# Power and Grounding for Audio and Audio/Video Systems
# A White Paper for the Real World

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Considerable confusion seems to surround power and grounding for audio and audio/video systems. This "White Paper" is an attempt to cut through the confusion and set out a collection of good engineering practice that is both safe and effective. The author believes that the recommendations and practices outlined herein are safe, and that they conform to building codes in most of North America. The author is an electrical engineer by training and an audio systems consultant by profession, but is not a registered Professional Engineer. No warranty is made or implied as to the extent to which these practices conform to local codes or regulations. Qualified professional engineers and electrical contractors should design and install all electrical systems.

## AUDIO AND VIDEO SYSTEM POWER REQUIREMENTS

With the exception of a few very large power amplifiers and video projectors, virtually all audio and video equipment sold in North America utilizes single-phase 60 Hz power at 120V. Few individual pieces of equipment require more than 20A; most require far less current. The largest projectors and amplifiers may require 240V, 60 Hz, single phase power, at up to 20A.

Most audio and video equipment draws relatively little power. Audio and video equipment falls into two basic categories – small signal equipment and large signal equipment. Small signal equipment amplifies, processes, mixes, routes, and controls the signal. Mix consoles, crossovers, equalizers, digital signal processors, routers, and switchers are all examples of small signal equipment. Nearly all small signal equipment has two characteristics in common – 1) it draws relatively little current, with the exception of very large mix consoles, and 2) the current draw is essentially constant, independent of what the equipment is doing at any given time (as long as it is powered on). Power consumption ranges from 4-120 watts for most devices, including small mixers, to 500 watts or more for large mix consoles and tape transports.

Large signal equipment is simply equipment that supplies an audio (or video) signal with considerable power – power amplifiers and video projectors. Within this type, there are two kinds of equipment – those whose power consumption is essentially constant, independent of the signal, and those where the power depends strongly on the signal level. Video projectors fall into the first class – they are either off or on, and their current draw will generally depend only on the light output.

The current drawn by power amplifiers is very strongly dependent on how much audio power they produce, which in turn depends both on the signal level and the load impedance. There will be an "idle" or "quiescent" current that the amplifier draws when connected and turned on, but with no signal passing through it and only its small signal circuitry is operating. This power will generally be listed on the product data sheet, and 30-120W is typical of modern stereo power amplifiers. The power draw when the amplifier is actually providing output current is a far more complex matter, both because audio signals have very wide dynamic range, and because the average power is usually far less than the rated power.

Consider, for example, an amplifier that is part of a system for an auditorium that may be used for lectures, pop music, jazz, folk music, and live theater. Sound levels may vary by 30 dB from the loudest to the softest of these programs, and the system will rarely be required to get within 10 dB of full output. On the other hand, most power amplifiers exhibit their lowest efficiency when providing sine wave power at roughly 30% of full rated power.

Not only that, but well-designed systems will have compression and peak limiting built in to maximize loudness and their ability to handle peaks, which will, in turn, increase the current draw by reducing the peak to average ratio. Thus, in a real system, the actual power drawn is not easy to know unless you actually measure the current.

Now, let's look at the "nameplate" power listed on the amplifier itself, or on its data sheet. Most often, that's the electrical power required to produce rated sine wave power, at clip. But we don't use amplifiers to amplify sine waves, we use them to amplify audio program material, and the average power is virtually always at least 6 dB below that of a sine wave at clip. A far more useful data point is thus the current consumption under the more realistic conditions of pink noise (or, better yet, compressed pink noise) at full output. Even taking compression and peak limiting into account, audio systems actually draw far less power than the designer asks the Electrical Engineer to provide, even when pushed to the threshold of pain. When the program material is simply a person speaking, or even an amplified acoustic jazz band, the power amplifier will rarely draw more than about twice its quiescent power!

That doesn't mean we don't want to ask for an electrical system that can provide a lot of power – we certainly do – not to actually provide that power, but so that the power system will have good voltage regulation. That is, when the bass drum hits and the power amplifiers need a lot of current, we don't want the power line voltage to "sag," because the performance of most audio gear degrades quickly with low line voltage. That requires big copper, both in the power distribution transformers and in the wiring to our system. It's hard to explain the dynamics of audio signals and the complex behavior of power amplifiers to an electrical engineer, so we simply ask for a lot more power than we really need. He responds by giving us big copper and a big isolation transformer for our system.

Cooling for audio and video systems is another issue that an audio/video system designer must address. The designer of the HVAC system needs to know:

- That the system will not always be on, and that it produces varying amounts of heat, depending on how it is being used.
- The quiescent (turned on and idling) heat produced by the system, in watts (I let the ME do the conversion to BTU). This is essentially the sum of the nameplate power rating of all small signal equipment plus the idle current rating of all power amplifiers. If the equipment is split between rooms, the information is needed on a room-by-room basis.
- The maximum heat under full loading – that is, the system running at full power. This is essentially equal to the quiescent loading plus the dynamic power drawn by the power amplifiers, minus the electrical power fed to the loudspeakers. As noted in the discussion on dynamic power, this is a pretty tough number to come up with, but a value equal to 10 dB less than the combined nameplate AC current rating of all of the power amplifiers is probably conservatively high for their dynamic loading. This data is also needed on a room-by-room basis.
- That the ambient temperature in all rooms housing equipment racks must remain within the range of 50° – 80° F.
- That control rooms and rooms housing equipment racks be controlled and served by the HVAC system independent of all other spaces.

## THE START-UP PROBLEM

Most big power amplifiers have big power supplies with big filter capacitors connected directly to the output of the rectifiers. If, by chance, the power switch applies power at the peak of the AC cycle, a very large current will be drawn to charge the filter capacitor. This current can be much larger than that for rated sine wave power, but the current peaks quickly, and rarely lasts more than a few hundred milliseconds.

Circuit breakers are designed and specified to protect the electrical system in the case of a fault, especially from overheating due to excessive current. Conventional circuit breakers operate by a combination of thermal and magnetic means. The thermal means – a bimetal contact expands and contracts as it heats due to the current flow – has an intentional delay as sufficient heating takes place before the breaker trips. This delay allows the breaker to tolerate a moderately high turn-on surge current, as long as the current quickly settles to less than the long term rating of the breaker. The second mechanism is magnetic – it operates much more quickly, but takes a very large current to operate. A "high-magnetic" or "high-mag" breaker is designed such that the magnetic trip operates at a higher multiple of the steady state rating – that is, it allows a higher surge current.

To prevent tripping at turn-on, high-mag breakers should generally be used as main breakers and on the branch circuits of panelboards feeding power amplifier racks (and for convenience outlets around a facility that may be used with portable amplifiers). Ordinary circuit breakers will pass the turn-on surges associated with most medium-sized power amplifiers, and the use of high-mag breakers increases this capability. On the other hand, a breaker is much more likely to trip if several power amplifiers all turn on at the same time, and a main breaker for a large system may trip if many amplifiers in branch circuits all turn on simultaneously.

There are several good solutions to this problem. One is to use a sequencing system that turns on one power amplifier at a time in intervals on of the order of one second, either by connecting only one power amplifier per branch circuit (i.e., one per breaker) and sequencing the breakers (Lyntec), or by using a sequencer after the breaker for multiple power amplifiers per breaker (SurgeX). Another good solution is to "soften up" the turn-on of each individual amplifier, reducing its peak amplitude by spreading it out a over much longer interval (SurgeX ICE). Another good method is to sequence the turn-on of the amplifiers themselves, either with an integrated control system (AMX, Crestron, etc.) or with control circuitry integral to the power amplifiers.

These systems must, however, have one thing in common if they are used in an assembly space -- in the event of a power failure, the system must "remember" whether it was off or on when power dropped, and when power is restored, must automatically turn itself back on if it was on when the power dropped. Why? Simple. A power failure can easily coincide with an emergency condition, or could generate concern on the part of an audience. If the sound operator, seated in the audience, had to make a mad dash for the breaker panel to restore power after the failure, not only is time lost, but a panic could be triggered by the commotion of someone running to restore power.

## POWER SYSTEM ARCHITECTURE

The connection of a building to a source of power is called the *service* and the point where the connection is made is called the *service entrance*. The power company's local distribution lines (just outside the building) operate at relatively high voltages (typically 2.3 kV – 12 kV) to minimize the $I^2R$ losses in the wire. The power company installs large transformers (typically on poles or in underground vaults) to step down the high distribution voltage (high impedance) to a lower voltage (impedance) suitable for interior wiring (called *premises* wiring).

Power is typically distributed to a facility in one of several forms. A few very small facilities (typically homes and small churches) may have only 240V or 120V single-phase service. Single phase power is nearly always provided by a transformer having a center-tapped 240V secondary, as shown in Figure 1 (this system is often called "split single-phase"). The center-tap is grounded and becomes the neutral for 120V equipment and for outlets connected to either Line 1 and Line 2. Note the voltage waveforms for Line 1 and Line 2 are out of polarity with each other, and 240 volts is obtained by utilizing the entire secondary winding, usually without the neutral. A few older homes may have only a 120V service, but it is likely that the distribution transformer outside the home has a 240V center-tapped secondary, with only one side is brought into the home.

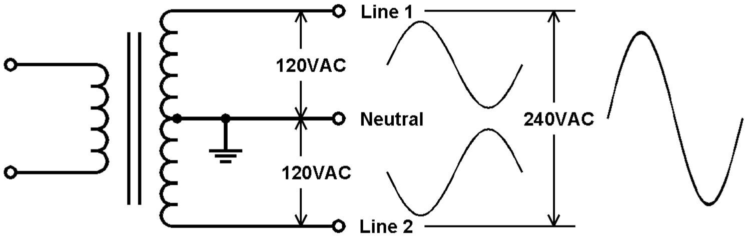


Figure 1 – Single Phase 120V/240V Power System ("split single-phase")

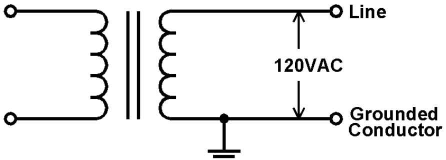


Fig 2 -120V Single Phase System

At this point, a comment about terminology is in order. The National Electric Code uses the term *Grounded Conductor* when referring to the return conductor of a 120 volt circuit. Almost everyone else calls this conductor the *Neutral*, and we shall use the two terms interchangeably here.

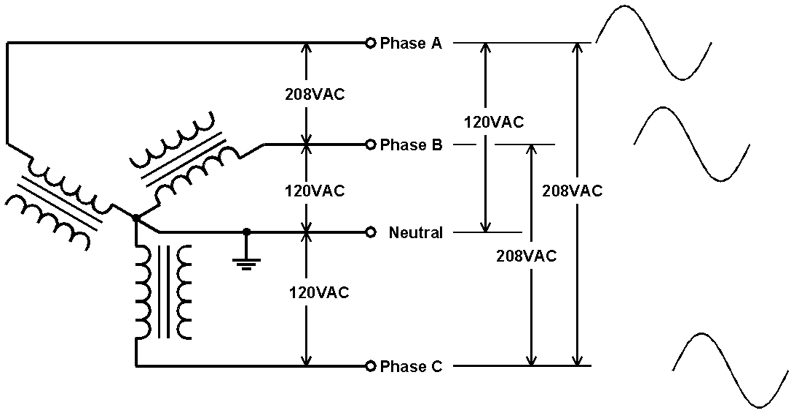


Figure 3 – Three Phase 208V/120V Power System

Nearly all power is produced by rotary generators, whose output is taken from three windings displaced by 120 degrees from each other around the generator shaft. The electrical phase of the power produced by the three windings is also displaced by 120 degrees at the 60 Hz power frequency. We call the power produced by such systems "three-phase" power, because the power consists of three components, each displaced by 120 degrees from each other.

Most smaller facilities are connected to a 208V/120V three-phase *service*, as shown in Figure 3. Some specialized equipment may require 240V single-phase power, typically provided by a stepdown transformer from one phase of the 3-phase *service*. Three phase power is required to run most large motors. Figure 3 shows that the voltage waveforms for the three phases are displaced from each other by 120 degrees. Figure 4a shows these voltages as "phasors," a mathematical concept developed to analyze and describe how voltages *of the same frequency* but out of phase with each other combine with each other. We can think of these phasors as vectors that rotate around an origin, with the vertical height of the vector tracing a sine wave as it rotates.

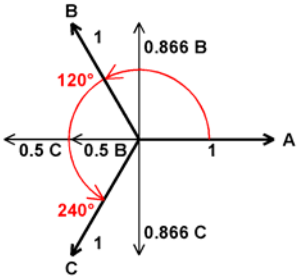


Figure 4a – 3-Phase Voltages

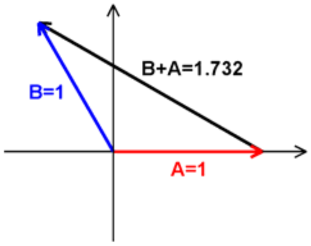


Figure 4b – Phase to Phase Voltage

We can "stop" these phasors at any point in time and analyze how they combine. Figure 4a shows them at the point where the voltage on phase A happens to be at 0 degrees, but we could have stopped them at any other point on the cycle. Figure 4b shows that when any two windings are in series (that is, we measure phase-to-phase) the voltage is 1.732X the voltage of any one phase. Thus, a 3-phase system that has 120 VAC between each leg and neutral will have 1.732X 120V = 208VAC from phase to phase. Why not 240 volts (or zero)? Because the two voltages are displaced by 120 degrees, not 180 degrees as in the case of a single phase (center-tapped) system.

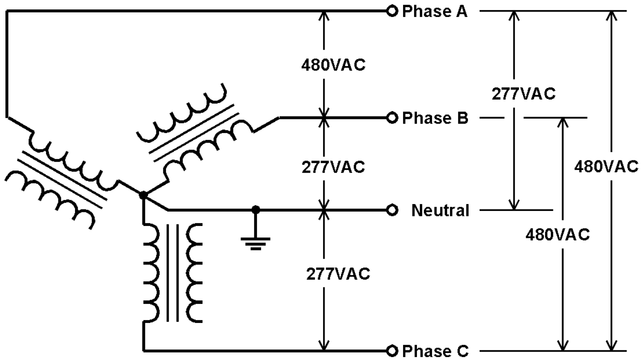


Fig 5 – Three Phase 480V/277V Power System

The largest facilities are typically connected to a 480V/277V service in a three-phase wye configuration, as shown in Figure 5. Some of that power may be utilized directly at the supplied voltage for large motors and fluorescent lighting, but distribution transformers inside the building will also step that voltage down to 208V/120 V wye for use by most equipment and systems. Again, three-phase power may be used to run motors, but most power will be distributed at 120V single phase to equipment and outlets. Phase relationships are the same as for 208V/120V systems – the two systems differ only in the turns ratio of the distribution transformers and the voltage rating of their components.

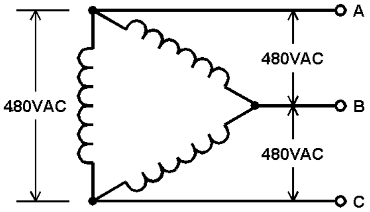


Fig 6 – 480V Delta

Figure 6 shows the three-phase Delta configuration that is commonly used in large facilities. Note that there is no neutral. This configuration is used only in industrial buildings and in a distribution outside of buildings. One leg may be grounded, but NEC does not require that there be a grounded conductor.

## NEUTRAL CURRENT AND HARMONICS

It is good practice to balance loads between the legs (phases) of a three-phase system. Fig 7 shows the relationships between the current in the neutral of a perfectly balanced three-phase system. Fig 7a and 7c show neutral current at the fundamental frequency of 60 Hz. Taking phase A as the reference, the .866 positive and negative components of phases B and C cancel each other, while the 0.5 components add to perfectly cancel phase A, so the total neutral current is zero. If all current in a power system is sinusoidal, Fig 7a and 7c tells us all we want to know about the current in the neutral.

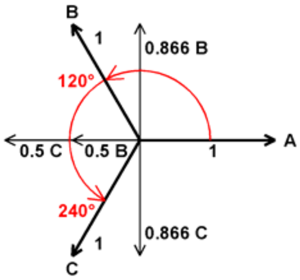


Fig 7a
Neutral current at 60 Hz

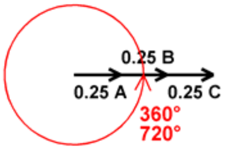


Fig 7b
Neutral current for 25% third harmonic

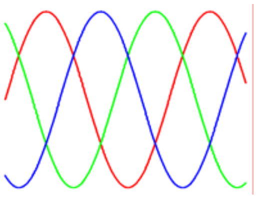


Fig 7c –Sinusoidal neutral currents (red=A, green=B, blue=C)

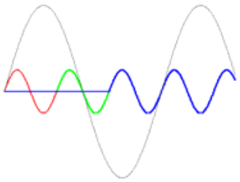


Fig 7d
(fundamental of one phase shown for reference)

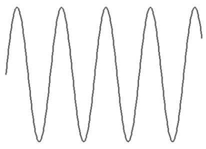


Fig 7e
three phases summed, each 25% 3rd harmonic

Unfortunately, the current drawn by the power supplies in electronic equipment is almost never a pure sine wave. Power supplies have some form of rectifier that then re-charges a filter capacitor at each peak of the input sine wave. This results in the current waveform being a rather distorted sine wave. Forty years ago, most of the current in a building was drawn by loads that were relatively sinusoidal – motors, incandescent lighting, heaters, and so on. We would say that these loads are relatively linear – that is, the current they draw is almost directly proportional to the sine wave voltage, so they are close to being an undistorted sine wave. There were a few electronic loads – radios, hi-fi rigs, etc., but they were a relatively small fraction of the total current drawn by a building. Over the past 20 years, incandescent lighting has been replaced by fluorescent lighting, and computers, office machines, and all sorts of electronic equipment have proliferated. Thus, non-linear (highly distorted sine wave) loads now constitute a very high percentage of the load on the power system in most buildings.

More than one hundred years ago, the mathematician Fourier taught us that any periodic (repeating) signal consists of an infinite series of sine waves – what we now call a fundamental frequency and harmonics. We now know that the greater the distortion, the greater the number and strength of the harmonics. Thus, the load current of virtually all buildings is rich in harmonics. Some very interesting (and potentially dangerous) things happen in a

3-phase system with some orders of harmonics. Figure 7b and 7d show why, this time using the third harmonic of phase A as the reference. Since the phasors are at three times the frequency, they are 3 x 120° apart at their third harmonic. We see that phase B lags 360° behind phase A, and phase C is 720° behind phase A. This makes these third harmonics exactly one complete rotation from each other in the neutral, so they add rather than cancel. A similar relationship exists for odd multiples of the third harmonic – 3rd, 9th, 15th, 21st, and so on (called "triplen" harmonics).

The practical meaning of Fig 7b, 7d, and 7e is staggering – they show that a relatively high harmonic distortion can cause neutral current to exceed the current in one of the phases of a system, even a system that is perfectly balanced! Fig 7b shows only a 25% third harmonic adding to 75% of the current in one phase. But the third harmonic can be even stronger, and there can be other triplen harmonics present. In fact, it is not unusual for the current in the neutral to exceed 175% of the current in one phase! This current can cause overheating of wiring and other hardware that make up the neutral circuit due to $I^2R$ losses.

Equally important, core losses in transformers and motors increase quickly with increasing frequency, so harmonic current significantly increases core losses (heating) in these critical components. The power industry has devised the "K-factor" to describe the harmonic current in a system, and transformers are assigned a K-rating based on their ability to handle these high levels of harmonic current. The K-factor takes the strength of each order of harmonic into account.

$$\textbf{K-Factor} = \sum (I_h)^2 h^2$$

where $I_h$ is the load current at harmonic $h$, expressed in a per-unit basis such that the total RMS current equals one amp. One problem associated with calculating K-Factor is selecting the range of harmonic frequencies that should be included. Some use up to the 15th harmonic, others the 25th harmonic, and still others include up to the 50th harmonic. For the same load, each of these calculations can yield significantly different K-Factors because even very small current levels associated with the higher harmonics, when multiplied by the harmonic number squared (e.g., $50^2 = 2500$), can add significantly to the K-Factor. Based on the underlying assumptions of C57.110 (the Standard defining K-Factor), it seems reasonable to limit the K-Factor calculation to harmonic currents less than the 25th harmonic.

What sort of K-factors should be expected from audio systems? The answer is complex, because the relative strengths and phase relationships of the harmonics produced by different equipment can vary significantly from one to another, depending on their design, and their mode of operation. Power amplifiers could have a much higher K-factor at idle than when providing their maximum output. Switching power supplies may have different harmonic structures from simple full-wave rectifier/filter supplies (but switching supplies include a full wave rectifier/filter supply to drive the switching oscillator). K-factors for loads that consist almost entirely of electronic equipment are typically in the range of 12 – 20, but many loads might combine for a K-factor of 3-6 for an entire building or system.

A common rule of thumb in 3-phase systems is to install neutral conductors and hardware rated for 2X the current in any phase. Electrical components are manufactured with K-ratings of 1, 4, 9, 13, 20, 30, 40, and 50. A relatively conservative designer might specify a K-rating of at least 13 for all transformers serving audio system loads. An applications note explaining K-factor is at

http://www.liebert.com/support/whitepapers/documents/sl_24200.asp

## HIGH LEG DELTA

Figure 8 shows a variation of the delta configuration that is widely used in older mixed residential and industrial areas, and in rural areas. One leg of the delta has a grounded center-tap that serves as the neutral for a single-phase 120/240VAC system, and 208 volts is available for certain industrial applications. The configuration can work for audio and video systems if there are no other loads on the transformer. But EMC consultant Neil Muncy has learned that when High Leg Delta is used to feed multiple customers from the same transformer, the neutral currents from one customer can circulate through another customer's ground system. When this happens, the neutral feed from the pole-mounted transformer may carry relatively large neutral currents from those neighboring buildings.

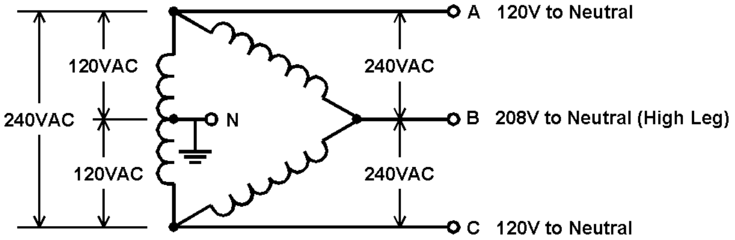


Fig 8 -High Leg Delta

The neutral current will find its way to ground through the *system ground* at the *service entrance*, and in general, the better the ground electrode system, the greater the circulating current will be! If the path to ground runs near audio equipment or wiring, the magnetic fields produced by these currents can couple into system wiring, guitar pickups and dynamic microphones without hum-bucking coils, and even the electronics of audio gear. The result is hum and buzz that can be eliminated only by eliminating the field. The hum component is 60 Hz, while the "buzz" consists of harmonics. When called in to diagnose problems in a small recording studio complex in a renovated industrial building, Muncy found a High Leg Delta power feed with 7A of neutral current finding its return path via a water main running under the guitar iso booth!

The solution is to use a transformer with a single-phase center-tapped secondary (also called a split single-phase transformer), to feed 120/240 v systems in the building, powering it from one of the ungrounded 240 volt phases. What matters is that the shared neutral feed to the building, with the offending currents, must be eliminated.

Also known as a Red Leg Delta, or Wild Leg, High Leg Delta systems are required to have that phase conductor marked with orange tape, orange finish or similar. This marking is only required where a connection is made and the grounded conductor is present.

## GROUNDING

The primary purpose of grounding is life safety and the protection of both property and equipment. The principal hazards are lightning, power line voltage spikes, and equipment or wiring faults (failures) that could place power voltages on exposed equipment (where someone might touch it and be electrocuted) or cause a fire.

While the power company's equipment and wiring are generally not covered by building codes, nearly all power distribution systems are grounded. Most distribution transformers have a conductor grounded to a driven rod. If that transformer is on a pole, there will be a downlead on the pole from the transformer to the rod. The primary function of this earth ground is for lightning protection – it is rarely a very good ground, and may carry considerable noise current.

Two types of grounding are required by building codes in North America. *System grounding* is the connection to earth of a conductor that normally carries current – the *Grounded Conductor* or *Neutral*. *Equipment grounding* is the bonding of all exposed equipment to ground.

Electrical codes require that most *systems* have a *Grounded Conductor*. A *system* in this sense of the word is any network of power wiring fed by a single source (a transformer or a motor generator), whether that source is outside the building or inside the building. When the source is outside the building, the *Grounded Conductor* must be bonded where it enters the building (this connection point is called the *service entrance*). The bond must be carried to all earth-connected metal in the building – building steel, cold water pipes, and driven ground rods. This connection of the *system* to ground is called the *System Ground*.

Which Power Systems Must be Grounded?

| Must Be Grounded | May Be Grounded |
|---|---|
| 120/240V single phase (Figure 1) | Systems that do not use a neutral as a circuit conductor |
| 120 V single phase (Figure 2) | 3-wire Delta (Figure 6) |
| 120/208V wye (Figure 3) | |
| 120/208V/240V High leg Delta (Figure 8) | |

If a system must be grounded, the bond must be at the point where the system is *established*. A power system is most often *established* when a transformer is connected to an existing system – for example, 480V/277V power coming into a building must be stepped down to 208V/120V to feed ordinary appliances and lighting circuits. The secondary of that transformer *establishes* a new *System*, called a *Separately Derived System*, and the *Neutral* of that new *System* must be bonded to create the *system ground*.

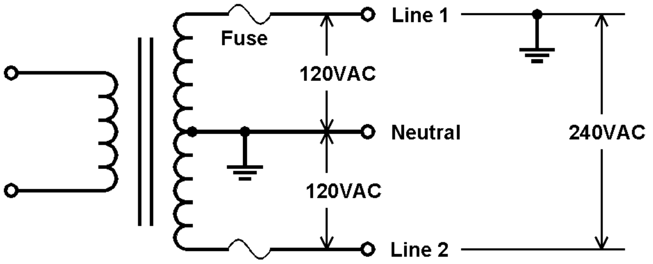
The principal function of the *System Ground* is to protect against lightning. Lightning occurs when a very large charge develops between the atmosphere and the earth. Eventually the charge builds to the point where it will arc over to complete the path to earth. Consider what would happen if the system was not grounded, and power wiring was struck by lightning (became part of that path). That very high voltage (thousands of volts) would appear on house wiring, and at some point of its own choosing, would arc over to other conductors that would take it to ground. That arc could easily start a fire, either directly or by the heat produced by $I^2R$ losses in the path to earth, and the buildup of voltage could seriously injure or kill a person nearby. If the *System* is well *Grounded*, the lightning charge is far more likely to be conducted to ground via a path that is safe, away from people that could be hurt by it, and, with a little luck and good wiring practice, without starting a fire or causing other damage.

Note that a transformer does <u>not</u> isolate grounds on one side for the transformer from those on the other side. That's because safety codes also require that all grounded objects (and all grounded *Systems*) in a facility must be bonded together.

Safety codes require that all exposed conductive objects (*Equipment*) that may be energized (that is, could somehow contact a "hot" phase wire) be grounded. This is called the *Equipment Ground.* Virtually ALL electrical equipment enclosures and raceway (conduit, cable tray, transformers, backboxes, etc.) are required to be bonded (together and to ground).

Figure 9 shows how *System Grounding* and *Equipment Grounding* combine to protect from faults. The transformer center-tap has been grounded (this is the *System Ground*), and some system failure has caused line 1 to be shorted to ground. Perhaps, for example, a line 1 wire has been mashed into a conduit fitting. Since Line 1 is now connected directly to its own neutral (via the *Equipment Ground* and the *System Ground*), the fuse in Line 1 blows (or the circuit breaker trips). The blowing of the fuse (or tripping the breaker) is how *Equipment Grounding* and *System Grounding* protect against power faults! In other words, ***the principal function of Equipment Grounding is to blow a fuse or trip a breaker when something goes wrong!***

Note also that codes require that all systems be protected by a fuse or breaker before the first means of disconnection, and that the ***System Ground*** bond must also be upstream of that disconnect. The reason is simple – the ***System Ground*** and fuse/breaker must be there to protect from faults!



Fuse

Figure 9 – A Fused Single-Phase System, with a Fault (short to ground) on Line 1

The ***Equipment Ground*** is not only the random bonding of every piece of building steel to every piece of conduit and electrical equipment. ***Equipment Ground*** is required to be carried with the ***phase*** and ***neutral*** conductors to every distribution panel, and from there to every place where power is extended. In some jurisdictions a dedicated ***Equipment Ground*** conductor is required (green is the assigned color). In other jurisdictions, the dedicated wire is optional if the ***Equipment Ground*** is carried by properly installed conductive raceway. If a raceway system is properly installed, including the correct installation of listed fittings at all junction points, it will generally provide a much lower impedance fault path than a dedicated green wire (***Equipment Ground***). But installing a dedicated green wire is always good practice, because it serves as a backup to the conduit connection, which can become intermittent, especially if the conduit not well installed. And when that wire is used, code requires that it be bonded to each enclosure through which it passes.

Virtually all electrical codes require that the ***Equipment Ground*** be in the same conduit with the associated circuit conductors. There are two very good reasons for this. First, any mechanical event that caused interruption of one would also cause interruption of the other. Second, the inductance of the fault path for the current is far lower, because the magnetic field for the current flowing through the phase conductor is cancelled by the field produced by the return current through the ***Equipment Ground*** conductor. Lower inductance means that the fault current will be greater, making it more certain that the protective fuse or breaker will be activated, and activated more quickly (before personnel are injured or a fire starts).

## GETTING TO EARTH – THE GROUND ELECTRODE SYSTEM

The principal function of the Ground Electrode system is to provide a very low impedance path to earth for lightning and other high voltage transients (spikes) that may be on the mains power line. IEEE studies have shown that lightning energy is very broadband, extending from dc to well into the MHz range, with a broad peak around 1 MHz. It is this energy for which we must provide a low impedance path to the earth. At 1 MHz, the dominant electrical characteristic of the System Ground conductor is its ***inductance***, not its resistance. And the inductance of a wire is almost entirely determined by its ***length***. To minimize the impedance (virtually all inductive reactance) of this conductor, it is critical that it be as ***short*** as possible. Inductance, like resistance, is reduced by having many paths in parallel, or by making the connection by means of a very wide copper strap or braid. Braid is generally less desirable, since it corrodes much more quickly than strap.

Much is made in the popular press of skin effect – it is well known that it causes the resistance of a wire to increase with increasing frequency as the magnetic field causes current to be pushed to the outer surface of the conductor. Figure 10 shows the resistance of stranded copper conductors that might be used for System and Equipment Grounding. At low frequencies, skin effect is negligible, so the curve is horizontal. Skin effect is responsible for the increasing resistance.

Skin effect increases with increasing frequency, and is a function of conductor diameter and geometry. The graph computed for Fig 10 is for round, non-magnetic conductors. It is interesting that, contrary to sales hype in the world of high futility, skin effect is essentially insignificant at audio frequencies for conductors of sizes normally used for audio system wiring. It is not, however, insignificant for the larger conductors used for system feeders. Indeed, the 4/0 conductors are already showing significant skin effect at 180 Hz, and should be de-rated when used as neutral feeders in 3-phase systems.

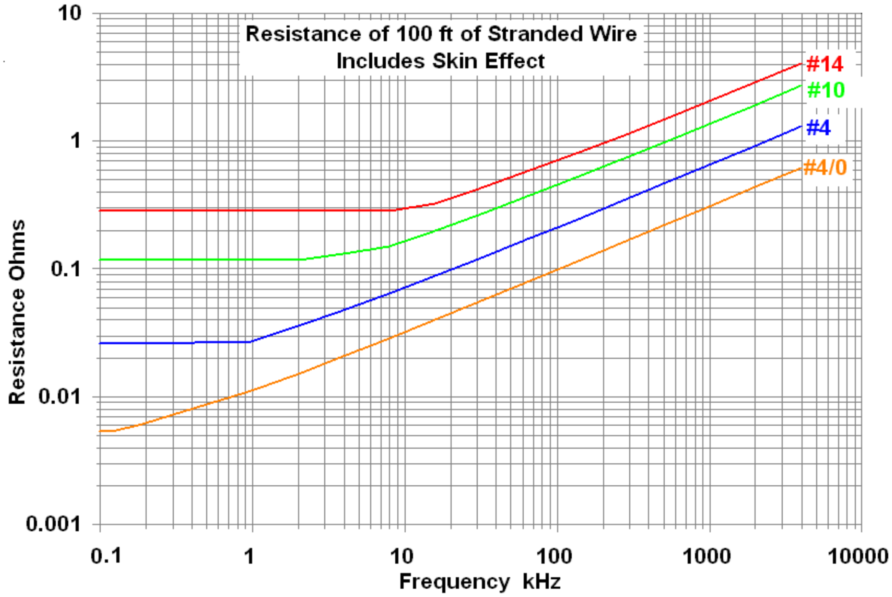


Figure 10 – Skin Effect for Typical Grounding Conductors

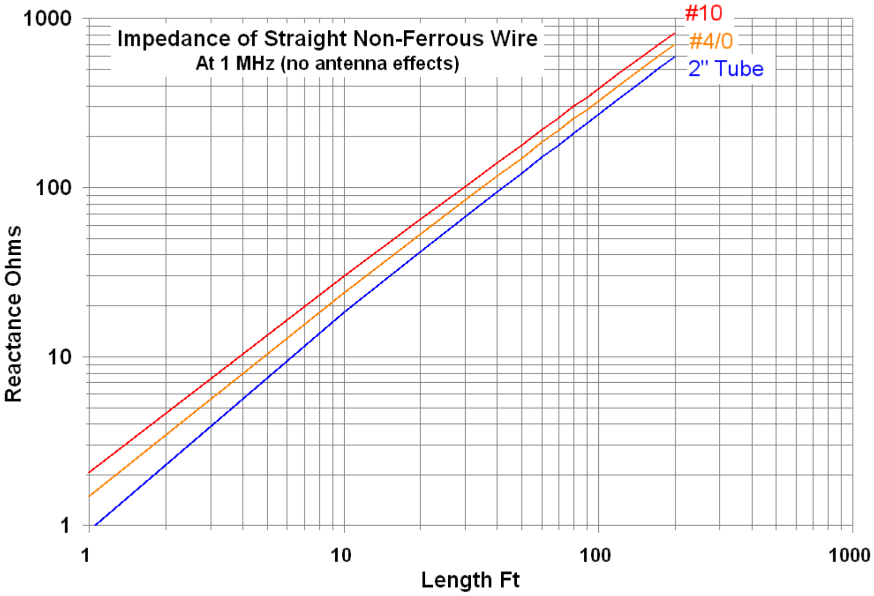


Figure 11a – Inductive Reactance of a Single Straight Conductor, ignoring antenna effects

Figure 11a shows the inductive reactance of a straight non-ferrous conductor in free space, ignoring resonances associated with the behavior of the conductor as an antenna. The free space wavelength of 1 MHz, the frequency for which this data is computed, is about 984 ft. Antenna effects will begin to show up when a wire is 1/10 wavelength at the frequency of the signal it carries, and a wire will resonate at multiples of one-quarter wavelength. The first resonance at 1 MHz would be around 240 ft, and the actual behavior of the wire could be expected to begin deviating from these curves when it is longer than about 100 ft. For a 2 MHz signal, the first resonance would be around 120 ft, and antenna effects would begin to show up when the wire was longer than about 50 ft.

Antenna effects can vary widely, depending upon many variables. Even the simplest analysis is beyond the scope of this white paper. Depending on whether the wire was connected on the other end, how it was connected, what it was connected to, and whether length was an odd or even multiple of quarter waves long, the wire might appear as a near short circuit, a near open circuit, or anything in between!

Figure 11a clearly shows that increasing the diameter of the grounding conductor reduces inductance only slightly. Indeed, the only good reason for using a large conductor is to reduce the resistance, which will, in turn, reduce heating during lightning strike conditions and might prevent the conductor from vaporizing!

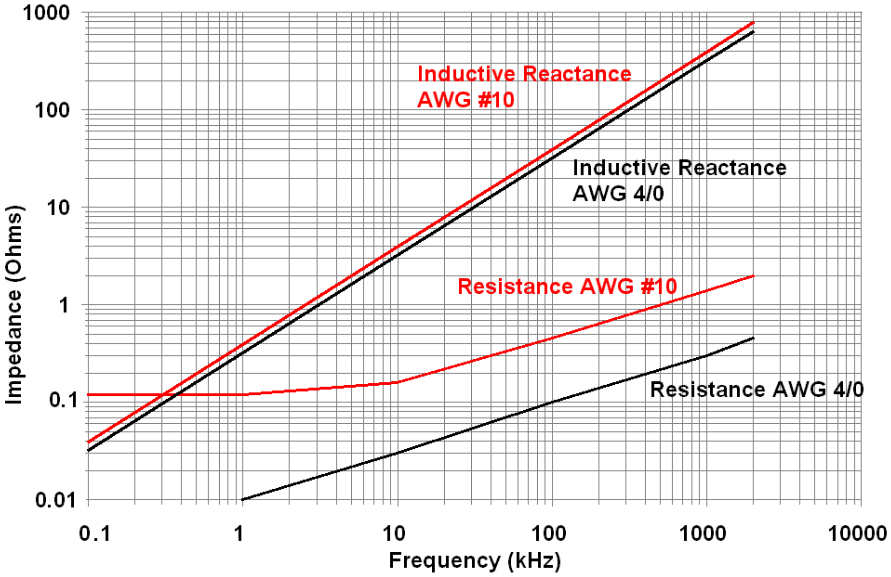


Figure 11b – Resistance (with Skin Effect) and Inductive Reactance Compared

Figure 11b makes it clear that, above a few hundred Hz, and for most practical conductors, inductance of is far greater significance than resistance! It also shows that to provide anything approaching effective lightning protection the System Ground must be very short, and many paths to earth must be provided in parallel. In many buildings, those parallel paths can be provided by building steel. In fact, if all of the structural steel in a building is well bonded, the impedance to earth through that structure is likely to be an order of magnitude lower than through any ground electrode system that can be installed at anything approaching reasonable cost. For this reason, most building codes (including NEC) call for making the *system ground* bond to building steel unless none is near the point where the *system* is established.

But there is another very important factor that these graphs don't take into account – if the ground conductor is running in steel conduit, its inductance will be greatly increased (by as much as 40X), because of the higher permeability of the steel! Luckily there is a simple solution – the ground conductor must be bonded to the conduit at each end, and at each junction. When this is done, the copper conductor and the conduit are in parallel. At higher frequencies, skin effect will cause nearly all of the current to flow on the outer skin of the conduit, while at power frequencies a greater percentage will flow in the copper. When this is done, inductive reactance can approach the curve for the 2″ diameter tube.

Inductance is not the only factor limiting the impedance between an electrical system and the earth. The conductivity of soil varies widely depending on its composition and is also a function of moisture content. Building codes are generally lax with respect to the quality of the earth connection that must be provided. The National Electric Code (NEC requires, at a minimum, a single ground rod be driven. If the resistance to earth is greater than 25 ohms, it requires that a second rod be driven and bonded to the first, but it does not require that the combined impedance be any specific value. Both NEC and good engineering practice require that all ***made electrodes*** (intentional grounds) be bonded together, and this bond should be outside the building.

The calculations to predict the impedance to earth of a ground electrode system are complex, and are rarely worth the trouble. Following the guidelines below is generally enough to satisfy the needs of audio and video system grounding. Also, the ground electrode system will be in parallel with building steel and the concrete foundation. In general, the impedance to earth of the ground electrode system will be minimized by:

1. Using more ground electrodes.
2. Making the ground electrodes longer, driving them deeper into the earth. Ten feet is generally considered to be a minimum depth.
3. Spacing ground electrodes as far apart as practical (at least twice their length). Separation is important because mutual coupling between closely spaced electrodes increases their impedance to earth.
4. Placing electrodes where they will be continuously exposed to moisture (rainfall). For this reason, ground electrodes should be outside the building footprint.
5. Avoiding chemically enhanced electrode systems. These systems require long term attention to maintain their chemical balance. Few facilities are likely to have staff trained to do this.
6. Increasing the surface area in contact with the earth, or by using an electrode of greater cross-section of greater length, or by means of a Ufer (a ground electrode buried in concrete). (Fig 12)

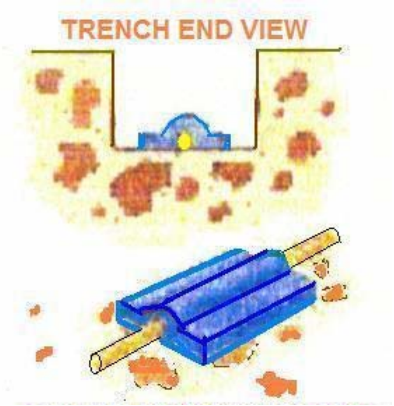
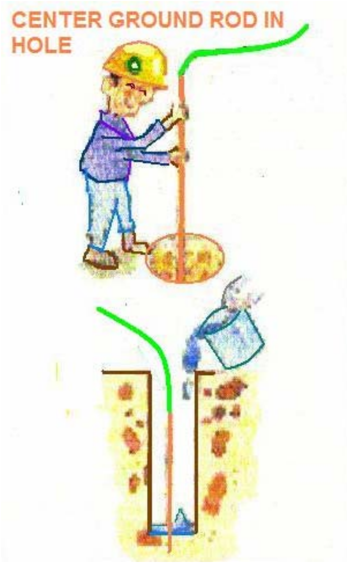


Figure 12 – Ground Electrodes in Concrete
http://www.conductiveconcrete.com



The resistivity of various types of concrete varies over at least four orders of magnitude, depending on the formulation and how it is poured. Some concretes are specifically designed to be conductive, and can be used to encase the grounding electrode (Figure 12), thus increasing the surface area in contact with earth. Such an electrode is called a Ufer. Other applications of concrete require that it be the best possible electrical insulator (for example, railroad ties for electric railways). Structural steel encased in concrete can made a part of the ground electrode system simply by thoroughly bonding all elements of the rebar together and bonding from there to the System Ground. This technique should be approached with caution -- it is well known that lightning currents can do serious damage to structural concrete in the case of a direct hit. There are also corrosion issues. See http://www.polyphaser.com/ppc_PEN1030.asp The Engineering Notes on this website are an excellent resource for understanding the engineering issues associated with grounding for lightning protection, especially for radio facilities. Not all of their methods are directly applicable to audio and video systems, but many are.

The conductivity of concrete must be considered when installing equipment racks on a concrete floor. As we will learn later, audio and video equipment racks should be isolated from grounded objects and then grounded through a *Technical Ground System*. One way to accomplish this is to place one or two layers of 5/8″ ribbed or waffled neoprene pads between a rack and a concrete floor. This provides both electrical and acoustic isolation of the racks. If the racks are bolted to the floor, suitable insulating grommets will be required.

## ISOLATION TRANSFORMERS

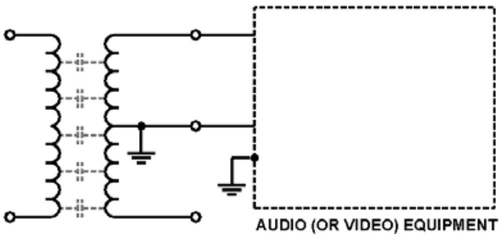


Figure 13a – An Ordinary Transformer

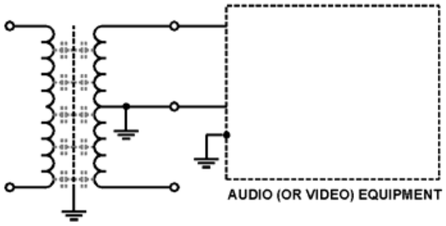


Figure 13b – An Isolation Transformer

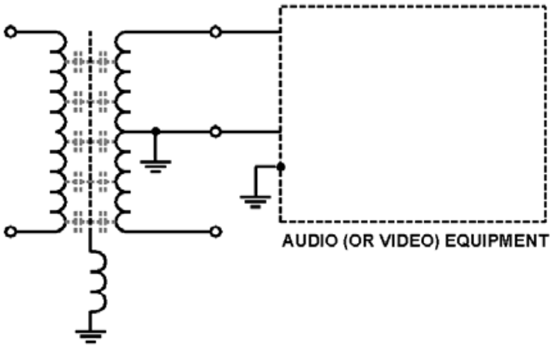


Figure 13c – Isolation Transformer showing inductance of grounding path

Common mode noise on the power line can be coupled into audio equipment via the power supply. In an ordinary transformer, shown schematically in Fig 13a, stray capacitance between the primary and secondary windings will couple high frequency energy across the transformer -- the higher the frequency, the greater the coupling. At low frequencies, where the capacitance is too small to provide much coupling, the transformer blocks common mode noise.

A Faraday shield, shown schematically in Fig 13b, can be added to a transformer, and can greatly reduce coupling by shorting high frequency energy to ground. A Faraday shield is simply a conductive barrier placed between the two windings. Fig 13c, and the equivalent circuit in Fig 13d, however, shows that the shield works by forming a voltage divider between primary and secondary. But it also shows that the attenuation will be limited by the impedance between the Faraday shield and earth. We learned in our discussion of the connection of systems to earth that this impedance consists mostly of the inductive reactance of the earth connection, along with a smaller (usually) resistive component.

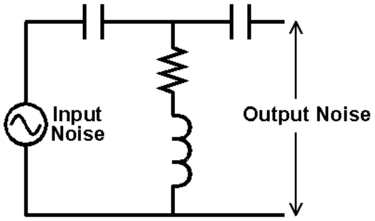


Figure 13d- Equivalent circuit

Thanks to their built-in stray inductance, capacitance, and high frequency losses, ordinary power transformers tend to provide differential-mode low pass filtering to block noise.

Note that an isolation transformer does not isolate grounds between primary and secondary, because building codes require that all grounds within a building be bonded together.

Thus, we see that isolation transformers can provide effective reduction of noise on the power line, but they must be installed in a manner that minimizes R and L in the grounding path if they are to be of any value. If the inductance and resistance of the ground lead are large, the isolation transformer will provide little if any noise reduction.

## TECHNICAL GROUND SYSTEMS – AVOIDING GROUND LOOPS

Up to now, we have talked only about grounding for safety and the protection of equipment. From this point on, we'll talk mostly about grounding to minimize noise in audio and video systems.

One of the fundamental rules of system interconnection is that the shields of cables carrying audio frequency signals should not carry current, especially at the frequency of those signals. A wiring error that allows noise current to flow on the shield is commonly known as a "ground loop. "There are three important reasons why shield current should be avoided. All relate to imperfections in audio equipment and wiring.

1. Much audio equipment has been manufactured with a design defect commonly known as "the pin 1 problem," whereby the shield of signal wiring is connected (improperly) to the printed circuit board rather than (properly) to the shielding enclosure. With this improper construction, any current flowing on the cable shield will be coupled into the equipment and heard as noise.
2. Virtually all shielded, twisted pair cables sold in North America for permanent installation exhibit a design defect that causes what Neil Muncy has named "shield-current-induced noise" (SCIN). The shields of these cables consists of aluminum foil with a copper wire (called a "drain" wire) in contact with the foil. In nearly all of these cables, the drain is twisted at the same rate as the signal conductors, but is closer to one signal conductor than the other. Any current flowing on the shield will induce a current in each conductor of the signal pair. Below about 4 MHz, nearly all of the shield current flows in the drain wire, because its resistance is much lower than that of the foil. Because the drain is physically closer to one conductor than the other, shield current will induce more voltage in one conductor than the other. In other words, shield current is converted to a differential voltage on the signal pair.
3. Much audio equipment is poorly filtered to reject radio frequency interference (RFI), so when SCIN places RF on the signal pair, that RF appears as noise in the audio.
4. In unbalanced circuits, shield current causes an IR drop that is added to the signal (because the shield is part of the signal circuit).

Four fundamental mechanisms can produce shield current.

1. *Potential differences between the two ends of the cable.* Current will flow on the

shield if the two ends of the cable are at different potentials. Consider a cable shield that is "grounded" at both ends, and the equipment at either (or both) ends of that cable has unequal capacitance between the two sides the AC power line and its chassis. Virtually all power transformers will have capacitance between their windings and the enclosure, and nearly all technical equipment has EMI filters that include capacitors between the power line and "ground." Many fault conditions in power system wiring can establish potential differences of several volts between equipment grounds at different locations. Ground leakage currents from building equipment such as variable frequency motors can also create these potentials.

2. *Magnetic induction.* Voltage will be induced along the shield if the cable passes through a magnetic field. If the shield is connected at both ends, current will flow.
3. *Antenna action.* In the words of Neil Muncy, "You say audio cable, but mother nature says "antenna." Any radio signal can cause current to flow on the shield.
4. *Leakage current.* Equipment connected to the power line will draw currents through capacitors intentionally connected between the power line and its enclosure (noise filters), and through unintentional parasitic (stray) capacitance and resistance that inherent in their power supply components. Since the enclosure must be connected to *Equipment ground*, the resulting IR drops raise the potential on the enclosure.

**A good technical ground system should minimize shield current.** There are two fundamental approaches. In the "mesh" or reference plane approach, a large, equipotential surface or grid is developed and bonded at many points to each other where they cross, and to ground. The shields of technical equipment and the shields of signal cables are bonded at multiple points to the reference plane. In the *ideal* implementation, the reference plane would be a solid conductor. This is, of course, practical only in a testing lab, and even then can be quite difficult. The practical implementation of a mesh or reference plane typically consists of a grid of conductors at right angles to each other, bonding them together at each point where they cross. All conductive objects (building structure, HVAC ducts, the raceway system, etc.) are also bonded to the reference plane. This approximates the solid plane at frequencies below that at which the conductors that make up the mesh begin to act as antennas (roughly 1/20 the wavelength of currents flowing in the plane).

The ideal *Mesh* would minimize potential differences between grounded objects at different locations by minimizing the impedance (resistance and inductance) between those points. Cable shields can, theoretically, be bonded to the reference plane at both ends, and at many points in between, because those points are (or are at least hoped to be) at equal potential. Shield current caused by potential differences is further reduced because the resistance and inductance of the shield is much greater than that of the reference plane. Signal wiring is bundled close to the reference plane, so magnetic induction is minimized because the loop area is reduced, and antenna action is minimized because the reference plane tends to "short circuit" the field.

Mesh ground systems are quite effective in video studios, and in facilities where all signals are digital. In addition to the benefits of the ground plane itself, the combination of hundreds coaxial cable shields reduces the current in any one shield to a very low value. Since only one or two video signals are "on the air" at any one time, the noise added to the signal by a ground loop tends to be insignificant. Mesh grounding is successful in digital installations for a very different reason. Because the very low frequencies of power-related noise currents are so widely separated from high speed digital signals, it is quite easy to filter them out of digital equipment without degrading the digital signal.

## ISOLATED GROUND SYSTEMS

The second fundamental approach to Technical System grounding is an *Isolated Ground System* (sometimes called a *single point* or *star* ground). An *isolated ground system* does not use a "separate" ground – it must be, in fact, bonded to *system ground*. But it is usually bonded at a single point, chosen by the system designer. A dedicated *Isolated Ground* conductor is run to every Technical system power outlet in the same conduit with the phase and neutral conductors and is connected to the *Equipment Ground* pin for outlets powering for technical equipment. *Isolated ground outlets* are different from standard outlets, in that their Equipment ground pin is isolated from the back box to which they are mounted. The back box must have an *Equipment Ground* – in many jurisdictions this must be a dedicated "green" wire, while in some the electrical conductivity of the conduit system itself can provide the *Equipment Ground*.

In every *Isolated Ground* system, there must be some single common point where the *Isolated Ground* is bonded to *Equipment Ground* and *System Ground*. This point is often called the *Technical Ground Common Point*. "Home" for the *isolated ground* conductors from each outlet is an *isolated ground* bus in the panel that feeds them, and that bus must be connected to the *Technical Ground Common Point*. In a system small enough to be fed by a single panelboard, the *Technical Ground Common Point* may be in that panelboard, or it may be back at the *System Ground* bond. In a larger system it will nearly always be at the *System Ground* bond.

In an *Isolated Ground* system, all technical equipment must be carefully isolated from random contact with grounded objects, but it must be grounded through the *Isolated Ground* system. This means that all equipment, including equipment racks, must be isolated from grounds (including building structure, raceway, and even concrete floors). When audio equipment is mounted in racks that have been carefully isolated from ground, power outlets inside those racks do not (and should not) be isolated ground outlets. The reason is simple – the racks are already isolated! It is good practice to use hospital grade outlets throughout the system, because their contacts are built so that they show less metal fatigue, and thus maintain better contact over time.

All signal and control wiring for audio and video systems must also be isolated from ground, which means that the wiring must be isolated from the raceway system. This means that connectors mounted on wiring panels around a facility must be of a type that insulate the connector shell from the panel on which they are mounted. Plastic-body audio connectors and insulated feed-through-type BNC connectors are the weapons of choice. Special care must be taken that video cameras and projectors, antennas for wireless mic systems, and even permanently installed microphones cannot corrupt the isolated ground system. All of these devices must be isolated from random grounds, but must be grounded through the technical ground system.

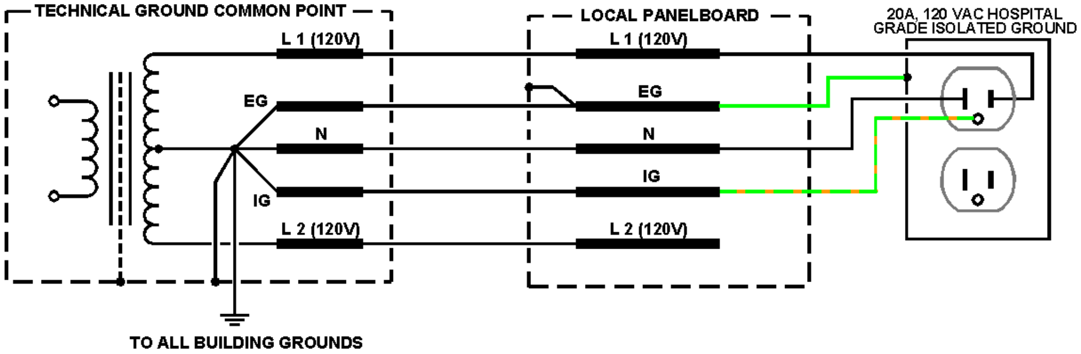


Fig 14 – A Technical Ground System Using Isolated Ground Wiring

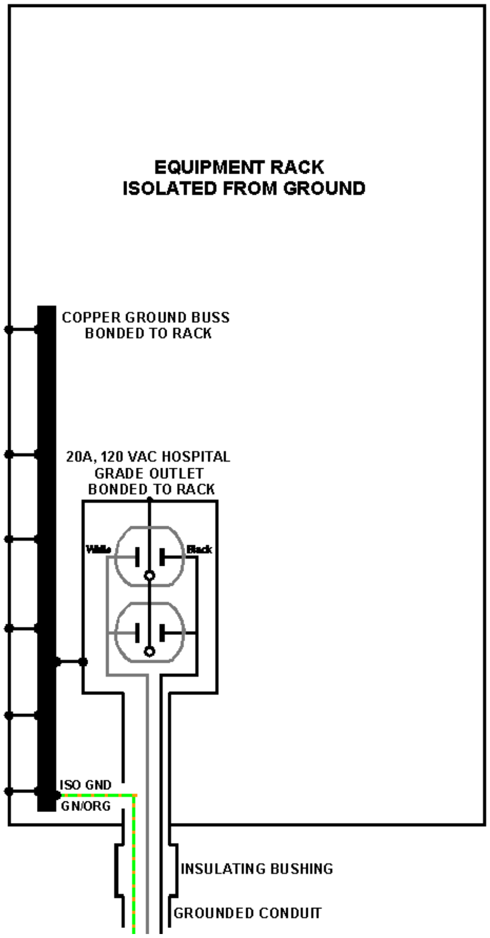


Fig 15a – Equipment Rack Wiring

Figure 14 illustrates typical implementation of a Technical Ground system using a star-connected isolated ground system. An isolation transformer establishes a separately derived 120V/240V system at the location at the left. The neutral of the separately derived system is bonded to the enclosure and to all building grounds at this location, which becomes the Technical Ground Common Point. The system feeds one or more local panelboards, which in turn feed isolated ground outlets throughout the facility. If other panelboards are needed, they would be fed from the panel at left, and wired in the same manner as the first panel. Some jurisdictions permit conduit to be used as the Equipment Ground, with no dedicated green wire. Green is the standard color for the Equipment Ground. When there is a second ground conductor (that is, an isolated ground), the second conductor must be green with an orange stripe.

Equipment Racks in Isolated Ground Systems must be isolated from ground. The rack must then be bonded to the Isolated Ground system. This typically requires the use of insulating fittings to isolate the rack from conduit, and neoprene pads to isolate it from a concrete floor or metal deck.

The Isolated Ground conductor is bonded to a heavy copper ground bus, which is itself bonded to the rack at multiple points. See Fig 15a.

Isolated Ground wiring inside equipment racks requires standard outlets, bonded to the rack. Isolated Ground outlets should not be used inside racks, because the rack itself must be isolated. This is the answer to the often asked question, "Why doesn't rack-mounted equipment like power conditioners and power switching units use isolated ground outlets?"

Equipment inside the rack should be bonded to the rack. This improves shielding of the equipment, and reduces potential differences between equipment within the rack. Bonding can be improved by scraping paint adjacent to mounting screws. Equipment should also be bonded to the copper bus.

Isolated ground systems minimize power-related shield currents by minimizing the potential difference between the opposite ends of cable shields. They work because they don't see the differences in Equipment Ground potentials from that other equipment because they are connected to the Equipment Ground at only one point, and because leakage currents produced by audio equipment are usually far lower than those produced by other equipment connected to the Equipment Ground. Isolated Ground systems do not reduce currents from magnetic induction, nor do they help reduce RF currents on cable shields.

Fig 15b shows proper rack grounding in an isolated ground system where multiple racks are required. In this example, there are racks at three locations. Four at two locations fed from one electrical panelboard, and four at a third location from a second panelboard. Each rack is treated as shown in Fig 15a, except that a row of racks that are bonded together may have a single ground connection.

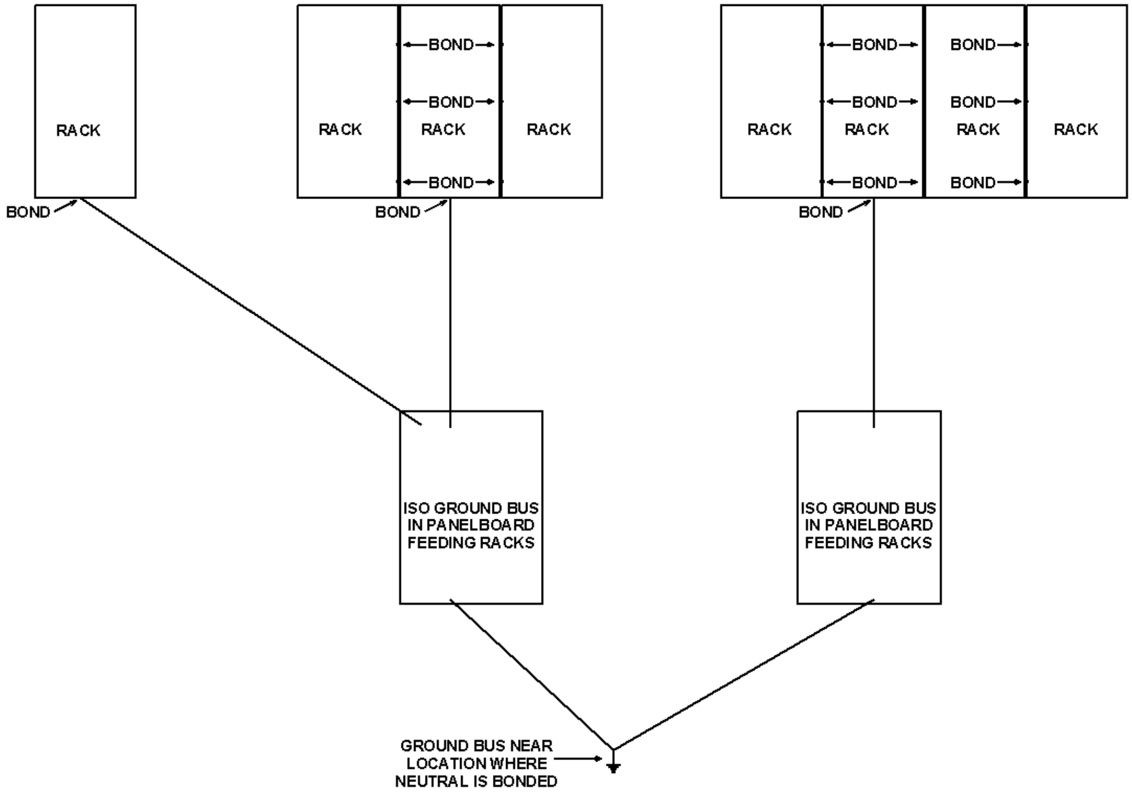


Fig 15b – Grounding Multiple Racks in an Isolated Ground System

Isolated ground systems are widely used for audio and video systems because they are far less costly to install than MESH systems for an equal level of protection from power-related noise, and because protection from magnetic induction and RFI can be achieved by other simple techniques without the cost of a MESH system.

## BALANCED POWER

Balanced power is often touted as the ultimate cure for hum and buzz in project studios. The reality is that it can offer no more than 6-10 dB of reduction in hum and buzz coupled into audio and video systems. How and why do these systems work? The answer is found in Figures 16 and 17. The power supplies in most audio and video gear have capacitance between each side of the power line and its enclosure. C1 and C2 are stray capacitance between the power transformer primary winding and its secondary, which is ultimately bonded to its enclosure. They are shown here as grayed-out, dashed lines, because you won't find them on the schematic, but they are a byproduct of the physical construction of the transformer, and they are quite real. C3 and C4 are part of EMC filters that are built into most equipment to prevent the transmission of RF noise into and out of equipment via the power line.

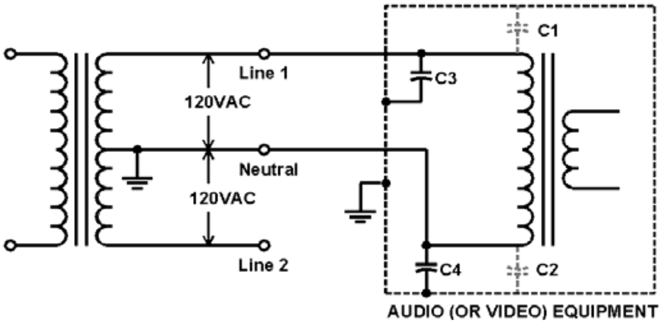


Fig 16 –A Conventional Un-Balanced Power System

In a conventional power system, shown in Fig 16, C1 and C3 have the full line voltage across them, and provide a path for a small leakage current from the power line to the equipment ground. 100 ma of leakage current is quite common, and this current will couple power line hum and buzz onto the equipment ground by virtue of the IR drop.C2 and C4 are between the neutral (grounded conductor) and the Equipment Ground, so carry little if any current.

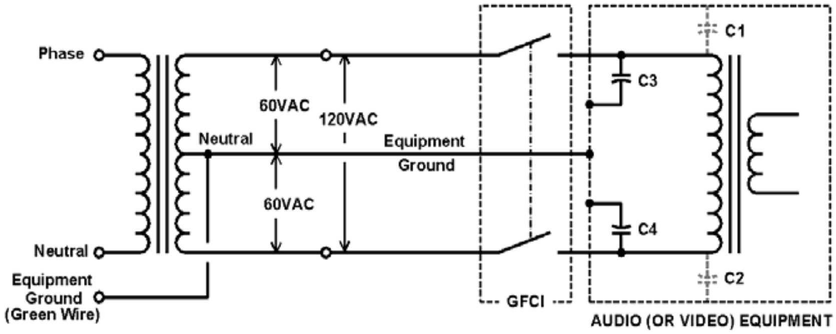


Fig 17 –A Balanced Power System per NEC 647 (2002)

In a balanced power system, shown in Fig 17, a transformer with a center-tapped 120 VAC secondary has its neutral bonded to the equipment ground, to produce 60 VAC to ground from both sides of the line. This places equal voltages across C1, C2, C3, and C4. IF (C1+C3) were precisely equal to (C2+C4), the leakage currents would cancel to zero. In reality, C3 and C4 are of approximately equal value, while C1 is usually appreciably larger than C2. As a result, there is generally modest cancellation between the current from the two legs. Reductions on the order of 8-10 dB are typical. This reduction in noise voltage on the equipment ground translates directly into reduced noise current on audio and video system wiring. How does this reduce system noise?

1. Reduced shield current causes an equal reduction in the IR (and IZ) voltage drop along the shield. In unbalanced systems, any voltage drop on the shield is in series with the signal, so a 10 dB reduction in shield current will reduce noise by 10 dB. In balanced systems, it will reduce the need for high CMRR by 10 dB.
2. Shield current flows into pin 1. In equipment that has a pin 1 problem, any shield current will be heard as noise. Again, a 10 dB reduction in shield current reduces noise by 10 dB.
3. Shield current causes noise to be introduced onto the signal pair by SCIN (shield-current-induced noise). SCIN won't couple enough 60 Hz and 180 Hz to be heard, but it's far more likely that any high frequency noise that may be shorted to the enclosure by those capacitors <u>will</u> be audible.

NEC 647, which defines the requirements for balanced power systems, places some important restrictions on both their installation and use.

1. Conductors must be sized so that the IR drop does not exceed 1% of the line voltage under a load equal to 50% of the branch circuit current rating, and so that the combined IR drop of the feeders and the branch circuit wiring does not exceed 2%.
2. A dedicated *Equipment Ground* conductor must be run to all equipment and each receptacle.
3. All receptacles must be protected by a GFCI.
4. The neutral must be bonded per NEC 250, and must also be connected to the grounded conductor of the circuit that feeds the system.
5. Balanced power systems are restricted to industrial and commercial occupancies.
6. All outlets "shall have a unique configuration" and must be identified using specific language called out in NEC 647.7.
7. There must be a receptacle having a grounded circuit conductor (i.e., conventional unbalanced power) within 6 ft of each receptacle for the balanced power system.
8. All lighting fixtures connected to balanced power must be specifically rated for 60/120 VAC balanced power, must "have a disconnecting means that interrupts all ungrounded conductors," and must be permanently installed.
9. Isolated ground receptacles are permitted.

Balanced power systems are expensive, and their noise reduction capability is limited to about 10 dB. Isolated ground systems are generally a far more effective and less costly solution.

## IDEAL POWER AND GROUND SYSTEM ARCHITECTURE FOR AUDIO/VIDEO SYSTEMS

The ideal power system architecture for audio and video systems is a separately derived 240/120 VAC single phase system shown in Figure 14. The transformer that derives the system should be a high quality isolation transformer with two Faraday shields, and the transformer should be located such that the system can be bonded to a good earth ground by means of a very short conductor. A star-connected isolated ground system is the most practical technical ground system for most audio and video systems.

If touring sound systems will be used in the facility, a separately derived 120/208 VAC 3-phase system as shown in Figure 3 should feed a disconnect switch at a suitable location on stage. If there will be occasion for use of a recording or broadcast truck, a second disconnect switch powered from either the same or an additional 3-phase system should be located near where the truck can be parked. The isolated ground bus should be extended to both of these locations.

Each outlet for audio and video systems should have its own dedicated phase, neutral, and isolated ground conductors home run to the panel from which it is fed. Wiring that is shared between outlets provides a common impedance by which noise can be coupled from one piece of equipment to another. Using individual conductors for each outlet also minimizes voltage drops under load, improving regulation.

## PREVENTING MAGNETIC COUPLING – SHIELDING, TWISTING, CONDUIT SPACING

Virtually all of the crosstalk from power circuits to audio circuits is magnetically coupled. There are four basic techniques by which magnetic coupling between power circuits and audio/video systems can be avoided, and the beneficial effects of each are cumulative. They are:

- Increase spacing between the noise source and the A/V system and its wiring.

- Run the wiring for the noise source and wiring for the A/V system at right angles to each other. Magnetic coupling is multiplied by the cosine of the angle between the wiring – it will be greatest when the runs are in parallel, and least when the runs are at right angles.
- Run the phase and neutral conductors for each power circuit as twisted pairs within their conduit so that the radiated magnetic field cancels. Additional magnetic field rejection will be achieved if audio circuits are twisted pairs.
- Shield either or both systems with steel. Feeders and branch circuit wiring is most effectively shielded by enclosing it in rigid galvanized conduit – roughly 32 dB at power frequencies – or roughly 16 dB if in EMT (Steel Electrical Metallic Tubing) conduit. The shielding these conduits provide is additive – if both power and signal wiring are in EMT, a total of 32 dB of shielding will exist between the two types of wiring. Aluminum and PVC conduit should be avoided -- aluminum conduit provides only electric field shielding, and PVC conduit provides no shielding at all.

If conduits are relatively widely spaced, audio/video system signal wiring and power wiring for branch circuits can be in EMT conduit. Power feeders should always be in rigid steel conduit. If conduits must be very closely spaced, branch circuits or audio/video signal wiring, or both should be in rigid steel. Table 1 provides suggested minimum spacing between audio/video system conduits and conduits carrying power wiring. Ampacities are for the combination of all phase conductors in the power conduits. NO indicates that the use should be avoided. Spacings assume that power conductors will not be twisted pairs. Closer spacings can be used if power conductors are twisted pairs.

| Audio/Video Conduit | Power Conduit | Under 60A | 60 A | 120 A | 240 A | 400 A |
|---|---|---|---|---|---|---|
| EMT | EMT | 2 ft | 3 ft | 4 ft | NO | NO |
| EMT | Rigid | 4 in | 8 in | 1 ft | 2 ft | 4 ft |
| Rigid | Rigid | 1 in | 2 in | 4 in | 8 in | 16 in |

Table 1

Large transformers and motors produce strong magnetic fields that can be picked up and amplified by A/V system equipment and wiring. No large power transformers or motors should be located within 50 feet of recording or broadcast studios, stages, worship platforms, control rooms, A/V equipment rooms, or sound control positions. Where this limit must be stretched because of building layouts, we offer these guidelines.

In order of significance in terms of **interference production**, rated beginning with most significant, are:

Transformers and large motors
Switchboards, panels and feeders
Branch circuits.

In terms of A/V systems **receiving interference**, the most sensitive elements, in order beginning with most sensitive are:

Areas where microphones and guitars will be used
Mix locations, including sound control rooms
Mic wiring
Video monitors and projectors
Equipment racks

Table 2 lists suggested minimum spacings between power conduits and locations where audio/video equipment is installed or will be used. Ampacities are for the combination of all phase conductors in the power conduits. Spacings assume that power conductors will not be twisted pairs. Closer spacings can be used if power conductors are twisted pairs. The “pull path" is the path that portable cables (audio snakes, video wiring, etc.) takes from a stage to a mix location or a broadcast truck.

| | Under 60A | 60 A | 120 A | 240 A | 400 A |
|---|---|---|---|---|---|
| EMT - Control Room | ok | 1 ft | 30 in | 5 ft | 10 ft |
| Rigid Steel - Control Room | ok | ok | ok | 2 ft | 5 ft |
| EMT - House Mix/Pull Path | ok | 2 ft | 4 ft | 8 ft | 16 ft |
| Rigid Steel - House Mix/Pull Path | ok | 6 in | 1 ft | 2 ft | 4 ft |
| EMT - Platform, Pit | ok | 2 ft | 4 ft | xx | xx |
| Rigid Steel - Platform, Pit | ok | ok | 1 ft | 2 ft | 4 ft |
| EMT - Equipment Rooms | ok | 1 ft | 30 in | 5 ft | 10 ft |
| Rigid Steel - Equipment Rooms | ok | ok | ok | 2 ft | 4 ft |

Table 2

## POWER FACTOR

The fundamental definition of power factor is the ratio of the real power to the product of voltage and current (volt-amperes) in a circuit. Until recently, sinusoidal loads were assumed (that is, the current and voltage were both essentially sine waves), so engineers were taught that an alternate definition of "power factor" was the cosine of the phase angle between the current and the applied voltage. As non-linear (non-sinusoidal) loads (electronic power supplies, fluorescent lighting, etc.) have become an increasingly dominate fraction of the load in most facilities, the IEEE has modified its definition of power factor to include the highly impulsive nature of the current drawn by these devices. Thus there are now two IEEE definitions for power factor.

*power factor, displacement* (A) The displacement component of power factor. (B) The ratio of active power of the fundamental wave, in watts, to the apparent power of the fundamental wave, in volt-amperes.

*Power factor, total* The ratio of the total power input, in watts, to the total volt-ampere input. *Note*: This definition includes the effect of harmonic components of current and voltage and the effect of phase displacement between current and voltage.

## POWER QUALITY

In an ideal world, the voltage on the mains power lines would be constant, but the real world is far from ideal. Power can be "non-ideal" in several ways.

1. Poor regulation i.e., under-voltage or over-voltage. The basic causes are 1) overloading of the power grid, causing utilities to reduce voltage, and 2) IR drops in distribution lines under heavy loading. A Backup Power Supply (BPS) is designed to take over when the voltage drops below a certain level, and many BPS units have voltage regulation capability.

   *[Note: Backup Power Supplies are often mistakenly called Uninterruptible Power Supplies (UPS), a mistake begun and perpetuated by those selling them. Unlike a BPS, which stands by idle until the power fails, an Uninterruptible Power Supply is always charging its battery and always providing power to the equipment it protects. UPS units are much more expensive to manufacture than BPS units because they must run continuously – they require more highly rated components and greater cooling. A BPS (or a UPS) large enough to run an entire sound system will be very large and very expensive.]*

2. Intermittent loss of power – i.e. drop-outs. These can be as short as a fraction of a second and as long as hours or days. A BPS is designed to take over and provide

power in the case of a drop-out.

3. High voltage transients – i.e., spikes or surges. The most common causes of transients are 1) lightning; and 2) inductive current being switched at some remote location (typically a motor or generator). These transients can be anything from a few volts to several thousand volts, and typically last for a few seconds or less.
4. The displacement power factor (the cosine of the phase angle between the current and the voltage in a power system) may be low. For a load that is essentially sinusoidal (motors, heating elements excited at the power frequency, incandescent lighting operating at the power frequency), real power delivered is equal to the voltage multiplied by the current multiplied by the power factor. When the power factor is much less than one, the current required to provide a given amount of power will be much higher than if the voltage and current were in phase. The primary cause of a low displacement power factor is the presence of highly inductive loads (primarily motors, but also the magnetizing and leakage inductances of large transformers).

   The principal concerns with a low displacement power factor are that 1) the power company must deliver more current for a given amount of power, and 2) that current causes increased heating in wiring, connectors, transformers, and generators. Displacement power factor is generally not a major concern with audio and video systems.
5. As noted in the discussion of harmonic current, current is drawn by the power supplies of electronic equipment in relatively short pulses, but those pulses can be of relatively high amplitude. The IR and IZ drops produced by these pulse currents will be superimposed on the supply voltage. For example, a power supply specified to draw an average current of 1A might draw its current in the form of pulses that lasts for only 10% of the positive half cycle and 10% of the negative half-cycle, but with a peak amplitude of 12A. If the impedance (resistive and inductive) between the power source and the load were 0.6 ohm (the resistance of 100 ft of #14-2), the line to neutral voltage would sag by (120 * 1.414 8 0.6) volts = 10 volts at the peak of that current pulse, and the peak to peak value of the noise would be 10 volts! Not only that, but the RMS value of the current could be nearly double the average value.
6. Radio frequency noise may be coupled onto the power line (or onto the equipment ground) by switch-mode power supplies, especially those that are poorly designed. This noise can cause serious interference to radio reception (AM and FM broadcast tuners, wireless mic receivers, hearing impaired systems). If this noise is impressed onto cable shields, it could couple into signal circuits by the mechanisms of pin 1 problems, SCIN and capacitance imbalance in balanced circuits, and IZ drops on the shield of unbalanced wiring. Power supplies and battery chargers for large consumer and commercial equipment such as power tools, electric blankets, low-voltage lighting, golf carts, etc. are notorious sources of RF noise. Ironically, this noise is coupled onto equipment grounds by the capacitors within line filters that most national governments require to be built into electronic equipment!

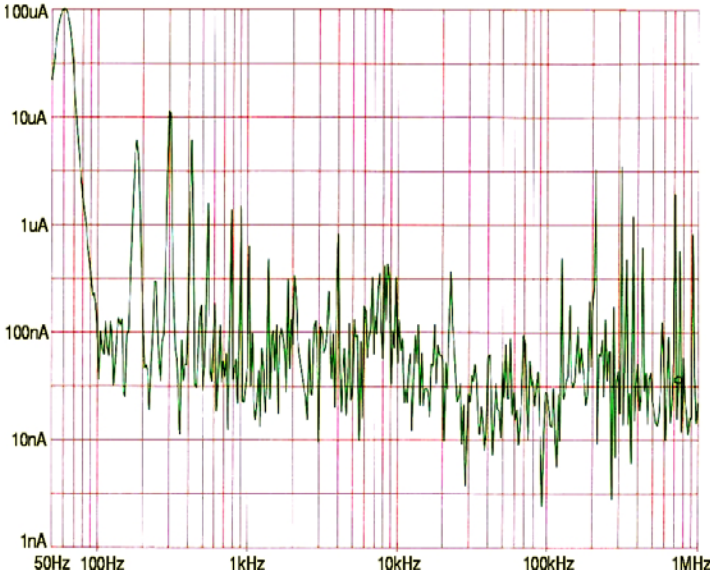


Fig 18 – Noise spectra on a typical equipment ground (courtesy Bill Whitlock)

Fig 18 shows the spectra of the noise current on the shield of wiring connected between equipment at widely separated locations. The large peaks at the left are the 60 Hz fundamental and low order harmonics. Components above 100 kHz are likely to be noise from switching power supplies, and some of those above 500 kHz may be AM broadcast stations. Components between about 1 kHz and 100 kHz are likely to be noise from various motors, fields radiated by CRT monitors, and switching noise from a wide variety of other equipment. The noise spectra extends well above the 1 MHz limit of this sweep.

## SURGE SUPPRESSION

Traditionally, facilities and equipment have been protected from power line transients by shunting them to “ground,” simply because that was the only method available. This is called *“shunt-mode”* suppression, and the shunt device most commonly used is a Metal Oxide Varistor (MOV). MOV’s have at least three serious shortcomings as protection devices. 1) They fail, often without warning, and often destructively. Once they have failed, they provide no protection. 2) MOV’s have a finite life, and their ability to shunt the surge to ground degrades over time, also without warning. Again, they provide little or no protection in this condition. 3) The act of shunting the surge to ground pollutes the ground with the surge voltage. Low surge voltages couple noise to the ground, which can often enter the audio or video system by causing shield current to flow. Very powerful spikes (lightning hits, very large voltage spikes produced by major power faults) can raise the ground voltage enough to cause destructive failure of system equipment connected anywhere in the building.

How MOV's CAUSE Equipment Damage When a shunt mode suppressor conducts a lightning strike to the equipment ground, the IR drop in the "green wire" raises the potential between the equipment ground at the "protected" outlet and other "grounds." Consider two pieces of gear plugged into different outlets, with signal wiring between them. One of them has a shunt mode suppressor, the other does not. Or perhaps they both have shunt mode suppressors, but because they are at different locations, they see different lightning currents and have different lengths of green wire to "earth." In either situation, ***the difference in potential between the two equipment grounds can be thousands of volts for the instant of the strike, and one or both of those pieces of equipment is likely to experience a destructive failure.***

*Series-mode* surge suppression operates very differently, storing the surge energy in reactive components and slowly discharging it back into the power line from whence it came. High quality *series-mode* surge suppressors overcome all of the limitations of shunt-mode devices – they do not have finite lifetimes, their performance does not degrade with time, and they do not pollute the ground (that is, they don’t couple noise to ground, and they the don’t cause the surge to damage other equipment). *Series-mode* suppressors currently have only one important limitation – it is practical to build them only large enough to protect branch circuits. Shunt-mode devices must still be used when protection is needed at the building service entrance and on system feeders.

## POWER CONDITIONING

Power conditioning is a rather broad term, describing processes to correct one of more of the problems noted above. In it's broadest meaning, it connotes voltage regulation to correct for the line voltage being higher or lower than normal, surge suppression to eliminate short term faults that can damage equipment, and bandpass filtering to reduce noise. Some may even attempt to reduce harmonic currents. Unfortunately, much of the equipment sold in the name of power conditioning does more to relieve purchasers of their money than to improve power quality.

## LINE FILTERS

Power Line Filters The power line is often both a conductor and a radiator of noise, both to and from our equipment. Most noise sources produce both common mode and differential mode signals, so both need to be addressed.

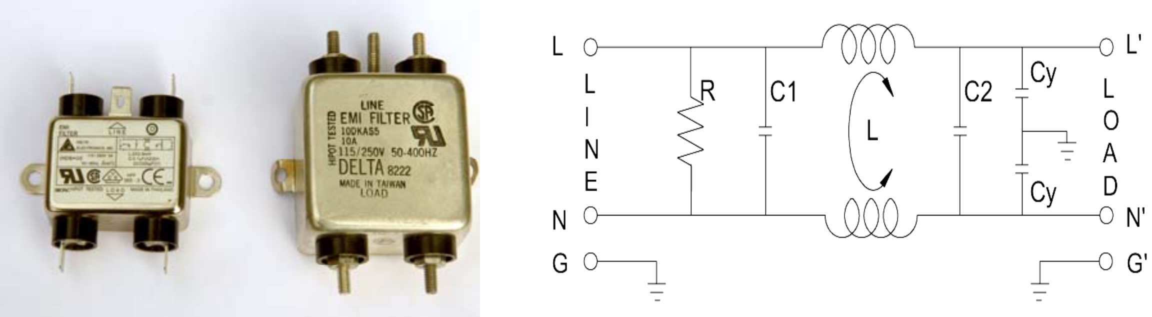


Fig 19 – Commercial Line Filters, and a typical schematic

Commercial AC power line filters (Fig 19) typically include both common mode and differential mode filtering. Like most products, line filters are built to a wide range of performance levels to fit needs and budgets. Like any passive network, line filters are directional, because their operation depends on both source impedance and load impedance. The filters shown are configured for good bi-directional performance (but thanks to the impedance relationships, they don't work ***equally*** well in both directions).

In the schematic of Fig 19, the inductor is a common mode choke. C1 and C2 function as voltage dividers with the imbalance and leakage inductance of the choke to form a differential mode filter. C1 minimizes noise coupling from load to line, while C2 minimizes coupling from line to load. The two capacitors Cy form a common mode filter for noise coupled from the power line to the equipment. Cy must be small in value to satisfy electrical safety codes, which limit leakage current to about 5 mA – 4.7 nF is typical. Typical values for C1 and C2 are 0.22 – 0.47 $\mu$F.

Specifications for most good filters are available on line. Study them carefully when choosing a filter. Note that these data are for a 50 ohm source and load network (called a LISN) specified by the FCC. While the LISN make the filters relatively easy to measure, it is a somewhat fictional representation of the real world – it is, in essence, the "mean" of data for typical power systems. The common mode impedance of a typical power system branch circuit ranges from about 30 ohms to about 300 ohms at radio frequencies. Filters work by forming voltage dividers, two elements of which are their source and load impedances, so the performance of any filter can vary widely from its published specifications, and will be better if the source impedance (at radio frequencies) of the AC line is lower.

Because capacitance from line to ground conducts noise onto the equipment ground, line-to-ground capacitors in filters can cause as many problems as they solve. This is because any noise on the ground will contribute to shield current. In an unbalanced circuit, the resulting IR drop will be added to the signal. In a balanced circuit, the noise can be coupled by the mechanism of shield-current-induced noise (SCIN). -

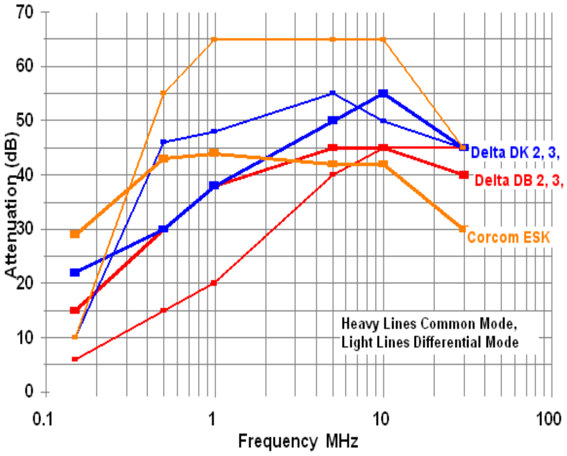


Fig 20 – Published Specifications for Some Small Power Line Filters

## UNINTERRUPTIBLE POWER SOURCES (UPS)

UPS's come in several basic forms, and there are several variants within those forms. The original form, now known as a "true UPS" or "on-line" UPS, continuously produces DC to keep a battery safely charged and simultaneously using that DC to power an inverter that regenerates the AC mains voltage (usually, but not necessarily 120VAC) needed to power the protected equipment. Ideally the regenerated voltage would be a sine wave; in reality, the voltage may be only a first approximation of a true sine wave. When power drops, the battery alone provides the current to run the inverter.

The second type, and now the most common, is the "off-line," "switching," or "standby" UPS. The UPS unit monitors the power line to make sure that mains power is present and within tolerance, and keeps the standby battery fully charged. When mains power is "good," the protected equipment operates directly from mains power. If power is interrupted, the UPS quickly goes into action, using the battery as a source of power to regenerate the AC line voltage, and switching the protected equipment from the power line to the regenerated source.

The "true UPS" always operates as a separately derived source, and by its nature, provides a high degree of isolation from line noise and transients. It also functions as a voltage regulator – as long as there is sufficient line voltage to operate the AC to DC to AC conversion process and the load current stays within limits, the output voltage is essentially held constant. In other words, the "true UPS" functions as a voltage regulator. The "standby UPS" is a separately derived system only when it is regenerating power, and only then does it provide isolation from the power line noise and transients. Many modern UPS units include a clever voltage regulator circuit that switches a "boost-buck" transformer in and out of the circuit if the mains voltage exceeds or falls below a specified tolerance (usually 5%).

Boost-buck transformers are power transformers (often auto-transformers) with a relatively high stepdown ratio. The primary is connected across the power line, and the secondary is connected in series with the load either in polarity ((boost mode) or out of polarity (buck mode). For example, A boost/buck transformer with a turns ratio of 10:1 would provide 12 volts on the secondary from a 120 VAC source. If added to the source when the line voltage drops to 105 volts, it would bring the load voltage back up to 115.5 volts; if subtracted from the line voltage when it rose to 132 volts, it would bring the load voltage down to 119 volts. A boost/buck transformer with 12:1 and 24:1 taps on the secondary could be switched to hold the load voltage within about 4 volts. Boost/buck transformers can be relatively small, because, they must provide only a small fraction of the total power in the circuit in which they are used (1/10 in the example). The secondary, of course, must be rated for the full load current, but for less than 10% of the load voltage.

Virtually all modern UPS units provide conventional shunt-mode surge suppression using MOV's. For this reason, there should always be a series mode surge suppression unit between the UPS and the power line. The reason is simple – we don't want the MOV to pollute the equipment ground with noise transients, and we don't want the MOV to dump a lightning strike or other destructive spike onto the equipment ground where it can blow up other equipment whose signal wiring may be connected to that equipment ground.

## SNAKE OIL AND OTHER BAD MEDICINE

In our discussion of grounding, we learned that the *Equipment Ground* must be extended to each outlet, and from there to each piece of connected equipment. It must be a *bond* – that is, a mechanically robust connection of very low impedance – so that breakers or fuses operate quickly and reliably to protect personnel and property in the case of a power fault. **Interrupting any portion of *Equipment Ground* (for example, by breaking off the ground pin of an AC plug or using a "ground lift" plug), or adding a series impedance (like an inductor or "choke") that reduces fault current is unsafe, and could cause electrocution. Products that add an inductance in series with the *Equipment Ground*, in the name of "cleaning up dirty grounds" are unsafe, because they reduce fault current, especially the leading edge of fault current, increasing the time that it takes a fuse or breaker to operate.**

## GROUND FAULT CIRCUIT INTERRUPTERS

The function of a Ground Fault Circuit Interrupter (GFCI or GFI) is to protect people from electrical shock due to excessive leakage currents or other faults. People are most vulnerable if their body is grounded, because that provides a path for leakage current from faulty equipment, so NEC requires the use of a GFCI to protect receptacles at certain locations where people are most likely to be in contact with ground (around plumbing, for example, and at most outdoor locations). The NEC all requires GFCI's for all receptacles in balanced power systems. Excessive leakage current could cause the external enclosure of equipment to be "above ground" by enough to cause a dangerous shock if a person touched the defective equipment with one hand and another ground (a water pipe, for example) with the other hand. [We tend to think of excessive leakage current as being generated by defective equipment, but it can also be generated by perfectly normal line filter capacitors (and transformer stray capacitances) in multiple pieces of equipment connected to same Equipment Ground point.]

A GFCI is a device that senses very small values of leakage current, and interrupts the circuit. A GFCI works by detecting the difference between the current on the "hot" or "phase" conductor and the current on the Neutral. If there is no leakage current, the hot and neutral current should be equal. Any difference between these two currents must be flowing to ground. NEC requires that GFCI devices trip if the imbalance (leakage current) exceeds 4-6 mA.

## GROUNDING FOR ANTENNAS

Many installations include some form of outdoor receiving antenna. Three key issues must be addressed.

1) Lightning Protection Antennas must be grounded via the shortest practical path. If possible, this path should be outside the building, and routed to the audio/video system in a manner that any lightning energy is far more likely to take the intended path to ground rather than go to ground through the audio/video system. A suitable lightning protection device should also be installed in series with the coaxial cable

to protect the input stage of the receiving equipment. Polyphaser is a well respected manufacturer of such devices.

2) Good RF performance The antenna must be coupled to audio/video receiving equipment in a manner that does not create excessive loss.

3) Prevent Ground Loops The cable shield should be broken by some form of RF transformer before the input to the receiving equipment (but not between the antenna and the lighting ground). Excellent isolation transformers are available from Jensen Transformers.

A solution recommended by experienced RF engineers that satisfies all of these requirements is to route the cable from the receive antenna outside the building to a point where it is bonded to building ground at or very close to the *service entrance ground*, then extend it to the audio/video system. The grounding point is also the recommended location for the protection device. If increased cable length results in excessive attenuation, either lower loss cable can be used, or an in-line amplifier can be added, or both.

An exception to the above advice applies to antennas inside buildings that provide a high degree of shielding. In general, receive antennas for wireless mic systems should be relatively low, and should be close to the stage or platform of a theatre or church. Lightning protection is probably overkill for a such an antenna. It is probably sufficient to isolate it from structure to prevent a ground loop, and ground it via the technical power system.

## Some Useful Troubleshooting Tools

Troubleshooting power and grounding problems essentially boils down to finding and eliminating magnetic fields and potential differences between grounds at the opposite ends of audio and video system wiring. If systems are wired properly, magnetic fields should be contained between the parallel conductors of power system wiring, and within the cores of transformers and motors. Likewise, a properly installed and grounded electrical system without faults should set up relatively small potential differences between grounded objects.

One of the most common wiring errors is a neutral that is grounded at more than one point. The neutral for the building service must be grounded at the service entrance. Each separately derived system (i.e., the secondary of a stepdown or isolation transformer) must be grounded at the transformer. That's all! Suspect this problem if, when using the troubleshooting tools listed below, you find strong magnetic fields at 60 Hz and harmonics of 60 Hz.

Another common wiring error is an unintended connection of the isolated ground bus to a building ground. This can happen when a piece of equipment plugged into an IG outlet is in contact with some randomly grounded object – the building structure, a catwalk, an HVAC duct, a grounded antenna lead-in. Such a connection will defeat the IG system because it establishes a path for shield current. To find this sort of error, have an electrician shut down power to the panel feeding the system and temporarily disconnect the bond between the IG bus and the building ground. An ohmmeter can then be used to find any improper ground(s), checking each conductor tied to that bus one at a time.

### OUTLET TESTERS

Outlet testers are an extremely valuable tool. People make mistakes, and it is common for there to be wiring errors in power systems. Some errors merely add hum, buzz, and noise to the audio system, while others can damage equipment or even kill people. Surely a skilled technician could drag an array of test equipment around a facility and test each outlet under load to find those mistakes, but testing each outlet would consume considerable field labor. A good outlet tester checks for virtually all common wiring errors, but it also tests for excessive IR drop under load for both live and grounding conductors, and does it all in a few seconds. One of the better units is the Inspector II, manufactured by Tasco, Inc. of Englewood, CO. Older products made by Tasco, and by Ecos, (long out of business, but available on the used market) are also very good. Simple units sold in consumer and industrial supply houses tend to test only for the most basic wiring errors. It is well worth searching out one of the Tasco or Ecos units.

One of the most problematic wiring errors, and also the most difficult to detect, is the neutral/ground swap. This error causes the full load current to flow on the equipment ground rather than the neutral. This establishes a current loop with a very large loop area, which can result in very strong magnetic coupling of hum and buzz into signal circuits.

## CLAMP-ON AMMETER AND PROBE

Clamp-on ammeters are large coils  designed to couple to a voltmeter or oscilloscope.  The most useful ones have more turns and can sense relatively small currents, and can be connected to a scope or RTA. Fluke and AEMC make very good ones in a wide range of sensitivities. You can also make your own current probe for shield current by interrupting one end and inserting a very small value resistor (less than one ohm).  Connect a voltmeter, headphone amplifier, scope, or audio spectrum analyzer across the resistor. Use Ohm's law with the voltmeter or scope to find the current.

## MAGNETIC FIELD PROBE

Effective probes for audio-frequency magnetic fields can be made from a CRT degaussing coil (the kind sold for use in a TV service shop), or from a good dynamic microphone that has no hum-bucking coil and relatively little magnetic shielding (an EV 635A, for example), or even a telephone pickup coil from Radio Shack. Simply connect the probe to the input of a battery-powered microphone preamp that can drive headphones, and walk around listening for the fields. A user receiver for an inductive loop hearing impaired system is also a convenient and inexpensive probe.

## AUDIO VOLTMETER

A simple audio voltmeter or scope connected between the ends of a cable is a very unreliable method of measuring induced voltage because its leads disturb the current loop (that is, change the loop area).

## SCOPE, AUDIO SPECTRUM ANALYZER

These instruments are most useful for tracking down power and grounding problems if they are battery powered. Use them to analyze the output of a current or magnetic probe, or connect them between the ends of the cable.

## THE JARGON

Building codes are filled with "jargon," and the National Electrical Code is no exception. As with many legal documents, the use of certain words within the document carry a special meaning beyond a dictionary definition or even standard usage.

*Bonding* – the permanent joining of metallic parts to form an electrically conductive path that will insure continuity and the capacity to conduct any current likely to be imposed.

*Bonding jumper* – A reliable conductor used to ensure the required electrical conductivity between metal parts required to be electrically connected.

*Main bonding jumper* – The connection between the *grounded circuit (neutral)* and the *equipment grounding buss* at the service.

*Branch circuit* – all wiring between the last means of disconnection and the load (outlets).

*Feeders* – all wiring between the service and the last means of disconnection (i.e., circuit breaker or fuse) before power outlets.

*Equipment* – material, fittings, appliances, raceway, conduit, fixtures, and apparatus.

*Load equipment* – equipment that draws power from the electrical system.

*Grounding electrode* – the conductor that makes contact with the earth.

*Solidly grounded* – the neutral and earth ground electrodes are directly connected with no impedance (intentionally) placed between them. Thus the word *solid* implies a d.c. connection -- i.e. nothing more than a short wire.

*Phase conductor* – the *ungrounded* (hot) power conductor.

*Neutral* – the *grounded conducto*r. (The white wire).

*Outlets* – connected equipment or receptacles.

*Panel* – an electrical enclosure.

*Panelboard* – an electrical enclosure with circuit breakers.

*Service, service entrance* – the connection of a building or other facility to the power company's wiring.

*Separately derived source* – a separate power source that is not directly connected to the power company's transformer – for example, the secondary of a transformer or the output of a generator.

*Listed* – Equipment, fittings, and hardware that is recognized by the Authority Having Jurisdiction (AHJ) as acceptable for use in electrical systems. Most AHJ's in North America require that all elements of electrical systems be listed (including most installed audio and video systems), and delegate responsibility for listing and testing for listing to a safety agency such as Underwriter's Laboratories (UL), Canadian Safety Agency (CSA), and Electrical Testing Laboratories (ETL).

*Authority Having Jurisdiction*: The local government agency having legal authority for establishing building codes and verifying compliance.

*Safety Agency (UL, ETL, CSA)*: An independent testing body, not affiliated with government, whose business is to test the safety of equipment, fittings, and hardware in their intended use. The focus of these agencies is the protection of life and property. They are not concerned with the effectiveness of equipment, except to the extent that it relates to these safety issues. These agencies test products primarily 1) to make sure that it will not start a fire; 2) that it will not contribute to flame spread; 3) that it will not create noxious fumes when it burns; and 4) that it will not create a shock hazard.

## REFERENCES AND RECOMMENDED READING\

OTT, HENRY W., *Noise Reduction Techniques in Electronic Systems,* Wiley Interscience, 1988 – An absolutely essential book. Henry Ott nailed it, in this definitive text that ties together both theory and practice in EMC. If you disagree with a single word in this book, you're wrong!

MUNCY, NEIL. A. "*Noise Susceptibility in Analog and Digital Signal Processing Systems,*" J. Audio Eng. Soc., vol 43, pp. 435-453 (1995 June) The paper that introduced both SCIN and the Pin 1 problem. A classic!

WHITLOCK, BILL "*Balanced lines in Audio Systems: Fact, Fiction, and Transformers*," J. Audio Eng. Soc., vol 43, pp. 454-464 (1995 June) How balanced audio circuits really work.

BROWN, JIM and WHITLOCK, BILL, "*Common-Mode to Differential-Mode Conversion in Shielded Twisted-Pair Cables (Shield-Current-Induced Noise)*," AES Preprint 5747, Presented at 114th AES Convention, Amsterdam, 2003 March This paper adds to the understanding of SCIN, proves that SCIN is active well into the MHz region, and shows that SCIN is a major contributor to RFI from AM broadcast and ham transmitters.

GIDDINGS, PHIL, *Audio Systems Design and Installation*, Focal Press, 1990. An excellent reference for power and grounding. Some of the material on balanced signal wiring is wrong. Study Whitlock instead.

MORRISON, RALPH, AND LEWIS, WARREN; *Grounding and Shielding in Facilities*, Wiley Interscience, 1990 Especially helpful in describing standard practice in power and grounding, and also with deciphering jargon. The authors are staunch advocates of MESH grounding for technical systems, but their focus is primarily industrial and data centers – audio systems are barely on their radar.

*IEEE Recommended Practice for Powering and Grounding Electronic Equipment (IEEE Emerald Book)*, IEEE Std 1100-1999, Institute of Electrical and Electronic Engineers, Inc., New York. 1999

*IEEE Recommended Practice for Grounding of Commercial Power Systems and Equipment (IEEE Green Book)*, IEEE Std 142-1991, Institute of Electrical and Electronic Engineers, Inc., New York. 1991

*NEC 2002 Handbook* National Fire Protection Association, Quincy, MA 2002 The Code by itself is deadly dry, full of jargon, and hard to read. Buy the Handbook version, which helps a lot. Both are revised every three years.

*Comprehensive Dictionary of Electrical Engineering Terms* P. Laplante, Editor; CRC Press, 1999 A useful reference when you run into jargon.

*The ARRL Handbook* American Radio Relay League, Inc. Newington, CT Published annually. More engineers have learned electricity, electronics, and radio from "The Handbook" than from all other sources combined! Very readable, solid science, minimal math.

## ACKNOWLEDGEMENTS

This applications note was commissioned by New Frontier Electronics (the SurgeX people), who wanted "something to pass out to contractors who didn't quite understand technical power and grounding," and wanted to know "why isolated ground outlets aren't needed inside racks." I suspect they got far more than they bargained for. The section on balanced power is based on analysis by Bill Whitlock. Dale Svetanoff (WA9ENA) and Tom Rauch (W8JI) contributed solid thoughts on lightning protection and RF grounding issues. Neil Muncy and Dale Shirk reviewed the manuscript and offered useful comments. As always, I thank them for their good counsel and encouragement. Neil also shared some of his troubleshooting techniques.

The author, and our entire industry, are greatly indebted to Henry Ott, whose excellent workshop on EMC I attended this fall, and whose book, cited above, should be on everyone's shelf. It is difficult to conceive of an issue related to EMC that he hasn't thought through in great detail, considering every possible ramification, from the micro to the macro, and from circuit performance to manufacturability to user-friendliness to where things will be in 20 years. A side-comment in his book (first published in 1976, updated in 1988) makes it clear that he knew about SCIN then.

# Appendix – European and North American Systems Compared

Courtesy John Woodgate

Divided by a common language The words used for this subject differ on the two sides of the Atlantic, and some of them are used quite vaguely, to mean different things in different contexts. So, here is a short guide to the words.

| British English | US English |
|---|---|
| Earth | Ground |
| Line or Phase conductor (brown) | Line or phase conductor (black) |
| Neutral conductor (blue) | Neutral or grounded conductor (white) |
| Protective (earth) conductor (green and yellow) | Grounding conductor (green) |
| Screen, screening | Shield, shielding |
| Mains lead | Power cord |
| Trunking | Raceway |

There are also some words in use that should not be, because they are vague or misleading or both, and we need to look at those:

~~Signal earth (or signal ground)~~: the better term is '*signal common*'.

~~Chassis earth (or chassis ground)~~: the better term is '*enclosure*', assuming it is electrically conducting. If it isn't, the concept doesn't really exist.

## EUROPEAN POWER SYSTEMS

Five different systems are used for the distribution of electric power in public 'low voltage' systems, and these may also be used in private systems. These systems differ primarily in how they treat the grounded conductor. ('*Low voltage*' in this context means, in practice, systems with phase voltages between 100 V and 240 V.)

In all but one variant of one system, something in the system is connected to the planet by means of a buried electrode. This allows earthed equipotential bonding to be used as protection against electric shock.

**TN-C system:** One pole of the supply system is connected to one or more electrodes buried in the ground. This pole is also connected to the neutral conductor of the distribution cables, which is also used to 'earth' exposed conductive parts of a load installation. (Figure A-1)

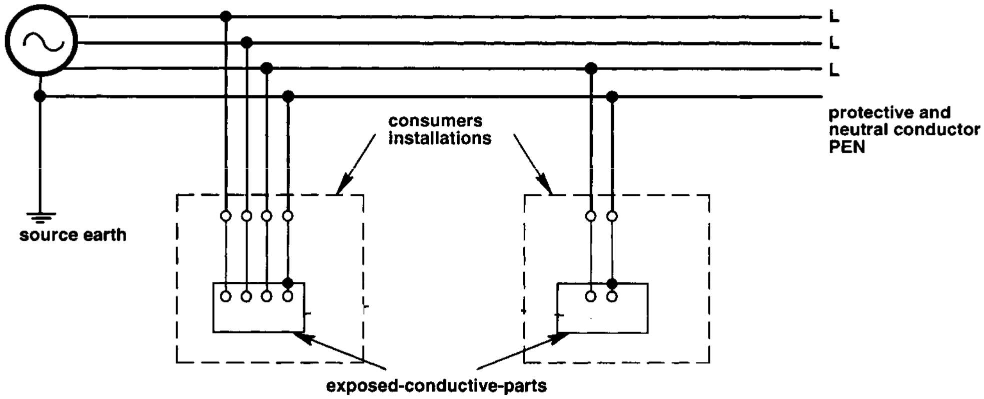


Figure A-1 – TN-C system

**TN-S system:** One pole of the supply system is connected to one or more electrodes buried in the ground. This pole is connected to the neutral conductor of the distribution cables, and also connected to a protective conductor in the distribution cables, which is used to 'earth' exposed conductive parts of a load installation. The neutral and protective conductors are insulated from each other in the distribution network and in load installations. (Figure A-2)

The TN-S system is one of two systems used in the United Kingdom (the other is the TN-C-S system). The bond between the Neutral and Earth occurs only at the power utility (that is, within power company equipment).

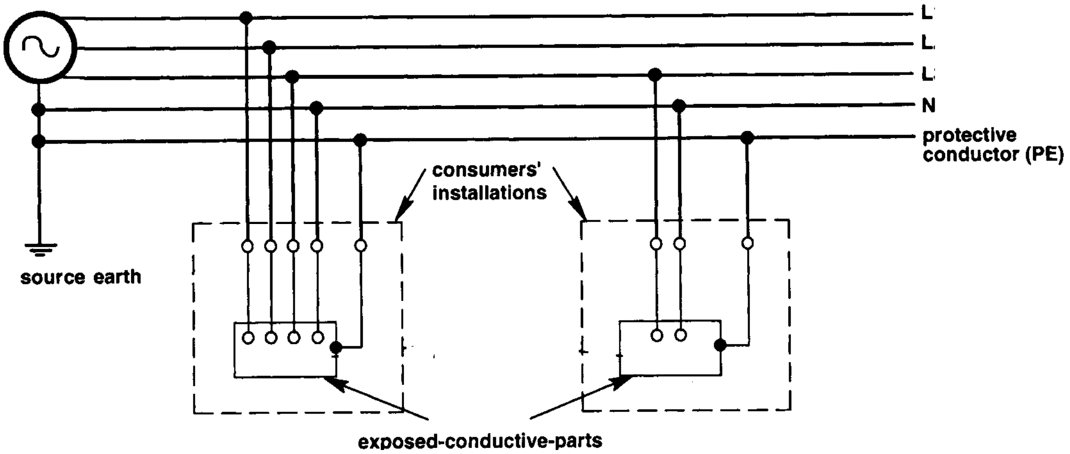


Figure A-2 – TN-S system

**TN-C-S system:** Both TN-C and TN-S configurations are used in different parts of the system. This configuration is also known as 'Protective Multiple Earthing' (PME). (Figure A-3)

The TN-C-S system is used in most of Europe and in part of the United Kingdom. In continental Europe, the bond between neutral and earth is made at the service entrance. In the United Kingdom, the bond between neutral and earth is mode only at the power utility.

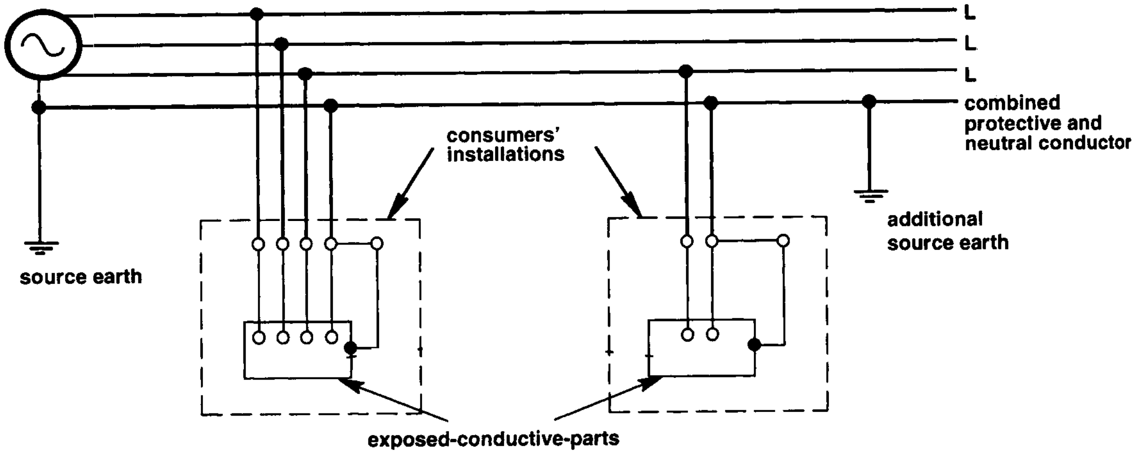


Figure A-3 – TN-C-S (PME) system

**TT system:** One pole of the supply system is connected to one or more electrodes buried in the ground. Local buried electrodes are used to 'earth' exposed conductive parts of a load installation. (Figure A-4)

The TT system is a rather dangerous system, since it offers no protection against electrical shock if a fault occurs within equipment. It is dangerous because fault current through the earth is unlikely to be strong enough to cause a protective device (circuit breaker, fuse) to disconnect the power before a person might die from an electrical shock.

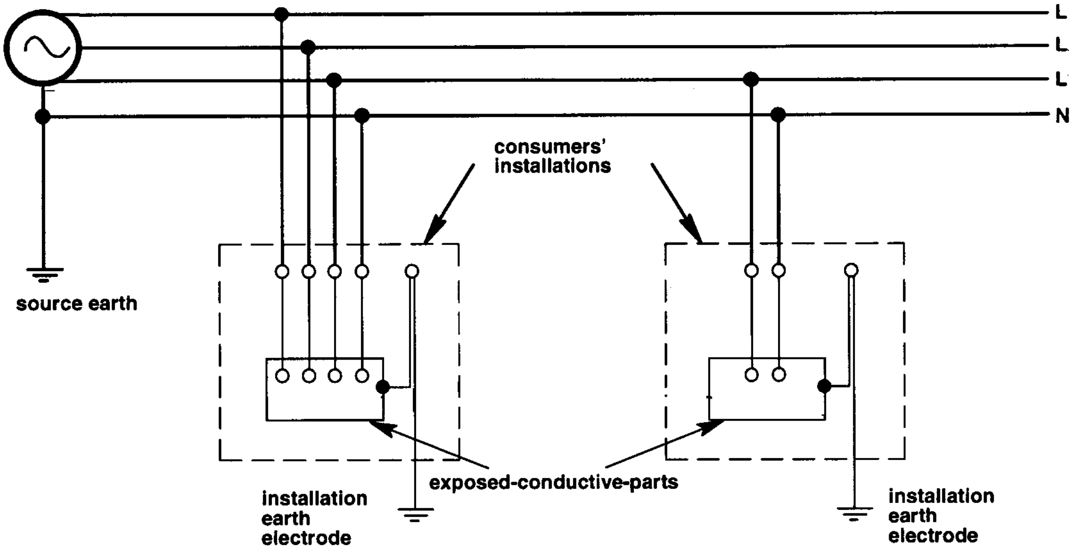


Figure A-4 – TT system

IT system: One pole of the supply system is connected through an impedance to a buried electrode. Local buried electrodes are used to 'earth' exposed conductive parts of a load installation. (Figure A-5)

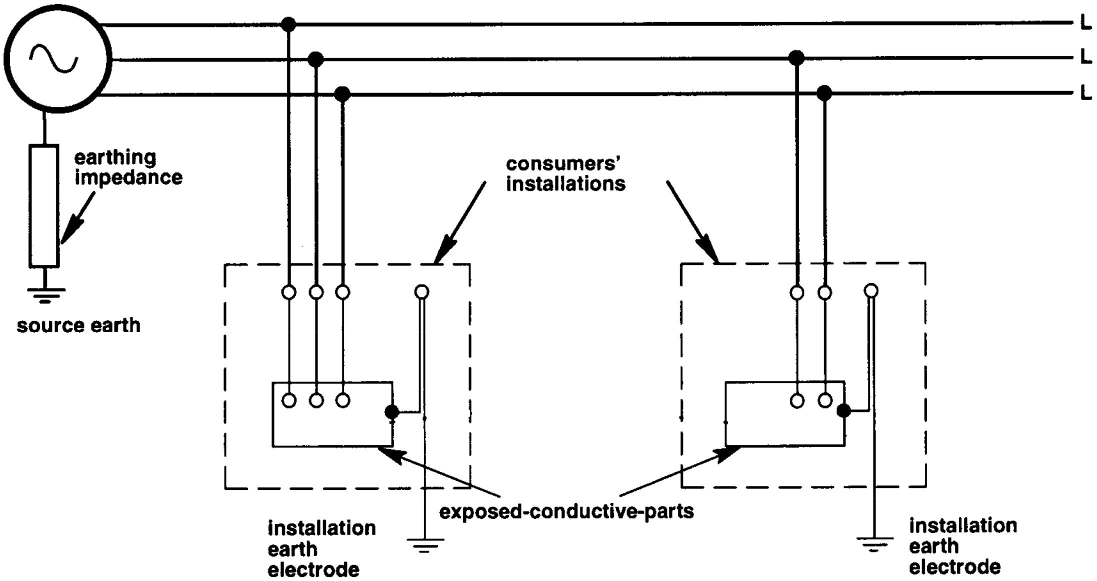


Figure A-5 – IT system

NOTE - Another variant of the IT system, used in hospitals for example, has no connection of any part of the supply system to a buried electrode. This is because patients may be connected to mains-powered equipment via invasive electrodes, bypassing the partial insulation normally provided by the skin. Consequently, leakage currents from the mains supply must be kept to an absolute minimum, even though the actual voltage of the patient with respect to any 'earth' may be unknown. Special measures have to be taken to discharge any common-mode charge built up on the supply system.

Ideally, the protective conductor should carry no current, so that all points on it are at the same potential. This is clearly impossible in those systems where the neutral and protective conductor are partially or completely combined. But, even in a TN-S system, there is at least capacitance in cables and load equipment, and there may be leakage resistance in load equipment, between the phase conductors and the protective conductor, so that some current still flows in the protective conductor. Because it has a finite (albeit very low) impedance, there must be voltage differences between different points on it.

## TRANSATLANTIC DIFFERENCES

While 3-phase distribution is used all over the world, there are important differences in low-voltage power supply configurations between Europe and the Americas.

Europe In Europe, local low-voltage distribution is at 230 V single phase (and thus 400 V 3-phase). While perfectly balanced 3-phase loads produce no fundamental neutral current, single-phase loads and most non-linear loads produce significant, possibly very large, neutral currents. Consequently, to minimize magnetic field generation, neutral and phase conductors are normally required to be kept physically close together. However, there are, unfortunately, exceptions. (Figure A-6)

Power distribution, except in very rural areas, is at medium or high voltage, feeding large transformers that supply typically 500 sites at low voltage. In most Continental countries, the TN-C-S system is used, with the neutral and protective conductor joined at the site service entrance. In the United Kingdom, TN-S and TN-C-S systems are used, but connections between neutral and protective conductors are strict kept within the supply system and it is not permitted to connect them at private sites. In a few countries, IT systems are used, in areas where ground conductivity is poor.

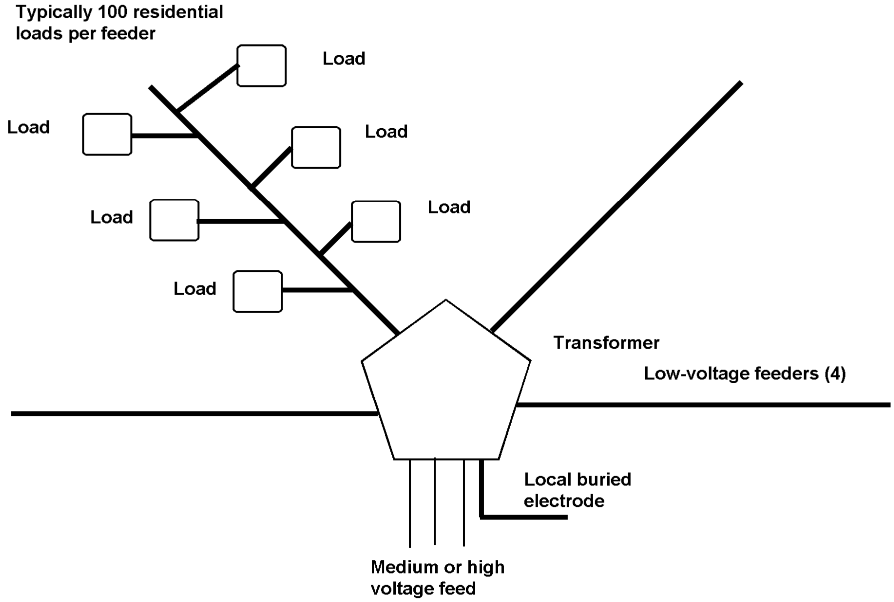


Figure A-6 – European power distribution

Normally, an insulated protective (equipment ground) conductor is run together with all power conductors, and metal conduit and raceway is connected to the protective conductor (equipment ground) but is not intended to carry any current.

Functional earth conductors must be connected to the main earthing terminal and not only to a separate buried electrode.

## North America

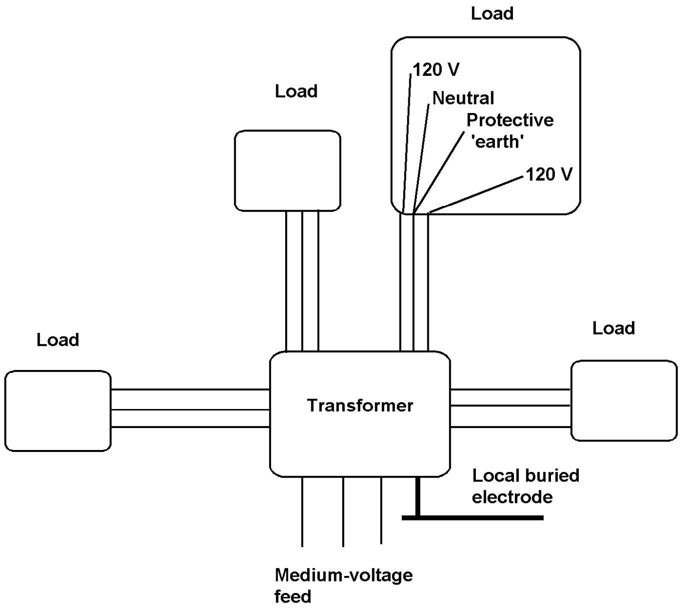


Figure A-7 – North American power distribution

In North America, local low-voltage distribution is either at one of several three-phase systems or at 240 V from a centre tapped transformer. This may be regarded as a 240 V single-phase system with centre neutral or as a 2-phase 120 V system, with 180 electrical degrees between phases. Loads, which may be connected at 240 V or between either 120 V line and neutral, should, in the latter case, be kept as closely balanced as possible, so *there should be little current in the neutral* and there has in the past been seen no particular need to keep it physically close to either line conductor to minimise magnetic field emission. Unfortunately, non-linear loads can produce very large neutral currents, so strong magnetic fields, at odd multiples of three times the power frequency, can in fact be generated if the neutral is separated from the line conductors. (Figure A-7)

Power distribution in built areas is at medium voltage, feeding normally 2 to 12 sites. The PME system is used, with the neutral and protective conductors bonded at the service entrance and connected to a buried electrode, to metallic plumbing, and to building steel. An earth connection is also made by the power company at its distribution transformer (outside the premises). The transformer may be on a pole, on the ground, or underground.

While the use of an insulated protective conductor, run together with all power conductors, is in many configurations strongly recommended, metal conduit and trunking connected to the protective conductor may be used to carry protective conductor current. This can result in unpredictable current paths in a building, especially an elderly one, and unexpected magnetic field generation may occur.

## GROUND FAULT INTERRUPTION

Ground fault interruption is also handled differently in different countries. Ground fault interrupters sense the difference between the current in the "phase" conductor and the neutral conductor, and disconnect the circuit if the imbalance exceeds a specified level. In North America, a Ground Fault Circuit Interrupter (GFCI) is required on circuits around plumbing and in outdoor locations (see page 26). These interrupters are set to trip on an imbalance of about 5 mA. In Europe, a single interrupter (called a Residual Current Device, or RCD) is installed at the service entrance, and is set to trip at about 30 mA.