# Production power on a budget: How to generate clean reliable power, Part 1

BY **GUY HOLT**

GIVEN THE WIDE VARIETY of portable generators manufactured for different markets, it is important to understand the benefits and drawbacks of each when it comes to their use in motion picture production. Especially since the increasing use of personal computers and microprocessor-controlled recording equipment in HD production has created an unprecedented demand for clean, reliable power on set at a time when the trend in lighting is toward light sources that create dirty power.

The power waveform below right in **Figure 1** is typical of what results from the operation of a couple of 1200 W HMIs with non-power factor corrected (non-PFC) ballasts on a conventional portable generator. The adverse effects of the voltage distortion exhibited in the Power Quality Meter (PQM) reading below, can take the form of overheating and failing equipment, efficiency losses, circuit breaker trips, and instability of the generator voltage and frequency.

As production gets more electronically sophisticated, a thorough understanding of the demands placed on portable generators by production equipment is necessary to generate power that is clean and reliable. This is the first in a series of articles in which we will explore the factors that contribute to the severe voltage waveform distortion in **Figure 1**.

## Part 1: Hard versus soft power

At some point in our working lives, we all have experienced inexplicable equipment failures. I experienced just such a nightmare when I was gaffing a night shoot for *American Experience* with a 25 kVA Multiquip Silent Star generator. Our lighting package consisted of a 4 kW, 2.5 kW, and a couple of 1.2 kW HMIs, a couple of Kino 4'-4 Bank fixtures, and an assortment of 1 kW and 650 W tungsten fixtures. After carefully balancing our load on the generator so that no leg was overloaded, we turned on all of our lights. In a short while one of the HMIs shut down in the middle of a shot. We re-struck the head and then another shutdown. This continued for a while, until each time an HMI went out unexpectedly, we eliminated a light in our set up until we found a happy medium of a couple of babies and Kino 4'-4 Banks, a 1.2 kW and a 2.5 kW HMI—much less than I would have expected a generator of that size could run reliably. Once back at the studio, we tested each light until we had the entire original lighting package operating without issue. That hellish night was my first introduction to the difference between hard and soft power.

The reason the lights that worked reliably on our stage but didn't work on the set must have had to do with the source of power,

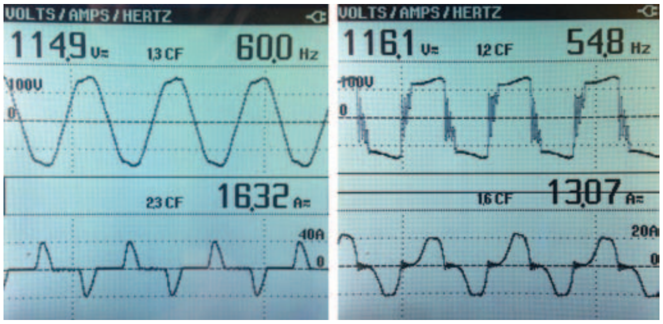


**Figure 1 – Left: The near perfect voltage waveform created by non-PFC 1200 W HMI ballasts on grid power. Right: The severely distorted power waveform created by non-PFC 1200 W HMI ballasts on a conventional portable generator.**

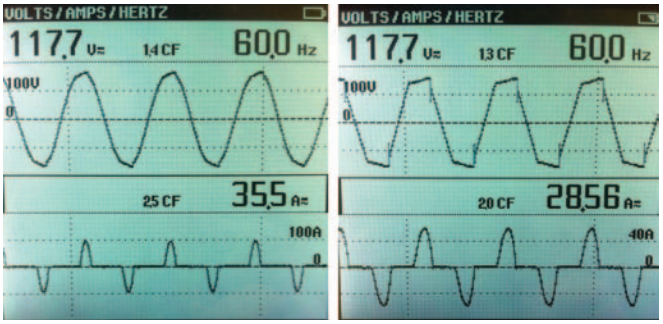


**Figure 2 – Left: Near perfect voltage waveform created by a non-PFC 2500 W HMI ballast on grid power. Right: Distorted power waveform created by a non-PFC 2500 W HMI ballast on a conventional generator.**

I reasoned, since that was the only variable. What differentiates power? Impedance. Generators typically have 15-20% internal reactive impedance. This is much higher than the local utility connection where the source impedance is established by the closest distribution transformer, which is typically only 4-5% impedance. To see what affect this appreciable difference in impedance can have, let's look closely at the power consumed by a 2.5 kW HMI with a non-PFC electronic ballast on both a generator and on the utility grid (**Figure 2**).

At first glance we see that the voltage waveform of the power generated by the generator is distorted, which raises a number of questions. The first question is why would the higher impedance of generated power result in voltage waveform distortion? The answer lies in the fact that there is less inertia available to nullify load-induced electrical distortions. Electrical power grids, which are typically measured in thousands of megawatts, exhibit high inertia. This high inertia results from the millions of tons of rotating steel and copper in the form of turbines, engine flywheels, and alternators. Where our 2.5 kW load represents only a small percentage of the grid's capacity, the inertia in the grid easily overcomes electrical distortion induced by loads. The power is said to be stiff.

In contrast to a utility grid, a genset powered system is small (measured in tens of kilowatts rather than thousands of megawatts), so inertia is much, much, lower, too. Our 2.5 kW load now represents a significant percentage of the genset's capacity, which means that less inertia is available to nullify load-induced electrical distortions. The power is said to be soft.

Where impedance is defined as the opposition to change in power flow through an AC circuit, the "stiffness" or "softness" of a power supply has to do with its impedance. Where the stiff power of the grid can overcome load-induced distortion without a detrimental effect, it has low impedance. And since the soft power of a generator is susceptible to load induced distortions, it has high impedance.

The second question raised by the results of our test is what is it about our 2.5 kW HMI that induces electrical distortion in soft power? To answer that question we must first understand that all lighting loads 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. Because some of these loads can affect the power supply adversely, their individual characteristics are worth exploring in more detail. Even more so, because they adversely affect generated power more than they do grid power.

An incandescent light is a simple resistive load. The resistance of its tungsten filament creates heat until the filament glows, creating light. The current in a simple resistive AC circuit increases proportionally as the voltage increases and decreases proportionally as the voltage decreases. For a sinusoidal voltage, the current is also sinusoidal. The load is said to be linear.

Electronic HMI, fluorescent, and LED ballasts often belong to a category of power supplies 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 each other. The load is said to be non-linear for this reason (see **Figure 3** for comparison of current waveforms).

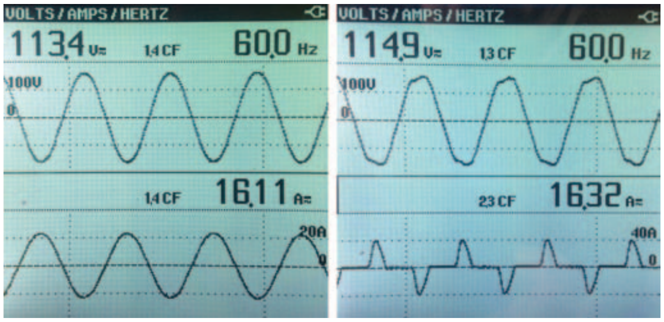


**Figure 3 – Left: A linear 2 kW tungsten light on grid power. Right: A non-PFC 1200 W HMI on grid power. (Note: spiked current drawn by non-PFC 1200 W HMI in lower right PQM reading.)**

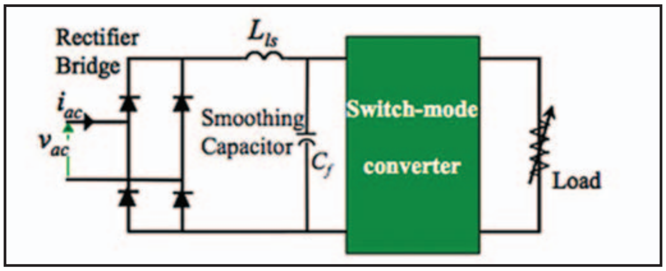


**Figure 4 – Typical circuit diagram of a switch-mode power supply**

As illustrated in **Figure 4**, the first power stage of a SMPS consists of a rectifier bridge of diodes and smoothing capacitor that convert the AC input to DC. In the case of HMI and Kino lights, a switch-mode converter stage then converts this flattened DC back to an alternating waveform that powers the lamp (see the simplified schematic of the power stages of a non-PFC electronic HMI ballast and the resulting voltage waveform in **Figure 5** for an example). In the case of AC powered LEDs, the switch-mode converter conditions the DC output from the diode-capacitor outputs. HMI and fluorescent ballasts differ in the shape and frequency of the alternating power waveform generated by the switch-mode converter. In the case of electronic Kino ballasts, the switch-mode converter generates a high frequency (>20 kHz) sine wave that creates an arc through the mercury vapor in the tube, making UV light that in turn excites phosphors in the tube to generate visible light. In the case of electronic HMI ballasts the switch-mode converter generates a low frequency (75 or 300 Hz) square wave (illustrated in **Figure 5**) that creates an arc between the lamp electrodes. While the output of the switch-mode converter stage of a power supply varies from light to light, they all use a rectifier bridge (A) and capacitor section (B) to first convert the AC to DC.

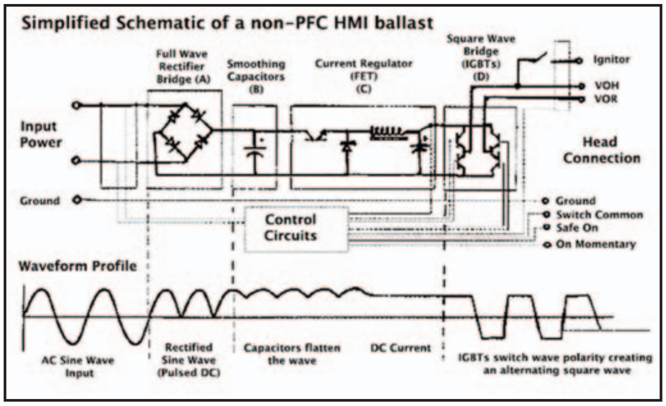


**Figure 5 – A simplified schematic of a non-PFC electronic HMI ballast (top) and the voltage waveform that corresponds to each power stage of the ballast from input to output to the lamp (used by permission of Harry Box.)**

As it charges, the smoothing capacitor only draws current during the peaks of the supply waveform. After the peak, the voltage from the rectifier bridge drops below the capacitor voltage, 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. Since the capacitor has only a short interval to receive the full charge, as illustrated in **Figure 6**, it draws current in high amplitude bursts, which explains the higher apparent power and hence lower power factor of non-PFC HMIs. The voltage drop, according to Ohm's Law applied to impedance (V = I x Z), during these high amplitude bursts of current, distorts the voltage waveform and causes the flat-topping we see in the oscilloscope shot of our 2.5 kW HMI in **Figure 2**.

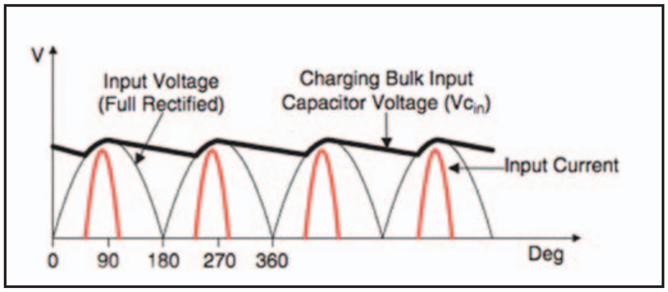


**Figure 6 – Thin black trace: The rectifier bridge converts AC power to a fully rectified sine wave. Thick black trace: The stored capacitor voltage. Red trace: The current drawn by capacitors once the input voltage is greater than the voltage stored in the capacitor (thick black trace.)**

If we wanted to do the math, a Fourier analysis of the harmonics of the current waveform drawn by our 2.5 kW ballast, and the voltage drop they cause with the high impedance of the generator, will calculate the waveform distortion we see in **Figure 2**. But 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 non-sinusoidal, distorted periodic waveform is equivalent to a mathematical model in which the 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 (e.g., 60 Hz) and a number of sinusoidal waves at higher frequencies, which are whole number multiples of the fundamental frequency.

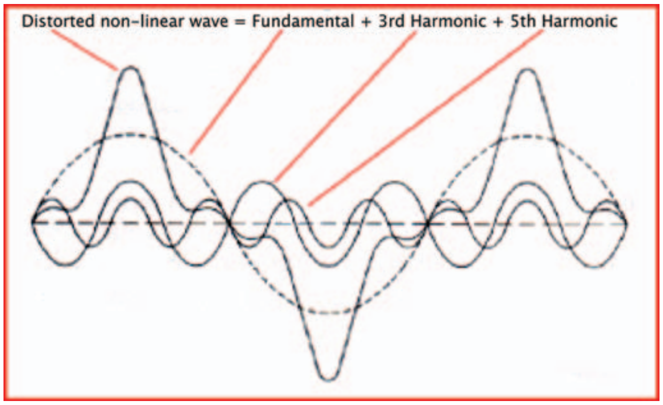


**Figure 7 – The harmonic components that make up a distorted non-linear periodic waveform**

As illustrated in **Figure 7**, the distorted current drawn by SMPSs can be broken down into components that include the fundamental wave and third order and fifth order harmonics. The third order, the third harmonic, is an 180 Hz sinusoidal wave. The fifth order, the fifth harmonic, is a 300 Hz sinusoidal waveform. The energy at any point is equal to the sum of the energy in the fundamental and all of the harmonic waveforms at that same point. The process of mathematically deriving the frequency components of a distorted periodic waveform is achieved by a Fourier transform. Microprocessor-based test equipment, like the power quality meter (PQM) we are using here, can do this analysis quickly using a technique known as an FFT (fast Fourier transform), which it displays as a bar graph (**Figure 8**.)

In any discussion of harmonics it is imperative that we always keep in mind that what we are actually dealing with are wave shapes. Harmonics are mathematical entities that allow us to analyze the resulting effects generated by non-linear loads when they interact in an electrical distribution system. In the Fourier modeling of this interaction, a third harmonic current will, according to Ohm's Law (V = I x Z), produce a voltage drop at the third harmonic frequency, a fifth harmonic current will produce a voltage drop at the fifth harmonic frequency, and so on.

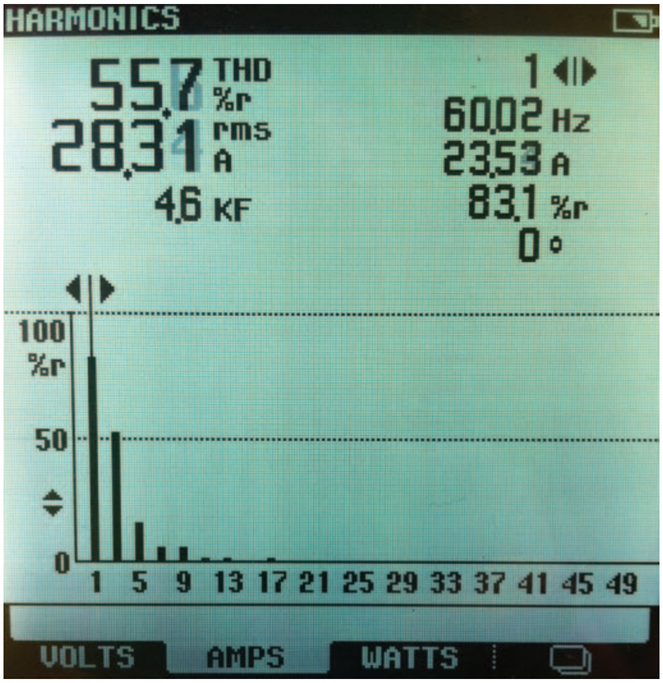


Figure 8 – The FFT of the harmonic currents drawn by a 2.5 kW non-PFC HMI ballast.

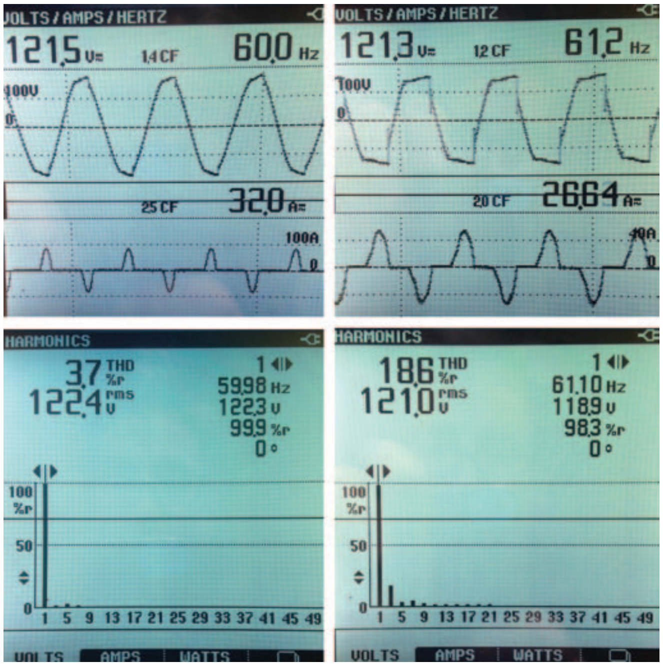


Figure 10 – Left: Voltage waveform distortion (top) and harmonics (bottom) of grid power from 2.5 kW HMI with non-PFC ballast. Right: Voltage waveform distortion (top) and harmonics (bottom) of generator power from 2.5 kW HMI with non-PFC ballast.

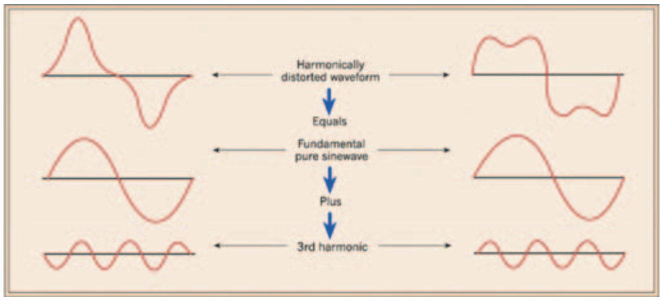
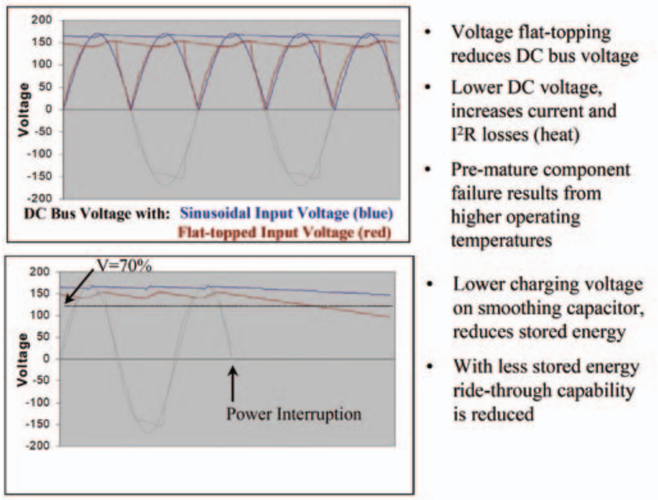


Figure 9 – The components of a distorted current waveform (left) and the resulting components of voltage waveform (right) after it has been distorted by voltage drop as a consequence of the third current harmonic encountering the impedance of the power system.

The distorted current waveform drawn by our 2.5 kW HMI ballast is made up of the fundamental plus one or more harmonic currents, and each of these currents flowing into the impedance of a generator results in a voltage drop, which results in voltage distortion appearing at the load bus. This does not appear in the voltage waveform of our 2.5 kW HMI operating on grid power (**Figure 10**) because of the grid's much lower impedance.

As we can see in the PQM readings in **Figure 10**, just one 2.5 kW HMI can cause appreciable voltage distortion. If we were to add another non-linear load, say a 1.2 kW HMI with non-PFC ballast, the distorted current-draw causes the peak voltage to drop further, which can be problematic for other fixtures that also draw current only at the peak of the supply voltage. This phenomena is illustrated in **Figure 11**:



- Voltage flat-topping reduces DC bus voltage
- Lower DC voltage, increases current and $I^2R$ losses (heat)
- Pre-mature component failure results from higher operating temperatures
- Lower charging voltage on smoothing capacitor, reduces stored energy
- With less stored energy ride-through capability is reduced

Figure 11 – The effects of flat-topped voltage on loads (used by permission of Mirus International.)

When a SMPS is supplied by a voltage waveform with a flattened peak (the red trace) rather than a nearly pure sinusoidal voltage (blue trace), the DC bus voltage is reduced proportionally from what the ballast is designed for (blue trace) to significantly less (red trace.) Although the Automatic Voltage Regulation system (AVR) of a genset will maintain the desired RMS voltage, it cannot restore the voltage peak. As a result, a load can be starved of power and shut down even though you may read full line voltage with an RMS meter and the power indicator lights light.

Without a doubt, this is a more plausible explanation for what I experienced that fateful night than the malicious intent of production gremlins. When severe flat-topping occurs from powering multiple non-linear loads, the peak-to-peak voltage throughout the distribution system can be reduced 30 percent, causing an “under-voltage” condition. Other production equipment—battery chargers, laptops, and camera AC power supplies—will also be starved of power when supplied with flat-topped voltage. Reducing the number of non-linear loads on a generator is one solution.

Unfortunately the impedance of a generator is not an easily known quantity. Depending on its size and design, the impedance of a generator will be five to 100 times that of a utility transformer, and it will change as the load changes. For this reason the industry has adopted a general rule of thumb to oversize generators by a factor of two, at the expense of increased rental costs and fuel consumption. ■

*Part 2 of this multipart exploration of how to generate clean reliable power on a budget will pick up with the other factors that contribute to voltage waveform distortion and how to mitigate it so that smaller more fuel-efficient generators can be used to generate set power.*

**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.