Power quality in the age of LEDs: Part 2

BY GUY HOLT

IN THIS SECOND PART of a series of articles exploring the adverse effects harmonics drawn by LED power supplies can have on stage power distribution systems, we will first look at the trend of using large soft boxes comprised of 8' Quasar Science Q100 LED tubes can have on the distribution system of a typical motion picture stage. In subsequent parts we will examine how these effects may require, according to *NEC 310.15*, the de-rating of stage distribution equipment by 50% or more and how the use of harmonic mitigating transformers (HMTs) can be used to reclaim the lost distribution ampacity.

In Part 1, we saw how LED luminaires generate harmonics. In this section, we will examine why the harmonics drawn by a large number of Quasar Science Q100 LED tubes can severely effect stage distribution equipment. Let's start by reviewing the power characteristics of the 8' Quasar Science LED tube.

As we see in the power quality meter (PQM) readings in **Figure 1**, the power drawn by the 8' Quasar Science LED tube is very distorted with a power factor of 0.51. Their relatively poor power factor is a consequence of the large smoothing capacitors used in their switch-mode power supplies to drive the LEDs with DC so they don't flicker. With a power factor (PF) of 0.51, each 8' Quasar Science LED tube has an apparent power of 140 VA for its 70 W output. While it draws RMS current of 1.12 A with a crest factor of about 3.3, its peak current is 3.7 A. (A comparatively-sized incandescent luminaire would draw only 0.58 A.) The current they draw is harmonically rich with a total harmonic distortion (THD) of 68.1% and large third, fifth, seventh, and ninth components. It is the heat that these harmonic components generate that has an adverse effect on stage distribution equipment.

Harmonic currents generate heat disproportionately to that generated by the fundamental current (50/60 Hz) because the magnetic fields they generate modify the spatial distribution of current in a conductor, displacing it toward the periphery. Since the current pushes through a smaller area, the resistive value of the conductor increases considerably. The higher resistance leads to the generation of heat (called I^2R loss.) This phenomenon is called "skin effect."

Skin effect is not the only means by which harmonic currents generate heat in a stage distribution system. When current carrying conductors are bundled in close proximity to one another, as in a raceway or conduit, the magnetic fields generated by the harmonic currents in one conductor cut across the other conductors, further restricting the area in which current flows in the conductors. This phenomenon is called "proximity effect." The resistive value of the conductor increases even more and the generation of heat increases again. How much?

To get an idea, let's look at recent research done in the European Union. In "Calculation of harmonic losses and
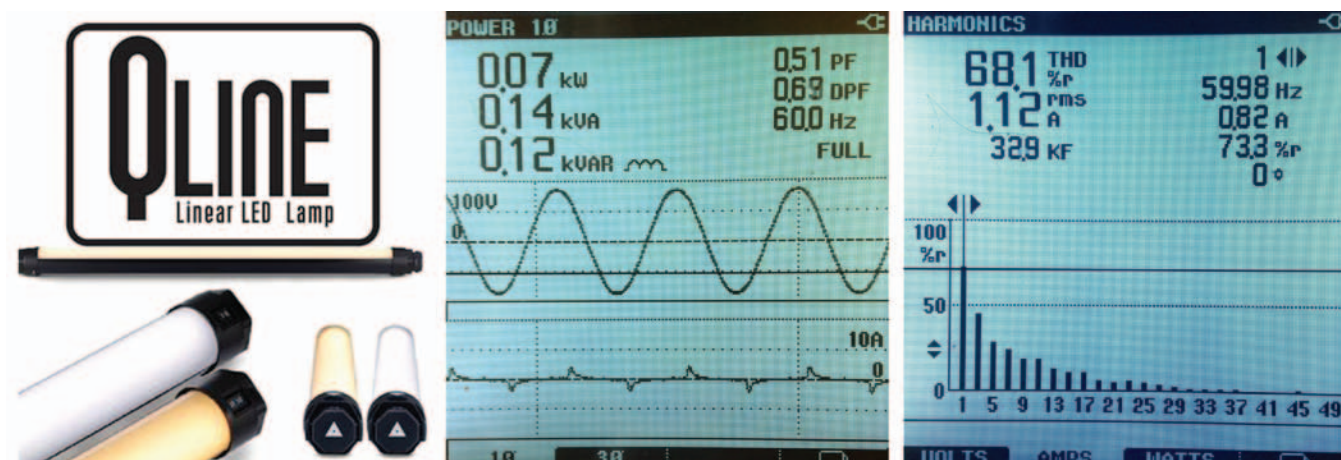

Figure 1 – PQM readings of the Quasar Science LED tubes. (Note: disproportionate amount of third order harmonics (third, ninth, etc.) in the FFT on the right).

ampacity in low-voltage power cables when used for feeding large LED lighting loads" *(Advanced Electromagnetics*, Vol. 3, No. 1, October 2014), the authors examine the harmonic disturbances in low-voltage distribution systems feeding large LED lighting loads. They found that the cross sectional current carrying area of the conductors they tested were so reduced by skin and proximity effect that the resistive value of the conductors increased significantly, resulting in a substantial increase in heat generated; so much, in fact, that the authors recommend de-rating a conductor's capacity to power a load when powering large quantities of LED fixtures.

For example, when carrying just 15 A of fifth-order harmonic current, the authors found a substantial reduction in the effective area of current circulation within conductors in a bundle. (The spatial distribution of current caused by 15 A of the fifth harmonic, along with the magnetic field lines that produced it, is illustrated in **Figure 2**.)

After examining the harmonics drawn by the non-power factor corrected LEDs in their sample, the authors found the power lost to heat was 2.3 times greater than that produced in an identical bundle of cable carrying an undistorted current of the same RMS value. That amount of heat should not be ignored when distributing power on a stage.

The heat generated in phase conductors by skin and proximity effects is not the only adverse effect caused by the harmonics drawn by LED light fixtures like the 8' Quasar Science LED tubes. The accumulation of these currents on the neutral of the stage distribution system, and the disproportionate heat they generate, is another major consideration when distributing power on a stage.

The reason harmonics accumulate on the neutral of motion picture stages in the US is that the standard configuration of service transformers providing power to stages in the US is delta-to-wye. With three-phase legs, each 120 degrees out of phase with one
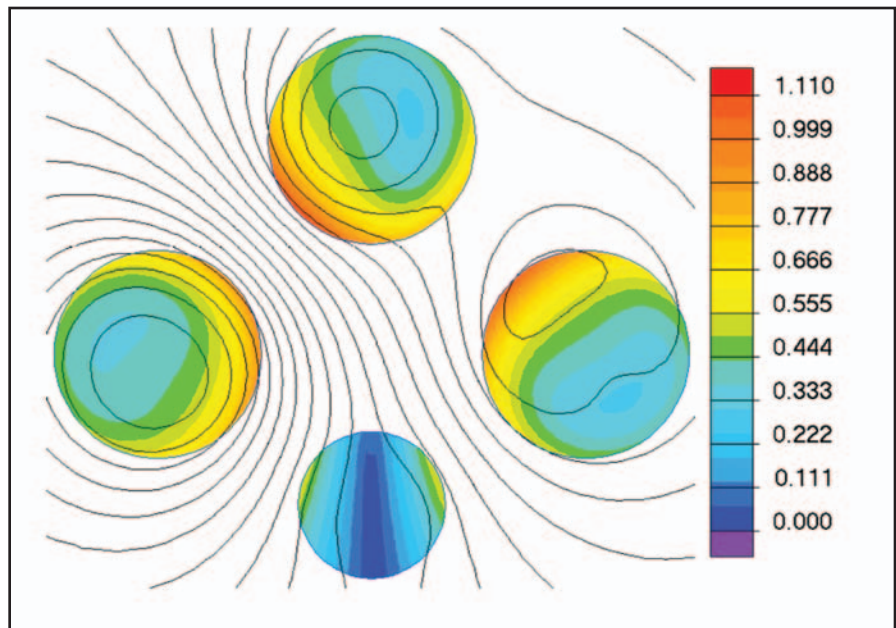
Figure 2 – Spatial distribution of the rms current density for the fifth-order (h = 5) harmonic in four single-core cables (3 x 240 + 120 mm²) in close proximity in open air. Note: 240 mm cable is 500 MCM (roughly twice the size 4/0 cable, 120 mm cable is the same size as 4/0 cable.)
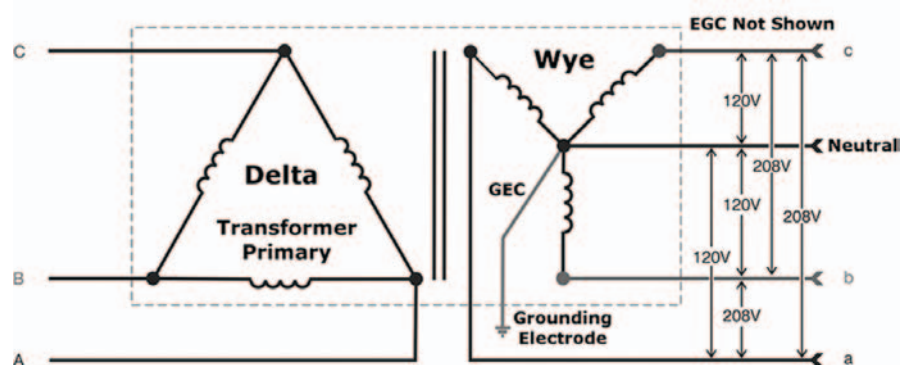
Figure 3 – The configuration of the delta-to-wye service transformers that provide power to motion picture stages in the US.

another, this transformer configuration will return third-order harmonic current (third, ninth, etc.) on its neutral because they add, rather than cancel, as the fundamental does. To understand why, let's look more closely at the configuration of delta-wye connected transformers.

As illustrated in **Figure 3**, the delta primary is fed by three-phase wires (A, B, and C). On the secondary wye-connected side, there are three-phase wires, each separated in phase angle by 120 degrees, and a neutral return 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, such as 20 kW quartz lights and HMIs from 6 kW on up, are connected phase to phase.

In this transformer winding scheme, when the harmonic currents drawn by non-linear loads (like 8' Quasar Science LED tubes) on the phase legs are dumped into the drain pipe of the neutral, something interesting happens. Balanced linear loads
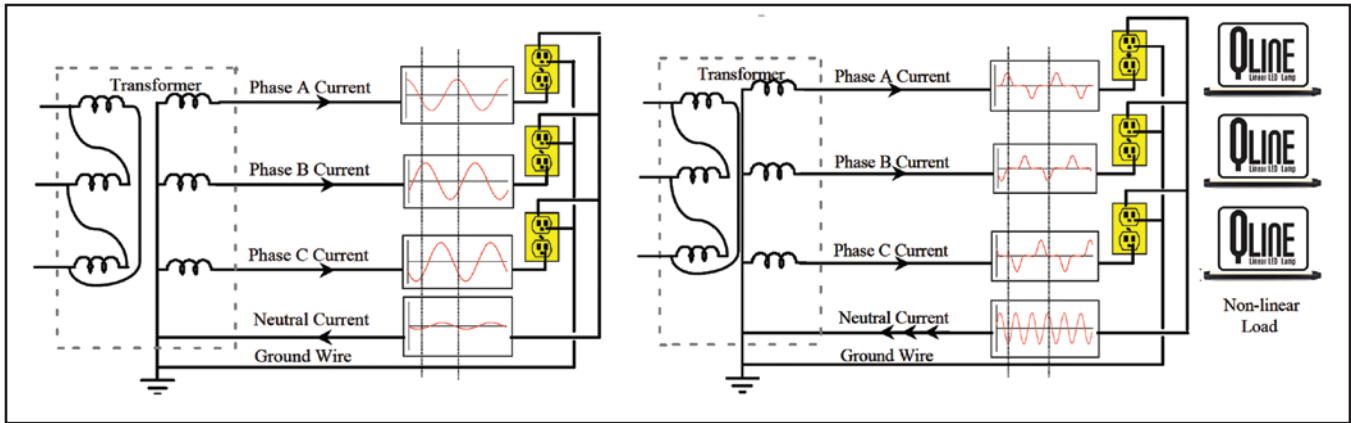
Figure 4 – (Left) Balanced linear loads cancel each other out so that the neutral returns only the difference between the phase legs (nearly nothing on a well-balanced system). (Right) The third-order harmonics (third, ninth, etc.) of balanced non-linear loads return on the neutral conductor.

will cancel each other out so that the neutral returns only the difference between the phase legs (nearly nothing on a well-balanced system). Balanced non-linear loads, by contrast, return on the neutral conductor as much as 1.7 times the average of the current drawn on the phase legs.

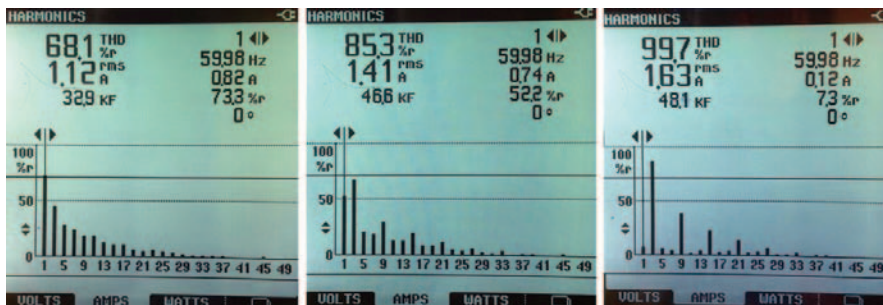For example, in **Figure 5**, if we look

Figure 5 – PQM FFTs of the neutral current on a three-phase distribution as 8' Quasar Science LED tubes on each phase leg are turned on one at a time. (Left) One tube on phase "a." (Middle) One tube on phase "a" and one tube on phase "b." (Right) One tube on each phase leg.
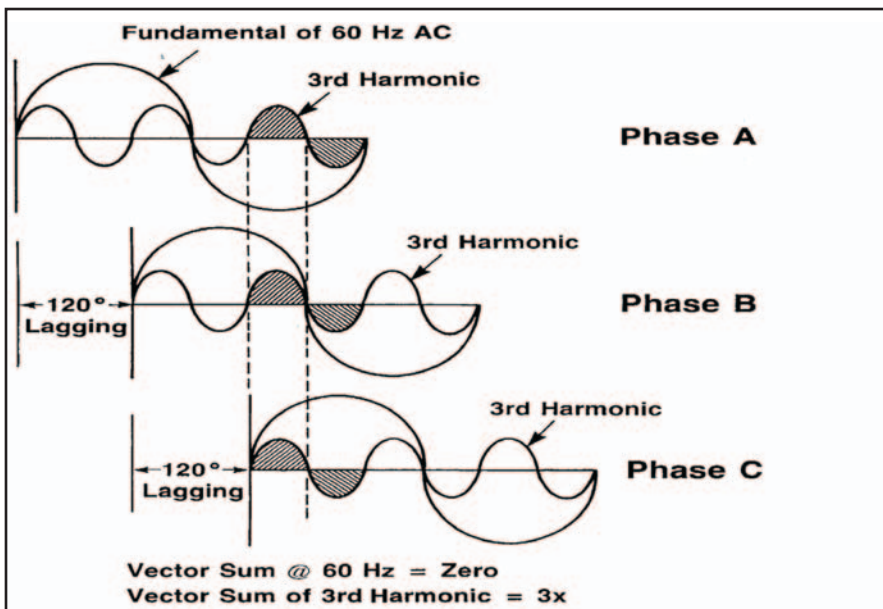

Figure 6 – Illustration of third harmonic half cycles that are in phase

closely at the Fast Fourier Transformations (FFT) of the neutral current on a three-phase distribution as 8' Quasar Science Q100 LED tubes on each phase leg are turned on one at a time, we see that the 50/60 Hz fundamental current (a_1, b_1, and c_1) still cancel each other out. The (+) sequence harmonics (fourth, seventh, etc.) cancel each other out and the (-) sequence harmonics (second, fifth, etc.) also cancel each other out. But the third-order or zero sequence harmonics (third, ninth, etc.) do not cancel out. Instead they add. Why?

If, for a moment, we consider only the third harmonic (180 Hz) of each phase as they return on the neutral, you will notice in **Figure 6** that in each positive half-cycle of any of the fundamental waveforms, you will find exactly two positive half-cycles and one negative half-cycle of third harmonic. The net result is that the third-harmonic waveforms on phase conductors that are separated 120 degree (three-phase power) are actually in phase with each other and so stack on one another rather than cancel out as the fundamentals, positive, and negative sequence harmonics do.

That third-order harmonics accumulate on the neutral of delta-wye transformers accounts for the fact that three 8' Quasar Science Q100 LEDs (one on each phase leg) will return current of 1.63 A on the neutral when each draws only 1.12 A. The neutral is carrying 145% of the load of the individual
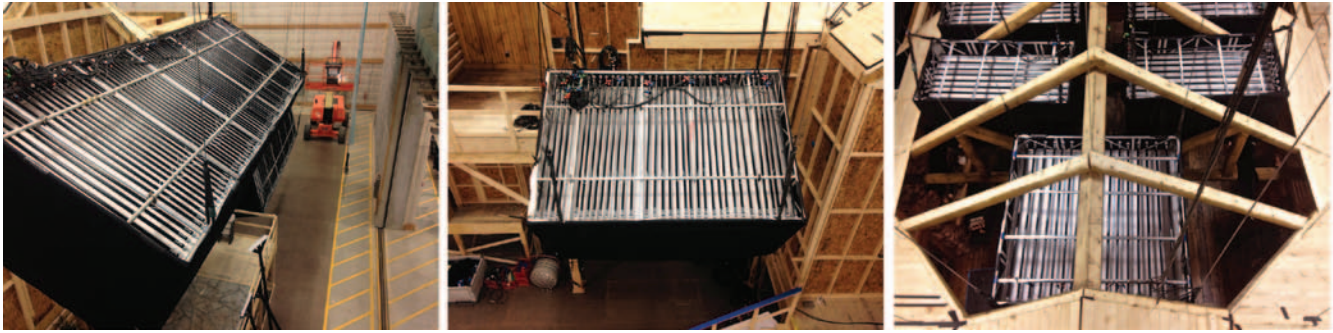
Figure 7 – (Left) 8' x 20' Quasar Science soft box. (Middle) 8' x 12' Quasar Science soft box. (Right) 8' x 6' Quasar Science soft boxes.

phase legs. This can be significant when powering many of these luminaires because in a typical delta-wye transformer, the secondary neutral wire has the same current carrying capacity as the phase wires. In the past this was not a problem because, with linear loads, the neutral would carry only the out-of-balance current of the phase legs, which meant that the neutral conductor could never carry more current than any one of the phase conductors. But, now that the third order harmonics (third, ninth, etc.) drawn by non-linear loads stack on the neutral, the neutral conductor can carry more current than the individual phase conductors. Where this current travels only on the outer edge of the neutral conductor, considerable heat is generated because of the increased resistance through skin effect. The high I^2R heat losses caused by

harmonics can cause the neutral to overheat quickly.

The authors of the EU study cited above observed as much. The spatial distribution of current to the outer edges of the neutral conductor is clearly evident in **Figure 2**. After taking into account the third-order harmonics drawn by the non-power factor corrected LEDs in their sample, the authors found that the neutral conductor of their three-phase distribution system carried 1.7 times the average current drawn on the phase legs. Since, these currents flowed along the outer edge of the neutral conductor, increasing its resistance, the authors observed a significant rise in the temperature of the neutral conductor, much more than that observed in the phase conductors.

To get a handle on the magnitude of the

problem caused by the harmonic heating of the phase and neutral conductors in three-phase stage distribution systems, let's look at the effect the number of Quasar Science Q100 LED lights on the show mentioned in Part 1 had on the 400A three-phase company switch powering them (**Figure 8**). On that production there were a total of five 8' x 6' boxes, two 8' x 20' boxes, as well as an 8' x 12' box (see **Figure 7**) for a total of 250 8' Quasar Science Q100 LED tubes. In addition, there were three 24 kW quartz Fresnels, and 55 ARRI S60 Skypanels.

Placing the amp probe of my power quality meter on the phase conductors of the company switch serving the 250 8' Quasar Science Q100 LED tubes, I measured the harmonic currents they drew. According to the FFTs of the current drawn on each phase leg and the neutral, there
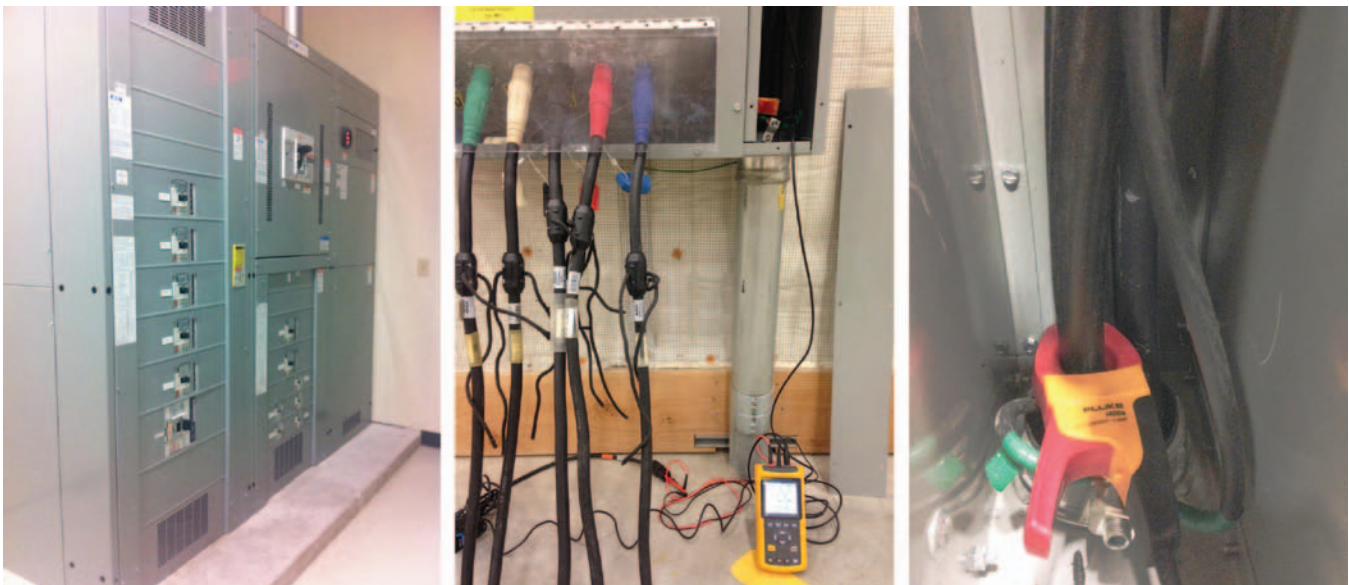

Figure 8 - (Left) Stage main switchboard with 400 A branch circuits (row of breakers on left). (Center) 4/0 CamLok connections to 400 A branch circuit (company switch) fed by conduit from floor of stage. (Right) PQM amp probe on 500 MCM neutral of company switch before it enters conduit.

was considerable harmonic content. For example, the high leg (shown in **Figure 9**) carried 300 A of current, 63.8 A of which was third harmonic and 16.8 A of which was fifth harmonic, with a total harmonic distortion of 22%. Since a 24 kW quartz fresnel is a linear load and the ARRI S60 Skypanel is power factor corrected to draw a near sinusoidal waveform, the harmonics I measured could only have come from the distorted current drawn by the 8' Quasar Science Q100 LED tubes.

Figure 9 – The FFT of the high phase leg shows that it carried 300 A of current, 63.8 A of which was third harmonic and 16.8 A of which was fifth harmonic.

To all appearances, the 300 A load is well within the 430 A rating of the 500 MCM feeder supplying the company switch, but when we consider the heat generated in the EU study cited above, the temperature rise as a result of skin effect may in fact exceed the allowable heat rise for the cable. (We will explore this in more detail when we examine how the *National Electrical Code* deals with harmonics in the next part of this series.)

Now, let's look at the current generated by the third-order harmonics drawn by the 8' Quasar Science Q100 LED tubes stacking on the neutral of the stage company switch. Moving the amp probe of my power quality meter to the neutral conductor of the company switch serving the 250 8' Quasar Science

Figure 10 – Of the 105 A returning on the neutral, 99.3 A consists of third harmonic current.

Q100 LED tubes, I measured 105 A on the neutral consisting mostly of 180 Hz third harmonic current, 99.3 A.

While the 500 MCM neutral of this distribution system is not overloaded (the cable is nominally rated for 430 A), given the frequency of the currents traveling on it and the I^2R losses they generate through skin effect, the neutral may become overheated nonetheless. (We will explore this in more detail in the next part of this series as well.)

In the case of stage-based productions like this one, the fact that the phase conductors are bundled with the neutral conductor in conduit between the stage main switchboard in the electrical room and the company switch located on the stage floor (see **Figure 8**) further exacerbates the problem in two ways. First, the magnetic fields generated by the harmonic currents in one conductor cut across the other conductors when bundled together, further restricting the area in which current flows in the conductors. Since the current now has to push through a smaller area, the resistive value of the conductor increases and the generation of heat increases, again due to this proximity effect.

Second, trapping the heat generated by harmonic-carrying conductors inside conduit has the effect of raising their temperature even more. To the heat

generated by the harmonics on the phase legs, add the heat generated by 105 A on the neutral that consists mostly of third-order harmonic currents, enclose it in a confined space, and you can see how stage distribution cables can get dangerously hot when powering large quantities of LEDs. Since the neutral is not protected by an over-current device, the heat generated by four harmonic current carrying conductors enclosed in conduit can cause the insulation of the neutral conductor to deteriorate or even catch fire.

The authors of the EU study cited above arrived at their recommendation to de-rate feeder cables by a factor of 2.5 times based upon test results obtained from conductors in open air. In the next part of this series we will see why the *National Electrical Code (NFPA 70)* prescribes a further de-rating of conductors when enclosed in a conduit or raceway. ■

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.