Production power on a budget: Ground-fault protection strategies, Part 2

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The second in a multipart exploration of how to safely use small portable generators in motion picture and live event production.

IN PART 1 WE SAW that for GFCIs to operate effectively, the equipment-grounding conductor must be bonded to the system neutral. Furthermore, as a consequence of recent code revisions, GFCIs of the type used on portable generators smaller than 15 kW do not use a lenient inverse-time trip curve permitted by *UL 943*, thus making them prone to tripping with non-linear loads, such as those used in motion picture lighting and event staging production. Even though the *UL 943* inverse-time curve was meant to enable GFCIs to operate more reliably in real-world conditions, manufacturers of lower-priced Class A devices, such as those found on portable generators and for sale in hardware stores, do not implement the curve because it makes the design more complicated and the GFCI more expensive. Instead they use a more aggressive response (like that illustrated in Part 1) that is lower and faster than that required by *UL 943* (typically 25 ms at 6 mA where *UL 943* permits 5.59 seconds at 6 mA.)

While this more aggressive trip curve does not generally pose a problem in one-tool per circuit applications, it has proven to be a problem when powering multiple non-linear loads because of the current these loads leak to ground. In these applications, small leaks from multiple devices on top of minor ground faults in the distribution, can easily approach, and possibly even exceed the 5-6 mA trip threshold of Class A GFCI devices. If, as is the case with many portable generators, a single GFCI is protecting many devices (referred to as a "blanket" strategy) then it is possible that the cumulative result of all these small leakages will be enough to either:

- Trip the GFCI outright
- Or, use up so much of the GFCI's allowed leakage current that it becomes excessively sensitive to momentary transient leakage currents caused by the switching on and off of electronic devices.

Let's look at each of these sources of leakage current in more detail.

Portable equipment is prone to leaking current simply from wear and tear. As temporary power distribution equipment is connected and disconnected, cords, plugs, and receptacles become worn. Likewise, portable equipment is subjected to abrasion, vibration, and impact as it is unpacked and packed into trucks. All of this leads to the potential for minor ground faults. Capacitive reactance in a generator, a nicked extension cord, a shorting distribution box, will all leak a little current (to name just a few causes.) Equipment wear and tear is not the only source of leakage currents. In a typical production there are numerous pieces of equipment, such as HMI, fluorescent, and LED lights, as well as computers, hard drives, audio and video processing equipment, that leak small amounts of current called "residual current."

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The source of residual currents in these devices can be intentional or unintentional capacitance. Some sources of unintentional capacitance can be the spacing of components on printed circuit boards, poor insulation between semiconductors and grounded heat sinks, and the primary-to-secondary capacitance of isolating transformers within the power supply. A source of intentional capacitance is the use of RF filters to reduce the amount of RF signals emitted.

UL permits manufacturers of electronic devices to capacitively couple high-frequency harmonic currents to ground in order to reduce the amount of RF signals emitted. To accomplish this, equipment manufacturers include a mains input filter to stop electrical noise from being passed in or out of the equipment via its mains lead. Such filters typically include a pair of small capacitors, one connected between the live and earth, and the other between the neutral and earth wires of the incoming mains. The value of the capacitors are chosen to snub the high-frequency noise by shorting it to earth. As such, these RF filters can be a source of appreciable residual current.

In the case of electronic lighting ballasts, one source of electrical noise is the switching of transistors. Switching voltages that rise and fall 400 volts in less than 0.1 microseconds generate currents of several amps that rise and fall in the same time. The switching frequencies of transistors in electronic ballasts range from 50 Hz (square wave bridge) to 100 kHz (current regulator and PFC circuit.) Even though the capacitor values are chosen so that they conduct at high frequencies, a tiny amount of current at the mains frequency (either 60 or 50 Hz) still flows through the capacitors resulting in leakage of both the fundamental and harmonic frequencies to the equipment-grounding conductor. In total, such filters can generate constant leakage currents in the order of 0.5 to 30 mA depending on the type of light, sometimes without the light even being turned on. When there are several loads of this type on the same circuit, the leakage currents add vectorially.

Since these currents do not return to their source via the neutral conductor, they can cause a hardware store type GFCI to see a difference between the current leaving on the hot line and the current returning on the neutral line. If the residual current does not trip the GFCI on the generator panel outright, it can reach the point where surges in residual current will trip the GFCI. This typically occurs when the sum of residual leakage reaches approximately 30% of the GFCI's rated sensitivity threshold (1.5 mA). Once GFCIs have become sensitized by residual leakage current, transient events can result in surges that cause them to trip. Here are just a few transient events that may push a hardware store-type GFCI over the edge and cause it to nuisance trip once it has become sensitized by residual leakage.

Switch on surges

Devices that use switch-mode power supplies (HMIs, Kino Flo luminaires, AC power supplies for LEDs, computers, etc.) will absorb a large inrush of current when first turned on as their smoothing capacitors charge. During this time, which lasts less than a second, more current can pass to ground than usual. If there is not sufficient headroom above the residual noise of the circuit and the GFCI trip curve does not accommodate transient surges of such duration (hardware store type GFCIs do not), it will nuisance-trip and shut down the whole circuit.

For example, the 600 W Kino Image 85 fixture pictured above that generates a steady state residual leakage current of only 3.69 mA while powering the light, will pass many times that when first turned on. That is because their electronic ballasts use large smoothing capacitors to convert rectified AC current into DC current, before switching it back to a much higher frequency sine wave of 25 kHz to excite the phosphors in the fluorescent lamps. When the unit is first switched on, an inrush of many times rated current (175 A verses the 8.73 A steady state draw) occurs due to the charging of its smoothing capacitors.

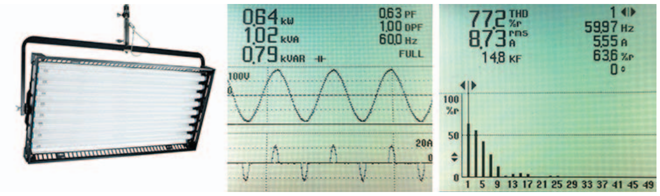

Figure 1 – The waveform and FFT of current drawn by the non-PFC electronic ballasts of a Kino Flo Image 85

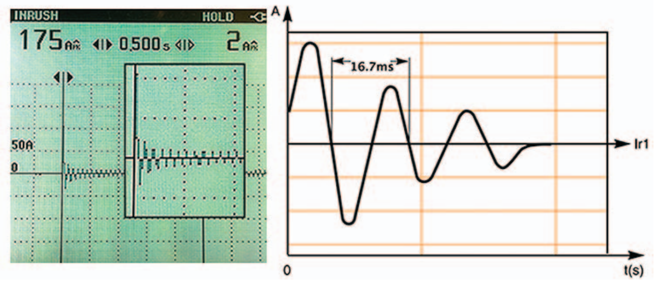

Figure 2 – Left: The momentary inrush current of a Kino Image 85 striking can be as high as 175 A (more than 23 times its steady state load.) Right: residual current following operation of a switch.

Even though this inrush current lasts for less than a second, the result is a surge in leakage current lasting hundreds of milliseconds since each cycle of AC current lasts 16.7 ms in a 60 Hz system and inrush currents can last ten or more cycles. Even if there is sufficient headroom above the noise floor of the circuit to accommodate the 3.69 mA of steady state residual leakage current generated by the Image 85, the aggressive trip curve of hardware-store style GFCIs will not accommodate an additional transient surge of such magnitude and duration, as depicted in the scope shot above. It will likely nuisance-trip and shut down the whole circuit.

The striking of HMI lights (with both electronic and magnetic ballasts) can be a major source of transient over-voltages that can also cause surges in leakage current. HMI lighting uses high voltage pulses to initiate the arc between the lamp electrodes. These pulses are of short duration, but can be as high as 17,000 V. If the insulation of conductors in the head has deteriorated, or there exists excessive dust and debris (such as an accumulation of dead bug carcasses) inside, the debris can conduct high inrush current to the case causing a surge in leakage current. A simple remedy to prevent such current leaks in large tungsten and HMI lights is to vacuum out the interior of the head.

Finally, the residual currents generated by some lights can be of sufficient magnitude to trip a GFCI without the aid of transient leakage currents. For instance, the harmonics drawn by non-PFC HMI ballasts can be a large source of residual current. If a HMI ballast is not power factor corrected, it draws a harmonically distorted current waveform. In addition to snubbing the switching noise of transistors to ground, an RF filter will also snub the high frequency harmonics drawn by the ballast, significantly increasing the residual current generated by the light. For instance, some non-power factor corrected 1200 W HMI ballasts will draw 1.15 mA as soon as you throw its breaker to power it up, and an additional 15.32 mA after you strike the light, for a total residual current of 16.47 mA—which is why these lights are guaranteed to trip hardware store-style GFCIs and wall receptacle GFCIs.

In the waveform and FFT of the ballast's residual current (below) one can see the small amount of mains current inadvertently passed by the filter as well as the harmonic currents it is designed to pass to ground.

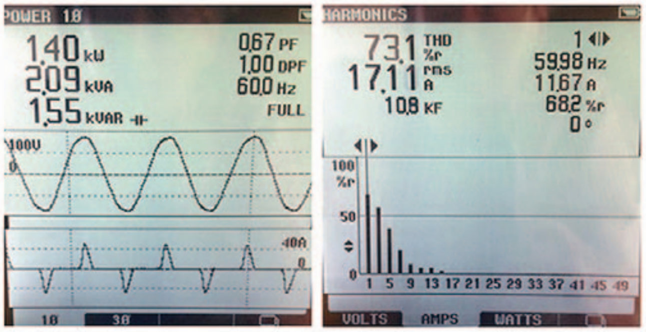

Figure 3 – The waveform (left) and FFT (right) of current drawn by a 1200 W non-PFC electronic HMI ballast

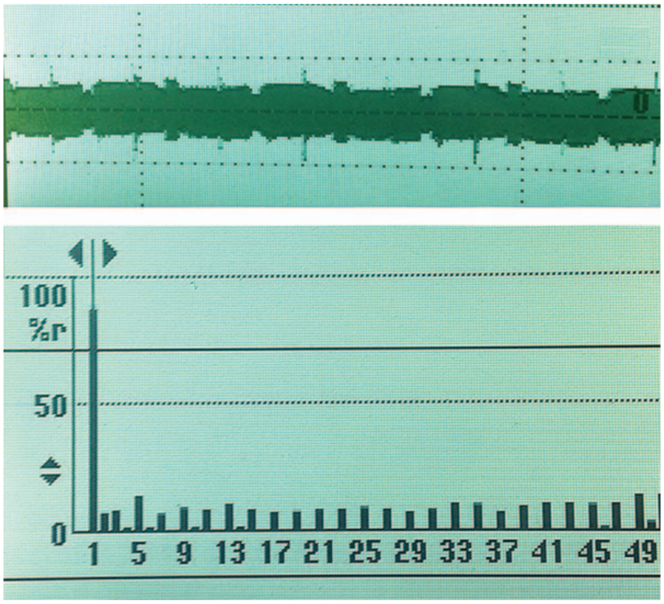

Figure 4 – The waveform and FFT of the residual current generated by a 1200 W non-PFC electronic HMI ballast

These high frequency leakage currents will cause a GFCI to nuisance-trip because they do not return via the neutral conductor, and so cause the GFCI to see a difference between the current leaving on the hot line and the current returning on the neutral line. It is a nuisance because the currents in fact pose no hazard, and shutting down the circuit is therefore unnecessary from a safety standpoint. These high frequency leakage currents do not pose a hazard because they are safely confined to the equipment grounding conductor.

To avoid nuisance tripping from GFCIs becoming sensitized by residual currents, *UL 943* also permits GFCIs to incorporate high frequency filters (as well as trip on an inverse time curve.) Attenuated by a filter, high frequency harmonic currents drawn by non-linear loads don't sensitize GFCIs.

The more aggressive trip curve of hardware store-style GFCIs has proven to be a problem in applications involving extensive distribution to multiple non-linear loads, which is the type of distribution that characterizes motion picture production and event staging. So what is a conscientious set electrician to do when they have to operate a portable generator in wet hazardous conditions?

One approach is to use GFCIs that are specifically designed for motion picture and event staging applications with a small 240 V-to-120 V step-down transformer on the generators 240 V receptacle. A step-down transformer converts the 240 V output of the generator into a single large 120 V circuit capable of powering lights, but it also, as a Separately Derived System, bonds neutral

Figure 5 – (Left to right) 100A/120V Shock Block, LifeGuard, Shock Stop GFCIs

Figure 6 – Shock Stop offers ground fault protection downstream of 60 A transformer/distro

to ground on its secondary or load side, thereby establishing the equipment grounding conductor necessary for GFCIs to operate reliably. (See part one of this series for more details.) Now a film-style GFCI, like the LifeGuard, Shock Block, or Shock Stop GFCIs, that employ high frequency filters and a trip curve that uses the slower response inverse-time curve allowed by *UL 943*, can be used to provide nuisance-free ground-fault protection. ■

Part 3 of this multipart exploration of how to safely use small portable generators in motion picture and live event production will pick up with how to use film style GFCIs with portable generators.

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.