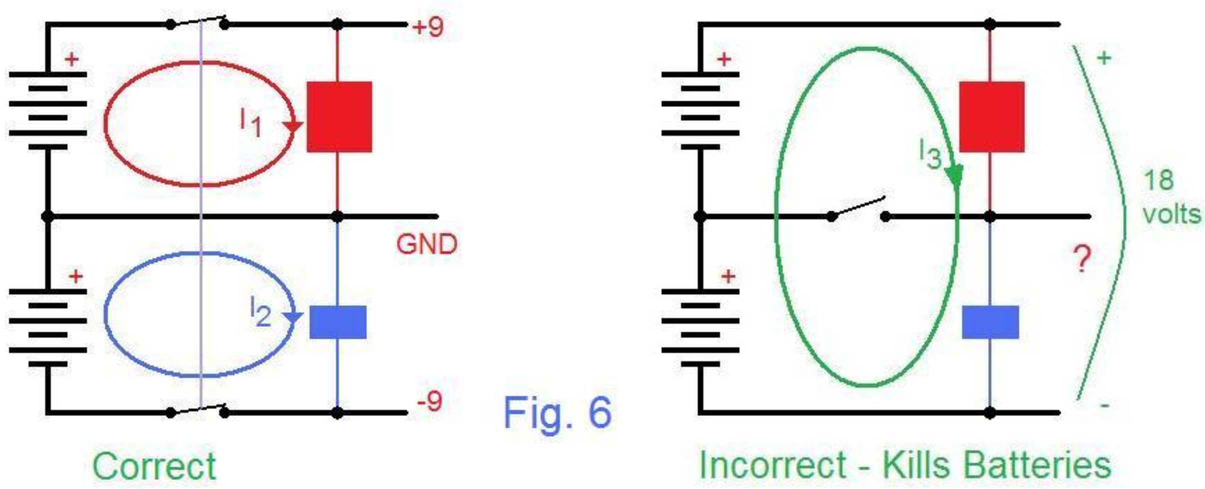


Fig. 6

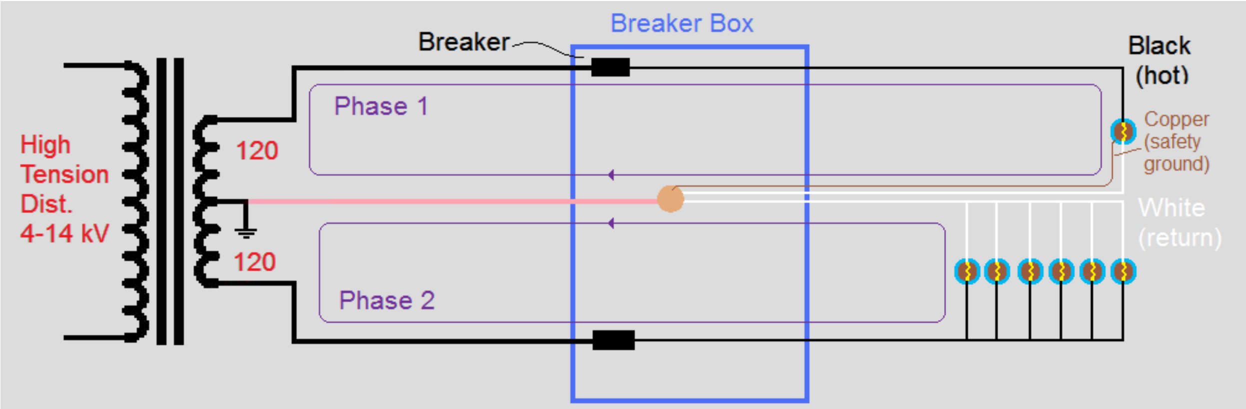
separate currents I_1 and I_2 which reach ground through two (assumed different) loads. Because the ground of the circuit is connected to the midpoints of the batteries, everything is fine.

The problem comes up when someone gets the idea of using only a SPST switch, disconnecting the circuit ground from the midpoint of the batteries – see Incorrect in the figure. With the switch closed, everything is just fine. Now when you open the switch, thinking you are disconnecting the batteries, you now have a single current I_3 that flows through the two loads in series, driven by 18 volts total. The 18 volts is distributed according to the actual loads, in the manner of a voltage divider. Here we suggest a smaller blue load and a larger red load. This will mean that the former ground (now=?) will float upward more positive than the midpoint of the batteries. It is possible to suppose that you could have the red load being much larger (a smaller impedance) so that nearly all of the 18 volts is across the blue load. There might be a few chip types (as part of the blue load) that don't like 18 volts. However, far more likely is that when you come back, the current I_3 has left you with dead batteries.

It is unlikely that any reader here would make this mistake, although it is not uncommonly suggested. Here we will look at it in terms of the quite analogous situation that is the classic case of a lost neutral in household power. In that case, you won't run down the power source – but you could well fry an appliance!

NEUTRALS AND NEUTRALS

In the US, the household electrical supply is usually 240 volts in two phases of 120 volts, 180° out of phase (Fig. 7). That is, a center-tapped secondary with the center tap grounded or neutral, a configuration like the power supply above in Fig. 5. There are three wires coming into your house, probably all the same black color. Your electric stove and a few other appliances (water heater, clothes dryer) may run on the full 240 volts. [Note that the single phase voltage is variously called 120, 117, 115, or 110. Not an important distinction here.]



Normal two-phase with in-place Neutral Fig. 7

Fig. 7 shows a simplified typical setup. The transformer shown belongs to the power company, is outside your home, probably a large “can” up on a pole, or in a metal box on a concrete slab in a corner of your yard or nearby. It probably serves two to as many as six homes.

Each of the two phases entering your breaker box has many individual branch circuits (perhaps a dozen each), each branch beginning in the breaker box with its own circuit breaker. From the breaker, the wiring typically is fed to a certain room or area of your home by a three wire cable. In that room or area, the cable likely branches (daisy chains) to several sockets, lights, TVs, clocks, etc. so that a given breaker is expected to have several appliances attached. The three wire cable has a black insulated wire, a white insulated wire, and a bare copper wire. Keep in mind that local electrical codes and practices may vary.

[As an aside - most codes and common sense suggest certain practices. For example, you would normally run only a single phase to a particular room or area. If not, you could have two hot terminals in the same room that were actually differentially 240 volts, and willing to deliver that voltage. Another precaution is to have a food freezer on its own circuit – not shared by other appliances. The reason is not that the freezer requires full amperage, but because if some other appliance blows the breaker, you might not notice it for days, and your food could spoil. Your refrigerator in contrast is opened many times a day, and you would also see the light was out.]

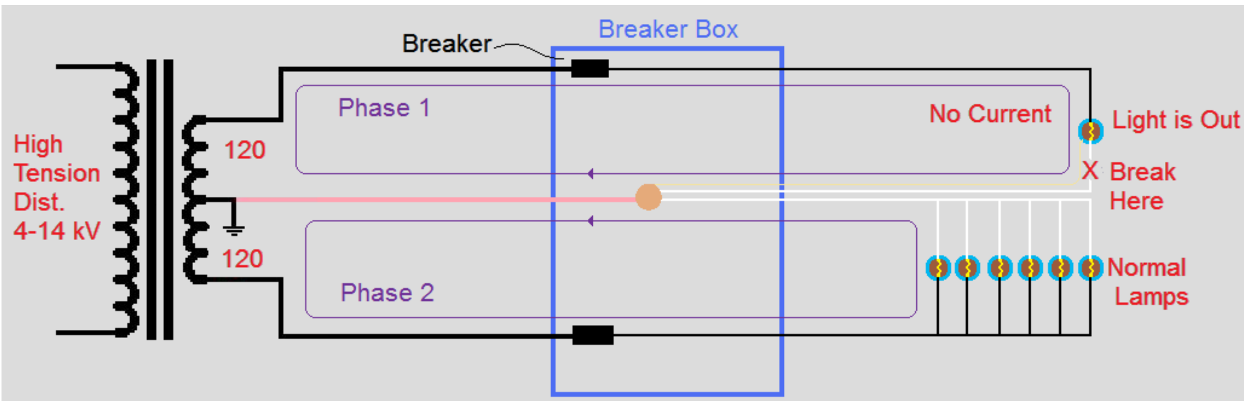
The black wire is generally the hot wire, and the white wire is the return or ground. However, never assume that white is grounded. For one thing, it may be part of a multiple switched setup where a complex set of switches/lamps may be installed, and while a white wire that is hot is supposed to be taped black at the ends, this may not get done. Another reason is that a white wire not clearly grounded in the box could have its corresponding black wire live, and with a bulb (or whatever) in place, it is still at a dangerous line voltage.

So the black wire is from a breaker, and the white should be coming back and be grounded in the breaker box (usually into a bus in holes with set screws). At the same time, this same exact grounding bus has bare copper wires also attached, seemingly interchangeably. The bare wires are used to ground metal workboxes and the center pin of three wire cords. They are not supposed to carry any current. In a malfunction situation, they can divert current to ground, almost certainly popping a GFI (ground-fault-interrupt) breaker, and likely even an ordinary breaker. They are only there for safety – that’s enough.

All this said, Fig. 7 shows as an example with one branch circuit (of many) to a single bulb on Phase 1, and a second branch circuit (of many) on Phase 2, this one driving 6 bulbs. The phases are unbalanced, and we expect they generally will be to some degree. Additional branch circuits in your home, and in your neighbors, will statistically tend to balance the load back at the transformer – but this is just desirable, and not essential or a real concern. For the moment, let’s assume you have only the seven bulbs and nothing else in your house.

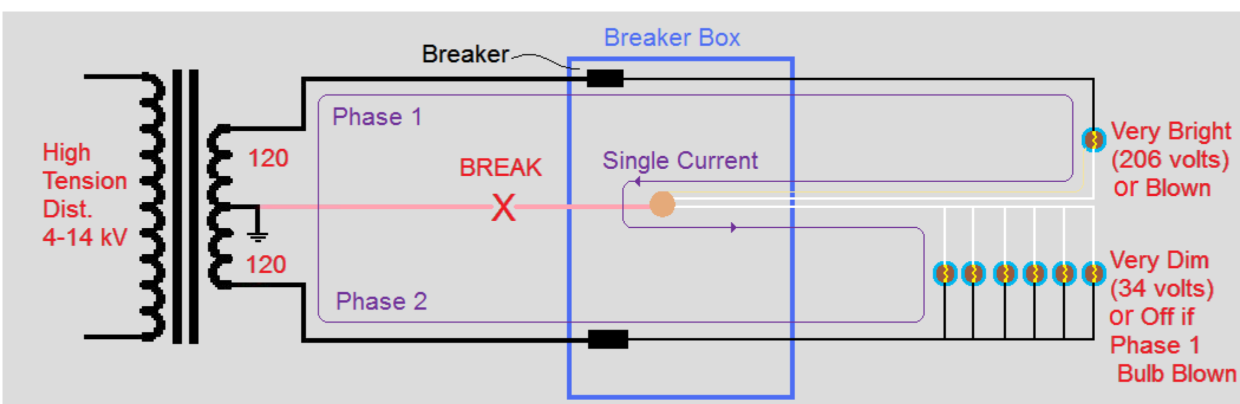
Collectively, the white wires, and the pink wire in the diagram from the transformer are considered “neutrals”. You may also think of them as “returns” or even as “grounds”. Indeed, inside that breaker box there seems to be a mass of wire all trying to be grounds. So what happens if a neutral fails? It depends on where it is. And it depends on how else redundant grounding is present. It even depends on your water pipes if they are metal.

The simplest type of failure we can imagine in the return system is when the individual white wire in one branch circuit opens up. In some sense this is a failure of the neutral wire. What happens is your light goes out. In fact, we can argue that half the time when you wiggle a plug into a socket (or unplug), the hot wire makes contact first, and the return wire is temporarily a failure. Fig. 8 shows this failure mode. At worst, you will need a wiring repair. The bulb (or more expensive appliance) is unharmed. Note that the failure here is on the way back to the center tap of the transformer, but <u>before the common tie points in the breaker box</u>).



Break in Neutral/Return of One Branch Circuit Fig. 8

Various discussions of a failure of a neutral on the web say different things, and this would be okay if there were not total contradictions, remarks that are clearly wrong, and people yelling at each other. If you know a good deal about electricity, as readers of this note almost certainly do, you are probably well ahead of many comments which seem to relish impending doom everywhere. Fig. 9 shows the often postulated scenario for a failed neutral.



Failure of the Main Neutral - Looks Bad - But.... Fig. 9

Here we show a break in the actual third wire, and as described, this could possibly be a disaster. With the neutral wire broken, there is now a single current driven by 240 volts. This is very similar to the connection of two 9-volt batteries, Fig. 6. Note that it would be true that if both phases had very similar loads (like four bulbs on each phase) the common return point in the breaker box would still be near ground potential. Here however we have shown for our example, one bulb on one phase, and six bulbs on the other phase (and nothing else). In this case, we would expect to blow the single bulb. Even if we considered all the bulbs as resistors (they aren't – because the resistance goes way up with heating), there would be 206 volts across that 120 volt bulb. FLASH. The six bulbs on phase 2 would likely never even start to glow before the single bulb burned out. Not a terrible situation in our simple example. But of course, that one bulb might well be a valuable appliance instead. And it must not be terribly uncommon to lose that wire. So what is the back-up?

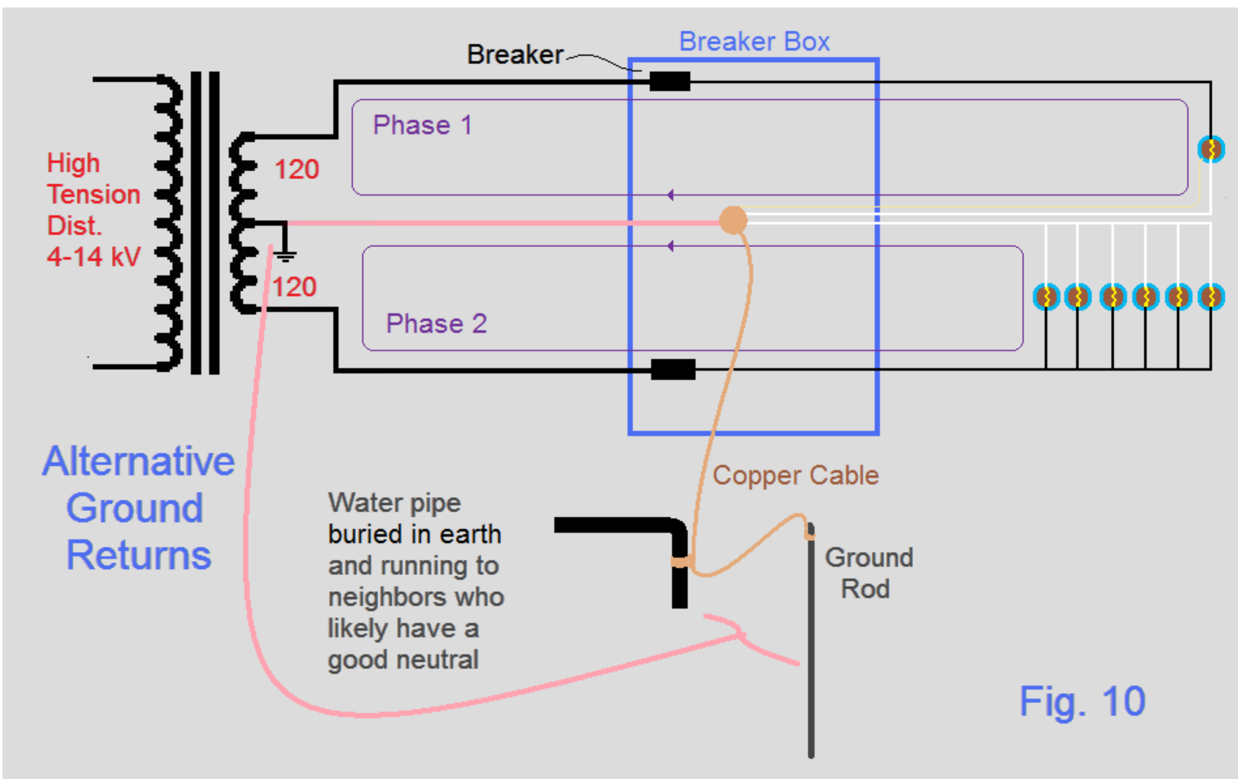


Fig. 10

Fig. 10 shows the case where additional grounding inside the breaker box is provided. The center tap back at the transformer is assumed adequately grounded. [We need to assume this here, grounding seems robust - although it is not clear how this is done in general.] Proceeding we find that the typical installation (looking in the breaker box) has two additional grounds reached by heavy copper cables. These are attached to that neutral and ground bus. First, there is a ground rod driven into the earth outside the home. This might be enough. But more importantly, the ground cable is also connected to the metal water pipe which enters the home underground, and may be 100 feet or so long, going back to a metal main that may be miles long. Further, it may also be the case that the water pipe at your neighbors is connected to <u>their</u> still-connected neutrals, running back to the very same transformer.

It is certainly true that a disaster due to a complete loss of neutral is possible, but clearly it is also very rare, at least <u>relative to normal “loss-of-power outages”</u>. Most of us have power off at least several times a year. Few of us can even cite an actual occurrence of a loss of neutral. Apparently the redundant grounds, and the likely approximate balance of loads on the two phases protects us. From time to time, it might be a good idea to measure the voltages on the two phases (I just did, one was exactly on the 120 volts mark and the other a just-detectable hair over). But how would you know which phase a give circuit is on?

Well, you can very carefully open up the breaker box, and measure it right there. Or you can look carefully and visually observe what breakers are on which phase. [Likely they are in two rows which may be all the same phase, or more likely alternate.] Or, you may be like me, having lost power in one phase completely and remember what was off. Further still, you are looking for the voltages of the phases to be <u>significantly</u> altered. One phase at 100 volts and the other at 140 volts would be cause for alarm. As a final resort, measure every room. Somewhere I read that a loss of neutral occurred and was noticed when the homeowner noted that when a refrigerator turns on, instead of a light bulb dimming, it brightened. Normally it should only dim due to the turn-on larger load. If a light brightens (unexpected) it might well indicate that the neutral is not working properly and the increased load on the refrigerator phase draws that phase down and increased the voltage on the opposite phase (hence the brighter bulb there). As always, notice anything out of the ordinary.