Production power on a budget: Paralleling portable generators

BY GUY HOLT

WHETHER YOU ARE PRODUCING A LIVE EVENT, regional commercial spot, or independent feature film, one of the biggest financial hurdles to overcome is location power. Portable gas generators made by manufacturers such as Honda and Isuzu can inexpensively provide power up to 5.5 kVA. The next step up is generally a 45 kVA diesel tow plant. The problem with these larger diesel generators is that, not only do you need a qualified electrician to operate them (who have to distribute and balance the load), they are also expensive to rent and they come with hidden costs. The hidden costs start with the fact that rental trucks, such as those from Ryder or Penske, are not equipped to tow, so you have to pay to have the generators delivered and picked up. Since film productions will change locations frequently, sometimes within the same day, delivery and pick-up of diesel generators is generally not an option. For these reasons, the only option for production is to hire a grip truck to tow them. Furthermore, since most rental houses require that one of their employees drive their trucks for insurance reasons, you have to hire a driver at roughly \$575 for 10 hours—which is probably more than anyone else on a typical indie crew is getting paid. Even if an indie production could afford to rent the big light, the cost of powering it has made it prohibitively expensive. For those reasons, Honda's announcement on January 21, 2014 that it would release a new 7,000 W inverter generator capable of operating in parallel with another generator for a combined output of 14 kVA (116.6 A at 120 V) was met with much anticipation.

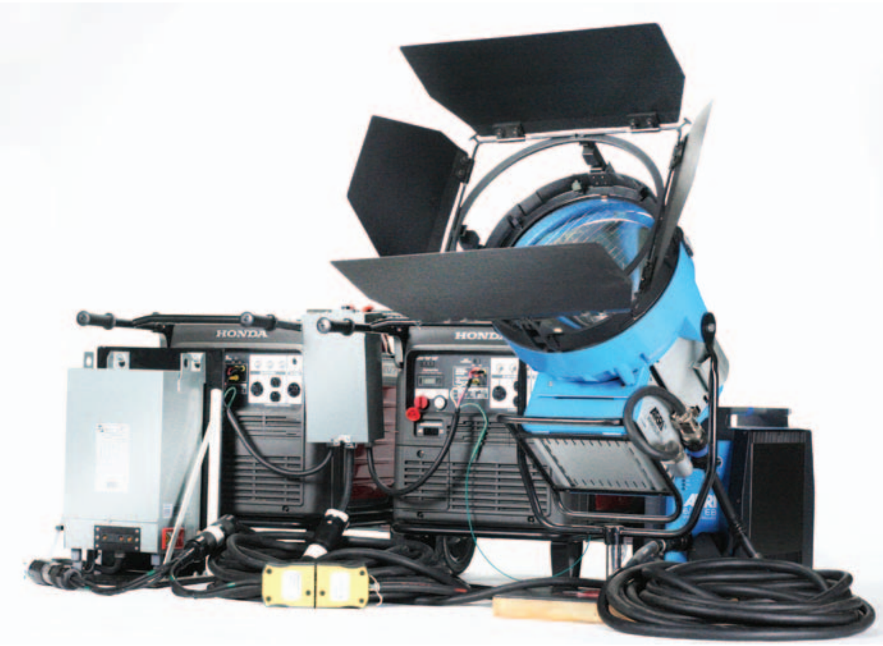

Figure 1 – The combined output of unmodified Honda EU7000 generators makes it possible to operate the 9 kW ARRIMAX M90. (Modification to the generators is required to operate 12 kW HMIs.)

Honda introduced the paralleling-capable EU7000 generator in March of the same year but has yet to release a paralleling kit for the generators a year and a half later. Honda is being tight lipped about the reason for the delay. Perhaps it has to do with the numerous impediments to paralleling generators of any kind. However, once one understands these impediments, it is possible to parallel not only the new EU7000is, but also the older EU6500is for a combined output of nearly 120 A, or enough to power even 12 kW HMIs, thereby clearing a major hurdle to obtaining high production values on a low budget.

Impediments to paralleling the EU6500s/EU7000

One impediment is what is known as "cross current." When any two generators are operated in parallel, a current will circulate continuously between the generators. If we trace this current in the illustration in **Figure 2**, we see that it flows out the line leads of one generator, through the neutral paralleling bus and into the second generator. It does not flow into the load.

Generators with very dissimilar voltages can readily experience cross current equal to 20% to 25% of their ampere rating with no load (zero kilowatts) on the generators.

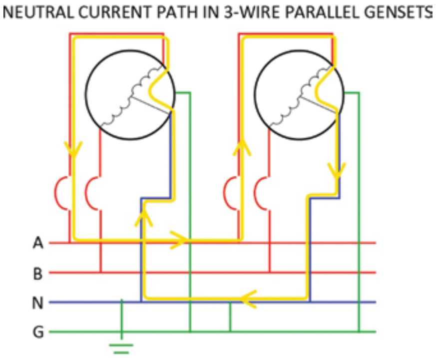

Figure 2 – How neutral current flows between two paralleled generators.

These "watt-less amperes" are a concern because they stack onto the normal line current drawn by the connected load and thereby interfere with normal operation. For example, since the circulating cross current is superimposed on the load current passing through the generators' circuit breakers, cross current can cause a breaker to trip unexpectedly because the breaker sees the combined current and not just that drawn by the load. A second cause of concern is that cross current contains a large third harmonic component, for reasons we will explore below. Observed line current (that which would be read by a true RMS ammeter) is then a summation of two or three currents, including:

1. The load fundamental current—the 50 Hz or 60 Hz current drawn by the load.
2. The circulating cross current fundamental—the 50 Hz or 60 Hz current which flows between generators for reasons we will explore below in more detail.
3. Harmonic currents—the third harmonic component of the cross current as well as the harmonic currents drawn by any non-linear loads.

A third cause of concern in paralleling operation is that each of the above currents contributes heat to the generators' conductors, stator coils, and inverters. Since, as is evident in the illustration above, cross current passes through the generator's stator coils, this current heats the stator just as does the 60 Hz load current but to a far greater extent because of its third harmonic component.

The source of this additional heat is eddy currents induced in the stator windings by the changing magnetic field. The heat caused by eddy currents is frequency dependent and increases with increased harmonics. The formula for eddy current heat loss to harmonic frequency is as follows:

$$P_{EC} = P_{EC-1} \sum_{h=1}^{h_{max}} I_h^2 h^2$$

Where: P_{EC} = total eddy current losses, P_{EC-1} = eddy current losses at full load based on linear loading only, I_h = RMS current (per unit) at harmonic h, and h = harmonic number.

What is significant about this relationship is that the harmonic current (Ih) and harmonic number (h) are squared, which means that instead of increasing in a linear fashion they increase exponentially. Put another way, the heat generated by harmonic currents circulating continuously just doesn't increase gradually at higher harmonic frequencies, but it jumps drastically, as illustrated below. Since eddy current losses at the fundamental frequency typically contribute 5% to 10% of the total load losses, the effect of harmonic currents will substantially increase the overall losses.

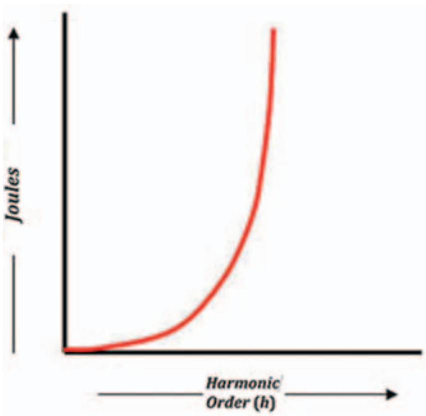

Figure 3 – Heat loss versus harmonic content in a generator.

If the generators are also supplying power to non-linear loads, the amount of heat generated is even more severe because the third harmonic component of cross current is additive with that drawn by non-linear loads. Severe heating of the generator's stator coils and inverters will lower efficiency and possibly even cause a breakdown of the insulation between the stator's windings.

Voltage adjustment of the generators, careful selection of loads, and proper power distribution can significantly reduce the heating effect of harmonic currents, thereby increasing the generator's combined load capacity. Given the potentially dire effect these currents can have on generators operating in parallel, understanding their origin and how to mitigate their adverse effects is paramount to the successful operation of two EU6500 or EU7000 generators in parallel.

Basic concepts:

To see how this is the case we must first understand the source of cross current.

The initial voltage waveform created by a generator is not an ideal sinusoid, and no two generators produce identical waveforms. Furthermore, its shape is affected by its load insofar as harmonic currents cause voltage harmonics when encountering system impedance, according to Ohm's Law. The shape of the resulting voltage waveform may be described mathematically in terms of the magnitude of the fundamental frequency and the magnitude and frequencies of the harmonic voltages. This harmonic voltage distortion, while small in the case of inverter generators, may still be significant, particularly in paralleling applications.

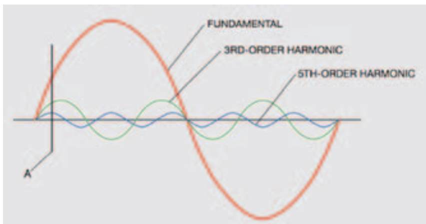

Figure 4 – Harmonic content of a generator's voltage waveform.

The illustration above shows the relationship of first-order (fundamental frequency) to third- and fifth-order harmonics of a slightly distorted waveform. The harmonic voltages are effectively added to the fundamental waveform, resulting in voltage distortion. For example, the resultant voltage at time A in **Figure 4** will be the sum of the blue (fifth-order), green (third-order), and red voltage magnitudes. So the voltage at that instant in time would be somewhat higher than the voltage of the fundamental.

When generators are paralleled, the voltage of the two machines is forced to the same RMS voltage magnitude at the common load bus. Differences in the harmonic makeup of the voltage waveforms result in the cross current flowing in the common conductors of the two machines even when there is no load. Its source is illustrated below:

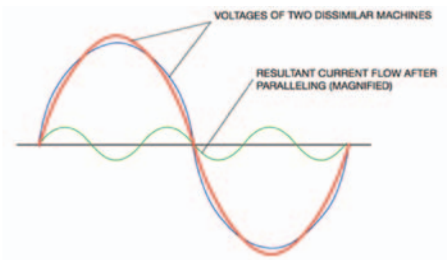

Figure 5 – How third harmonics are generated.

In this illustration, two voltage waveforms of the same RMS value (the red and blue lines) are superimposed upon each other. Note that even though these voltage waveforms have the same RMS magnitude (they would read the same on a true RMS meter), at different points in time the blue voltage is higher than the red, and vice versa. Since there exists potential (voltage) between the two machines at these points, when the machines are connected together on a common bus, current will flow between the machines (cross current) even if there is no load. Note that because the blue and red voltage lines cross each other three times in each half cycle, the cross current includes a third harmonic component (this current is represented by the green line.) Because the conductors of the two machines are tied together, this cross current will continuously circulate (as illustrated in **Figure 2**) between the two generators.

This no-load cross current can become a problem if we add to it the harmonics dumped onto the neutral by non-linear loads, such as non-power factor corrected audio amplifiers, power wedges, HMIs, Kinos, and LED lights. Because some of these harmonic currents (the load generated third harmonic and the third harmonic of the cross current) are in fact in phase with one another, they do not cancel in the neutral as the fundamentals do, but instead reinforce each other. And because this elevated third harmonic current is at a higher frequency (180 Hz) it generates a lot more heat, contributing significantly to the overheating of paralleling generators and especially to the inverters of paralleling Honda EU6500s and EU7000s.

The source of load harmonics

The process of mathematically deriving the frequency components of a distorted periodic waveform is achieved by a technique known as a Fourier transform. Microprocessor-based test equipment, like the power quality meter pictured below, can do this mathematical analysis very quickly using a technique known as a fast Fourier transform (FFT), which it displays as a bar graph. Each bar represents the magnitude of a harmonic frequency, be it voltage or current. Below is a power quality meter reading of a Chauvet Slim Par LED stage light. Because the harmonic currents drawn by the light contribute nothing to the light output, they result in a reduction of the light's power factor. There are power factor correction circuits that will increase the power factor of a light to near unity, but they are expensive and add considerably to the cost of a fixture.

Since power factor correction (PFC) is not mandatory in the US as it is in the EU, a lot of LED AC power supplies distributed in this country are not power factor corrected, making them draw more current than incandescent lights of the same wattage or lights that have unity power factor. With power factors as low as 0.45, LEDs can draw twice the current than a purely resistive load of the same wattage. If you don't take into account the extra current they draw and the harmonic currents they will generate, you

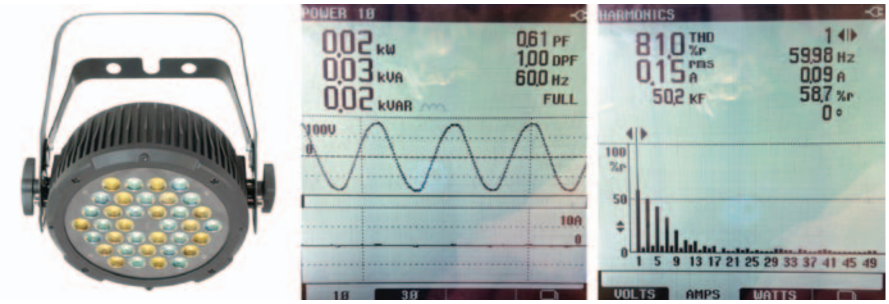

Figure 6 – The Chauvet Slim Par Pro RGBA has a PF of 0.61 and total harmonic distortion of 81%.

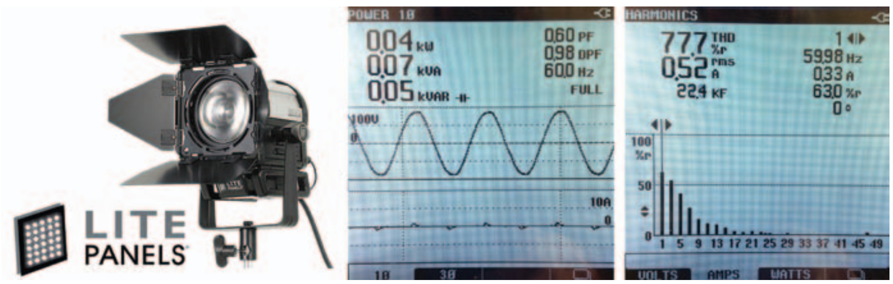

Figure 7 – The Litepanel Sola 4 has a PF of 0.60 and total harmonic distortion of 77.7%.

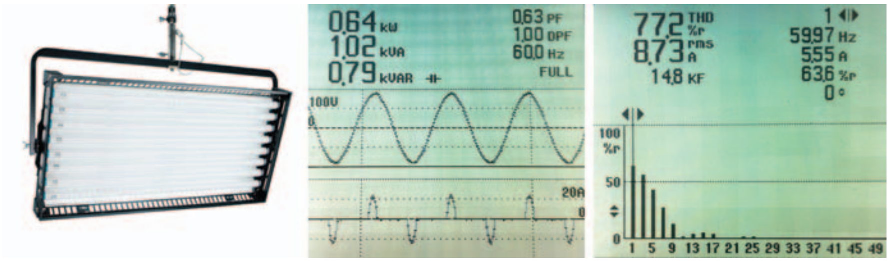

Figure 8 – The Kino Flo Image 85 has a PF of 0.63 and total harmonic distortion of 77.2%.

may find breakers tripping and portable generators running erratically.

A surprising number of the luminaries available in the US are not power-factor corrected. Until the introduction of their new DMX-compatible Universal ballast this year, all Kino Flo ballasts in this country driving fixtures with T12 tubes were not power-factor corrected, including the 4, 2, and Single Bank fixtures as well as the Flat Head 80, Image 80, and Image 85 fixtures.

But the biggest source of harmonics in location lighting packages, by far, are HMI fixtures. Because of the added cost, weight, and complexity of PFC circuitry, HMI distributors in the US only offer PFC circuitry as standard in luminaries larger than 6 kW, and only then by necessity. The early line of Lightmaker electronic ballasts were nicknamed "Troublemaker" ballasts by film electricians because they were not power-factor corrected. They proved that PFC circuitry was absolutely necessary in large ballasts to reduce heat and return current on the neutral, which increases ballast reliability. Because of the added cost, HMI distributors in the US still only offer PFC circuitry as an option in medium-sized 2.5-4 kW ballasts.

Until very recently, manufacturers did not offer PFC circuitry in HMI ballasts smaller than 2.5 kW because PFC circuitry adds about 25% to the cost of the ballast. That means that almost all 575 and 1200 ballasts in the US are non-PFC. For the same reason, the Joker 200, 400, and 800 ballasts sold in the US are not power-factor corrected. What this means is that most of the lighting rental inventory in this country that would likely be used on a portable generator is not power-factor corrected.

As can be seen in the power quality readings (**Figure 9** below), a non-PFC 4 kW HMI operating on paralleled Honda EU6500s draws significant third, fifth, seventh, and ninth harmonic currents. The net result is that nearly 30 A of harmonic currents are generated, with 94% of that consisting of triplen harmonics (third = 26.2 A, ninth = 2.1 A.) While the system could easily handle 30 A at 60 Hz, it is an altogether different situation when the current includes higher frequencies as is the case here.

As we saw above, it doesn't take much third harmonic to substantially increase heating of the generator's stator. Since eddy current heat losses generated by third harmonic currents increase exponentially by a factor of 9 (3^2), one amp of the third harmonic will generate as much heat as 9 A of current at 60 Hz. In this discussion, we are focusing on the third harmonic because, between the inherent no-load third harmonic component of cross current and the contribution by non-linear loads, it can reach elevated levels. It is also worth noting that higher order harmonics will generate as much eddy current heat loss as the third, but at much lower amplitudes. For instance, 1 A of the ninth harmonic will generate as much heat as 81 A (9^2) of current at 60 Hz. For this reason harmonic currents of even low magnitudes should not be taken lightly in paralleling set-ups.

Cutting-off load third harmonic currents

If it is not an option to use power factor corrected ballasts that generate virtually no harmonic currents, the other option is to simply break the link between harmonic generating 120 V non-linear loads (that require a neutral) and the neutrals of the paralleled generators. This can be accomplished by using a 240 V-to-120 V step-down transformer to supply 120 V loads from the combined 240 V output of the paralleled generators. Since transformers are, in the parlance of the *NEC*, a "separately derived system" (meaning they are a new source of power), there is no direct electrical connection between the transformer's primary and secondary windings, which means that the electrical distribution downstream of the secondary is completely independent of the generator system upstream of the primary. As illustrated in **Figure 10**, the only conductor that connects these two systems is the equipment

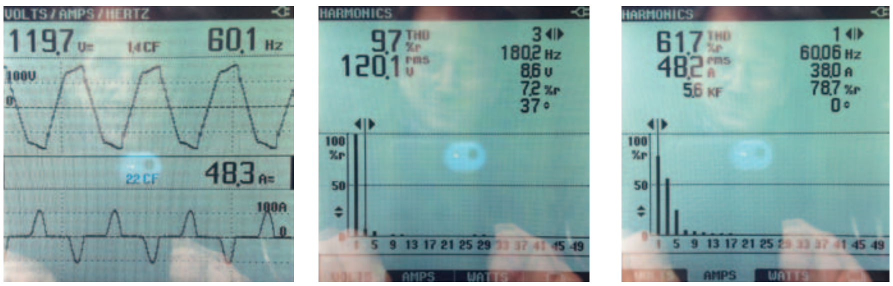

Figure 9 – (L-to-R): Distorted voltage (top) and current (bottom) waveforms and their corresponding Fourier transforms (voltage on the left and current on the right.) ***Note that the individual harmonic currents encountering the impedance of the generator cause voltage drop at the peak of the voltage waveform distorting it so that it is no longer a pure sinusoid. The FFT analysis of the distorted voltage waveform (center) shows voltage harmonics that correspond to the current harmonics that created them.***

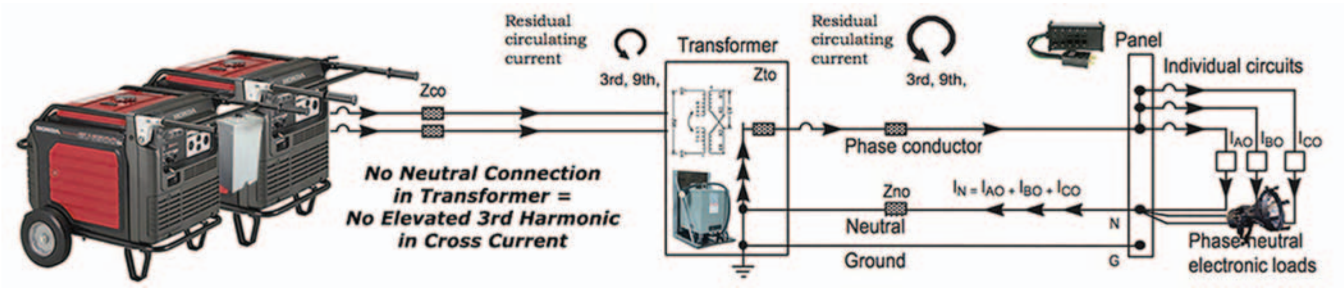

Figure 10 – A transformer/distro isolating triplen harmonics from the generators so that they cannot elevate cross current to a hazardous level.

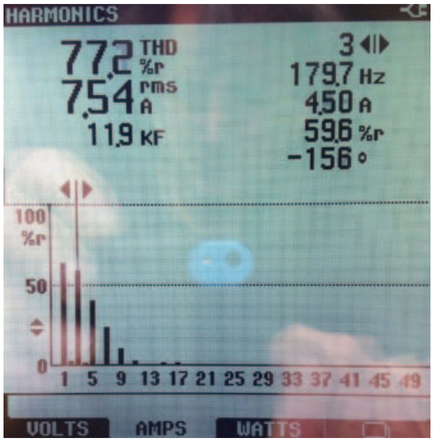

Figure 11 – The harmonic spectrum of a non-PFC 1.2 kW HMI operating on a Honda EU6500 through a splitter box.

Figure 12 – Powering the same non-PFC 1200 W HMI by means of a transformer instead virtually eliminates the third harmonic current circulating between the two generators.

grounding conductor.

A step-down transformer creates the required neutral connection for smaller 120 V loads, but at the same time isolates the generators from the third harmonics created by these loads that would otherwise lead to elevated neutral current, hot conductors, and overheated inverters. For sure, the harmonic currents generated by non-PFC amplifiers, power wedges, HMIs, Kinos, and LEDs will cause heating of the primary of the transformer (use a K-rated transformer for this reason), but the disruptive effect of their flow in the paralleled generators is eliminated so the generator inverters remain cool.

For example, if we compare the harmonic currents returned on the neutral by a non-PFC 1.2 kW HMI operating on a Honda EU6500 thru a "splitter box" (**Figure 11**) to that returned by the same light operating on a transformer (**Figure 12**), we see a dramatic decrease.

As can be seen in the power quality meter reading above, the result is that the third harmonic content is substantially reduced (by a factor of 150x), which means the generator's inverters will operate cooler and will not melt down. By eliminating a neutral connection between the gen-set bus and the loads, a transformer eliminates one of the reasons (overheating by harmonic currents) that prevented the successful parallel operation of Honda EU6500s and EU7000s for 120 V loads, making it possible to operate more lights, or larger lights, on portable Hondas than has ever been possible. ■

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.