Diary of a Generator Operator, *or how my IA training kept me one step ahead of disaster. (Part 2)*

By Guy Holt

Day 2 (Continued)

9:30 PM: *Production came over the walkie to ask if one of the 9600W heaters could be plugged back into the set lighting distro so the lock up PA out back doesn't freeze. After some hesitation the Gaffer acquiesced. As soon as the heater was plugged-in, the generator began to rattle. Over the walkie I called for the heater to be shut off. The rattling stopped. When I called for the heater to be turned back on, the rattling started again. I tell production we will have to run power from the distro system that we set up that morning specifically for the quartz heaters and toilet trailers. After running 300' of 100A/220V Bates extensions around the building, I plug the heater in, half expecting the 500A plant to start rattling as well. It doesn't. Now I'm baffled.*

The rattling caused by the quartz heater, the continued voltage disparity, and the frequency fluctuations, has got to mean something. I begin to wonder how much voltage disparity is too much voltage disparity

10 PM: *A Google search reveals that voltage-balanced circuits are not possible in the real world. Even under normal loading, voltages will differ by a few volts - any more is an indication that something is wrong. I look online for specific values in the hope that they will provide some guidance. What I find is that in part 14.36 of its 2016 Motors and Generators Standards, The National Electrical Manufacturers Association (NEMA) recommends a voltage unbalance of no more than 1% for optimum operation of generators and motors (like that found in our Ritter fan.) Calculating the percentage deviation is pretty straight forward: you simply divide the maximum voltage deviation from the mean of the three phases by the average voltage and multiply by a hundred (see Figure 1.)*

$$\text{percent voltage unbalance} = 100 \times \frac{\text{(maximum voltage deviation from average voltage)}}{\text{(average voltage)}}$$

Figure 1: Formula for calculating percentage deviation in voltage in a 3-phase system

Plugging the phase voltages when the 18kw ballasts wouldn't strike (113V, 130V, 120V) into this equation, the percent unbalance was 7.44% - no wonder the ballasts wouldn't strike. Plugging the phase voltages we currently have (122V, 119V, 125V) into this equation, the percent unbalance is still 2.46%. According to the NEMA guidelines, we're not out of the woods yet.

Figure 2: Richard Westall's Sword of Damocles, 1812

I feel like King Dionysius in the fable of the Sword of Damocles. The set electrics, like the fawning servant Damocles in the fable, envy me my cushy job, like Damocles envied the king his good fortune. From their perspective it looks like all I do is sit in my car all day. What they don't know is that, like King Dionysius in the fable, who arranged that a sword hang above his throne, held at the handle only by a single hair of a horse's tail, as a constant reminder of the dangers that might overtake him at any moment, I too live in constant fear of the generator shutting down again and throwing the set into darkness. I check the generator oil and coolant. I carefully balance the set load over the three phases of the generator. I scrutinize the frequency of the power generated and listen for unusual sounds emanating from the generator that might indicate its eminent demise. I live in constant fear of suddenly becoming the most important person on set when the power goes off. I would gladly exchange places with any one of them, but know that, like Damocles, they would not last a day under the weight of the responsibility if they understood the job requires constant vigilance against looming disaster.

Day 3:

9:30 AM: *The Best Boy gets the autopsy report on the generator that went down on day one: clogged fuel filters. The service mechanic found the filters clogged with the residue that collects on the bottom of a fuel tank. He said something had stirred the residue up and it was sucked into the fuel line clogging the filters. Likely the mechanical vibrations caused by our quartz heaters.*

Like the degenerative disease C.T.E *(the infliction suffered by pro football players who have had multiple concussions), the symptoms of a resistive neutral can go undetected up until the point the generator blows up and can only be properly diagnosed by an autopsy. To paraphrase one engineering white paper on the subject::*

"Unlike a short circuit condition or a balanced-overload condition, unbalanced voltages often exist for a long period of time before causing catastrophic failure. Because the variations on the generator side are not that great (usually only a few volts) unbalanced voltages may go undetected and only become apparent by the unbalanced three-phase currents drawn by induction motors (like our Ritter fan for instance. The persistence or lingering of an unbalanced voltage condition can pose serious problems to a generator."

If not for the high voltage indicator on the 18kw HMI ballast, we may have never discovered the voltage unbalance. Even now, with the voltage between phases still out of balance, the HMIs show no indication that there is a problem. In the old days, a change in the intensity of lights (like in Phil Reilly's workshop demo) was a obvious symptom that something was wrong. But, now that the constant power supplies of HMIs and LEDS keep their intensity from changing, and they will strike as long as the voltage is not too too high, what are the symptoms of a load induced voltage unbalance? Is the rattling caused by our quartz heaters, the clogged fuel filters, the continued fluctuation of the generator frequency (Hertz) symptoms? It's hard to tell, but to have them all at once is too much of a coincidence not to mean something. Clearly, we're *not out of the woods?*

This reminds me of what I learned about harmonic currents from Tony Hoevenaars, the president of Mirus International, as we were developing a workshop on power quality for Local 481. Harmonics aren't real. They are only a mathematical model that allows us to analyze the effects that distorted current waveforms, and the magnetic flux they create, have on one another when they recombine in the common nodes of transformers, the common buses of a distribution system, and in this case the stator of a generator.

In ideal conditions, i.e. with only balanced linear loads connected to a generator, each phase of power is identical - a pure sinusoid with an RMS voltage value of 120V and a peak factor of 1.414. As such, the alternating magnetic fields generated by the current drawn on each phase of power cancels when it is recombined in the common conductors of a distribution system. As this case makes clear, imperfections in the common conductor can cause unbalance in the three phase voltages and the distortion of the voltage waveforms. Since, a minor distortion in the voltage at the generator will significantly distort the current waveform drawn by loads connected to it, unbalanced voltages can cause severe distortion of phase currents - making linear loads non-linear. The percent of phase current unbalance can range from 6 to 10 times the percent voltage unbalance. As an example, if voltage unbalance is 1%, then the unbalance of normally balanced load currents could be anywhere from 6% to 10% greater than normal.

As you can imagine, the math involved in quantifying and comparing two or more alternating distorted waveforms in a three phase system gets very complicated. One of the methods for the analysis of an unbalanced system is to employ symmetrical component theory, a mathematical model that substitutes balanced positive-, negative- and zero-sequence equivalent circuits for unbalanced three phase circuits because balanced circuits are easier to analyze than unbalanced ones. Developed by the engineer Charles Fortescue in 1918 to make asymmetric fault analysis in three phase systems tractable, symmetrical component theory greatly simplifies matters and offers an insight into why the quartz heater would cause the generator speed to fluctuate and the generator to vibrate.

Fortescue developed a spacial model of a rotating power vector, called a “Phasor”, that makes it easier to analyze the differences between two or more waveforms in a three phase system. Power vectors are simply a means of representing the position of an alternating quantity, be it voltage (V) or current (I), at some particular instant in time using the Phasor Diagram depicted in Figure 3.

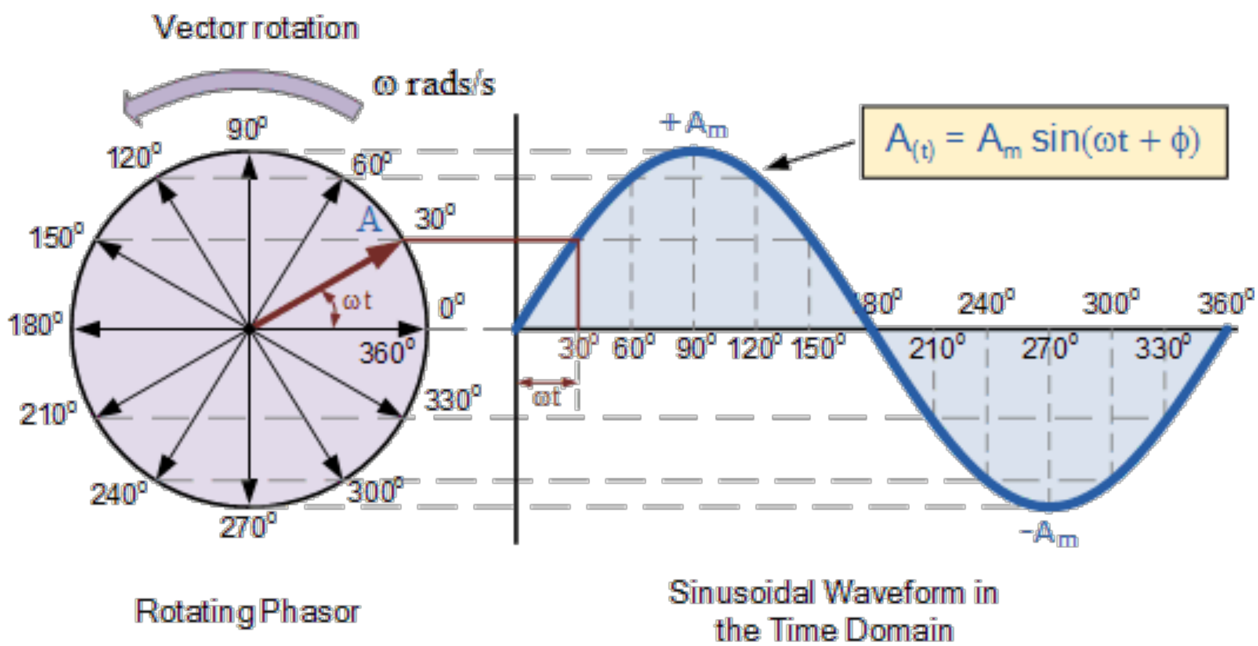
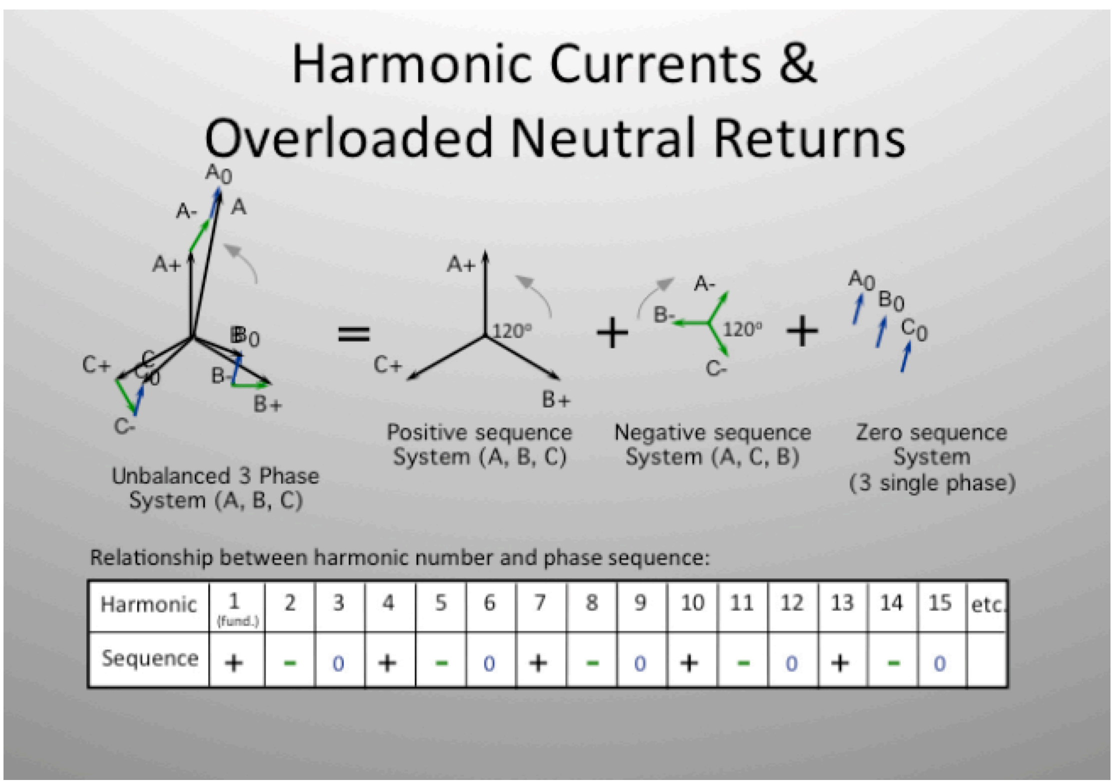


Figure 3: Phasor Diagram

As Figure 3 illustrates, a Phasor is basically a rotating vector frozen at a point in time. It’s length represents an AC quantity that has both magnitude ("peak amplitude") and direction ("phase".) If not frozen in time, Phasors are assumed to pivot at one end around a fixed zero point known as the "point of origin” while the arrowed end representing the quantity, freely rotates in either a counter-clockwise direction (considered to be a positive rotation), or a clockwise direction (considered to be a negative rotation.) A Phasor rotates one full revolution for every sine-wave cycle. Using this method, any alternating quantity, be it voltage (V) or current (I), can be quantified at any instant in time. The power of Fortescue’s rotating vector method is that vectors can be summed using basic geometry (the parallelogram law.) After developing Phasors as a means of quantifying voltage (V) or current (I) at any point of time in a three phase system, Fortescue uses them to describe the interaction of harmonic currents in a power system.

Fortescue said that the three unbalanced phasors of an unbalanced three phase distribution system can be represented by the sum of three sets of balanced phasors. (Balanced phasors are much easier to work with mathematically.) He called these the positive, negative and zero sequence phasors. The phase shift of harmonic currents can be broken down into these three categories.

Positive sequence components (the 4th, 7th, 10th, etc. harmonics shown in the table in Figure 4) rotate in the same direction as the power system voltage and current components. Positive sequence currents comprise the balanced load condition. That is if the phase currents of a generator are equal and the vectors are displaced by 120 degrees (supplying balanced load), by definition only positive sequence components will flow in a power system since fundamental 50/60Hz current is positive. When an unbalance exists in either the magnitude or phase angle of the voltage or current components in a three phase system, negative sequence components flow in the power system (the 2nd, 5th, 8th, etc. harmonics shown in the table in Figure 4.) Negative sequence components rotate in the opposite direction of the voltage and current components in a power system. Components which don't “rotate” at all because they're in phase with each other, are called zero sequence (the 3rd, 6th, 9th, etc. harmonics shown in the table in Figure 4.) As illustrated in Figure 4 any unbalanced set of 3-phase phasors can be represented by the sum of these three sets of balanced phasors.



Harmonic	1 (fund.)	2	3	4	5	6	7	8	9	10	11	12	13	14	15	etc.
Sequence	+	-	0	+	-	0	+	-	0	+	-	0	+	-	0	

Figure 4

The brilliance of Fortescue's mathematical model is that it identifies and provides a means of quantifying the electro-mechanical forces in an unbalanced system that oppose the free rotation of the rotor of a generator, and therefore the free flow of electrons in a distribution system. In Fortescue's model, an unbalanced condition generates negative sequence harmonic components which produce a reverse rotating magnetic field opposite to the primary rotating magnetic field that generates power through electromagnetic induction between the stator and rotor of a generator. Since, this reverse rotating magnetic field rotates at synchronous speeds but in the opposite direction to the rotor of the machine, it effects generators adversely in several ways.

Since negative sequence currents rotate in the opposite direction of the fundamental, positive, and zero sequence currents, they create torque on a generator's rotor in opposition to its primary rotational torque, resulting in a pulsating torque which produces speed pulsation, mechanical vibration, and acoustic noise. Which explains a lot. It explains the fluctuation we experienced in the generator's electrical frequency, the vibration of the generator when we turned on the 9600W Quartz heater, and how the tank residue was stirred up. Under normal operating conditions, a quartz heater draws a sinusoidal current free of harmonics. Under unbalanced voltage conditions it will draw unbalanced current with a negative sequence harmonic component that adds mechanical stress to the moving parts of a generator. Given the effect of the heater on the generator, I don't want to see what effect the Ritter fan would have. I suddenly understand Russ Saunders' fire hose analogy.

According to the literature online, the mechanical vibration created by negative sequence harmonics will lead to the fatigue, and eventual failure, of the mechanical components of a generator's alternator such as its rotor shaft and engine coupling. It looks like we still aren't out of the woods yet.

If the prospect of the alternator shaft coming loose isn't scary enough, the online literature also describes the invisible damage that negative sequence harmonic currents can do to the stator of a generator. Damage that, like that caused by C.T.E, can only be diagnosed after the fact.

The website for EASA (a trade association serving companies that repair, service and sell electric motors and generators) is a morgue for generators. There you will find an autopsy report for every type of generator failure. The picture for unbalanced voltages (Figure 5) shows stator damage caused by spot heating within its coils.

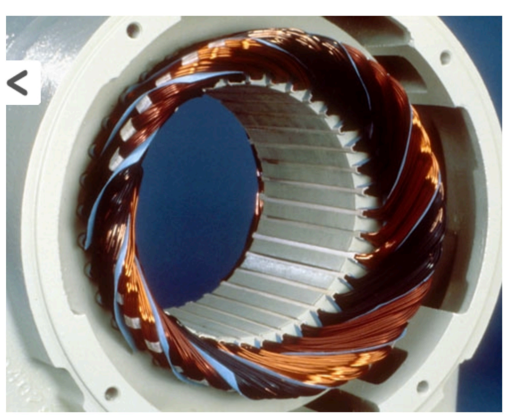


Figure 5: The dark spots are evidence of severe overheating of the coils for one phase.

In Fortescue's model it is the negative sequence components, whose rotation is opposite to the rotation of the fundamental that cause such spot heating. The heat generated by the internal reactance caused by the opposite rotation of the negative sequence harmonics, when added to the I^2R heat loss caused by the current (I), can set up a vicious feedback loop where the heat generated by the internal reactance of the generator increases the resistance the current flowing through the circuit encounters, thereby increasing the amount of I^2R heat generated even further. As the resulting losses increase, the heating intensifies rapidly. This may lead to a condition of uncontrollable heat rise, called "thermal runaway", which results in the rapid deterioration of the winding insulation (evident in Figure 5) and ultimately the winding shorting out, and possibly catching fire.

Reading this sends my anxiety through the roof. Suddenly, eminent disaster hangs over the set like Damocles sword, but only I see it. It could be triggered by the next light or heater; but, definitely by the Ritter fan if it comes off the truck. Like King Dionysius I am living in a private hell.

10:30 AM: *Not willing to wait until the Ritter fan comes off its' truck, and the generator shits the bed, to find out we still have a problem, I suggest to our Best Boy that we swap out all the neutral conductors in our distribution system.*

Swapping out all the neutrals in a distribution system is crazy. It's like changing a tire on an 18 wheeler while it is barreling down the road at 70 mph. Like an 18 wheeler, production is slow to get started, but once it has, it builds momentum, and then shouldn't be stopped - too much money is at stake. Which puts a Gaffer (the chief electrician on set) in a difficult situation when an electrical issue arises. Unless it poses an immediate threat to life and limb, it is better to let production continue to roll on. Even when the problem is finally diagnosed and a solution is at hand, it must be implemented without disrupting production momentum. For this reason, our Gaffer is rightfully reluctant to do something as drastic as swap out the neutrals. He points out that the problem could have been harmonic resonance triggered by the distorted current drawn by the toilet trailer. But after explaining that the reason I suspect that we have a bad piece of cable is that our voltage is floating as a function of load, and hearing the possible consequence if we ignore the problem, he agrees we should swap out the cable.

11:30 AM: *Transpo delivers the cable and I get the outside Third Electrics to help me lay it out along side the neutrals in our distro system.*

2 PM: *Lunch is called. Rather than go eat, the electrical department goes to work swapping out all the cable. The Gaffer reminds us over the walkie of the consequence if we cross the neutral with one of the phase wires is a great ball of fire. An electrical arc of 0.25 ohms at 120 VAC will draw upwards of 480 amps for a very short period of time. This can produce 57600 watts of heat when it takes just 20,000 watts to produce 1/16" diameter copper globules at >2500 EF flying in all directions. I wonder if swapping out the neutrals is worth the risk. Would it be better to let production roll on and accept the consequences in equipment damage. But then I remember what happened to our first 1400A tow plant. I walk the line to make sure nothing is criss-crossed.*

2:30 PM: *After swapping out all the neutral cable the voltage disparity is gone. Now there is only a volt difference between the three phases under the same load. We are finally out of the woods.*

3:00 PM: *To isolate the source of the resistance we meter each of the neutral cables and find one that measures 110 Ohms where all the others measure less than .5 Ohms. This piece of cable was our resistive neutral. The cause of our 18k ballasts not striking. The cause of our voltage floating. The reason our generator crapped out. A single piece of 4/0 cable. It gets tossed around, run over, and generally ignored, yet, as this tale demonstrates, a bad piece of 4/O cable has the potential to bring even the largest production to a crashing halt. The next time I have to run cable across a road, I'll be sure to lay out cable ramps.*

It occurs to me that what to most observers would appear to be coincidences (an 18k ballast fails to strike, floating voltages, a rattle in the generator, clogged fuel filters) I am able to recognize as the symptoms of a resistive neutral condition only because of my Local 481 TECs training.

We shoot three more days without incident and then wrap the show. Crisis averted.