GROUNDING *REVISITED*

An Effective Protection & Shielding Implementation Method

by Greg Hanks

In an ideal world, audio equipment performance is not compromised by interconnection wiring, physical placement or the external environment in which it operates. We do not live in an ideal world, and thus we often find hum in the 2-track mix, buzz coming from all channels of the multitrack and excessive noise from our digital devices.

Various sources contribute to noise interference. The source of hum and noise may be electrostatic radiation to unshielded conductors, magnetic induction in transformers, spikes in the electrical service, currents flowing in shield wiring or other fault conditions. Noise and distortion performance of any given system can only be as good as that of the components and the interconnection scheme employed. To obtain maximum performance with a given equipment installation, each of the contributing hum, buzz and noise sources must be addressed: electromagnetic interference (EMI), electrostatic and radio interference (RFI) and power line noise.

Whenever a current flows in a conductor, a magnetic field surrounding that conductor is generated. The strength of this magnetic field is directly proportional to the amount of current flowing in the conductor. The magnetic fields that cause us concern are those from utility power, transmission lines, internal utility feeders and power supply lines.

A magnetic field can be described in terms of lines of flux or tubes of flux. The study of magnetism and magnetic radiation is not our intention here, but some fundamental principles bear examination:

1. Currents can be made to flow in a conductor by moving it past a magnetic field. Changing the magnetic field and having a stationary conductor produces the same phenomenon. Experimentation reveals the following: the current is dependent on the loop area, described by the physical layout of the conductors. The current is greater if the magnetic field changes more rapidly. The rate of increase is **6** dB/octave. When a multiturn coil is the conductor, the current is proportional to the loop area, the number of turns and the rate of changing flux. The strength of the field is inversely proportional to the distance from the field. The field decays geometrically, and any currents generated by the field follow the inverse square law.

2. The permeability of a material, or the index of magnetizability, can be expressed as the ratio between a given flux density and the ampere-turns per unit of length required to establish that given flux density. This

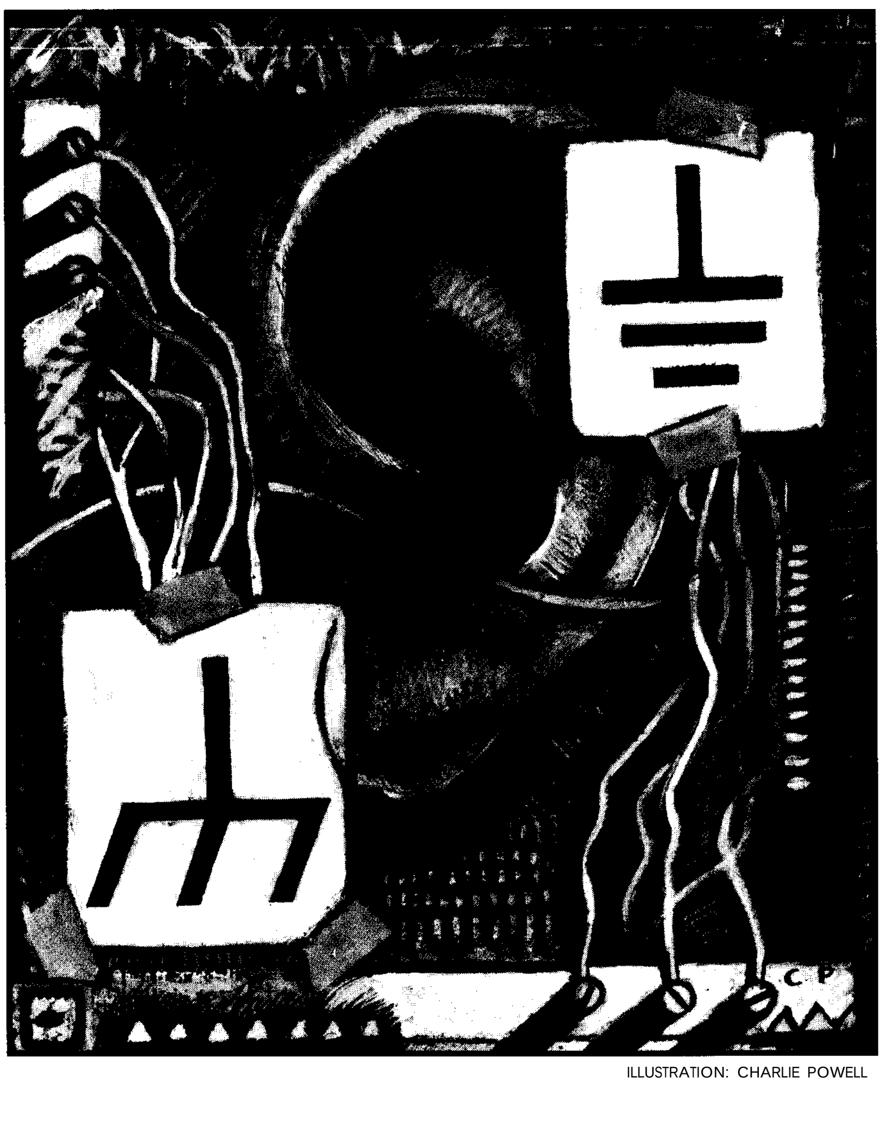

ILLUSTRATION: CHARLIE POWELL

reduces to Ampere's law: the sum of the products of magnetization force ("H") multiplied by the length equals the ampere-turns threading that loop. A resultant concept is that a very large loop of current will produce a very large magnetic field (such as when the neutral of a utility feed is run to a load along a much different path than the hot lead). Coaxial current flow produces an external magnetic field of zero; in fact, the magnetic field is not absolute zero, because the currents cannot remain truly coaxial at either terminus. The flux field propagates tangentially to the orientation of the conductor. Parallel conductors carrying equal and opposite currents will have a small external field. Symmetry does not exist near the conductors, but at a large distance this is not important. Parallel conductors often are twisted to maintain proximity and minimize residual loop area effects to reduce the external field even further.

3. Whereas electrostatic charge is a potential caused by a different charge level of two surfaces, electromagnetic flux lines are force lines that do not respect surface charges but follow permeability. A magnetic field's behavior depends upon the conductor geometry and the materials near the conductors. For example, if these materials are iron, the fields tend to concentrate in the materials, indicating that they prefer the simplest path. More accurately, the energy stored in the system is minimum when the field follows the path of the magnetic material. Therefore, a magnetic field cannot be eliminated by shielding because of the conservation of energy. Thus the magnetic field can only be reshaped and redirected. The shielding material must be permeable in order to conduct the magnetic field. The higher the permeability, the better the magnetic path redirection.

The performance of the components in many electronic circuits can be impaired by interference from magnetic fields emanating from other nearby components or originating from external sources. These fields can be produced by motors, generators, solenoids, transformers, permanent magnets and other devices.

Some components are especially sensitive to magnetic fields. For example, a cathode ray tube's electron beam will be distorted by the field(s) generated by the power and flyback transformers located in the same area. A large console's summing buses prove especially sensitive to current demands from nearby power transformers or from utility feeds that run parallel to the orientation of those buses. Perhaps the most sensitive devices are multitrack tape recorder heads. They are constructed on highly permeable forms, using multiple turns of fine wire. In fact, when I'm chasing down the source of an electromagnetically based hum, I often use a cassette machine as a hum detector.

Several methods or approaches (not including component modifications) can minimize the interference problems associated with EMI:

Double the distance. Since the flux field density around a current-carrying conductor follows the inverse square law, as we double the distance between the offending conductor and the receiving device, we see the square root of the original level. Simply put, keep as much distance between hum fields and sensitive devices. I once made the mistake of orienting a multitrack tape recorder area right next to the power amp rack. This resulted in an additional 12dB of hum in the playback circuit (before we moved the amplifiers).

ORIENTING A MULTITRACK RIGHT NEXT TO THE POWER AMP RACK RESULTED IN 12 dB OF HUM IN THE PLAYBACK CIRCUIT.

Orient properly. A flux field is circularly polarized and oriented tangentially to the current-carrying conductor. To minimize the influence of the flux field on the component picking it up, move the source or the receiver so as to minimize the field influence. (In our previous example we determined that the hum source was magnetic by moving the machine around, and we were able to achieve a 4dB to 6dB reduction in hum by rotation.)

Shield the source. The best time to consider the prime EM1 sources within the control room is during the preconstruction stages. Common problem areas include the path of the building utility feeder cables and the path of the sub-panel lines. The most cost-effective shielding for these lines is steel conduit. Standard aluminum and PVC tubing may provide for electrostatic shielding but provide little in the way of magnetic protection. When coping with power lines, the best method is to put distance between your receiver and the conductors, but a suitable alternative is to cover the lines with l/4-inch, "diamond plate," steel plating. When coping with large power supplies, such as power amps and console power supplies, use a steel rack with enclosed sides. (With our power amp rack, we achieved approximately 3dB of hum reduction by employing a steel rack instead of a wooden one.>

Shield the receiver. The receiving device is usually shielded by the manufacturer. However, this does not mean the shielding is sufficient. In my experience the manufacturer can offer suggestions and materials so you can more effectively shield a sensitive circuit. (We were provided with a new head and nest shielding assembly, offering a hum reduction of about 4 dB.)

In practice, each of the above four approaches must be applied in concert with each other. Usually, it is not sufficient to experimentally apply a single method. Optimize each of the different situations. In the example above, our overall improvement in hum was in excess of 12 dB, and at the same time we ended up with a machine that was almost impervious to external hum fields, a power amp rack that generated a minimal field and-most importantly-a quiet system.

DEFINITIONS

Next, let's discuss electrostatic shielding. This is the protection provided by a conductive surface that surrounds our electronic systems and keeps out the buzz. We face a few problems when we discuss "grounding." The first is the relative flippancy with which we bandy terms about, so let's clarify some definitions.

Ground is the material that we live on. It is also the connection point between the power company's neutral line of incoming AC service and the earth. Practically speaking, we refer to the point where the electrical company's common (the third pin), the conduit and all other electrical-service metal enclosures bond to the big ball of dirt, referred to as theearth. Conceptually, this is done to ensure that the maximum voltage existing at any point in the electrical service is the voltage between the conductors of the incoming service. Therefore, the term "ground" refers to the actual location of the connection between the power company neutral and the conduit. The National Electric Code (NEC) requires that this be a cold-water pipe or a separately driven grounding rod.

Technical ground is the location where the audio common(s) and electrostatic shielding system are brought together. This is a location, not a "system" or wiring point. Technical ground may or may not be taken to "ground."

Earth, when used in this article, does not refer to the circuit point described above but to the "screening" or enclosure connection. We also use this term as "the earthing wire" to refer to the conductor used to bring an equipment enclosure to the studio "zero reference," or technical ground. When discussing the electrical system, the third pin is the earth connection

Shield describes an enclosure that is designed for electrostatic or electromagnetic protection. In this article, the electrostatic shield refers to the screen, or the "drain" wiring. Electrostatic shielding is what the shield wire addresses. When we refer to wiring, the shield is the conductive braid or foil that surrounds the signal conductors, whereas in theory, the shield is the electrostatic barrier composed of the given equipment enclosure coupled with the screening provided by the conductive sheath of the cable.

Common, often called "the audio common," is the circuit point shared by both the input and output of a circuit. In the past, when transformers commonly were used for both input and output, the audio common was brought out as a connection for use in conjunction with the shield.

Neutral is the wire that feeds your electrical outlets that is most often taken to "ground" at the electrical service entrance. The neutral wire provides the return path for the "hot" lead(s) and carries any load imbalances.

THEORY

With these definitions in mind, we'll provide a system of shielding that prevents interference from the electrostatic hum field(s) in a room. Another area of "grounding" confusion concerns the difficulty that exists in drawing the equivalent circuit of a grounding system, then differentiating that from a shielding system. The most often used representation of signal common is ⏚; for earth, or chassis connection, we use ⟂ All too often the chassis connection (earth) and signal common are both referred to with the ↓ symbol, and where they are tied is never indicated! Here we only refer to ⟂ when dealing with wire, and ⏚ when describing a circuit return or audio common.

Static charge must be understood when investigating electrostatic shielding. Whenever an excess of electrons exist on a body, that body is negatively charged. If there is a lack of electrons, that body is positively charged. Oppositely charged bodies attract each other and like-charged bodies repel. When we have two charged bodies near one another, a force exists, an electrical field. And the field that radiates from a charged body produces electrostatic force. Because the earth is at zero potential, any charged body has a field that possesses force. This force exists because the earth-for practical matters-is considered an infinite source of charge because it is at zero potential. This force radiates from a charged body and terminates at infinity, or another charge.

GROUNDING THE SHIELD CONDUCTOR IS NOT NECESSARY FOR THE SHIELD TO FUNCTION.

When surrounded by another conductor, a conductor with a charge on it radiates a field that terminates at the surrounding conductor. Any fields outside of this surrounding (shield) conductor also terminate at this conductor. If this shield conductor is taken to the earth, the (signal-carrying) conductor(s) surrounded won't be affected by any charges outside of the shield conductor. Since the earth is at zero potential, a conduction path to the earth brings the shield to zero potential.

Be aware that grounding the shielding conductor is not necessary for the shield to function. The potential that exists between two shielded conductors remains unaffected by any fields outside the shield, and the fields outside the shield will not be modified by the potential(s) within it. The purpose of taking the shield to ground is to make the mutual capacitance of the conductors to the conductors outside of the shield zero. What occurs in the real world involves many conductors within shielding enclosures whose mutual capacitance is not zero. The mutual capacitance is defined by the geometry of the conductors and the shielding system itself, but optimized when the topology identifies the power supply common as the ground point from which the shielding center emanates.

Capacitance, in this discussion, is multi-influential. It is the self- and mutual-capacitance of shielding and shielded conductors that make electrostatic shielding work. When a potential is impressed upon a single insulated conductor, and that potential is varied, the charges existing between that conductor and surrounding conductors vary. When a charge varies, current flows. This seems to defy the law that a circuit must be closed for current to flow. The capacitance that couples these systems provides the path for current flow. One primary source of hum in our audio signal is the capacitive coupling of the power mains to our audio commons through the primary windings of the power transformers in the system.

The other primary source of hum is "room pickup." An electrostatic field at power frequencies exists in all inhabited areas. The field originates on unshielded wiring and terminates on the lower potential conductors in the vicinity. The room can be considered a large capacitor, with the signal-carrying conductors as one plate and the lowest potential conductor(s)earth-as the other. A typical room's induced reactive current flow is about l00na per square foot at **60** Hz. This is the source of the buzz that occurs when you touch an amplifier input. This brings us back to why we're discussing this in the first place-to keep buzz and RF out of our audio lines.

We accomplish this through electrostatic shielding. The individual components used in a studio installation will achieve this through their own chassis. As we interconnect the system's individual components, we must bring all these enclosures to the same potential. Minimizing current flow within this interconnection is the goal, accomplished by making the audio signal "see" this shield charge as being the lowest potential. In almost any studio environment, the most desirable point to consider as the technical ground (the point of lowest potential) is the electrical point where the console takes audio common to the console chassis. When all chassis are brought together at this point, we reach our goal of providing electrostatic shielding.

Common sources of interference in studio installations are due not only to electrostatic coupling from external fields to the audio wiring, but to coupling from the currents flowing within the shield itself, to both the shielded conductors and to the audio common. Current flowing through the shield structure is not necessarily only at AC power frequencies, but has a broad power-spectrum response, and as a rule the system noise suffers from current flowing in the shields.

To optimize the operation of each component, the audio common and the audio shield must be tied together. If not, all the conductors within the shielded enclosure will be tied together through the mechanism of distributed mutual capacitance. This phenomenon results in excessive crosstalk at high frequencies and an overall reduction in high-frequency performance (ringing, oscillation, premature roll-off and the like).

Ideally, all the different audio commons return to the technical earth independently, and the shields also return to this same point independently of the audio commons. Carried out to the extreme, all digital commons, video commons and the digital shields, video shields and the electrical service neutral terminate at this one point with independent runs. Yet this is difficult-if not impossible-to achieve. We do not attempt to make these runs independently. We look at each component as an individual common-to-shield connection and take the shields to the technical earth individually on a "star" basis.

Achieving electrostatic shielding and providing an interconnection of the audio commons requires the following:

1. The "system" audio common and the shielding system must be tied together at some point;
2. Each component connects to technical ground at one point only;
3. Earthing wires all terminate at the technical ground bus and do not daisy-chain in a serial manner to get to technical ground;
4. The third pin of evey AC cord is lifted whenever an independent earthing wire is employed;
5. Every signal line has its own shield (the only acceptable exceptions are data and control lines);
6. The shield wire is not shorted to other shield wires at any point other than the signal source reference;
7. Only equipment that provides true power transformer isolation from the chassis is used;
8. Shields connect at one end only, and the connection point is at the signal source;
9. The technical ground is located at the power distribution panel or at the terminus of the audio cabling (usually at the console termination area).

In the above scenario we're trying to reach three different goals with the same wiring system. The first goal is to provide a safe system to use. A professional installation provides for operator safety, free of shock hazards. When we follow the above rules, we assure that there is no possibility of any voltage existing between two interconnected devices. Another way to look at it is that a quiet system is a safe system. Whenever a shock hazard exists, there is a considerable amount of hum and buzz present.

The second objective is to bring all the different signal commons together at one point only. This practice minimizes noise and provides greater system stability. This is traditionally the area that results in "ground loops." A considerable problem exists when we encounter a single-ended input. The signal common is brought from both the source and the receiver within the signal wiring. At the same time, the signal commons are both referenced to the technical ground through the chassis shield connection. If both these paths are made, then we have a ground loop.

The last objective is to complete the conductor paths of each piece of equipment for an effective electrostatic shield that must exist around the wiring system.

POWER LINE NOISE

Every audio system requires "juice." The AC supply lines that feed provide the path for corruption, which takes the form of spikes, hash and general nastiness. Brownouts and overvoltage surges cause the system to sag, then bounce. These anomalies impress considerable noise upon the shield lines, and if they're of sufficient amplitude when the line voltage is low, they can come sliding right through the regulators of the power supply and end up in the audio. This problem must be addressed carefully, because brute force protection is expensive. If not judiciously applied, this same expensive brute force can be highly ineffective.

If you are starting out, there is no guarantee that what is now good power will stay that way. The ideal condition would provide a separate transformer feed for the studio(s) and control room(s). This would be used only for technical power. All lighting, refrigeration, office equipment and other dirty stuff would be fed from the "other" building utility supply. This would be fairly close to the head end of the high-tension distribution, so any other users of the utility would affect your supply minimally. Hopefully, the zoning of your area is mature enough that heavy power use further down the utility line is limited.

Unfortunately, the aforementioned situations rarely apply. Fortunately, power is not a common source of problems. To determine if you have a power problem you must look for some common signs: ticks and pops in the monitor and on tape that do not directly relate to any switching action in the control room. Usually you can trace these noises to a copier, elevator, refrigerator (including a soda machine!) or some other form of high switch-current device. Another obvious giveaway is intermittent "hash."

Exercising proper care in the original electrical wiring and wiring design goes a long way toward eliminating power problems. The following rules illustrate how to stay out of trouble when installing the electrical system:

- Keep the control room, and all equipment used in it, on the same phase of the AC line.
- Isolate the electrical feed from everything else. Keep the audio power separate from copiers, fluorescent lights, refrigerators, etc.
- Shield all AC power lines with steel conduit.
- Never run the power and audio lines in the same conduit.
- Bring the third pin of each outlet back to technical ground separately. Only use multiple-outlet distribution strips if the third pin connections are independent of their enclosure.
- Never allow the third pin to contact the conduit.
- Never let the technical ground bus touch any building conduit, *except* at the point where technical ground is taken to ground.
- If the technical ground is to be taken to ground, then make sure that the ground bar, the neutral-to-ground, conduit bond-to-ground, and technical ground-to-ground connections are all clean and tight. Take technical ground to earth with a single, very large conductor.
- Never use the electrical conduit for technical ground.

The first thing to do when you suspect power problems is monitor the line with an RMS-reading voltmeter and an oscilloscope. You can buy the meter from most test equipment houses; it's a good thing to set in the amp closet as a handy monitor. Look for spikes on the line and see if the 'scope will trigger whenever you hear some of the offending noise. If the problems are more intermittent in nature, you can rent a dedicated line monitor from a test equipment rental house and leave it unattended on the line for a week or more. This yields a "histogram" of power line activity that can be analyzed later.

The solution to these power problems is often as simple as moving the offending device(s) off the studio power and onto another system or another phase. Most electricians try to put the outlets of the control room and studio on both phases of the power line. Don't let 'em. Put your lights, heaters, pumps and the like on one side and use the other for your audio. If the imbalance is too great, then find a solution that does not require splitting the audio power or corrupting it with other stuff. Lights can go on the audio supply, as long as the only dimmers used are the Variac type and the lighting is incandescent.

Power problems that are not cured by the above "remedies" may result from a dirty neutral-to-earth bond, a

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corroded pole-peg ground wire, or other forms of intermittent or highly resistant connections. Most electrical problems are caused by line imbalances, multiple earth bonds, audio ground wiring problems, outlet wiring errors, mixing AC phases and installation or design errors.

Worst-case, it may be necessary to condition the incoming power to supply a clean feed. Power conditioning is not accomplished easily. You need about 75 amps to run a standard 24-track room. This equates to a 10kVA conditioner. If you want to run two digital machines with a digitally controlled analog console, make that around 150 amps. New technology means new power demands.

A power conditioner must provide:

- Output voltage regulation within 15% of nominal with a 25% input fluctuation;
- Spike and surge protection (must be "able to remove spikes of extremely short duration, although usually of great amplitude);
- Low distortion of the output waveform (we can't accept any more than 10% third-harmonic distortion and significantly less even-order distortion);
- High operating efficiency (lack of efficiency translates directly to heat, with a concurrent increase in air conditioning expense, which directly affects utility costs);
- Low primary-to-secondary capacitive coupling;
- Low primary-to-secondary common mode coupling;
- Low output impedance at all frequencies.

While running out to buy a power conditioner is not the first thing you'll want to do, it is one of the most cost-effective methods of dealing with a serious power problem. You can accomplish power conditioning in two different ways: first, by conditioning all the "tech-power" with a single conditioner; second, by conditioning equipment "locally." The concept of local conditioning makes sense when there are only one or two sensitive pieces of gear.

The primary reason for purchasing power conditioning is voltage fluctuation. Brownouts and overvoltage conditions stress any piece of electronic equipment dramatically. In this light, you can look at power conditioning as a form of insurance. You hope that you will never need it, most of the time it won't be used, and when it is, you thank your stars you have it.

ZERO-VOLT, GROUNDS, HUM AND PROTECTING MUSICIANS' LIVES

An astonishing number of studios have hum problems. Astonishing, because nobody wants hum, and most studios have spent a great deal of time and energy to eliminate it. When these efforts are successful, well and good. When they're not, the engineers, who have other things to do, will eventually give up, declare whatever hum remains to be an act of God and live with it. Not happily, but if you can't fix it,

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