Power quality in the age of LEDs: Part 4

BY **GUY HOLT**

THUS FAR, IN THIS SERIES, we have only examined the effect that the harmonic currents drawn by non-pfc LED power supplies have on distribution cable. Let's now look at the effect they have on distribution transformers.

Transformers are affected in two ways; there are increased I^2R heat losses similar to what we saw in cable in part two of this series; and there are eddy current heat losses (P_{EC}). Harmonics increase both of these heat losses, but in different ways. Let's first look at the copper losses (I^2R).

As we saw in part two of this series, magnetic fields generated by harmonic currents induces eddy currents on the conductor itself, which modifies the distribution of current displacing it toward the periphery. Called skin effect, this phenomenon increases the value of the resistance in the conductor in proportion to the root of the harmonic frequency. The higher resistance leads to higher I^2R heat losses.

A second, greater cause of heat loss, are the eddy currents induced in a transformer's windings, laminated iron core, and other structural parts by electromagnetic fields generated by stray harmonic currents. This is a problem particular to stage distribution systems in North America.

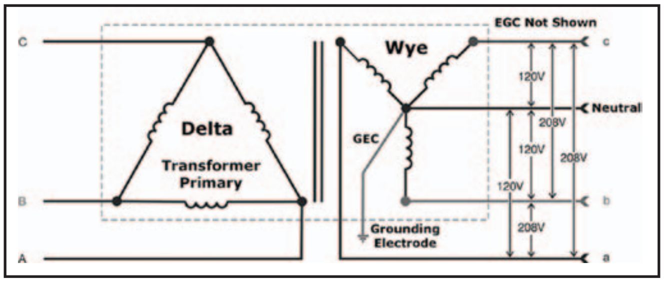

Figure 1 – The configuration of the delta-to-wye service transformers that provide power to motion picture stages in the US.

In North America, the standard configuration of service transformers providing power to motion picture stages is delta-to-wye (see **Figure 1**). On the wye wound secondary there are three phase wires and a neutral wire. Since the phase angle between each of the conductors is 120 degrees, the voltage between any two phase wires is 208 V, and the voltage between any single phase wire and the neutral wire is 120 V. All 120 V loads are connected between a phase leg and neutral. 208 V loads, like 20 kW quartz lights and HMIs from 6 kW on up, are connected phase to phase. The delta wound primary is fed by three-phase wires, and since loads placed on the secondary are split evenly between the three phases of the primary, phase cancellation eliminates the need for a neutral on the primary side.

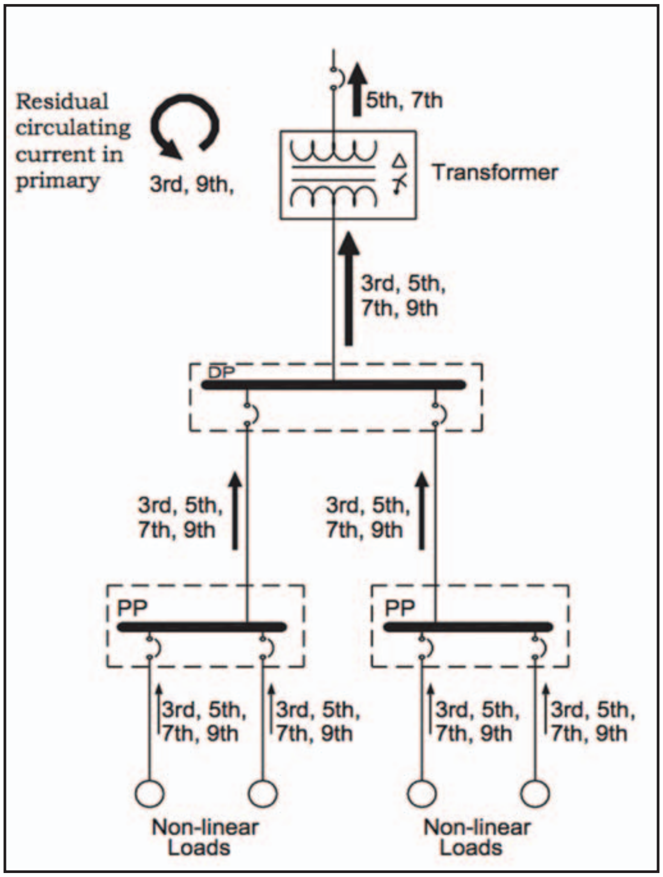

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Figure 2 – Harmonics couple to a transformer's primary where they circulate until dissipated as heat.

The third order harmonic currents (third, ninth, etc.) generated by non-linear loads do not cancel in the neutral bus of the secondary as the fundamental frequencies do. Instead, they circulate in the wye winding, inducing harmonics back to the delta winding of the transformer. The primary windings, therefore, will have the same percentage of third and ninth harmonic currents (compared to the fundamental current) circulating as the secondary (as illustrated in **Figure 2**). Heat is generated because the magnetic field generated by these stray high frequency currents create currents, called eddy currents, in all of the metal parts of a transformer. These closed loops of current flow in planes perpendicular to the magnetic field creating them, and dissipate their energy as heat. Eddy currents can generate substantial heat in transformers, and eddy current heating increases at higher harmonic frequencies. The relationship is illustrated in **Figure 3**.

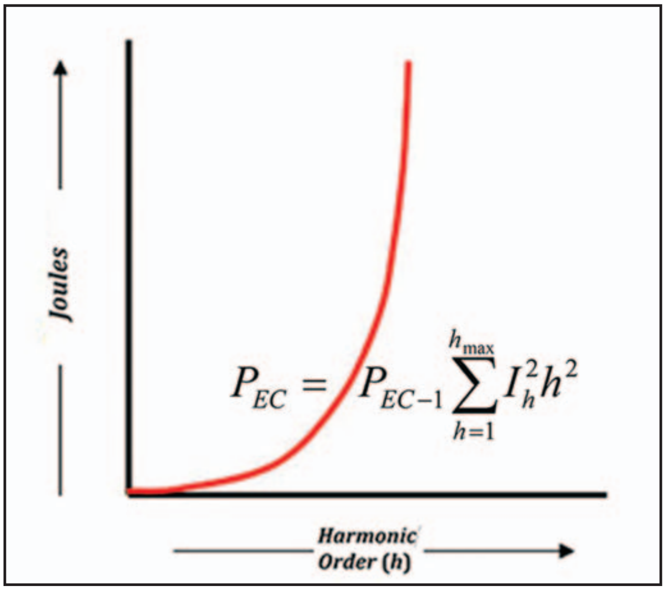

Figure 3 – Relationship between heat generation and eddy currents where PEC = total eddy current losses, PEC-1 = eddy current losses at full load based on linear loading only. Ih = rms current (per unit) at harmonic h, and h = harmonic #.

As you can see in **Figure 3** the math gets pretty complicated, so let's focus instead on the underlying principles contained in this equation. What is significant about the relationship of eddy current heat as a result of harmonic currents expressed in this equation is that the harmonic current (I_h) and harmonic number (h) are squared—instead of increasing in a linear fashion they increase exponentially. The heat generated by harmonic currents just doesn't increase gradually at higher harmonic frequencies (as illustrated in **Figure 3**), it jumps drastically.

For linear loads, eddy currents are a fairly small component of the overall load losses (typically about 5%). With non-linear loads however, they become a much more significant component, sometimes increasing by as much as 15x to 20x. It doesn't take much third harmonic to substantially increase the temperature of a transformer. Each ampere of third harmonic drawn by a non-linear load will generate as much heat as 9 A (3^2) of fundamental current at 60 Hz drawn by a linear load. For this reason, a transformer can exceed the allowable temperature rise of its full load rating (typically 55º C) when it's only partially loaded.

High operating temperatures can drastically shorten the life of a transformer. In fact, if it's loaded to capacity with non-linear loads the lifetime of a transformer can be reduced from around 40 years to no more than 40 days! Even though transformers are seldom loaded entirely of non-linear loads, at partial load the effect can result in severely overheated coils, and, in the worst case, insulation failure, which can lead to fire.

Heat is not the only adverse effect non-linear load harmonics can have on a stage distribution system; they can also cause voltage waveform distortion called "flat topping." Flat topping occurs because the current drawn by non-pfc LEDs is spiked (see **Figure 4**). When spiked current encounters the impedance of the distribution system supply there is a voltage drop. Since non-power factor corrected LEDs draw current only at the peak of the voltage waveform, Ohm's Law (V = I x Z) puts the voltage drop at the peaks as well, which results in a flattened voltage waveform. The flattened voltage reduces the LED's power disturbance ride-through capability, and increases both its current draw and I^2R losses.

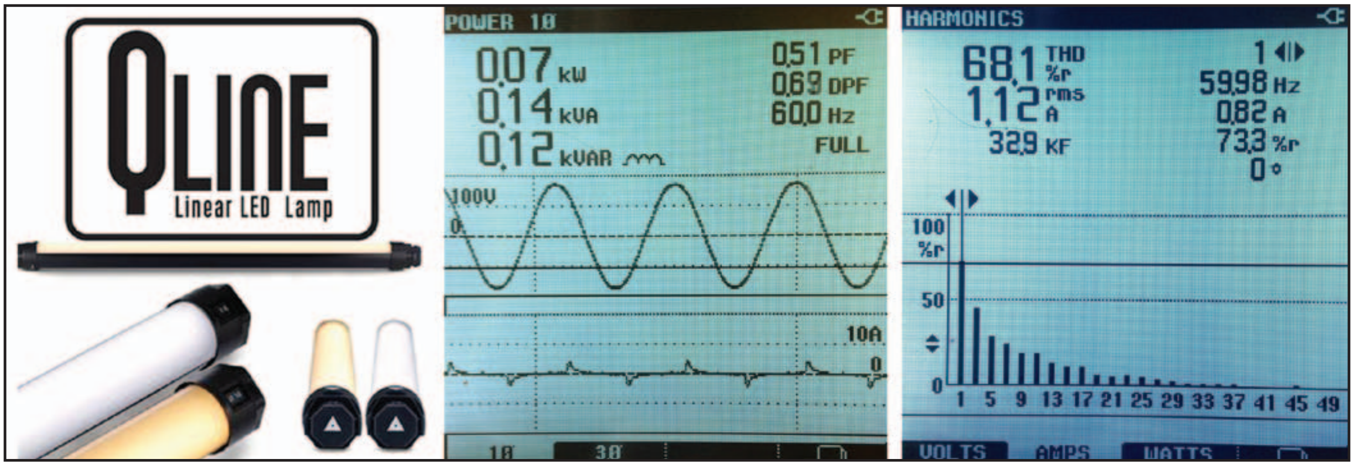

Figure 4 – Power quality readings of 8' Quasar Science LED tube with Fast Fourier Transform of harmonic components on the right.

Though not as pronounced as when harmonics encounter the soft power of diesel generators, the flat topping on studio grid power still can have adverse effects on the distribution system and on the loads. The delta-wye transformers used in stage distribution systems create high impedance to the harmonic currents drawn by the non-linear loads. In fact, the voltage distortion at the output of a delta-wye transformer can reach the 8% maximum voltage distortion limit recommended by *IEEE Std. 519 – 2014* with just one-half of full-load RMS current. At closer to full-load, these transformers can produce critically high levels of voltage distortion.

In the Fourier modeling of this interaction, harmonics current drawn by a Quasar Science LED (**Figure 4**) will result in a voltage drop at that harmonic frequency when it flows through the impedance of the stage's distribution system, creating voltage harmonics at the same frequency. The amount of voltage drop follows Ohm's Law ($V_h = I_h \times Z_h$) where: V_h = voltage at harmonic number h, I_h = amplitude of current harmonic current, and Z_h = impedance of the system to the harmonic current.

Using Parseval's Theorem, we can calculate the resulting voltage waveform distortion with a great deal of precision. Since the fundamental is not a distortion component, the voltage waveform distortion caused by harmonics, called the Total Harmonic Distortion (THD), is equal to the square root of the sum of the squares of the harmonic components. The math gets pretty complicated, but let's not lose site of the underlying principle.

$$V\,thd = \frac{\sqrt{V_2^2+V_3^2+V_4^2+V_5^2+\dots}}{V_1} \times 100\%$$

In any discussion of "harmonics" it is imperative that we keep in mind that what we are dealing with are wave shapes. Harmonics are only mathematical tools that allow us to precisely analyze the effects that the distorted current waveforms drawn by non-linear loads will have on an electrical system. While the math to calculate the precise amount of voltage waveform distortion (THD) is complicated, the simple fact is that voltage flat topping is caused when the current that non-linear loads draw at the peak of the voltage waveform encounters the impedance of the distribution system supplying them. Voltage distortion is a function of both the system impedance and the amount of harmonic current in the system. To reduce voltage distortion we must then either eliminate harmonic currents or reduce the impedance they encounter.

It appears that harmonics are here to stay. More than half of the LED fixtures I have tested in Boston area lighting rental and sales houses are not power factor corrected. So, often our only choice is to lower the impedance they encounter. The impedance of a distribution system can be lowered in two ways: either by de-rating the current carrying capacity of the stage's electrical distribution system, perhaps by as much as 50%, or by the use of a special type of transformer called a Harmonic Mitigating Transformer (HMT). Without a doubt, the high cost of oversizing a distribution system by a factor of two makes HMTs the more sensible choice; they can accomplish the same thing very cheaply with secondary windings that create zero sequence flux cancellation and phase shifting.

Before exploring phase shifting, let's first take a look at how HMTs create zero sequence flux cancellation. Simply by winding each leg of a transformer's iron core with the conductors of two different phases in opposite directions (a zig-zag configuration), the third order harmonic currents that were in phase and stacked on the neutral become 180 degrees out of phase producing fluxes that cancel each other. The resulting low impedance on the secondary at the same harmonic frequencies redirects the harmonics returning on the neutral and circulating in the secondary back to the load via the phase conductors. In effect, it off-loads the third order harmonics from the neutral bus before they can be induced into the windings of the transformer's primary (see **Figure 5**) thereby greatly

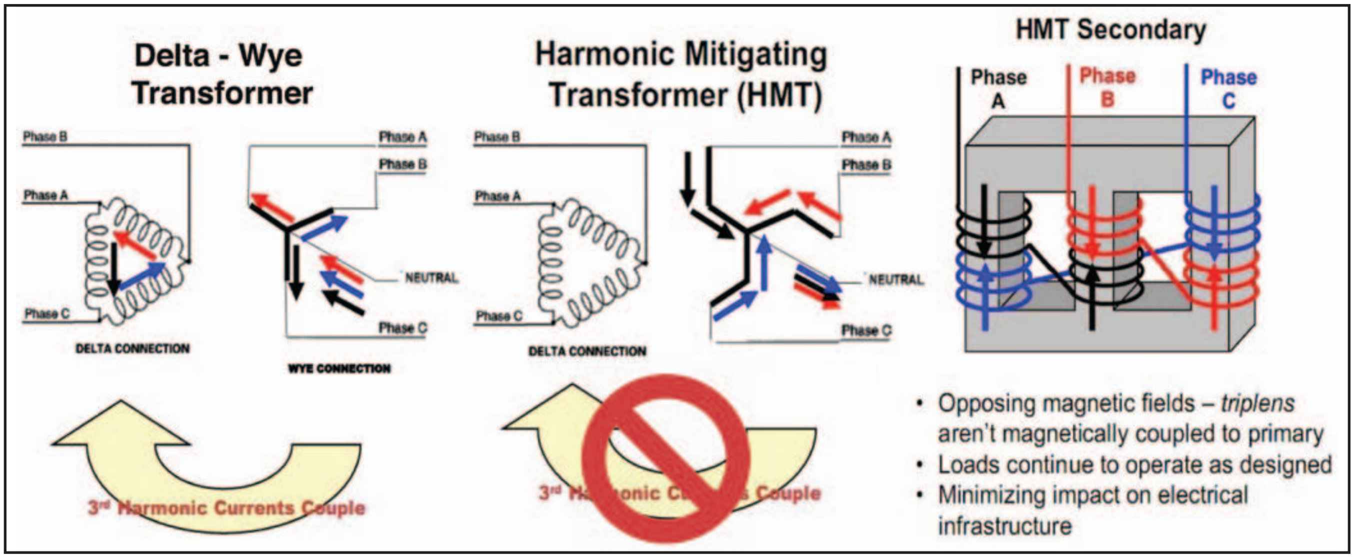

Figure 5 – As illustrated here, the coils of each phase are split between two core legs and wound in opposite polarity. Since the zero sequence current vectors (red, blue, black) are always in phase, the flux produced on one coil in each leg will cancel with the flux produced in the second coil on the same leg.

reducing the number of heat generating eddy currents upstream of the HMT.

The zig-zag winding of HMTs accomplish several other benefits as well.

First, it creates a path back to the load for not only the third order harmonic currents but also for the unbalanced portion of the fundamental current. Where the balanced portion of the fundamental on each phase is a positive sequence they cancel each other out. The unbalanced portion is zero sequence current and so it is diverted along with the third order harmonic currents to the phase conductors, which has the effect of partially balancing out the phase legs. The transformer in effect balances itself. This self-balancing characteristic of HMTs has the beneficial effect of also reducing the voltage unbalance in systems where the load is not equally distributed between phases.

By far the most important additional benefit gained by re-directing third order harmonics back to the load via the phase conductors is the reduction in voltage distortion that results. By re-directing third order harmonics back to the load, HMTs satisfy the demand for these frequencies by the load and they do not appear upstream of the HMT. In this fashion, HMTs offload not only the neutral of third order harmonics, but the phase conductors as well. This eliminates not only the I^2R losses they would create in the cables and the upstream transformer, but also the voltage distortion as well.

Let's now look at the second way HMTs mitigate the adverse effects of the harmonics drawn by non-linear loads: phase shifting. This involves separating the electrical supply into several outputs. Each output is phase shifted with respect to the other output such that the eddy currents created by the targeted harmonics in the cable and upstream transformers are eliminated when the flux they create is recombined.

HMTs accomplish this by incorporating two zig-zag wye windings in their secondary (**Figure 6**). A HMT is, in effect, two transformers in one. Each zig-zag wye winding is out of phase with the other by a small degree. The degree to which the outputs are phase shifted is determined by which harmonic frequencies are targeted. Since, in the case of non-pfc LEDs, the fifth and seventh are all that remain after the third order harmonics are off-loaded from the phase conductors (see **Figure 4**), HMTs intended for use on motion picture stages (like those built by Mirus International pictured in **Figure 7**) phase shift their outputs by 30 degrees.

As illustrated in **Figure 8**, a shift of 30 degrees between the two zig-zag windings results in a 150 degree shift of the fifth harmonic voltage. Since fifth harmonics are negative sequence, the transformer also applies a shift of 30 degrees between the current drawn on one

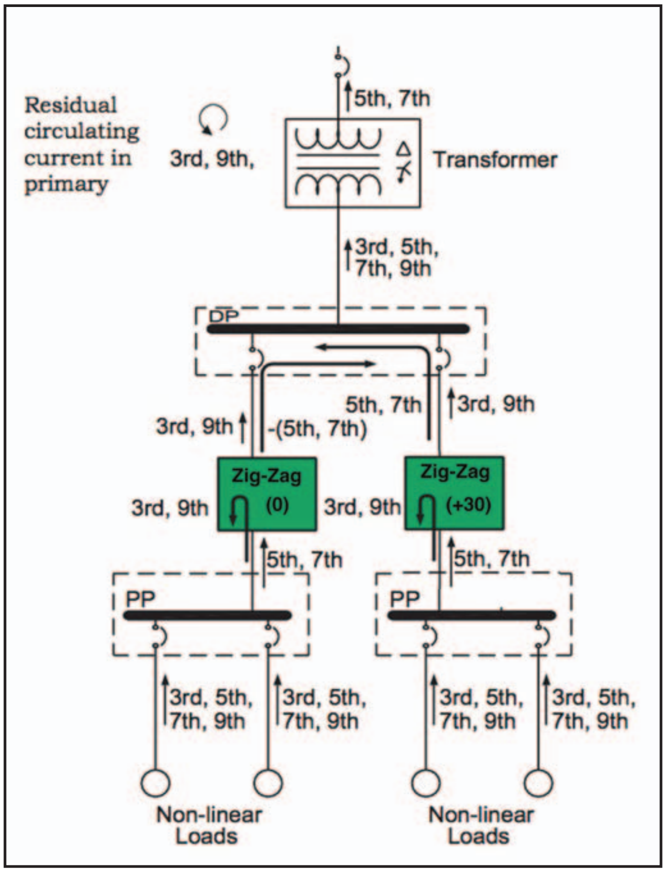

Figure 6 – With dual zig-zag secondaries, HMTs are in effect two transformers in one, as illustrated here.

Figure 7 – Mirus International Dual Output HMT Autotransformer equipped with optional Camlok connectors.

zig-zag winding relative to the other, which makes the total shift in phase angle between the current drawn on one winding relative to the other to be 180 degrees. Now that there are two sets of fifth and seventh harmonics (180 degrees out of phase of each other) being drawn on each phase conductor, their fluxes cancel, which has the effect of greatly reducing the eddy currents they generate in the conductor. The reduction in eddy currents lowers the impedance the harmonic currents encounter, which in turn has the effect of reducing skin effect, the resistance they encounter, and the heat they generate. The same is true of the seventh harmonic. Only the residual unbalanced portions of these harmonics will generate eddy currents in the cable and transformers upstream of the HMT. Another important benefit to reducing the fifth and seventh harmonic currents upstream in this fashion is that the voltage distortion they would create based on Ohm's Law is also reduced.

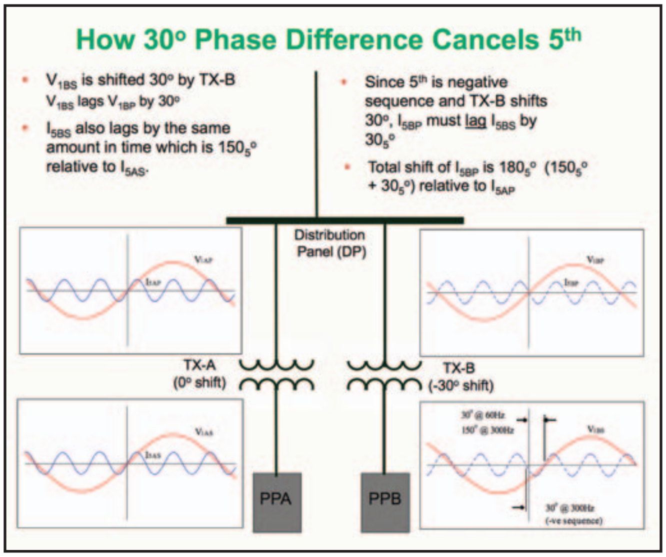

Figure 8 – Current shift at fifth harmonic, with 30 degree fundamental (60 Hz) phase shift, results in a 180 degree shift in the fifth harmonic current drawn on one of an HMT's two secondary windings, which results in fifth harmonics canceling when they are recombined on the neutral bus of the transformer.

Although the angular displacement is only 30 degrees, the electromagnetic effect of this phase shift, in combination with the zero sequence flux cancellation that occurs in each of the secondary zig-zag windings, results in lower I^2R power losses in the system, lower current on the neutral, and lower voltage distortion. Since temperature rise is a limiting factor in the loading of both transformers and distribution cables, the substantial reduction in operating temperature that results (see **Figure 9**) increases the load that a distribution system can safely support.

While the cost of shipping HMTs is not cheap, the savings that can be had by eliminating the need to double the size of a distribution system, reducing the amount of energy consumed,

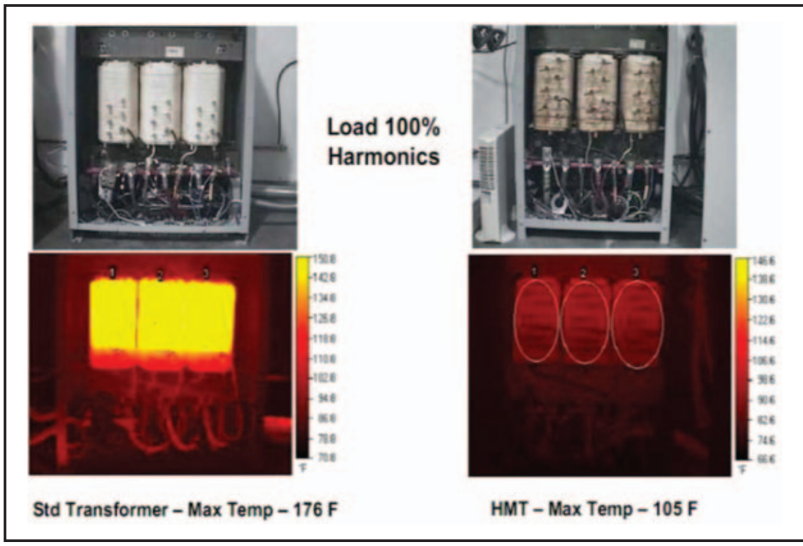

Figure 9 – Effect of harmonics on the temperature rise of a standard delta-wye transformers (left) and after mitigation by HMT (right.)

and extending equipment life expectancy, will more than offset the expense of procuring one for your next production. For now, they are hard to find, but are becoming more common in our industry because of the increasing use of LEDS on motion picture stages.

Guy Holt has served as a gaffer, set electrician, and generator operator on numerous features and television productions. He is recognized for his writing on the use of portable generators in motion picture production (available soon in book form from the APT Press). Guy has developed curriculums on power quality and electrical hazard protection that he has taught through the IATSE Local 481 Electrical Department's "TECs" Program. He is the owner of ScreenLight & Grip, a motion picture lighting rental and sales company that specializes in innovative approaches to set power using Honda portable generators.