Grounding and Shielding for Sound and Video

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Table of Contents

Note: None of the figures presented in this article were available.

1. A Perspective on Noise in Audio and Video Systems

To the uninitiated, the attraction of audio and video systems design, is the thrill and excitement of carefully selecting all the audio and video components, determining the correct interconnect of this equipment to provide the system's necessary functionality, the installation of this equipment into its new home, and the testing and commissioning of this equipment to bring it on line. It is not long, however, before our new audio/video and systems designer is disillusioned by the effects of the real world on his new system. These effects include noise, hum, buzzes, snow on video pictures, shadowing and a variety of other forms of distortion to what was hoped would be a clean signal. The challenge of designing audio and video systems not only includes that of the actual system design but all of the other detail necessary to keep these systems operating at the performance levels that the individual components are capable of. The veteran is all too familiar with the less than ideal performance that results when individual pieces of equipment are interconnected into larger systems in real world conditions.

The magnitude of this problem is illustrated by the simple fact that the editor of this magazine has chosen to run an entire issue on a solution of this problem; the proper use of grounding and shielding. Other organizations such as the Audio Engineering Society have in recent years devoted entire workshops to this problem. In a world of incredibly sophisticated audio and video systems where literally any form of signal manipulation, editing, transmission and reproduction is possible, we still suffer from extreme problems in executing all of these functions without producing additional distortion and artifacts due to the effects of the real world on our systems.

One of the difficulties that the audio and video industries face as a whole is that the designers of the electronic equipment work in the sterile environment of their laboratories and factories. The people who are designing the equipment are not those who are out designing the systems that are being installed into the theatres, churches, recording studios, concert halls, broadcast facilities and audio/visual facilities, to name only a few. The equipment that they design often tests out perfectly in the laboratory and seems to have all of the necessary input/output and internal wiring considerations necessary to provide signal integrity through their device. However, when this equipment is installed in the real world, the performance of the overall system is less than one might expect based on the performance of the individual components.

In recent times, particularly through the Audio Engineering Society, there has been a great deal of finger pointing. A number of system designers, including myself, have taken the time to document the problems that we as systems designers must deal with due to the inadequacies of the electronic equipment that is used in our systems. I am pleased to report that it appears that headway is being made and that manufacturers are becoming more receptive to the problems that people designing, building and using audio/video systems are experiencing.

The reason this is important is that grounding and shielding systems alone will not provide guaranteed freedom from noise problems. Further, the design of the grounding and shielding system is very much dependent on other factors in the system. Achieving the right level of hardware installation to optimize the system performance and the cost of the installation must be done with a clear head and a knowledge of all the issues that effect the noise in the audio or video system. It is very easy to overdesign and spend a lot of time with installation procedures that have little impact on the system's freedom from noise.

1.1. A Systems Approach

The complexity of the problem of noise in audio and video systems requires that an organized and methodical approach be taken to control or minimize its affects. The problem of noise in electronic signaling is universal and affects the computer, aerospace and manufacturing industries, as well as, the audio and video industries. The problems that we all face with regard to noise in signal systems is referred to as electro-magnetic interference (EMI). EMI is, in fact, a very well-studied and documented science and the problems of solving these types of system inadequacies are well developed. Several excellent texts on the subject are [15], [16] & [17].

It is possible to breakdown the problem of EMI into a number of individual components that can be studied and dealt with one at a time at the concept development, design, installation and testing phases of any audio or video system. This system's approach to dealing with EMI is an effective and efficient means of attacking these problems. The following section, an EMI refresher, will help systematize the ideas that are used in understanding and resolving EMI problems.

1.2. An EMI Refresher

1.2.1. EMI ?

In order for Electro-Magnetic Interference (EMI) to occur, three elements must be present. These are:

- a source of electromagnetic noise (any electrical device)
- a transmission medium for the electrical noise to propagate in
- and a receiver that is sensitive to the nature of electrical energy being radiated by the source.

When each of these three elements exists, then the performance of the receiver, often referred to as the victim, may be adversely affected.

When this short coming exists, there are a number of ways of controlling EMI. The trick in the proper design of any audio or video system is to select the means of control that will most effectively deal with the problem without incurring undue cost. There are a select number of techniques that can be used in our quest for an EMI free world and these are discussed in the following section.

Specifically there are four means of transmission for electrical noise. It is important to identify how the noise is being transmitted to the receiver as this is a key factor in determining how it may be easily and effectively controlled.

The first form of transmission is referred to as common impedance coupling. This form of transmission occurs when there is a shared conductor (wire) between the source and the victim. This is obviously the case between any two pieces of equipment that are hard wired together be it through signal lines or AC power or ground lines. This subject is discussed in more detail in Section 2.2. See the figure in that section.

The next form of transmission is electric field coupling. The model of an electric field emanating from a wire is shown in Figure 1-1. This type of coupling is determined by the capacitance between the source and the receiver. It is proportional to: the area that the source and the receiver share between each other; the frequency and amplitude of the noise voltage; and the permitivity of the medium between the source and the receiver. It is inversely proportional to the square of the distance between them. Electric field coupling is a function, then, of the voltage of the source and it creates a voltage in the victim conductors.

The third form of transmission is magnetic field coupling. The model of a magnetic field emanating from a wire is shown in Figure 1-2. This type of coupling is determined by the mutual inductance between the source and the receiver. It is a positive function of the loop area of the receiver circuit, the frequency and the current of the source, and the permeability of the medium between the source and the receiver. It is inversely proportional to the square of the distance between them. Magnetic field coupling, then, is a function of the current of the source and it creates a current in the victim circuit.

The final form of EMI transmission is electro-magnetic radiation. This type of coupling occurs when the source and the receiver are at least 1/6 of a wavelength apart placing the receiver in what is known as the far field. The far field is defined as that distance away where the wave front is a plane and the ratio of the electrostatic and electromagnetic field strength is a constant (equal to 377). An example of an electromagnetic radiation is radio frequency interference (RFI) due to radio stations, CBs and other high powered transmitters.

1.2.2. Controlling EMI

There are a number of well established techniques to controlling EMI as discussed here.

1.2.2.1. Shielding

As the name implies, shielding consists of placing a conductive material between the source and the receiver. It can be done close to the source or close to the receiver. It is a very common technique with a well known application being the conductive outer covering on most audio and video cables.

1.2.2.2. Balancing and Twisting

Balancing refers to inputs and outputs of electronic equipment that have both an in-polarity and an out- of-polarity signal. Twisting refers to the twist in the interconnecting wire between balanced input and outputs. Together these two techniques provide substantial EMI immunity in interconnects. Twisting reduces magnetic pick-up almost completely by reducing the loop area of the cable to zero. Twisting the wires causes electric fields to induce common mode signals on the wire. As a balanced system allows only differential mode signals to pass through, these common mode signals are rejected. (For further detail on this subject see [1].

1.2.2.3. Separation and Routing

By proper separation and routing the effect of the EMI source on the victim can be reduced by the simple fact that the strength of the EMI is reduced with distance. Therefore, careful separation and routing of audio and video cables and the electronic equipment from noise sources is a simple and effective means of reducing EMI problems. The field strength for a point source drops 6 dB per doubling of distance while a line source drops 3 dB per doubling of distance.

1.2.2.4. Isolation

Anytime there is a conductor between a noise source and a victim there is a great opportunity for EMI via common impedance coupling. A very common and successful technique is to provide electrical isolation between the two. Isolation is typically provided by transformers, opto-isolators, or more recently fibre- optic connections.

1.2.2.5. Grounding and Bonding

Grounding and bonding consists of using conductive connections between equipment (bonding) and between equipment and the earth (grounding). The effects of this are two-fold. The connection to earth provides an infinite sink for the electromagnetic energy. The effect of this is to keep all of the equipment connected to the ground at a stable potential. The effect of bonding is to keep all of the equipment that is bonded together at the same potential. Bonding alone can be very effective. Bonding and grounding connections must be of very low resistance to avoid common impedance coupling.

1.3. When to Ground and to What Extent

It is difficult to know the trade-off between shielding, balancing, separation, isolation and grounding. There have been countless installations, particularly in the recording studio industry, where substantial efforts have been made to install grounding systems of extremely low impedance. Often these extreme measures are taken to obtain the last ounces of performance from the audio systems. In small systems the expense associated with going to these extreme measures is not large and consequently it is not a big issue as to whether these measures were really required. Often it may be more of a point of pride with the studio owner or builder with regard to the rigorousness of his grounding system. However, in larger installations or more cost sensitive ones, the necessary degree of complexity and robustness of the grounding system may be more of an issue. Depending on the architecture of the system it may be easier to use isolation techniques, such as balancing transformers to obtain the necessary results. Further as audio and video equipment improve with regard to the robustness of the input and output interconnections, the need for grounding systems will diminish.

1.4. Conclusion

Shielding and grounding are only two of many other means available for controlling EMI. The effectiveness of shielding will normally be determined by the designers of the equipment being used, such as the cable, the equipment racks, the electronic equipment cases, and so on. Designers have little control over most of these items other than by proper selection of the wire, racks and equipment. Grounding, where it pertains to large systems, is very much under the control of the system designer and the installers and it is an area where proper application of good engineering principles can result in benefits.

2. Technical Grounding Theory and Issues

Technical grounding refers to special grounding procedures, hardware or techniques used for the benefit of technical or electronic equipment. For example, the special grounding that is used in a recording studio or broadcast plant for the purposes of grounding the audio, video or control equipment is properly referred to as technical grounding.

2.1. The Isolated Star Ground

The isolated star ground system is an approach to grounding that has a minimum of technical compromises and meets the requirements of equipment grounding (as discussed in Section 4) while also providing a system that is relatively practical to install, troubleshoot and maintain. There are other approaches such as using a ground plane that will be discussed later, however, the isolated star ground is the most common system for technical grounding.

Figure 2-1 illustrates the basic geometry for a star ground system. We can see from the illustration that the ground system consists of a central point that stars out to local points that further star out to equipment within a given area. Within that equipment these grounds can further star out to the electronics, the shields and other systems and sub systems requiring a ground reference.

The entire technical ground systems of conductors and ground busses is insulated and isolated from all other systems with the exception of a single point at the centre of the ground system that must be, by electrical code requirements, connected to the other grounding systems within a facility.

There are several key points to be recognized regarding why this approach works. They are:

1. All of the electronic equipment within a given area has individual conductors providing it with a reference.
2. Each piece of equipment within a given area has a ground reference to the same level.
3. Every piece of equipment has only one possible path to earth.
4. Each piece of equipment has a similar resistance to ground.

Item one means the common impedance coupling is eliminated by pieces of equipment within a given area. As this equipment will normally have many signal interconnections it is subject to this type of EMI generation.

Item two means that all of the equipment in a given area will all have a similar reference as they are connected to the same point. Again, this will reduce common impedance coupling and the effects of common mode noise on differential lines. This item also means that any ground loops between equipment in a given area will have a minimum loop area.

Item three means that there will not be any ground loops as there is only a single path to earth. Note that while ground loops are not being creating by the grounding system it is possible through interconnecting cable to create a ground loop. This will be discussed later.

Item four means that given the system is picking up a certain amount of electromagnetic interference and sinking these noises to ground that all branches in the system will have a similar ground reference voltage (potential).

2.1.1. Levels of Ground

The star grounding system results in various levels of ground as follows.

2.1.1.1. Circuit Ground

All electronics require a ground that is routed through the circuit board. Each circuit board is housed within a chassis that has an equipment ground. At one point within the chassis the circuit ground is grounded to the equipment ground point for that chassis. This point being the star ground point for the unit.

2.1.1.2. Shield Ground

Each piece of electronics will have interconnecting cables for its signal inputs and outputs. The shields of these cables are normally grounded (often at one end only). The most common place to ground the shield is at the electronics unit where it terminates. Therefore, it is necessary to take the input/output connector ground pin to a ground within the chassis. How this is done is in fact critical and will be discussed later in Section 7 on equipment wiring.

Shield grounding can, of course, also occur at interim jackfields. In this case it is necessary to take a technical ground wire to the jackfields for this purpose.

2.1.1.3. Equipment Ground

The equipment ground refers to the ground reference to each individual piece of electronic equipment within an audio or video system. This ground is part of the safety ground of the electrical system and enters the equipment through the AC power cord via the third prong. This is a requirement of the electrical code. The code’s intention is that when the piece of equipment is plugged in, so that it may be powered up, that it is also grounded with that same connection point. In this way, it is not possible to have a piece of equipment that is powered up and not grounded. Tampering with this equipment ground, is illegal.

2.1.1.4 Master Technical Ground Reference Bus

This is the central hub for all technical ground conductors. There is only one within any given facility and it is this point that connects the technical ground system to the ground electrode system of the building as well as the electrical grounding system for the building. This point also grounds to the neutral conductor for the power distribution.

2.1.1.5 Local or Area Technical Ground Reference Bus

This point is connected to the master ground reference by a single heavy conductor. There are typically one or more of these in a facility and they are located near the equipment centers such as control rooms, machine rooms, remote amplifier rooms or mobile truck locations.

2.2. Common Impedance Coupling

Common impedance coupling can occur between any two pieces of electronics whenever they have a shared conductor, which has impedance, between them. A common example of this is a shared grounding conductor used by more than one piece of equipment. This is one of the main reasons why the star ground system is employed, however, the trade-off between loop area and common impedance coupling has to be considered. Figure 2-2a/b shows two examples of common impedance coupling. In Figure A, the example shows common impedance coupling via the neutral conductor. Figure B, shows common impedance coupling via a daisy chain ground. In this figure we see that any noise currents created by the two left amplifiers will create a voltage across R3 which will modulate the ground reference of the third amplifier. The common impedance R3 results in common impedance coupling.

2.3. Ground Loops

A major cause of failure of technical ground systems is ground loops. They result in electromagnetic interference. A ground loop, as the name implies, is created when a conductive loop is formed by the technical ground conductors and some additional conductor. A ground loop can be formed when a short to ground occurs in a technical ground system as shown in Figure 2-3 a/b. It is also possible to have a ground loop in a technical ground system when two points of the technical ground system are connected together usually through a piece of interconnecting signal cable as shown in Figure 2-4. In otherwords, ground loops can occur when a piece of technical equipment becomes grounded to building steel or some other conductive member. Alternatively, ground loops can occur when a piece of signal cable has the shield terminated to the technical equipment (and hence ground) at both ends.

The reason ground loops are detrimental to audio and video and related equipment is that when they occur stray currents begin to flow within the technical ground conductors. These ground conductors are used as the ground reference to the electronic equipment of the system. The stray currents consequently induce noise in the ground reference and this noise can be induced into the signal lines of the system.

2.4. Loop Area and Impedance

The idea of loop area is important to technical ground systems. We discussed earlier that when a conductive loop is formed, a magnetic field will induce a current into that loop. The current will be a function on the size of the loop and/or the strength of the magnetic field. (A larger loop will contain more magnetic field lines.) If the field increases or the loop area increases the current will increase. Obviously the EMI problem associated with this, then, increases with the loop area or the magnetic field strength. Figure 2-5 shows different scenarios where the loop area varies because of how the wiring was done and illustrates the effect that this has on the magnitude of the EMI. In one case, the equipment is grounded locally and the loop area of the ground loop is small. In the second case, the equipment is not grounded locally but some distance away and now the loop area is much larger. We would anticipate that the EMI problem, when a ground loop is present, is more in the latter case. This example illustrates an important issue of technical grounding and, that is, that it is necessary to consider the geometry of the ground and wires. While two different grounding systems may look equivalent, the fact the one has a larger loop area (a geometry problem not a circuit problem) means they may behave quite differently in practise.

Figure 2-6 presents another illustrative look at loop area and EMI.

2.5. Conductor Impedance

Impedance is defined as the AC resistance to electrical current flow. Impedance describes the resistance of a piece of wire in the presence of an AC or alternating current. Interestingly, impedance will vary with the frequency of the current in the wire. As the frequency increases so does the impedance. There are two major effects that cause the impedance of a piece of wire to increase with frequency. As many forms of EMI are high in frequency and in some cases very high in frequency - in the MHz - the impedance of the wire becomes a significant factor in determining its ability to drain away stray electrical noise.

The two main effects that increase impedance are the skin effect and the inductance of the individual conductor. One explanation of skin effect is that the internal inductance of a wire increases towards the centre making current flow easier toward the outside of the wire. The effect of this is that at very high frequencies most of the current flows around the outside of the conductor and consequently the conductor has effectively a smaller area causing its resistance to increase. The incremental self inductance of a single piece of wire is a function of its length and the radius of the conductor in centimeters. A piece of wire with a bend in it will have a greater inductance than a single straight piece. Therefore, it is important to route ground conductors with a minimum number of bends and turns.

Due to of the skin effect problem it is very common to use braided conductors or flat pieces of copper plate or ribbon. The reason for this is that they have a greater surface area and hence less skin effect. However, it should be noted that under normal EMI conditions the use of braid and straps is not required.

2.6. Standing Waves

As the frequency of alternating signals increases, the manner in which the signals propagate through a wire is governed by transmission line theory. While this topic is beyond the scope of this article an intuitive understanding of this topic can be gained by considering waves traveling down a river or channel. If there are any obstacles in the channel the waves become broken up and may be reflected back up the channel. The extreme case of this, is a wall at the end of the channel where the waves will be reflected complete back up the channel. It is possible under these conditions to have standing waves in the channel, where the waves traveling down the channel and the waves being reflected back up the channel interact with each other to create waves that are not moving longitudinally in the channel but simply moving up and down.

One of the effects of standing waves is that at certain frequencies of excitation a wire behaves as an open circuit. In otherwards, no electrical energy is transmitted through the wire. In this case, where a wire is being used as a grounding conductor, there is no grounding taking place. The frequency at which the standing waves take place is a function of the length of the wire. So for a given frequency there is always a wire length that given that there is a termination discontinuity at the end of the line, some energy will be reflected back down the line resulting in an impedance characteristic as shown in Figure 2-7. One solution to this problem is to provide multiple grounding paths of varying length. This, however, may create ground loops. This phenomena is one of the reasons why good high frequency grounding (in the MHz region) is so difficult to achieve.

2.7. Ground Planes - The Final Solution?

Given that at certain frequencies a conductor of a given length acts as an open circuit or at least its impedance increases, multiple ground routes are desirable. A ground plane consists of a large conductive surface. Obviously any two points between the surface can be connected through a large number of paths through the ground plane. This means that at any frequency the impedance between any two points on the ground plane will always be low. For this reason, ground planes are a very common technique used in circuit boards where they are easily implemented. The concept of ground planes can be applied to audio and video systems grounding, however, its clear that implementing a ground plane is considerably more difficult than implementing discreet insulated grounding conductors. Consider for example a recording studio with a large conductive mat placed below a carpeted floor. Every piece of equipment in the studio could be grounded to this mat at a point immediately below the equipment. Such a system would provide extremely low impedance between all pieces of equipment in the studio. However, it would be difficult to ensure that this ground plane did not become inadvertently shorted to building steel. Consequently these systems are somewhat unusual and found in only the most challenging of electromagnetic interference environments. One example of how grounding planes might be used in a facility is shown in Figure 2-8.

3. Shielding

Shielding is a technique used to control EMI by preventing transmission of noise signals from the source to the receiver. Shields can be located at the source or at the receiver or anywhere in between. In the case of electric fields where it is most effective, it is a function of the shield materials thickness, conductivity and continuity.

Shielding can be applied at many points in audio and video systems. Starting at the circuit level all the way up to the systems level such as in the case of shielded rooms. Regardless of the size of the shield, the physics of shielding remains the same.

3.1. The Shield and How it Works

There are two principle shielding mechanisms. These are reflection and absorption. When an electromagnetic wave traveling through space encounters a shield two things happen. First, much of the energy is reflected as shown in Figure 3-1. Second some of the energy that is not reflected is then absorbed by the shield. Only the residual energy emerges from the other side of the shield. These two effects of reflection and absorption are independent but they combine with each other to give the overall shields effectiveness.

A third factor called re-reflection occurs in very thin shields. This is also shown in the Figure. This secondary reflection occurs at the shield boundary on the far side of the shield material. This factor is fairly minor and is often ignored.

Most high frequency shielding problems are caused by openings in the shield material, not in fact by the material itself. Most conductive materials such as aluminum, copper and steel provide substantial electric shielding. For example, at frequencies from 30 to 100 MHz, even aluminum foil exceeds 90 dB shielding effectiveness. Unfortunately though, the same aluminum foil is extremely inadequate against low frequency magnetic fields where you need a thick steel or highly permeable material for adequate shielding.

3.1.1. Types of Fields

In analyzing shielding it is helpful to consider the three types of fields that occur. These different field types explain why the same shield can behave differently under different operating conditions.

3.1.1.1. Planes Waves

Planes waves exist greater than about 1/6 of a wavelength from the source. In this condition the ratio of the electric field to the magnetic field is a constant and equal to 377 in free space or air. The field is known as a far field or a radiation field. Examples of this, are radio waves.

At 30 MHz a wavelength is 10 metres, and so any transmitter more than about 10/6 or 1.6 m away is in the far field.

3.1.1.2. Electric Fields

If you are less than 1/6 of a wavelength to a high impedance source, the wave impedance is greater than 377. This is known as the near field and capacitive energy dominates. In the near field the losses are greater because of the higher wave impedance. This is why it is possible to do effective shielding from electric fields.

Another way of looking at this is that electric fields produce voltages in victim circuits. If you suspect that a given analog interconnect is electric field EMI, try disconnecting the wiring from the circuit driving the line and then shorting the signal pair together. Any voltage differential will be shorted out and the input should go silent, confirming the electric field. A similar experiment will be discussed for magnetic fields.

3.1.1.3. Magnetic Fields

If you are close to a low impedance source, in otherwords a current source, the wave impedance is less than 377. This is also the near field, but in this case inductive energy predominates. Reflection losses are much less here because of the lower wave impedance and this problem worsens as you drop in frequency. This is the reason that shielding is ineffective against low frequency magnetic fields (and why balanced circuits over twist pair wire are important).

Another way of looking at this is that magnetic fields produce current in victim circuits. If you suspect that a given analog interconnect is magnetic field EMI, try disconnecting the wiring from the circuit driving the line and leaving the signal pair open. Any current will be stopped and if the input goes silent, this will confirm magnetic field coupling.

3.2. Types of Shields

Aluminum and steel are the most common shielding materials in use today. Even thin layers of these materials provide more than adequate high frequency shielding from electric fields. Low frequency shielding, however, against magnetic fields must be done with steel. Aluminum is virtually transparent to low frequency magnetic fields - those below 1,000 Hz.

The effectiveness of a shield can be compared to that of a bucket for water. Even a small hole in the bucket will render it useless under some conditions. It is very important when attempting to create shielding that the shielding surface be conductively continuous. For example, in the case of a foil shield on a cable it is important that the way in which the aluminum mylar shield is wrapped on the cable provides a continuous circumferential conductive bond or that there be substantial overwrap.

3.2.1. Shielding Materials

Raceway Shielding					
Raceway Type	**Thickness**	**60-Hz Magnetic Field Attenuation**		**100-kHz Electric Field Attenuation**	
		(Ratio)	**(dB)**	**(Ratio)**	**(dB)**
Free air		1:1	0	1:1	0
2-in aluminum conduit	0.154	1.5:1	3.3	2150:1	66.5
No. 16 ga. aluminum tray *	0.060	1.6:1	4.1	15,550:1	83.9
No. 16 ga. steel tray	0.060	3:1	9.4	20,000:1	86.0
No. 16 ga. galvanized ingot iron tray	0.060	3.2:1	10.0	22,000:1	86.8
2-in IPS copper pipe	0.156	3.3:1	10.2	10,750:1	80.6
No. 16 ga. aluminum tray	0.060	4.2:1	11.5	29,000:1	89.6
No. 14 ga. galvanized steel tray	0.075	6:1	15.5	23,750:1	87.5
2-in electric metallic tubing (EMT)	0.065	6.7:1	16.5	3350:1	70.5
2-in rigid galvanized conduit	0.154	40:1	32.0	8850:1	78.9

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* We assume this should be No.14.

3.3. Maintaining Shield Integrity

3.3.1. Penetrations

Whenever a conductive material passes through a shield, for example, when a conductor passes into a metal enclosure, the effectiveness of the shield is greatly diminished. This is simply because any fields impinging on the shield on one side are conducted through the shield on the conductor and re-radiated on the far side of the shield. See Figure 3-2. Even the smallest opening with a conductor through it is a significant shielding problem. This explains the very common use of A/C line filters at the boundary of the power conductor entering electronic units. (These EMI filters are commonly terminated on an IEC type power cord on the unit.)

While penetration through shields can be signal or power lines, they can also be unintentional conductors such as the control shafts on potentiometers and other switches as shown in Figure 3-3.

3.3.2. Openings

Any opening in the shield will diminish its effectiveness. The most interesting thing about electromagnetic leakage through slots is that the longest dimension on the opening is critical not the total area of the opening. For example, a ten by 1/10th inch slot will be about 10 times more leaky than a 1 by 1 inch square hole, even though both have the same total area. The general guide line is that slots should be kept shorter than 1/20th of the wavelength of the highest frequency of concern. For example, at 100 MHz the slot should be less than about 6”, 300 MHz about 2” and 1,000 MHz about 2/3 of an inch. These dimensions will assure at least 20 dB of attenuation at the highest frequency. For 40 dB of attenuation you would need to keep the slots shorter than 1/200 of a wavelength.

The compromises resulting from openings of any sort make the idealized “Barbell” approach to shielding attractive. See figure 3-3. Coaxial connector realize this ideal.

3.3.3. Grounding the Shield

An actual connection to earth plays no part in EMI shielding effectiveness. The ideal EMI shield forms a continuous conductive layer around those items that it protects as shown in Figure 3-3. In the case of twisted shielded pair cable, normally terminated with an XLR, clearly there is an opening in the shield at the connector. By connecting the shield to the ground of the equipment case the continuity of this shield is improved, however, clearly it is far from perfect as the conductors are clearly exposed. In the case of coaxial connectors such as BNC’s, the shield makes a circumferential connection to the cable connector and that in turn makes a circumferential connection to the panel mounted connector providing 100% coverage of the inner conductor. In the case of coaxial cable, we have 100% shielding throughout the length of the interconnect and we have a ground loop that is formed between the send and received ends. This has always been one of the difficulties of the single ended transmission system used for video. In the case of audio equipment, the shield is never grounded at both ends to avoid this ground loop problem. At the high operating frequencies of video, maintaining the characteristic impedance of the transmission line (usually 75 ohms) and high frequency shielding are more important than maintaining the ground system integrity.

It should be pointed out, however, that many shields are also the equipment housing and require grounding for power safety purposes. For example, equipment racks are required to be grounded along with conduit and raceway, as well as the chassis of most electronic equipment. In this case the grounding is for safety purposes.

4. Grounded Power Systems

4.1. System Grounding

System grounding is illustrated in Figures 4-1 and 4-2 that show 120/240-V, 3-wire, single-phase power and 120/208-V, 4-wire, 3-phase power. In both cases one of the current carrying conductors is connected to earth. System grounding is defined as connecting to earth one of the conductors that carries power under normal operating circumstances.

It is interesting to note that the neutral conductor is, in most existing power systems, the conductor that is connected to ground. However, this is not the definition of the neutral conductor. The definition of the neutral conductor is that conductor which under balanced load conditions will carry no current. In otherwards, in a 3-phase system where each of the 3 phases has an equal load, the current in the neutral conductor will be 0. In practise, it is easiest to ground the neutral conductor.

4.2. Equipment Grounding

Equipment grounding consists of separate conductors that bond various elements of the AC system together and to earth. These conductors under normal operating conditions, are not connected to AC power. In otherwards, equipment grounding conductors only carry current under fault conditions. As a result of this, it is possible to also use equipment grounding conductors to ground sensitive electronic equipment or other devices that need a stable connection to earth.

4.2.1. The Kaufmann Experiment

This experiment conducted in the early 50's and documented in reference [14] illustrates the importance of routing the ground conductor with the power conductors. The experiment setup is shown in Figure 4- X and illustrates the typical arrangement that could be found on any job site. A current source was connected to the phase conductor and to pairs of possible ground return paths that included a #4/0 conductor run with the phase conductor in the conduit, the rigid conduit itself surrounding the phase conductor, a #4/0 wire run one foot away from the rigid conduit, and structural building steel. In a comparison of the relative impedance's of 100 feet of the rigid steel conduit versus the insulated #4/0 ground conductors routed external to the conduit, 95% of the fault current flowed on the conduit and only 10% flowed on the equipment grounding conductor routed outside of the conduit. This illustrates that the impedance of the conduit was 9 times less than the impedance of the grounding conductor routed external to it. However, when the #4/0 equipment grounding conductor was routed with the phase conductor inside of the conduit, 80% of the fault current flowed in the equipment grounding wire and only 20% flowed in the conduit. This experiment proves conclusively that the fault current which will flow through a ground conductor will be much higher when it is routed with the phase conductor. The importance of this is simply that in the event of a fault the circuit protection devise will be tripped much more quickly due to the high fault current. This minimizes the duration of the hazard. The results of the Kaufmann experiment are a primary reason why electrical codes require grounding conductors to be run with phase conductors.

It is interesting to note, when the building steel was compared to the rigid conduit 95% of the fault current flowed on the conduit and only 5% flowed on the building steel.

4.3. Safety to People and Equipment

The reasons for power systems grounding (systems grounding and equipment grounding) are to improve the overall reliability and safety of AC power systems. There are several situations that should be analyzed to fully understand how these grounding systems work together to achieve this goal.

4.3.1. Lightning and Transients

AC lines are often exposed to lightning strikes. In the case of a grounded system, the energy from these lightning strikes can be drained to earth through the ground connection as shown in Figure 4-4. If this ground connection did not exist, arcing from the conductors to nearby earth members would be the only way for this energy to leave the power system. Similarly, when switching large inductive loads on AC power systems arcing can also occur. Again, connections to earth help reduce this possibility.