Power quality in the age of LEDs: Part 1

BY GUY HOLT

WHEN YOU LOOK AROUND a motion picture stage these days, linear loads (quartz lights) are greatly outnumbered by non-linear loads such as HMIs, Kino Flos, and increasingly LEDs. Without a doubt it is a whole new world, one in which we are still feeling our way. While a great deal has been written about the light quality and color performance of LED lamps, little has been said about how they can adversely affect stage power.

The purpose of this series is to explore the effect that LEDs can have upon the quality of power on a stage and how the heating effect of the harmonics drawn by LED power supplies may require, according to *NEC* 310.15, the de-rating of stage distribution equipment by as much as 50%. To reclaim distribution ampacity lost to heat, we will then explore how Harmonic Mitigating Transformers (HMTs) can be used to substantially reduce the heat generated by LED power supplies in 3-phase systems, thereby increasing a stage distribution system's capacity to safely power loads. But, let's start by looking closely at how an LED operates.

All lights do not consume power in the same way. Incandescent, fluorescent, LED, and HMI lights fall into two broad categories: Those that are linear loads and those that are non-linear loads. An incandescent light is a simple resistive load. The resistance of its tungsten filament creates heat making the filament glow, creating light. The current in such a simple resistive AC circuit increases proportionally as the voltage increases and decreases proportionally as the voltage decreases.

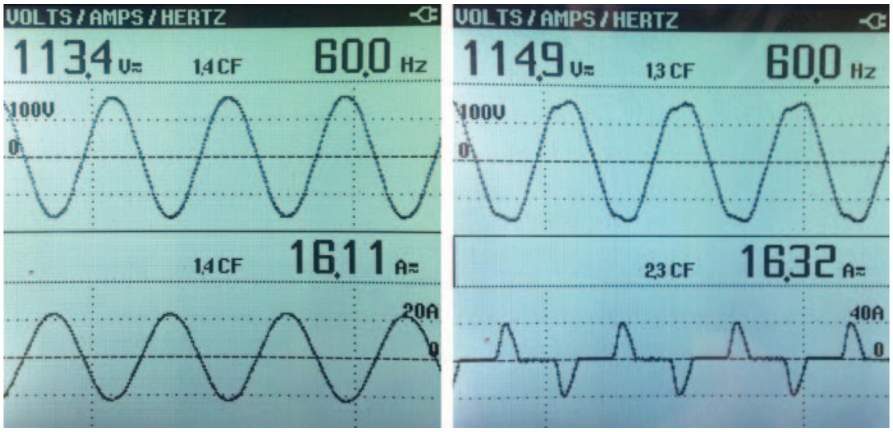

Figure 1 – (Left) A linear 2 kW tungsten light on grid power. (Right) A non-PFC 1200 W HMI on grid power. Note: spiked current drawn by non-PFC 1200 W HMI in lower right PQM reading.

For a sinusoidal voltage, the current is also sinusoidal. The load is said to be linear.

Electronic HMI, fluorescent, and LED power supplies belong to a category called switch-mode power supplies (SMPSs). SMPSs use only a portion of the AC voltage waveform. In the process, they draw a distorted current waveform rich in harmonics, and they pull the voltage and current out of phase with respect to one another. The load is said to be non-linear. (See **Figure 1** for comparison of current waveforms.)

As **Figure 2** illustrates, the SMPSs used in LED AC power supplies can draw a very distorted current, and can result in current that is significantly shifted with respect to the sinusoidal voltage waveform. For instance, the AC power supply that Litepanels uses for their 1x1 arrays have a leading power factor of 0.62 and generate high harmonic distortion (THD upwards of 68.1%). At these levels, the AC power supplies used with LEDs can have an adverse effect on power quality similar to that of HMIs and fluorescent lights if used in large quantities.

To understand why LED power supplies can have an adverse effect on a power distribution system, we have to look closely at how they consume power. An

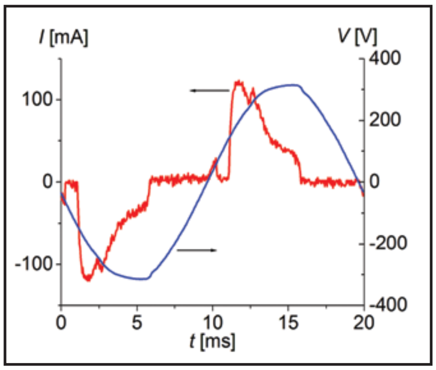

Figure 2 – The very distorted current drawn by an LED AC power supply (red trace) is significantly phase-shifted with respect to the sinusoidal voltage waveform (blue trace.)

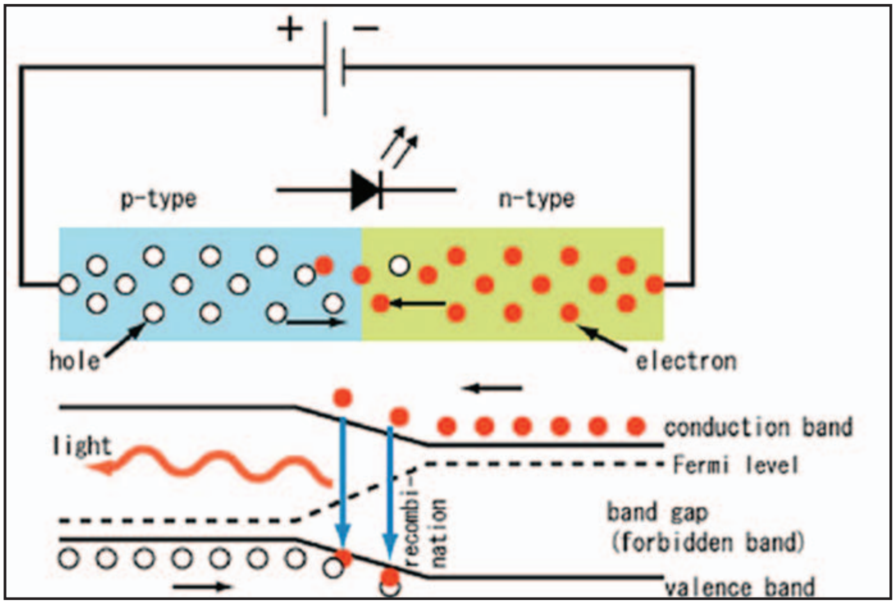

Figure 3 – How LEDs emit light.

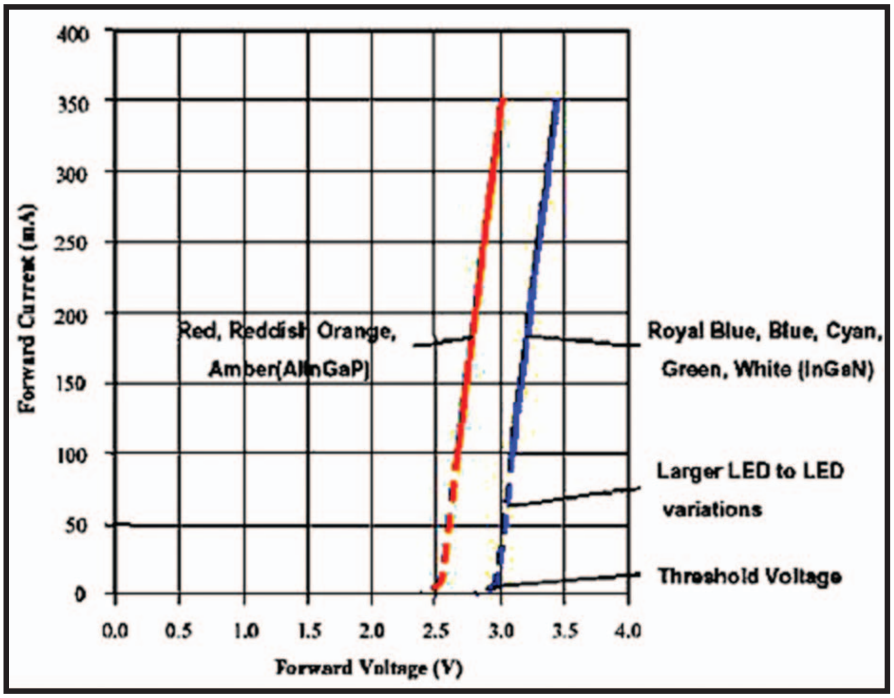

Figure 4 – A small voltage change results in an exponentially large change in current.

LED consists of a chip of semiconducting material doped with impurities to create a "p-n junction." As in other diodes, current flows easily from the p-side, or anode, to the n-side, or cathode, but not in the reverse direction. As illustrated in **Figure 3**, when the opposing electrodes of the p-n junction have different potentials, electrons fall into the lower energy level, releasing energy in the form of light.

LEDs require more precise voltage/current management than traditional motion picture light sources. Unlike incandescent lights, which illuminate regardless of the electrical polarity, LEDs will only light with correct electrical polarity. When the voltage across the p-n junction is in the correct direction, a significant current flows and the device is said to be forward-biased. If the voltage is of the wrong polarity, the device is said to be reverse biased, very little current flows, and no light is emitted.

While LEDs can operate on alternating current circuits, this approach is unsuitable for motion picture lighting applications because it will cause flicker in the image. When powered with alternating current an LED will light only with positive voltage, causing the LED to turn on and off at the frequency of the AC supply. As in the case of magnetic HMI ballasts, these pulsations of light will lead to flicker in the image unless both the power supply and camera shutter are tightly regulated. For this reason, when used in motion picture production, LEDs require direct current (DC) be applied to their diodes. To operate on AC mains power, LEDs need not only some type of AC-to-DC converter but also additional regulation of the DC current to the diodes.

LEDs require additional regulation of the DC to the diodes because, as illustrated in **Figure 4**, a small voltage change results in a large change in current. It is therefore critically important that the right DC voltage be provided to the diodes. If the voltage is below the threshold, no current will flow and the result is an unlit LED. If the voltage is too high, the current will go above the maximum rating, heating, and potentially destroying the LED. To make matters worse, as an LED heats up, its voltage drop decreases, further increasing current. For these reasons, the high-powered LEDs used in film production require a high degree of power conditioning (unlike incandescent light sources.) Given the power conditioning required, switch-mode power supplies are almost universally used to power LEDs on AC mains power for motion picture lighting applications.

To understand why LEDs can have an adverse effect on a stage power distribution system, we have to look closely at how SMPSs consume power.

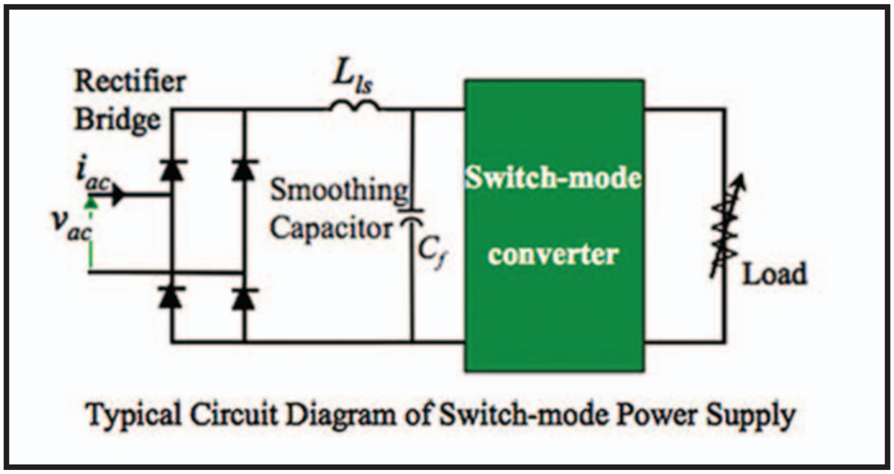

Figure 5 – Typical circuit diagram of a switch-mode power supply

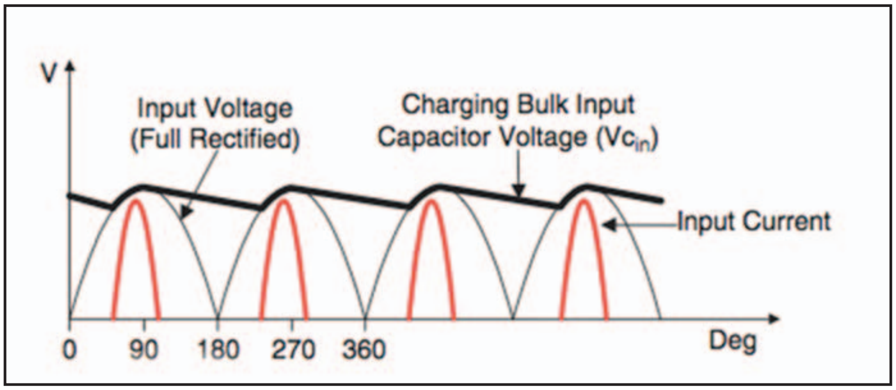

Figure 6 – Thin black trace: The rectifier bridge converts AC power to a fully rectified sine wave. Thick black trace: The stored capacitor voltage. Red trace: The current drawn by capacitors once the input voltage is greater than the voltage stored in the capacitor (thick black trace.)

As illustrated in **Figure 5**, the first power stage of a SMPS consists of a rectifier bridge of diodes and a smoothing capacitor. To convert an AC input to DC the rectifier bridge converts the negative half of the voltage waveform to positive. The smoothing capacitor then flattens the resulting pulsed DC by storing and releasing charge during the intervals between the peaks. The second power stage of SMPS consists of a switch-mode converter. In the case of HMI and Kino lights, the switch-mode converter converts the flattened DC back to an alternating waveform that powers the lamp. In the case of motion picture LED lights, the switch-mode converter further conditions the DC output from the diode-capacitor stage. While the output of the switch-mode converter stage of a power supply varies by type of light, they all use a rectifier bridge and capacitor section to first convert AC to DC. Without active power factor correction circuitry, this power conversion stage will draw a very distorted current waveform.

As it charges, the smoothing capacitor only draws current during the peaks of the supply voltage waveform. After 90 degrees of the pulsed DC waveform, the voltage from the bridge drops below the capacitor voltage, which reverse biases the bridge, inhibiting further current flow into the capacitor. The capacitor therefore only draws current when the input voltage is greater than the voltage stored in the capacitor. The capacitor, as illustrated in **Figure 6**, draws current in bursts of high amplitude, which explains the higher apparent power and hence lower power factor of non-PFC HMI, Kino Flo, and LED power supplies.

If we wanted to do the math, a Fourier analysis of the spiked current waveform drawn by LED AC power supplies will give us the harmonic currents they draw. The math can get pretty complicated; let's instead focus on the underlying principle. In 1897, Baptiste Joseph Fourier had the crazy idea 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 spiked current drawn by a LED AC power supply, 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 7**, the distorted current drawn by the SMPS of LEDs can be broken down into components that include the fundamental wave and a third order, and fifth order harmonic wave. The third order, or simply the third harmonic, is a 180 Hz sinusoidal waveform (3 x 60 Hz, the power line frequency). The fifth harmonic, is a 300 Hz sinusoidal waveform (5 x 60 Hz). The energy at any point on the distorted waveform is equal to the sum of the energy in the fundamental and all of the harmonic waveforms at that point. The process of deriving the frequency components of a distorted periodic waveform is achieved by a technique known as the Fourier transform. Microprocessor-based test equipment, like the power quality meter (PQM) we are using here, can do this mathematical analysis very quickly using a Fast Fourier Transform, which it displays as a bar graph. (The harmonic currents drawn by a Litepanel Sola LED Fresnel are displayed in **Figure 8**.)

One could argue that the wattage of LED fixtures is so low that the harmonics they draw don't matter from a practical standpoint. While that is true to a degree, when used as the predominant source of light on a stage, the harmonics drawn by even small LED fixtures will accumulate and effect power adversely, especially given the quantities of LED fixtures being used on stages today. To see why that would be the case let's look at a typical stage lighting scheme.

In the past, the two principal components to creating "natural" daylight on a stage set were a large quartz fresnel to create the hard crisp light of direct sun, and a large quartz or Kino soft-box to create the soft light of "sky shine," the diffuse light reflected by our atmosphere back to earth. These days, the go-to fixture to create large soft sources is the 8' Quasar Science Q100 LED tube. Sixty-eight of these fixtures tie-wrapped onto an 8' x 20' box truss frame skinned with diffusion creates a very powerful soft light, while drawing very little power (less than a tungsten 10 kW fixture.) In fact the individual LED tubes are powered with nothing more than runs of zip line with add-a-tap receptacles.

While a very efficient way of creating a

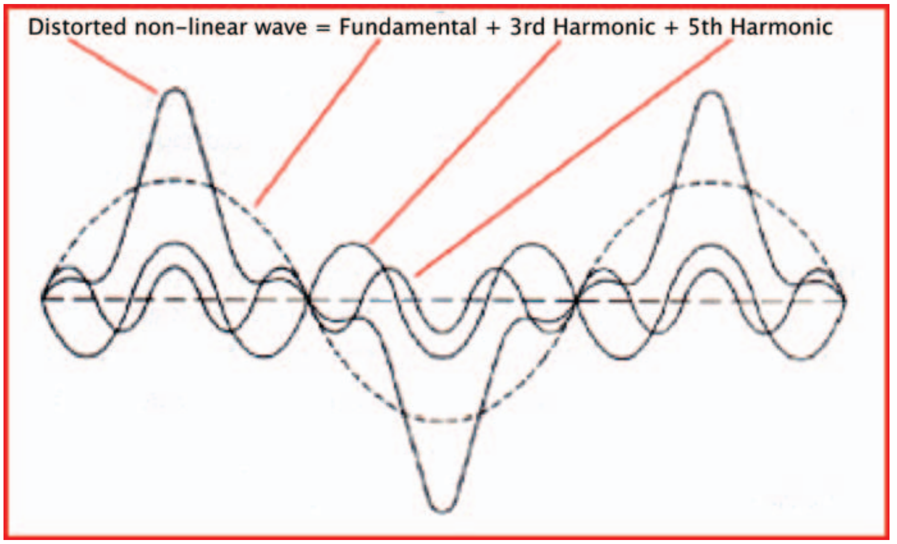

Figure 7 – The harmonic components that make up a distorted non-linear periodic waveform

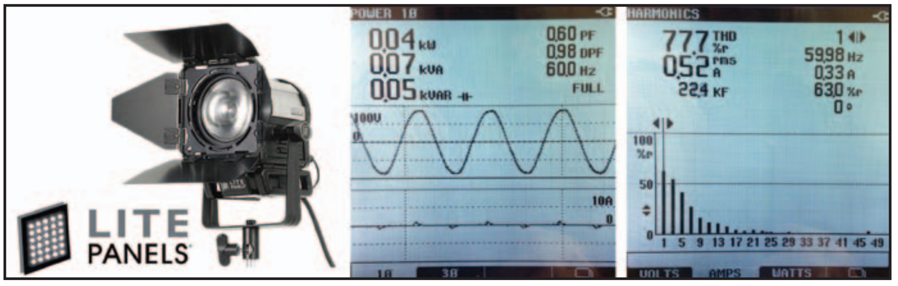

Figure 8 – Harmonic currents drawn by a Litepanel Sola LED Fresnel

Figure 9 – (Left) 24 kW tungsten fresnels create the feel of direct sun. (Middle) Large soft boxes consisting of 8' Quasar Science LED tubes creates the feel of sky shine. (Right) Smaller soft boxes consisting of 8' Quasar Science LED tubes creates ambient light in the interiors of the set.

Figure 10 – FFT of the Quasar Science LED tubes

large soft source, the harmonics drawn by a large number of Quasar Science Q100 LED tubes can severely effect stage distribution equipment. To see why, let's look at the FFT of the Quasar Science LED tube.

As we see in the power quality meter readings in **Figure 10**, 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 results from the large smoothing capacitors used in their switch-mode power supplies to drive the LEDs with DC, so that they don't flicker. With a power factor of 0.51, each 8' Quasar Science LED tube has an apparent power of 140 VA for its 70 W output. While its 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 fixture would draw only 0.58 A). The current they draw is harmonically rich with a total harmonic distortion of 68.1% and large third, fifth, seventh, and ninth components. As we shall see in the next installment of this series, it is the heat that these harmonic components generate that has an adverse effect on stage distribution equipment. More to come in Part 2. ■

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.