Lifting The Grounding Enigma

By Martin Glasband

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NOISE MAY BE THE MOST MISUNDER-STOOD PROBLEM in any professional audio or video facility. Today's recording technology offers unsurpassed quality and accuracy, yet grounding system noise still baffles the experts.

Grounding noise is one of the most common complaints from audio engineers, but it's difficult to explain noise and grounding problems without addressing power. Grounding noise is closely linked to AC power under a variety of impedance load conditions. At first glance, the causes of noise can seem mysterious and perplexing. But in fairness to the experts, remember that conventional power standards were adopted long before we had sensitive electronics. Eighty years ago, no one predicted the repercussions of industrial load effects on power integrity.

More relevant to today's studio is locally generated noise from power supplies and other impedance-type loads. Most people don't understand the relationship between AC power phase, distortion and objectionable RF program-signal noise. Conventional beliefs state that the causes of noise stem from the way a studio is grounded; however, the problem is deeply rooted in the background of the electrical industry and industrial power distribution.

A BRIEF HISTORY....

In 1882, Thomas Edison wired the town of Sunbury, Penn., using shared-common, three-wire DC distribution. The cost of copper wire was an important factor, so Edison's engineers devised a way to distribute two circuits using only three wires. The forerunner to modern power distribution, DC and AC versions of the "Edison Circuit," are still widely used.

Beginning with the Niagara Falls power project initiated by George Westinghouse and supervised by Nicolai Tesla, AC distribution overtook DC and became the primary power system. With mostly lights and electric heaters loaded on the power grid, there was never much concern for voltage phase beyond what was considered to be 'distribution convenience" for the utility. And from almost the very beginning, 120-volt AC wiring has been conveniently unbalanced - a "split" off half of a 240-volt, single-phase grid.

Eventually, three-phase power was developed as a standard to suit heavy industrial users. Little was known at that time about harmonic distortion or other adverse effects on power systems created by impedance loads. Meanwhile, single-phase took a back seat to bulk three-phase power distribution because of the huge demand created by the efficient three-phase industrial motor. The three-wire Edison circuit was expanded another phase: 120/208 and 277/480-volt three-phase "WYE" systems allowed for running three circuits using only four wires.

In electrical parlance, this multiple-circuit wiring method is called a "Round Robin." The three-phase WYE design enables single-phase fluorescent lighting, three-phase air conditioning and other three-phase motor loads (e.g., elevators) to be fed by one power distribution grid with the load current evenly distributed across the system-ideal for commercial use.

But this system has one glaring fault. The level of interference created when a three-phase WYE system is split up and used as three single-phase circuits is truly something to behold. For example, as much as 20% (or more) of the power used by fluorescent ballasts is repelled back onto the power grid in the form of reactive or harmonic currents - now that's a lot of distortion. In the early 1970s, a 40-plus-story office building in Los Angeles actually burst into flames because of these reactive currents. Incredibly, the origin of the fire was determined to be from excessive harmonic distortion in fluorescent lighting circuits, which created a high-frequency current overload and literally a meltdown of the electrical wiring system. The First Interstate Bank fire in L.A. in May 1988 was the event dubbed by the media as "the towering inferno," a la the Hollywood movie. Codes were adapted to remedy the fire danger, but the noise problem was never resolved.

Three-phase power nonetheless remains the bulk power of choice for utilities. When a utility furnishes single-phase service to an area, the standard procedure is for the utility to derive single-phase power by using one or two of the distribution grid's three-phase elements. So even single-phase power is linked to the distorted three-phase grid. Typically, electrical power furnished by utilities contains 3% to 5% harmonic distortion. Single-phase service remains "split" into two 120-volt circuits, as per Edison's original wiring design. In one form or another, these standards have been adopted and put into use around the world.

MEANWHILE, IN THE AUDIO INDUSTRY.... the post-World War II era brought a revolution in electronics. Among these developments was the balanced circuit. The result was a quieter, more stable signal circuit that was less prone to interference. The technique might have been extended to power applications but wasn't. Power was regarded as something altogether different from RF or audio signals, perhaps more as a sort of fuel. Bulk power generation and distribution standards were etched in stone. Today, data loss and common signal-circuit malfunctions attributable to background noise and power distortion are cited as critical issues in audio and other high-tech electronics.

A century after Edison, one might assume definitive answers to common problems would be self-evident truths found in any engineering textbook. Not so. In facilities with noise problems, there seem to be as many suggestions as engineers. Although volumes of theory have been written on electrical interference and noise problems, there are few standards that genuinely address the issues.

FIPS 94, for example, is a federal government publication that attempts to answer grounding noise problems in data-processing facilities. Having limited options, electrical engineers often apply this engineering material to online video and recording studios. Thousand of dollars worth of copper busing and expensive labor notwithstanding, an active and very expensive power-conditioning system is often prescribed to compensate for a signal reference grid that somehow failed to sink hum noise as expected.

FIPS 94 is hailed as the authoritative source in electrical engineering circles, but it fails to adequately cover all of the ways (right and wrong) for phasing and referencing a power signal for an intended load application. It is a mistake to provide a power system that is not properly configured to operate sensitive electronics. Industrial motors required a new and unique three-phase power design some 80 years ago. Now is an appropriate time for the electrical industry to do the same for high-tech electronics.

Unfortunately, even the cleanest power signal available and the most linear and low-impedance grounding system still yield AC noise in audio and video circuits. How could noise still affect a video production facility with top-of-the-line active power conditioning and a professionally engineered linear signal-reference?

FOCUSING ON THE PROBLEM

It all boils down to eliminating noise problems. What, for example, needs to be done to completely rid a production facility of video hum bars? Can the problem of AC noise common in Class A tube amps be addressed? How about noisy guitar amps? Many other stubborn noise problems have endured the test of time but have failed to yield substantial solutions.

Are RF engineers right in saying that the best thing to do with an AC ground is to avoid it? From and RF perspective, it certainly makes good sense. But how safe is applying separate RF and AC grounding systems - with a high-amplitude potential - just a matter of inches apart and potentially anywhere within reach? What happens when the AC ground fails to provide a fault current path if there's a short circuit? What happens if a power supply burns up? Will circuit breakers still work? Will rubber gloves and boots work? The practice is brilliantly effective but extremely dangerous.

Is the problem in the power itself? Certainly, there is room for power to be cleaned up. Conventionally, this is done in two ways: improving its level of signal purity, or improving a grounding system's linearity and lowering the impedance. Unfortunately, even the cleanest power signal available and the most linear and low-impedance grounding system still yield AC noise in audio and video circuits. How could noise still affect a video production facility with top-of-the-line active power conditioning and a professionally engineered linear signal-reference? The reason is that power-conditioning systems don't address all aspects of the noise problem. For that matter, the most damaging form of noise (reactive current in the ground) is left untouched. Low-impedance grounding has little effect on reactive current, so the problem persists. Clearly, a different approach is needed.

The answer is preventing reactive currents from propagating in the grounding system. This can be accomplished by re-phasing the power source. To get a clearer picture of this theory, one needs to look at the load; the ground reference and the voltage phase in the power wires. For some reason, the simple truth has been overlooked for years.

BACK TO BASICS

First, let's look at some basic electrical theory that has somehow escaped the view of the majority of the engineering community. To understand the solutions to noise problems presented here, it must first be understood how the power phase can be both referenced to ground and applied to a load. This area of electrical theory is poorly taught and narrowly applied. Except for filtering, a few multiphase industrial uses and some critical safety applications, the importance of voltage phase orientation to a reference source is generally ignored. Here are four examples of what is meant by the term "Mode."

Figure 1 shows an alternating current signal in direct mode (sometimes called Normal mode). One wire carries a voltage potential, the other wire is a ground conductor in which modulating current flows when a load (or signal pickup) is connected to complete the circuit. This mode is often used in low-power, unbalanced or high-impedance applications such as antennae, video feeds, data networks and test equipment circuits.

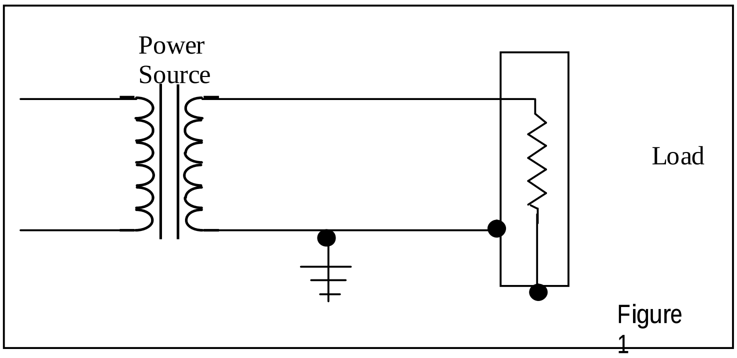
Figure 2 is an example of a similar mode, but a third wire is added to provide a safety ground that is not part of the circuit's normal current path. This is a much safer way to apply a high-amplitude signal such as feeding 120-volt AC power to a refrigerator or washing machine. When an appliance is grounded in this manner, the chassis of the appliance isn't part of the normal current path and has no potential unless there's and internal short circuit. This is the standard 120-volt power circuit configuration used in the United States. The two AC power conductors have unequal or different potentials with respect to ground. One wire is hot, the other is neutral. This single-phase power configuration is called Differential mode.

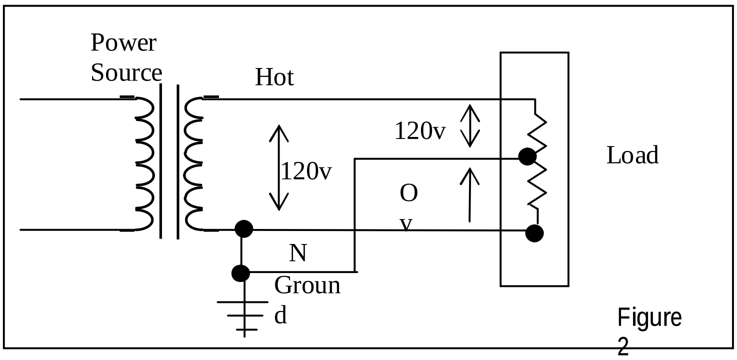
If one were to omit a ground reference altogether and simply apply a 120-volt signal to two wires from a source system such as a single-phase transformer or generator, the only voltage potential is across the two circuit wires (Fig. 3).

Figure 1: Power (or any modulation) applied to a load in direct mode

Figure 2: 120V/60Hz power applied to load in (standard) Differential mode

Figure 3: 120V/60Hz power applied to load in Transverse mode





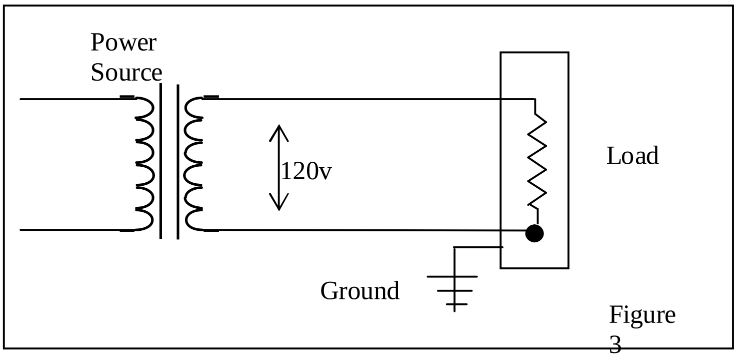


Figure 4: 120V/60Hz power applied to load in Common mode

Figure 5: Impedance load connected to power creates reactive currents that load up on the grounding system and neutral in proportion to the transformer's output Impedance.

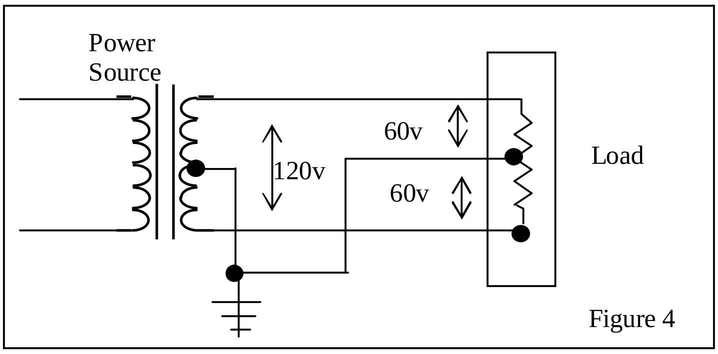


Figure 4

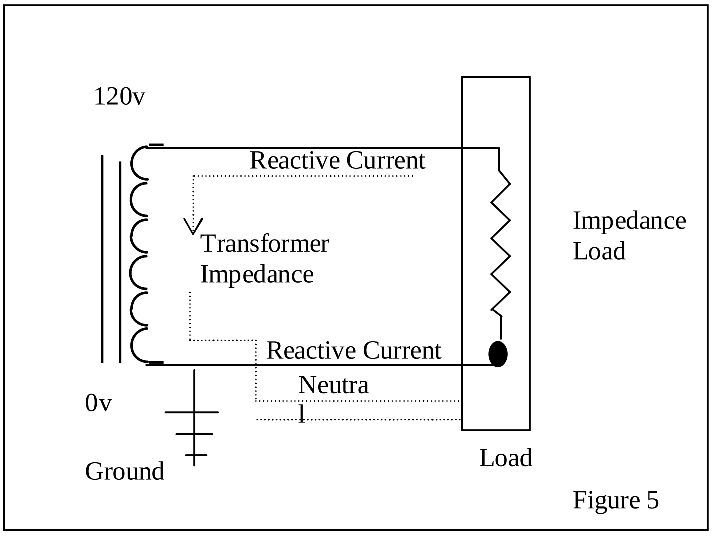


Figure 5

One conductor is referenced to the other and vice versa. No portion of the power circuit is referenced to ground. There is no current flow or significant voltage potential anywhere other than between the two circuit wires. This configuration of applied signal is called Transverse mode. The signal transverses two circuit wires without a grounding reference source. X-ray equipment in hospitals is one example of a Transverse mode power application.

A fourth variation is Common mode. The transverse voltage potential across a circuit is referenced to its own zero crossing point (Figure 4). The power resembles a balanced audio circuit or an XLR input from an unbalanced to balanced audio transformer. In this configuration, a center tap (ground) is placed on the transformer output winding, which divides the output into two 60-volt-to-ground potentials. But transversing the system's two current carrying output terminals, the usual 120 volts are present. At the center tap, the voltage potential to each side of the power source is the same.

THE CULPRIT IS EXPOSED

Let's look at some of the problems created by standard (Differential mode) 120-volt circuits when one applies power to a typical impedance load:

Figure 5 demonstrates how noise invades a grounding system through the AC neutral. Here, a load is applied transversely to a Differential mode power source - the usual case. Note how the grounding reference of the system loads up with harmonic currents and voltage potentials. These are commonly manifested as a sort of "voltage signature" in the grounding system, different with every piece of audio equipment. As more gear is turned on, more of these signatures appear. This is perhaps one of the trickiest of all noise problems to handle from both a power and grounding perspective.

If one opts to use a low-impedance transformer as a power source, some noise will be attenuated. However, the trade-off here is an increased danger of power spikes and voltage variations. In a low-impedance system, voltage variations and transient surges can be considerably greater than normal. This means that the possibility of damage to electronics is also considerably greater than normal. Protecting one's equipment from this exaggerated danger requires installation of an $800 facility transient voltage sure suppressor and a $2,000 line reactor - a lot to pay for 2 db to 3 db of background silence. Radial or star grounding may somewhat lessen the effect, but as with most known remedies, it's no better than a patch.

Before continuing, let's look at a problem that is very disruptive to an audio grounding reference. This occurs when a Differential mode (unbalanced) power signal is applied to a balanced circuit, for example an RF filter. Fig. 6 shows how capacitors leak current into the grounding system. This very reactive, nonlinear, half-pulse-width, leading current is perhaps the most stubborn, engineer-resistant type of AC interference (hum). Switching power supplies in digital gear and similarly reactive nonlinear loads shunt noise to ground in a similar fashion. Class A tube amplifiers are particularly vulnerable to this capacitive noise phenomenon, as are balanced microphone pre-amp inputs and other high-gain inductive circuits where low-level signals are critically referenced to ground.

Together, Figures 5 and 6 illustrate the source and the creation of almost all grounding noise (with the exception of interference originating elsewhere in a building's power or grounding grid, unmatched or defective components in audio circuits, substandard audio grounding schemes and occasional magnetic aberrations). A few chassis power supplies can also be included under aberrations. But most of these are rare, and when they do appear, they are easy to identify. The important thing to recognize is that the source of most grounding noise is linked directly to unbalance power.

THE SOLUTION

Let's apply a balanced (common mode) 120-volt power signal to the same RFI filter and to the same impedance load:

Figure 7 and 8 are illustrations of a balanced power application. In both cases, inversely phased power elements meet at the common ground. The effect on the grounding system is also observable in the power grid, with a near-total absence of locally generated noise under the balanced power/load condition. Note that when balanced power is applied, peak and inverse peak voltages are equally present with respect to ground. This means reactive currents generated by the impedance load are also perfectly balanced. (In the electrical industry, the term "Counter E.M.F." is sometimes used to describe these power artifacts.) Counter power elements that are balanced will null (sum to zero) in a balanced system at the ground or center tap, an obvious benefit in sensitive audio and video production facilities where overall noise floor and dynamic headroom are directly affected by grounding noise levels. However, in a three-phrase power system, there are no inverse phase relationships between power wires. Power wires are phased 120 degrees apart, so there is never a point in time where the system is completely off (common zero crossing voltage) as in single-phase systems. Consequently, reactive currents instead of nulling begin to "stack up," in a manner of speaking, end to end at very well ordered intervals on both the neutral and ground wires. As each phase peaks, a pulse of reactive current is released onto the common wire or neutral. This occurs at a rate of 60 times per second per phase. All three phases sum together in this way on the neutral, equaling 180 Hz, the third harmonic. Online video facilities powered by a three-phase (120/208V) grid are typically beset with noise problems. When three-phase-based, 120-volt power is used directly for audio or video electronics, one can be assured of more interfaces that other types of 120-volt systems.

SUBSTANDARD STANDARDS

One issue remains: What's wrong with grounding? The answer is simple. As a rule, the grounding circuit is not meant to carry any type of current except during a short-circuit, and then only momentarily. However, Underwriters Laboratories has been somewhat lax in this respect. "Objectionable ground current" is loosely defined in every area except hospital operating rooms. Outside of hospitals, "objectionable ground current" is gauged more closely to shock hazard levels (about 3.5 milliamps). It seems that this standard has backfired. Data corruption, disk crashes and simple hum noise cost time and money. Clearly, UL standards that define "objectionable ground current" are inadequate by today's standards. On the other hand, UL is not responsible for re-engineering audio equipment and AC systems. Normally, performance standards are left up to manufacturers and the marketplace.

The basic problem is that, when loaded, all Differential mode 120-volt AC circuits create noise in the ground reference. Noise problems occur in audio signal circuits due to unclean ground. The old Edison circuit (where a 240-volt circuit is split into two 120-volt circuits) is still used today as a standard means of 120-volt power distribution. Standard power is unbalanced. Even when a high-quality 120-volt isolation transformer is installed, one side is grounded (made neutral), which isn't much different at all. The way that AC voltage is referenced and carried by the circuit has everything to do with electrical interference in a grounding system. If any aspect of the circuit is applied or loaded in an unbalanced manner, noise will appear in the ground.

SUCCESS, AT LAST

Understandably, such a simple explanation of noise problems can invoke a kind of knee-jerk skepticism or denial. But, requiring proof is not an unreasonable demand. In locations using symmetrical 120-volt power systems, the results speak for themselves. When balanced power is applied system-wide, the results are often quite dramatic. On the average, a 16dB improvement in background noise has been noted. Where audio and video wiring is properly installed, in no known case has balanced AC failed to substantially lower the noise floor. In high-end systems utilizing 24-bit digital equipment, peripheral gear needs balanced power to approach the noise floor capabilities of the digital system.

A year ago, an audio dealer was checking some Class A tube gear before shipping the exhibit to the Audio Engineering Society convention. With several amps on the bench, he was resigned to spending six hours changing capacitors to clean up some hum problems. As fate would have it, a delivery arrived with two prototype 120-volt symmetrical power systems he had ordered for the show. Predictably, and nonetheless miraculously, the balanced 120-volt power systems rendered the hum inaudible, saving the fellow some capacitors and hours of work.

Few, if any, modifications to electronic equipment are ever needed. However, in cases where a device is supplied with a two-prong AC line cord, it has been found that retrofitting the unit with a standard three-wire grounded cord further reduces noise. With rare exceptions (extremely substandard internal grounding schemes), ground lifters should not be used. Notably, audio wiring is also much easier to configure, as is the case when connecting unbalanced outputs to balanced inputs. Audio isolation transformers are rarely required to eliminate noise. Another reason for grounding is to shunt RF away from grounded shields and chassis. A clean ground reference for attaching RF shields eliminates many problems. Such pleasantries are too numerous to mention. When balanced power is used, the general rule is: "If in doubt, ground everything and lift nothing." Grounding essentially works the way it was taught in school.

When symmetrical AC power is used, grounding tends to be more forgiving. Recently, a studio owner needed some consultation and assistance installing a 120-volt symmetrical power system for his home studio, a 24-bit digital facility that also included a fair amount of Class A tube gear. Despite careful planning, there was a miscommunication over some of the particulars regarding radial (star) grounding for the outlets. Consequently, the electrician, unfamiliar with studio AC wiring systems looped entire strings of outlets together using only one #12 gauge ground wire. In spite of the mishap, the system performed perfectly - quietly. This episode would indicate that unbalanced power is the true cause of noise, not a poor grounding design. The system was full of ground loops, but grounding currents and chassis potentials were nowhere to be found. This is how it should be. Star grounding and linear signal reference grids are nothing more than Band-aids that, at best, can only marginally mask some of the noise. To be free of noise problems, grounding circuits must remain clean - that's all there is to it. If not, a hundred ground rods won't help.

The symmetrical 120-volt system is unique in that it deals specifically with balancing all power and load elements with respect to a single-point grounding reference. This is the only prescription for maintaining a clean ground regardless of how big the facility or how much gear is turned on. A specially wound isolation transformer with a center-tapped 120-volt output, shown in Fig. 4 and again in Figs. 7 and 8, is basically the heart of the system. Both the load and the power signal are balanced with respect to the common output terminal (center tap) on the transformer. Here is the true single-point grounding reference for electrical safety and for shields, as it should be, not as an ineffective sink-hole for reactive current.

Every professional audio/video production facility that has tried a symmetrical power system has demonstrated a significantly lowered noise floor. Particularly, in cases where meticulous attention has been paid to selecting high-quality, balanc4ed audio equipment and well-designed audio wiring, the difference can be astonishing.

Interestingly, the most common "complaint" about symmetrical power comes from guitar players, who interpret hum as a sign of reassurance that the amp is turned on and up to speed. It seems that the silence is an annoying distraction to them. That's too bad. They'll get used to it.

Figure 6: Standard 120V AC applied to an RFI filter causes capacitive leakage into ground.

Figure 7: Balanced power applied to an RFI filter causes balanced capacitive leakage to null.

Figure 8: Balanced power applied to impedance load creates balanced reactive currents, which sum to zero (null) at transformer ground instead of build as more gear is turned on.

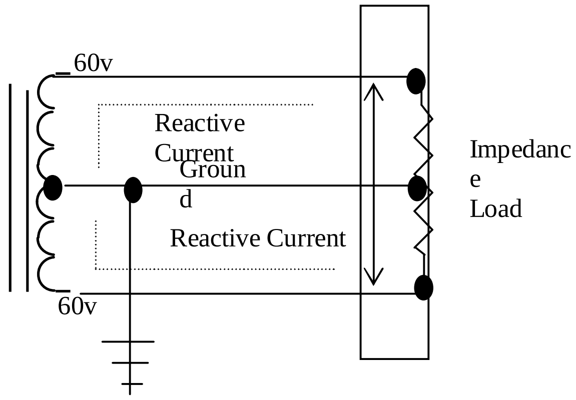


Figure 8