Diary of a Generator Operator, *or how my IA training kept me one step ahead of disaster. (Part 1 Unabridged Version)*

By Guy Holt

Like a diseased body, a defective portable power system will present symptoms. The professional generator operator, like the physician, must not only be able to recognize the symptoms but also have developed the analytic tools required to diagnose the problem and arrive at a cure. But, unlike a medical doctor, a genny op does not have the liberty of treating their "patient" in isolation - too much money is at stake to shut down a production for even an hour.

This is a diary of just such a diagnosis and eventual cure of an electrical problem that, before it was resolved, shut down two 18Ks, a 1400A generator, and threatened to shut down a major motion picture at any moment. The analytic tools I used to stay one step ahead of disaster until I could identify the problem to be a single piece of 4/O Camlok cable, I learned in IATSE Local 481's Training, Education, and Classification (TEC) program. The backbone of any portable power distribution system, 4/O feeder cable gets tossed around, dragged through debris, run over, and generally ignored by most of the crew, yet as this diary attests, a single piece of lowly 4/O cable has the potential to bring even the largest production to a crashing halt.

Day 1

8 AM: *Like a scene out of "Good Morning Vietnam" the day begins with the dulcet tone of our Gaffer's regular morning greeting and inspirational pep talk over the electric's walkie channel. It goes something like this: "Good morning LA and Massachusetts filmmakers. Day 31 of production. New location. Only 7 days to go before wrap, Christmas, and some well deserved down time. It's as cold as a witch's tit so lets get those quartz heaters running. Let's make some great images and some money."*

The FX Department's three phase Ritter fan that has been dogging me throughout this show has appeared again on this new set. Always on "standby", the beast has yet to be used. Damn, I wish Production would let us know where it will play so we can be sure to have the capacity and spare Camlok pockets to power it.

8:15 AM: *Possible indication of trouble. Our generator, which up until this point has run very smoothly, began to run rough today. Frequency, which doesn't usually fluctuate more than a hundredth of a cycle (60.01-60.02 Hz), is now fluctuating between 59.95 - 60.10 Hz. As frequency is a product of engine RPM it seems like the generator is having a harder time than usual carrying today's load.*

8:30 AM: An18k HMI ballast won't strike. The diagnostic LCD readout indicates an over voltage. But, the Set Electrics had read 208V between phases at the start of the day before turning on loads. The set electrics immediately swap out the "bad" ballast with another. It too fails to strike. One of the Set Electrics meters the phase legs. There is an appreciable disparity between them:

	Red	Blue	Black
Voltage	113V	130V	120V

Its no wonder the 18k ballasts won't strike. Power Gems and Arri ballasts have over voltage cut-off switches that are designed to shut the ballast down if the supply voltage is too high. In the heat of the moment no one had thought to note which legs were supplying the 18k ballasts, but I would bet it was blue and black since the combined voltage of those two legs is very high.

Out of 18k ballasts on our trailer, the Third Electrics pull an Arri M90 off as a replacement. It struck, thankfully, but in the rush to light the set the M90 was not put on the same phases as the original 18k. Now the generator is out of balance. Getting off to a bad start on this new location.

8:45 AM: *I go up to set to investigate. At the further most distro box, I read these voltages on the three phases of our power system:*

	Red	Blue	Black
Voltage	109V	134V	117V

A quick Google search reveals that there are many causes of unbalanced voltages. According to one engineering white paper, it can be caused by unsymmetrical transformer windings, transmission impedances, an open wye, an open delta, or simply by unbalanced loads. Unbalanced loads are by far the most common cause of unbalanced voltages. In large urban power systems, unbalanced voltage problems occur where heavy two-pole demands, particularly lighting loads, are distributed unevenly in large commercial facilities. A large manufacturing facility may have a well-balanced incoming supply of voltage, but unbalanced conditions can develop within the facility from its own two-pole power requirements if the loads are not uniformly spread among the three phases. A much less common cause of voltage unbalance is when a wye system loses its neutral connection.

Since we aren't supplying a large urban power system, and our two pole loads (the 18k HMIs) were well balanced before the swapping around of heads, I figured it had to be an open neutral. The way the voltage disparity changed after the haphazard redistri-

bution of loads, also reminds me of Phil Reilly's IATSE Local 481 workshop on how to identify open neutrals in a portable power system (pictured in Figure 1.)

Figure 1: Phil Reilly demonstrating to members of IATSE Local 481

Reilly had demonstrated that when the neutral is lost in a three phase power system, light fixtures don't go out as you would expect. Instead, some units get brighter while others get dimmer. On his demonstration board (Figure 2), Reilly "accidentally" disconnected (opened) the system neutral. He then unscrewed light bulbs, one at a time on the same leg, to demonstrate that the voltage on each phase leg floats according to the relative load on each leg. Multi-meters plugged into each phase revealed that the voltage of each phase is in an inverse relationship with the load. The higher the load, the lower the voltage. The lower the load the higher the voltage. Reilly then restored the neutral connection and the potential between legs stabilized at 208V phase-to-phase, and 120V phase-to-neutral, regardless of the load distribution.

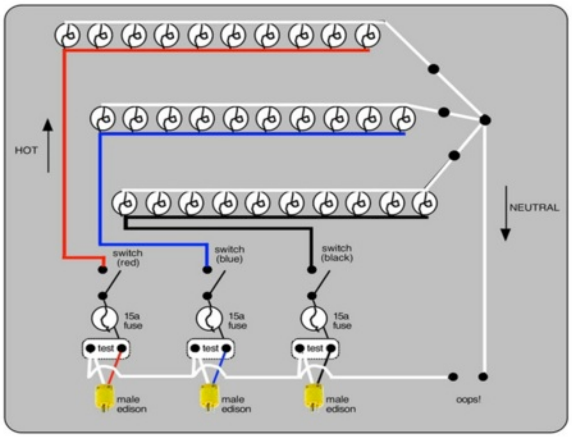


Figure 2: Graphic representation of Phil Reilly's open neutral demonstration board.

Are the unbalanced voltages on set in an inverse relationship with our loads? Yes. They are as follows:

	Red	Blue	Black
Voltage	109V	134V	117V
Load	260A	135A	230A

Our voltages are fluctuating in a very similar fashion as when a three phase system loses its neutral. Finally a clue, I suspect we have a bad neutral.

9:30 AM: *Checked all the neutral Camlok boots. Found several connections that tightened an additional quarter turn with my Channel-locks, but tightening the Cams did not change the voltage disparity. What next?*

10 AM: *Whenever I am stumped I find it helps to do a line drawing of the distro system. Even though it is spread out over thousands of square feet, a distro system is basically just a large circuit board. In a wye-connected system there are three phases, each out of phase with the others by 120 degrees, and a grounded (neutral) conductor (Figure 3.) Since the phase currents are electrically separated 120 degrees, the voltage between any two phase legs is 208v, and the voltage between any individual phase and the neutral is 120v. All 120v loads are connected between a phase leg and neutral. 208V loads, like our 18ks and large 20kW quartz lights are connected phase-to-phase. The Ritter fan runs on all three phases. The thing is a beast.*

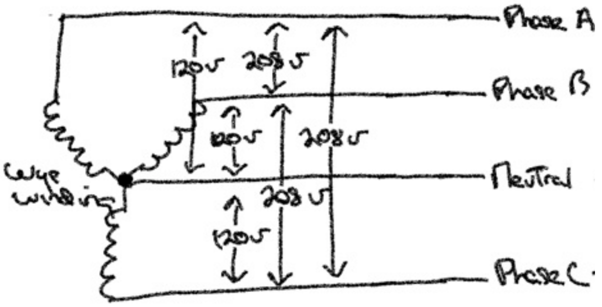


Figure 3: Line drawing of distro system.

To keep things simple, I imagine an extreme situation (Figure 4) where there are only two loads (R_x) and (R_y) connected on only two legs (A & C) and nothing on the third leg (B). I note the system impedances (Ra, Rb, Rc) and the impedances of our loads (R_x and R_y.) I disconnect the neutral.

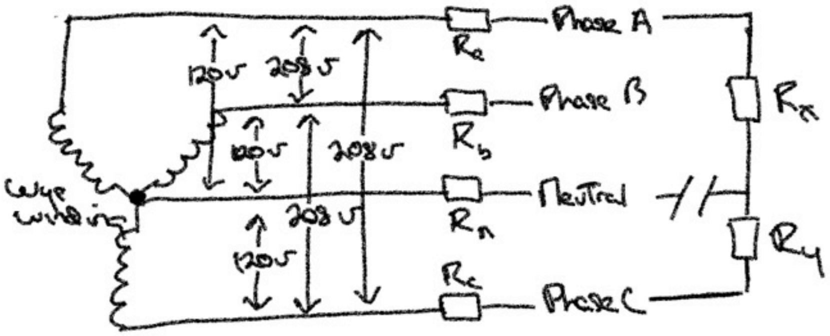


Figure 4: Line drawing of distro system with loads.

With the neutral disconnected my line drawing looks a lot like that of a voltage divider circuit. Could our troubled distro system be a voltage divider? In electronic engineering a voltage divider circuit is used when a component requires a voltage other than that supplied by the power source. As shown in Figure 5, a voltage divider is created by connecting two electrical impedances *(typically resistors) in series. The input voltage (V_I) is applied across the series impedances Z_1 and Z_2 and the output voltage (V_{out}) for the component requiring a lower voltage is the voltage drop across Z_2 since according to Kirchoff's law the sum of the voltages around a closed circuit is zero.*

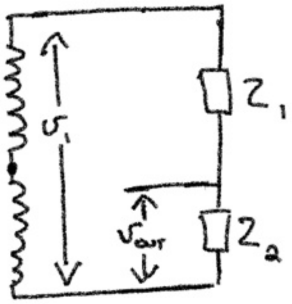


Figure 5: Line drawing of voltage divider circuit.

A voltage divider circuit on a circuit board typically consists of two resistors, the values of which are chosen according to the output voltage desired. On a film set, the impedances (Z_1 and Z_2) may be composed of any combination of elements such as large resistive loads (incandescent lights & our heaters), large inductive loads (the Ritter fan motor), and capacitive loads (our HMI and LED lights)(Figure 6.)

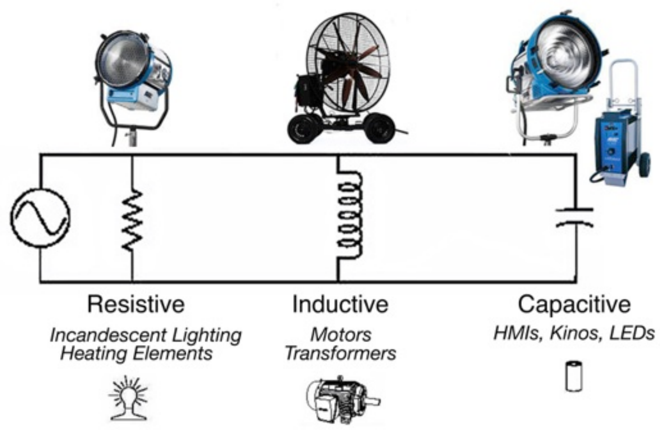
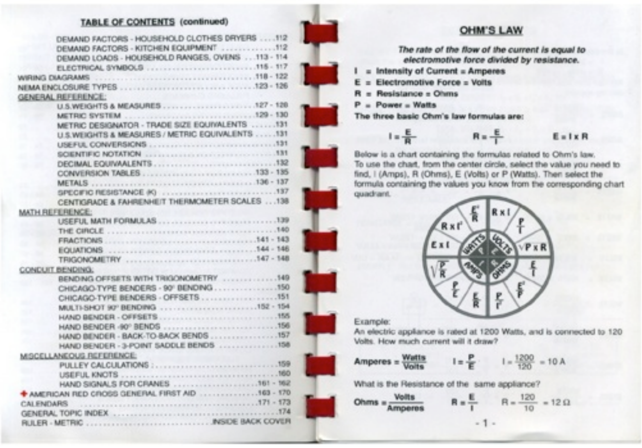


Figure 6: Types of impedances on a film set.

To see what happens, when a distro system loses it neutral and become a voltage divider circuit, I crunch some numbers. The math can get pretty complicated so to keep things simple I choose 12kW and 5kW incandescent lamps as loads Z_2 and Z_1 respectively. My reasoning goes something like this:

According to Ohm's law (V=IR), the voltage across Z_2 (the 12kW) is the current passing through the circuit (I) times the impedance of the 12kW. I use my trusty Ugly's to find the right formulation of Ohm's Law to calculate the resistance of the 12kW.



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OHM'S LAW

The rate of the flow of the current is equal to electromotive force divided by resistance.

I = Intensity of Current = Amperes
E = Electromotive Force = Volts
R = Resistance = Ohms
P = Power = Watts

The three basic Ohm's law formulas are:

$$I = \frac{E}{R} \qquad R = \frac{E}{I} \qquad E = I \times R$$

Below is a chart containing the formulas related to Ohm's law. To use the chart, from the center circle, select the value you need to find, I (Amps), R (Ohms), E (Volts) or P (Watts). Then select the formula containing the values you know from the corresponding chart quadrant.

Example:
An electric appliance is rated at 1200 Watts, and is connected to 120 Volts. How much current will it draw?

$$\textbf{Amperes} = \frac{\textbf{Watts}}{\textbf{Volts}} \qquad I = \frac{P}{E} \qquad I = \frac{1200}{120} = 10\ \text{A}$$

What is the Resistance of the same appliance?

$$\textbf{Ohms} = \frac{\textbf{Volts}}{\textbf{Amperes}} \qquad R = \frac{E}{I} \qquad R = \frac{120}{10} = 12\ \Omega$$

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Figure 7: The chart of Ohm’s law formulations in Ugly’s electrical manual

It is $W=I^2R$. To compute for resistance (Ω) I reformulate the formula as $R=W/I^2$. Plugging in the values for a 12kW, I get 1.2Ω (12000W/100A x 100A) = 12000W/10,000A = 1.2Ω.)

Calculating the current passing through the circuit is a bit more complicated, but I do know that the voltage in (V_{in}) is equal to the current (I) times the combined impedances (Z_1 + Z_2), or

$$V_{\text{in}} = I \cdot (Z_1 + Z_2)$$

To compute for the current, I reformulate the formula as

$$I = \frac{V_{\text{in}}}{Z_1 + Z_2}$$

If we plug this formulation for current into our equation for V_{out},

$$V_{\text{out}} = I \cdot Z_2$$

we get

$$V_{\text{out}} = V_{\text{in}} \cdot \frac{Z_2}{Z_1 + Z_2}$$

All that remains to calculate the voltage drop across the 12kW (V_{out}) is the resistance of the 5k. Using the same formula that we used for the 12kW ($W=I^2R$), we calculate the resistance of the 5k to be 2.83447Ω (5000W/42Ax42A = 5000W/1,764 = 2.83447Ω).

Now we finally have all the information needed to calculate how the voltage will divide if the system neutral is lost. Plugging the numbers into the equation for V_{out}, the phase with the 12kW will be at 62V. Here’s the math step by step:

V_{out} = V_{in} x (Ω of 12kW / (Ω of 5kW + Ω of 12kW), or
V_{out} = 208V x (1.2Ω / (2.83447Ω + 1.2Ω), or
V_{out} = 208V x (1.2Ω / 4.03447Ω), or
V_{out} = 208V x 0.29744, or

$V_{out} = 62V$

Running the numbers for the 5kW, the phase with the 5kW on it will be at 146V. Plugging in a second 5k, on the same leg as the first, divides the voltage differently; and, as in Phil Reilly's open neutral demonstration, it is inversely proportional to the load. This confirms it. Our distro system is behaving like a voltage divider.

Figure 8: 12kW ghost load on generator to balance load.

10:30 AM: *It occurs to me that, if our system is a voltage divider, I should be able to reduce the voltage disparity, and possibly get us through the day without another HMI ballast failure, by balancing the loads. With a couple of 18ks, an M90, and a number of Arri S360s and S60s, I read the following voltages and loads on the three phase legs:*

	Red	Blue	Black
Voltage	109V	134V	117V
Load	260A	135A	230A

I first pull a T12 incandescent fresnel off the trailer and put it on the blue leg (Figure 8) to see if the additional 100A load changes the distribution of voltage between the legs - it does. With the addition of the 12kW I read the following voltages on the three phase legs:

	Red	Blue	Black

Voltage	111V	132V	122V
Load	281A	216A	283A

Since the disparity in voltage is less, I pull out a pair of 5kW Fresnels and put them on the blue leg to see if the additional 84A load would change the distribution of voltages between the legs again - it does. With the addition of the 5kWs on the blue leg I read the following voltages on the three phase legs:

	Red	Blue	Black
Voltage	113V	130V	120V
Load	300A	293A	296A

The system is definitely acting like it has lost its’ neutral but we can’t find a break or bad connection in the system neutral anywhere. What gives?

11 AM: *I go online and find that a neutral does not have to become completely disconnected to cause voltage unbalance. A “resistive neutral” can have the same effect. A resistive neutral occurs when the neutral is connected, but it is of a high impedance. Good connections have extremely low electrical impedance (less than an Ohm), but a resistive neutral has an intermediate impedance (more than 10Ω.) Its impedance is low enough to conduct electricity, but too high to conduct it well. A neutral Camlok that is not twisted entirely, or a neutral feeder that has a severe kink in it where the copper strands are broken, are examples of a resistive neutral. Like an open neutral, a resistive neutral will cause voltages to float between the three phases but to a lesser degree. Since tightening all the neutral Camlok connections did not remedy the problem, our resistive neutral must be in either the generator, a distro box, or a stick of 4/O feeder cable.*

11:15 AM: *Talk to our Best Boy about swapping out the generator for another at lunch to eliminate it as the cause of our trouble.*

11:45 AM: *The back up plant arrives from the storage yard. But we still have to pitch the idea to the Gaffer since it will mean shutting everything down at lunch - an inconvenience to the other departments for sure.*

1:30 PM: *After hearing of the effect my dummy loads had on the voltage disparity, the Gaffer agrees we should swap the generators. He sends a couple of electrics to lunch early so that they can help me once the company breaks for lunch.*

It’s amazing how much Jesse (one of the electrics) can eat. At 6’4”and probably 240lbs, the Gaffer has nick named him the “Dozer” because of the way he plows through the set at wrap like a bulldozer. He certainly plows through lunch.

2 PM: *As soon as lunch is called, as if on cue, the first generator craps out. It starts to run erratically, belching black smoke. The set lighting goes on and off. The 18k HMI ballasts shut down and re-strike repeatedly. It was quite the show and with the whole company watching. I immediately shut down the plant.*

2:30 PM: *Swapping generators did not resolve the voltage unbalance. And, the second generator is running just as rough as the first.*

3:30 PM: *To find the cause of the continued voltage unbalance, the Gaffer orders all non-set lighting loads, such as the catering tent festoon lights, the portable toilet trailers, and the six 9600W quartz heaters (that offer some comfort for the production personnel left out in the cold), to be shut down one at a time. When one of the two stall toilet trailers is shut down the voltage disparity goes down considerably to:*

	Red	Blue	Black
Voltage	119V	125V	122V

To confirm the toilet trailer is indeed the cause, the Best Boy plugs it back in, and sure enough, the voltage disparity shoots back up. While there is still a disparity of 6 volts between the high and low phase legs with the trailer unplugged everything is working fine, so it looks like we are out of the woods for now.

Figure 8: Toilet Trailer.

Day 2:

8 AM: *As he does every day, the Gaffer begins the day with a pep talk. But this morning he is a little more somber than usual. It goes something like this: “Good morning LA*

and Massachusetts filmmakers. We had a rough day yesterday. Had some issues. Resolved some issues. But all that is behind us. We have a plan. So let's make some great images and some money."

According to the plan, we off-load the toilet trailers, along with the catering tent festoon lights and quartz heaters, from the main 1400A plant and onto a smaller 500A plant. The plants small but should just be able to support the load.

On the shooting set there is a change in the mix of HMI units. It seems the riggers were able to procure another 18k ballast and swapped out the M90 for an 18K before we came in this morning. To make sure the new load will be as evenly distributed over the three legs of the generator as possible, I do a paper calculation of the load and re-patch some of the 100A stage pin circuits into what would be the low phase after the big heads come up to speed.

8:30 AM: *Ugh! The voltage disparity is about the same:*

	Red	Blue	Black
Voltage	119V	126V	121V

And there is no disparity on the distro of the 500A plant that is now powering the toilet trailer. I'm not surprised. If, in fact, our distro is a voltage divider, off-loading the non-set lighting loads, would not eliminate the problem, but just change the voltage unbalance, which it has. It looks like we are not out of the woods yet.

9 AM: *That the toilet trailer has no effect on the 500A distro really bothers me. It means we still have an issue with the distro of the set lighting generator. To investigate further I pulled out my Fluke 43B Power Quality Analyzer and checked the power profile of the toilet trailer (Figure 9.) It draws a very distorted current waveform that is rich in harmonics. I checked the equipment compartment of the trailer and found what was drawing the harmonics - a non-power factor corrected switch mode battery charger.*

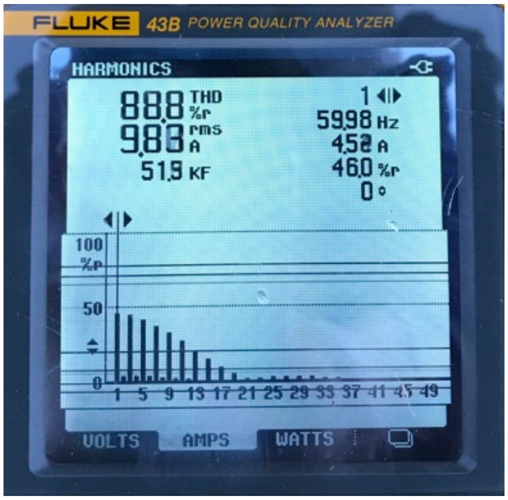


Figure 9: PQM reading of Flush Trailer

The harmonic currents drawn by the toilet trailer reminds me of the Advanced Power Workshop taught by Russ Saunders. In the course binder was an article he wrote on harmonics: “A Primer on Power Harmonics in the Entertainment Industry”. In the class, he likens the effect of harmonics on a distro system to that of a fireman rapidly opening and closing the spigot of a fire hose under pressure. The rapid opening and closing of the spigot at the end of the hose will make the fire hose behind him jump around. I didn’t get the analogy then, so I researched harmonics further.

Figure 10: The source of the harmonics drawn by the Flush trailer,
a 750W non-power factor corrected switch mode battery charger

In 1897, Baptiste Joseph Fourier had the insight that any periodic function can be rewritten as a weighted sum of sines and cosines of different frequencies. One implication of this insight is that a distorted non-sinusoidal periodic waveform (like the distorted distorted current waveform drawn by the toilet trailer), is equivalent to, and can be replaced by, a mathematical model in which the distorted periodic waveform consists of the sum of a number of sinusoidal waveforms. In such a modeling, the component waveforms include a sinusoidal waveform at the fundamental frequency and a number of sinusoidal waveforms at higher harmonic frequencies, which are whole number multiples of the fundamental frequency. As illustrated in Figure 11, a distorted *voltage waveform can be broken down into components that include the fundamental wave plus harmonic waves of a higher order. The third order, or simply the third harmonic, is a 180 Hz sinusoidal waveform (3 x 60 Hz). The fifth harmonic is a 300 Hz sinusoidal waveform (5 x 60 Hz).*

The process of deriving the frequency components of a distorted waveform is achieved by a technique known as the Fourier transform. Microprocessor-based test equipment, like my Fluke 43B Power Quality Analyzer can do this mathematical analysis very quickly using a Fast Fourier Transform, which it displays as a bar graph like that of the PQM reading of the harmonics drawn by the Flush trailer in Figure 9.

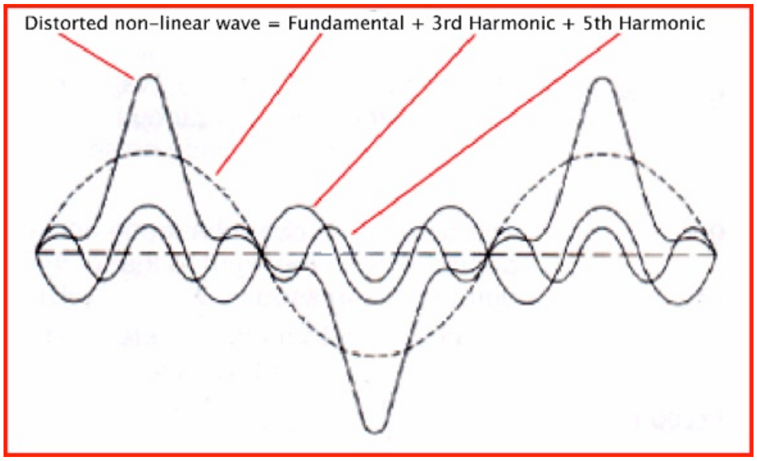
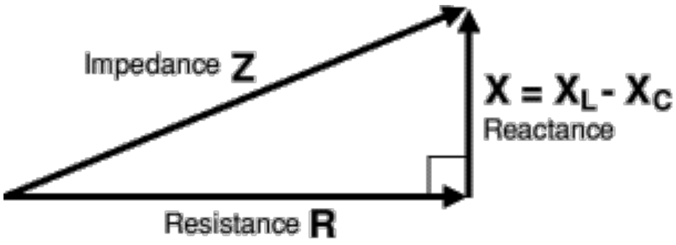


Figure 11: The harmonic components of a distorted waveform

According to Faraday's law of induction, the time-varying magnetic field generated by these high frequency harmonic currents create loops of current called eddy currents in all of the copper conductors of a distribution system. Since these closed loops of current flow in planes perpendicular to the magnetic field creating them, eddy currents create a magnetic field that opposes the change in the magnetic field that created it (Lenz's law), and so dissipates its energy as heat. For this reason, eddy currents can generate substantial heat in the windings of motors, transformers, and generator stators.

This reactive force that opposes the free flow of current is a second component of impedance, called reactance. So far in our discussion impedance and resistance have been pretty much interchangeable since our discussion to date has only been concerned with resistive loads (5 & 12kW lamps). Reactance is the other component of impedance that, as this case makes abundantly clear, can have as much, if not more, impact on an electrical distribution system as does resistance.



Impedance, $Z = \sqrt{R^2 + X^2}$

Figure 12: Impedance Triangle

The impedance triangle in Figure 12 illustrates the relationship between the resistance and reactance that makes up the impedance of an AC circuit. An impedance triangle is a right triangle, with the horizontal side representing the circuit resistance and the vertical side representing the combined capacitive and inductive reactance in the circuit. The hypotenuse represents the circuit impedance.

What's this have to do with floating voltages? By drawing a significant number of harmonic currents, the 750W power converter in the toilet trailer, introduced a new form of impedance to that phase of the system, capacitive reactance. The time-varying magnetic fields of the high frequency harmonics drawn by the battery charger generated a significant number of eddy currents. Since eddy currents create a magnetic field that opposes the change in the magnetic field that created it, they exerted another force, on top of the resistance of the conductor, opposing the free flow of electrons in that phase of the distribution system, thereby substantially increasing the impedance of that phase relative to the others. Since in a voltage divider circuit, voltage divides according to the relative impedances on the circuit, the sizable impedance contributed by only a 725W battery charger resulted in an even greater voltage disparity between the phases.

End Part 1