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 – 3^{rd}, 9^{th}, 15^{th}, 21^{st}, 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.

This behavior of triplen harmonics occurs anywhere they are summed – as leakage currents in the Equipment Ground (PE) conductor, and as magnetic fields produced by transformers, motors, and wiring. As we shall learn later, this makes power-line buzz far worse that it otherwise would be if no 3-phase currents were present.

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 in North America uses 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. K-Factor is discussed at greater length in the Appendix.

These issues are addressed in Europe and the United Kingdom by limiting the harmonic currents that any device can draw from the AC mains, and by very specific requirements for the size of conductors as a function of the total current, taking harmonics into account. In North America, a common rule of thumb for the design of 3-phase systems is to install neutral conductors and hardware rated for 2X the current in any phase, but the issue is not addressed by regulations. Harmonic current is addressed only on a voluntary basis by inclusion in the requirements for an Energy Star rating that indicates to the consumer that the product has good electrical efficiency.

HIGH LEG DELTA

Figure 8 shows a variation of the delta configuration that is widely used in North America, especially 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. See the Appendix for a more detailed discussion of this configuration and the quite severe hum and buzz problems it can cause.

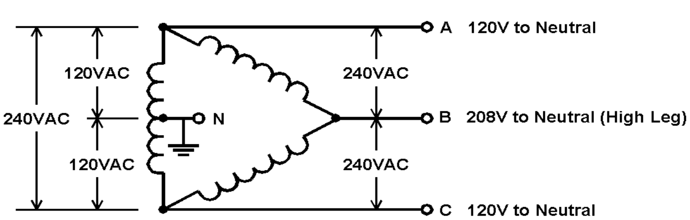

Fig 8 -High Leg Delta

GROUNDING (EARTHING)

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 earthed. Most distribution transformers have a conductor bonded to a rod driven into the earth. 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 connection is lightning protection – it is rarely a very good ground, and may be electrically noisy.

Two grounding functions are required by building codes. *System grounding (earthing)* is the connection to earth of a conductor that normally carries current – the *Grounded Conductor* or *Neutral*. *Equipment grounding (earthing)* is the bonding together of all exposed equipment and structure, and the connection of that bond back to the power system ground (earth). Equipment earthing is accomplished by means of the *Equipment Ground* conductor *("the Green Wire"),* in some countries called the *Protective Earth (PE) conductor*. The details of how and where these connections are made varies a bit from one country to another, but not by much. While this discussion specifically describes building codes (regulations) that apply in North America, the only significant differences in most parts of the developed world are the words (and jargon) used to describe practices and standards that are essentially the same, the extent to which all exposed metal is bonded together and to the Equipment Ground, and the extent to which outlets and plugs used in that country insure that equipment will be properly connected to the *Equipment Ground*.

Electrical codes require that most *systems* have a *Grounded Conductor (Neutral)*. 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 (Neutral)* 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 to create a *Neutral* is called the *System Ground,* or *System Bond,* or *Main Bonding Jumper*. [In some countries, including parts of the UK, neutral is bonded to earth only at the power company's equipment, external to the building.]

The *System Ground, (System Bond* or *Main Bonding Jumper)* 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*.

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
120/230 V single phase (Figure 2)	3-wire Delta (Figure 6)
120/208V and 230/400V wye (Figure 3a, 3b)	
120/208V/240V High leg Delta (Figure 8)	

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

Earthed, the lightning charge is far more likely to be conducted to earth 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 not 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 generally 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* (also called the *Green Wire, Protective Earth, or PE).* Virtually ALL electrical equipment enclosures and raceway – conduit (trunking), cable tray, transformers, backboxes, etc. are required to be bonded (together and to ground).

Figure 9 shows how *System Grounding (Earthing)* and *Equipment Grounding (Earthing)* 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 a grounded object. 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!***

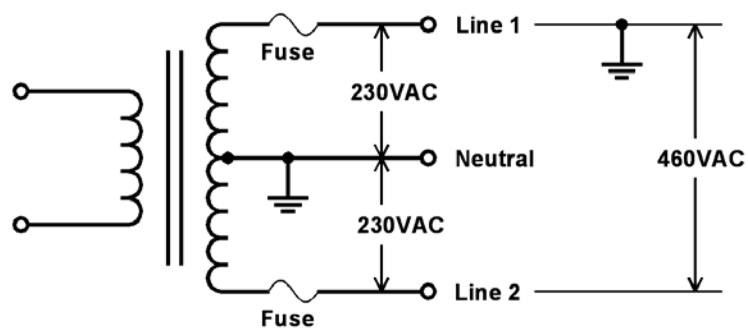

Figure 9 – A Fused Single-Phase System, with a Fault (short to earth) on Line 1

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

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/yellow is the assigned color). In other jurisdictions, the dedicated wire is optional if the *Equipment Ground* is carried by properly installed conductive raceway. The *Equipment Ground* includes the bonding together of every piece of building steel to every piece of metallic conduit (trunking) and electrical equipment.

If a steel raceway system (trunking) is used and 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 if there were only a dedicated green/yellow wire (*Equipment Ground, PE*) (green/yellow in Europe). 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 (trunking) is not well installed. When that additional wire is used, NEC requires that it be bonded to each enclosure through which it passes.

Virtually all electrical codes require that the *Equipment Ground* be run with the associated circuit conductors – that is, they must follow exactly the same path, and if in conduit (trunking), must be in the same conduit. If not in conduit, all three conductors – ***phase***, ***neutral***, and ***Equipment Ground (PE)*** should be in a single cable with all conductors molded together. There are two very good reasons for this. First, any mechanical event that caused interruption of one conductor is likely to also cause interruption of the others. Second, the inductance of the fault path for the current is far lower if the conductors are closely spaced, 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 (PE)*** conductor. Lower inductance means that the fault current will be greater and rise to a peak value more quickly, 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).

Some countries are more rigorous than others about making certain that the ***Equipment Ground (PE)*** is bonded to building steel and other earthed objects at multiple points and where outlets are installed. Steel conduit has long been used in North America to protect wiring, and it must be bonded to the Equipment Ground. But steel conduit is not required in most jurisdictions, and the cost of installing (mostly labor) has made it much less common. In much of North America, residential wiring uses three conductor cable in a flexible molded PVC jacket. The cable runs "exposed" (not in conduit) inside walls, over ceilings, and under floors.

In the Americas, an earth connection is required at the ***service entrance*** (the ***System Bond***). Additional earth connections may be made to the ***Equipment Ground (Green Wire, PE)*** anywhere along the system (but not to the Neutral), but all earth connections must be bonded together. In the UK, actual earth connections must be connected to the PE only at the ***service entrance***.

GETTING TO EARTH – THE EARTH ELECTRODE SYSTEM

The principal function of the Earth 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 Earth 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.

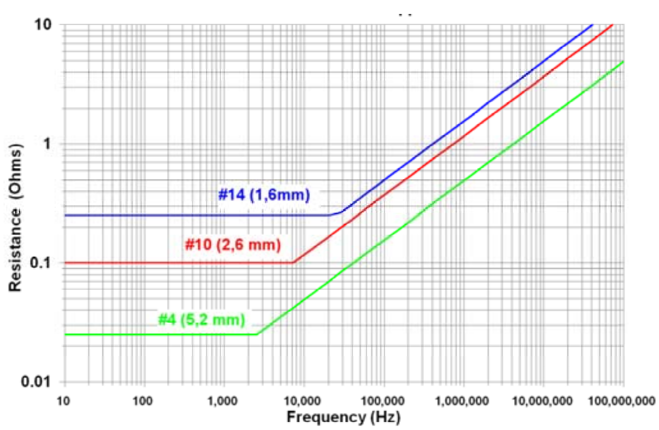

Figure 10 – Resistance of 100 ft (30,5m) of Copper Wire, including Skin Effect

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, there is negligible skin effect, 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 11a shows the inductive reactance of a straight non-ferrous conductor in free space, not close to the conductor carrying its return current. The loop inductance will be much smaller for a conductor running in close proximity to its return conductor (for example, in typical paired cable).

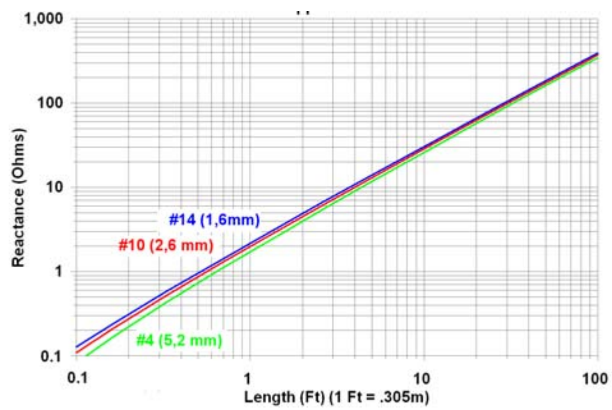

Fig 11a – Inductive Reactance of a Straight Conductor at 1 MHz, ignoring antenna effects

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. This graph ignores all antenna effects.

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 is connected on the other end, how it is connected, what it is connected to, and whether length is 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 makes it clear that, above a few hundred Hz, and for most conductors of practical size, 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.

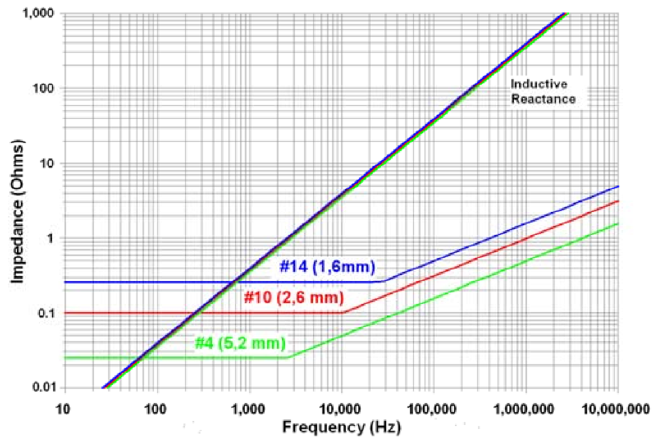

Fig 11b – Resistance, with Skin Effect, and Inductive Reactance for a 100 ft (30m Wire

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" (5cm) 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 impedance 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 earth connections) 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 earthing. Also, the earth electrode system will be in parallel with building steel and the concrete foundation. In general, the impedance to earth of the earth electrode system will be minimized by:

1. Using more earth electrodes.
2. Making the earth electrodes longer, driving them deeper into the earth. Ten feet (3 meters) is generally considered to be a minimum depth.
3. Spacing earth electrodes as far apart as practical (spacing equal to at least 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, earth 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 (an earth electrode buried in concrete). (Fig 12)

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. 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.

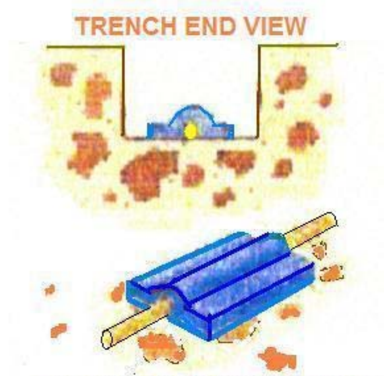

Figure 12 – Ground Electrodes in Concrete
http://www.conductiveconcrete.com

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 earthed objects and then earthed through a ***Technical Ground (Earth) System***. A good 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.

TECHNICAL EARTH SYSTEMS – MINIMIZING VOLTAGE BETWEEN EQUIPMENT

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

One of the fundamental rules of system interconnection is that the shields (screens) of cables carrying audio frequency signals should not carry current, especially at the frequency of those signals. A condition that results in noise current on the shield (screen) is often called a "ground loop." There are four important reasons why shield (screen) current should be avoided. All relate to imperfections in audio equipment and wiring.

1. Much audio and video equipment has been manufactured with a design defect commonly known as "the pin 1 problem," whereby the shield (screen) 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 (screen) will be coupled into the equipment, ampli-

fied, (and RF will be detected), and heard as noise.

2. Virtually all shielded (screened), 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 (screens) 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 (screen) will induce a voltage in each conductor of the signal pair. Below about 4 MHz, nearly all of the shield (screen) 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 (screen) current will induce more voltage in one conductor than the other. In other words, shield (screen) current is converted to a differential voltage on the signal pair. SCIN in foil/drain cables is less of an issue above 10 MHz, as skin effect takes over and a higher percentage of shield current flows in the foil.
3. Much audio equipment lacks filtering to reject radio frequency interference (RFI), so when SCIN places RF on the signal pair, that RF enters the equipment, is detected (converted to audio) and appears as noise (or the broadcast program) in the audio.
4. In unbalanced circuits, shield (screen) current causes an IR drop that is added to the signal (because the shield (screen) is part of the signal circuit. (See ***The Problem With Unbalanced Wiring***)

Three fundamental mechanisms can produce shield (screen) current.

1. ***Potential differences between the two ends of the cable.*** Current will flow on the shield (screen) if the two ends of the cable are at different potentials. Consider a cable shield (screen) that is bonded to equipment enclosures at both ends, the equipment is plugged into widely separated outlets, and the equipment at either (or both) ends of that cable has capacitance between the the AC power line and its enclosure. 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 the PE. Many fault conditions in power system wiring can establish potential differences of several volts between the PE connections at different locations. To understand how these voltages are produced, see the following discussion of ***leakage currents***.
2. ***Magnetic induction.*** Voltage will be induced along the shield (screen) 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 (screen).

LEAKAGE CURRENT AND APPLIANCES

Equipment connected to the power line will draw current through capacitors intentionally connected between the power line and its enclosure (noise filters), and through unintentional parasitic (stray) capacitance and resistance inherent in power supply components. The return path for this current is the ***Equipment Ground (Green Wire, PE)***. The resulting IR drop along the ***Green Wire (PE)*** raise the potential (voltage) on the enclosure.

IEC 61140 established four classes of electrical appliances that may be connected to the mains supply based on their leakage current. Class II products are those having no exposed metal parts, or exposed metal parts that are double-insulated from mains power. [Class III products are those having no internal voltages exceeding 50VAC or 120VDC.