THE HYBRID BARRIER: PROTECTING AGAINST EMP AND LIGHTNING

The majority of EMP-protected installations will be subjected to lightning phenomena during their working lifetime. Understanding the differences between lightning and EMP can bring about a joint solution for these hazards.

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INTRODUCTION

It is known that the design constraints for barriers to protect from lightning and from EMP are not the same, and the designer cannot assume that an EMP barrier will survive lightning unless both hazards have been considered at the design stage. Also the methods required for grounding and grounding topography differ. Unfortunately the majority of EMP-protected installations will be subjected to lightning phenomena during their working lifetimes. However, understanding the differences between lightning and EMP can bring about a joint solution for both hazards.

The mechanics and physics of both lightning and nuclear electromagnetic pulse (NEMP) have already been well documented, but it is necessary to reconsider certain salient features. When lightning occurs, strong updraft air currents prevalent in cumulonimbus clouds cause electrical polarization because of the ice formation and electron stripping. These potentials grow until a discharge path is made either between clouds or from cloud to ground. In the United Kingdom the number of thunderstorm days per year is known as the isokeraunic level and is typically twelve days per year. Obviously other countries are more prone to lightning because of different weather patterns, and in some parts of Africa the level can exceed a hundred days per year.

When a nuclear device is detonated, the resultant high energy gamma photons emitted will interact with atmospheric atoms to produce Compton electrons. In turn, these Compton electrons will experience a Lorenz force in the earth's magnetic field and will spiral round the field lines. This spiral motion will generate intense electromagnetic radiation termed exoatmospheric nuclear electromagnetic pulse (NEMP). Ground detonation will generate an endoatmospheric NEMP.

FUNDAMENTAL DESIGN CONSTRAINTS

By comparing the different design concepts, the design engineer can evolve a universal barrier solution that protects against both high energy lightning and fast-edged EMP. Depending on the scenario, it is most probable that NEMP will occur for a short duration in a battle situation after a relatively long working life for the system. Therefore, it is imperative that any protective barrier system be designed with a high MTBF (Mean Time Between Failure) of several decades. For lightning the time frame differs since it is a frequent occurrence and the protective device soon gives commercial returns, i.e., savings in system downtime and subsequent repair costs within a year or so.

Further the rise times and duration of lightning and EMP differ by several orders. Table 1 shows the comparisons. The values are only approximate for comparisons, and the rise time is defined as the 10 percent to 90 percent leading edge rise time in volts per nanosecond ($1E^{-9}$ seconds). The nominal duration is generally accepted as time to half-value from the leading to the falling edge of the pulse.

A Fourier transform analysis of the waveforms also highlights the spectral differences which are important when considering both barrier design and grounding systems. Ninety percent of EMP pulse energy (exoatmospheric pulse) is contained below the frequency of 10 MHz. Ninety percent of lightning energy is contained below the frequency of 10 kHz. The latter is an approximate figure; actual measurement depends upon the coupling method.

BARRIER DESIGN

Because the frequency spectra of EMP waveforms are higher than those of lightning, different design constraints must be considered. For frequencies above 1 MHz, the currents in a circuit will be subject to the skin effect and will travel on the surface of conductors. Also the impedance of the wiring is significant above these frequencies. Generally the wiring inside the barrier, the leads to the system, and even the ground cable can have appreciable impedances at these frequencies. For a specific

Waveform	Lightning	Exo EMP	Endo EMP
Rise Time	1 V/nsec	1000 V/nsec	400 V/nsec
Nominal Duration	300 μsec	0,2 μsec	

Table 1. Comparison of Waveforms.

Primary	Secondary	Miscellaneous
Fuse	Silicon Carbide	Transformer
Air Gap	Zener Diode	Relay
Carbon Block	Transorber	Opto
Gas Discharge		PTC
		Filter
MOV	MOV	
Thyristors	Thyristors	
Foldback	Foldback	

Table 2. Protection Devices

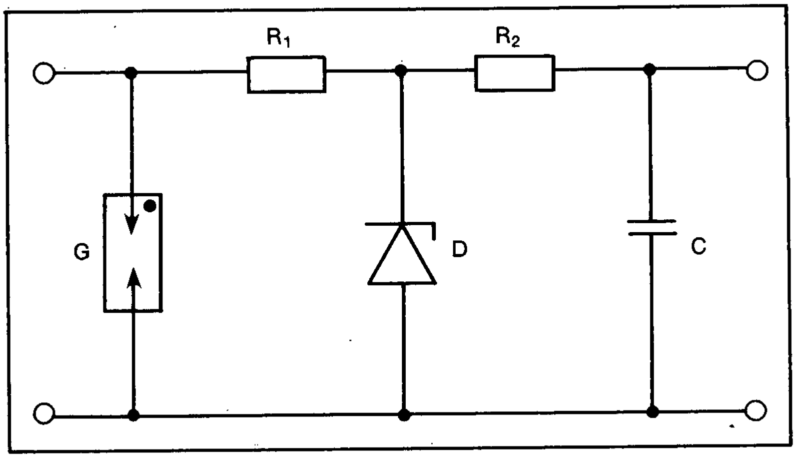

Figure 1. Simplified Drawing for Hybrid Barrier.

case, the inductance, L, of two parallel input wires can be shown to be:

$$L = \mu/\pi \cdot l_n\,(2D/d)$$

where

μ = permeability of free space

D = separation of the wiring

d = diameter of the cables

And the reactance, X, of the wire is given by

$$X = 2\pi\, f\, L$$

For wiring inside the barrier, the reactance is important. A small section of printed circuit board can have an appreciable inductance. As a matter of interest, a high value of reactance of series connections is generally desirable, and sometimes circuit designers deliberately increase the inductance. However, in looking at the merits of primary and secondary protectors which shunt the surge currents, it is obvious that this increased inductance is completely undesirable because emf voltages would be induced in series with the shunt element according to the formula:

$$\text{emf (volts)} = L\, d_i/d_t$$

As stressed earlier, the di/dt term (rate of rise of current with respect to time) for EMP waveforms is extremely high. For example, with 4 amperes per nanosecond with a circuit inductance of 0, 1 μH, the induced emf across the conductor would be 400 volts!

Of course, the concept of an ideal barrier involves the exact time period in which an electrical disturbance propagates along the barrier. This speed represents another practical reason for designing the shunt protector wiring as short as possible. In fact, there are two significant reasons. First, there is the inductance mentioned above. Secondly, the surge could travel past the shunt device before the protector turned on and tried to shunt the surge. The velocity of the surge as it transverses through the barrier wiring is less than that of the speed of light and can be calculated from:

$$C^2 = 1/\mu\epsilon$$

where μ is the product of both relative and absolute permeability and ϵ is the product of both relative and absolute permeability. A typical value for the propagation is 20 cm per nanosecond. The value indicates that if the shunt device had a turn-on time of 10 nanoseconds, the surge would have propagated 2 meters past the barrier.

Finally, to protect against EMP type waveforms with their high spectral content, it is vital that adequate shielding precautions be taken on both the barrier circuit and the protected victim circuit. All moveable doors and covers on the victim circuit should be mechanically secured, and electrical contact must be assured by using copper braid, phosphor bronze fingers, or the equivalent.

There is another consideration in dealing with lightning and with EMP waveforms, in particular. All power and signal lines entering into the protected zone or system under threat will act as transmission lines. Transmission line theory has been well documented. Essentially, surge currents will be limited by the characteristic impedance of the lines. The characteristic impedance, Z_o, of a pair of wires is given as:

$$Z_0 = \sqrt{(R + jwL)/(G + jwC)}$$

where

R = Resistance per unit length

G = Conductance per unit length

jwL = inductive reactance per unit length

jwC = capacitive reactance per unit length

Again by way of example, if the electrical breakdown characteristics of the cabling into the system were 10 kV and the characteristic impedance were 50 ohms, then by Ohm's Law, the maximum damaging current that could be caused would be limited to 200 amperes.

PRIMARY AND SECONDARY PROTECTION

Unfortunately there is one physical law that is never broken. One does not get something for nothing; there is always a trade-off. This maxim is particularly true when considering the merits of electronic protection devices. An examination of the merits of every protection device is beyond the scope of this article, but Table 2 shows the devices currently available. Obviously some are included only for comparison and for the reader's illumination, e.g., the fuse and the relay. Although they are important protection devices, they are totally inadequate for this application.

A primary protector is loosely defined as a device which can clamp, isolate or divert surges with a high energy content of approximately 10 joules or more. A secondary protector is loosely defined as a device which has a lower energy performance. However, secondary protectors generally work faster than primary devices; hence, the advantage of a hybrid solution.

Again referring to Table 2, there is a subgroup that falls midway between primary and secondary barriers. Among these devices is the metal oxide varistor, commonly known as an MOV, and the generic family of multilayer diodes, such as thyristors and foldback diodes. These devices are constantly being improved and may soon be allowed a place under primary protectors. It is also interesting to note that the manufacturers of primary devices are trying to increase their speed of operation so as to match that of secondary protectors and that the secondary device manufacturers are currently trying to improve their energy ratings to compete with those of primary devices.

An accepted primary protector is the gas discharge tube (GDT). This device has two significant failings.

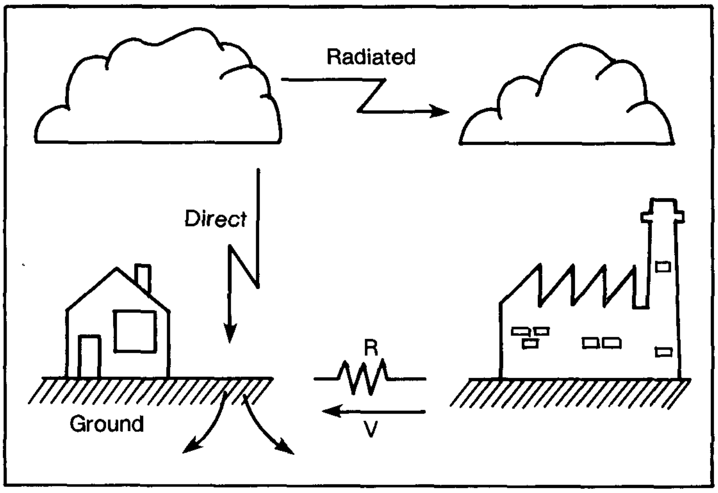

Figure 2. Mechanisms for Lightning Coupling.

	Lightning	ExoEMP	EndoEMP
Radiated	Low	High	High
Conducted	High	N/A	N/A
Ground Loop	Medium	N/A	Low

Table 3. Energy Summary.

The gas takes time to ionize; thus, there is a significant turn-on delay. Typical values are 0, 1 to 2 microseconds. Also the breakdown voltage is too high for semi-conductor devices. Typical values are 90 to 500 volts.

An acceptable secondary protector is the transorb diode. Although it has a lower energy rating, it more than compensates with its published turn-on times which are quoted as being in the order of several picoseconds.

THE HYBRID BARRIER

A hybrid filter ensures that device characteristics complement each other in an electrical protection circuit. The actual design values, final circuit and special resistor details are outside the scope of this article, but the general circuit is shown in Figure 1. This illustration is a simplified equivalent circuit for analysis only. A surge entering the hazard side of the barrier will be current limited by the resister R_1 until either the surge terminates or the primary protector fires. Because the current is limited, the secondary protectors will survive most anticipated conditions. Furthermore, they will clamp the surge to safe levels in a very short time. Resistor R_1 should be high-energy, wirewound and sand-filled. Self-inductance will cause a series reactance to EMP, and the sand-filling will absorb an instantaneous 5,000 watts when subjected to lightning as the air pockets surrounding the resistance wire suddenly expand. Any overshoots caused by shunt inductance mentioned earlier, firing delay of protectors or effects caused by stray capacitance will be attenuated by the output filter consisting of R_2 and C.

Thus with careful design, including shielding the output cables from the NEMP threat and segregating the "dirty" input connections, it is possible to create a hybrid which will handle both NEMP and lightning. Because it is technologically expensive and cumbersome to isolate all signal, data and power connections in a protected system, the hybrid barrier is often referred to as a "divert" barrier. With this barrier, potentially damaging EMP and lightning waveforms are effectively diverted away to ground. Even though this ground connection is fundamental and vitally important, a surprising number of systems engineers get it wrong.

GROUNDING

An understanding of the way energy from both NEMP and lightning is coupled into the system is fundamental to an understanding of the design of barrier grounding. Because lightning is a discharge process, there are several coupling methods as depicted in Figure 2. Radiated coupling results from a cloud-to-cloud or cloud-to-ground discharge. These discharges create electrical and magnetic fields which can couple into the system wiring thus destroying electronic devices through electrical breakdown. Fortunately the wavefronts for lightning are in the lower frequency spectrum, as compared to those of EMP; and the induced voltages, although frequent, are generally low in energy level.

A direct strike from cloud to system is extremely rare; and if the building itself is protected using the guidelines of BS6651, then this event is even rarer! For some situations, such as mobile tactical units in a hostile environment, this protection is not always practical; and severe damage can occur since the leader stroke from cloud to system is typically 30,000 amperes. Ground loop coupling results when a nearby cloud-to-ground strike induces high voltage potentials between different grounds in a system as the leader and subsequent currents neutralize the field potentials. This lightning phenomenon has a high probability of occurrence and can cause severe damage as the circulating currents pass between grounds and subsequently through the system wiring. The peak currents are generally limited by the ground resistance in the geographical area. In a granite terrain (high resistance) damage is

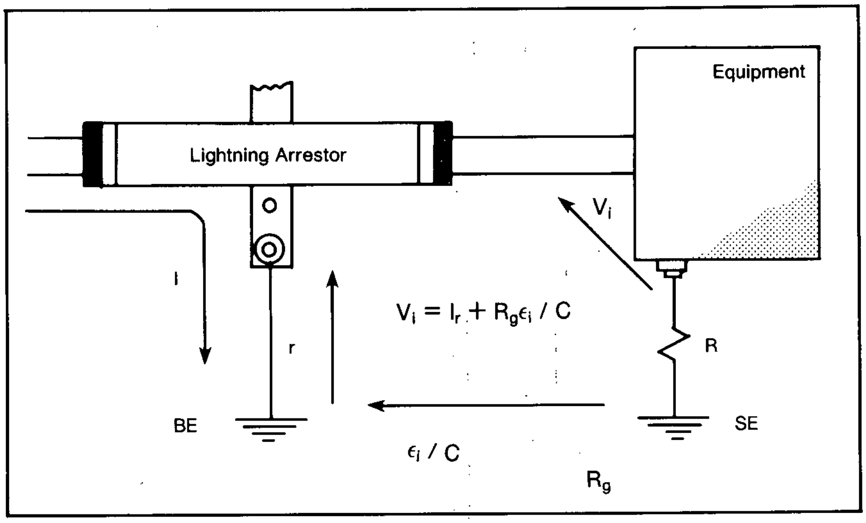

Figure 3. Currents Between Grounds.

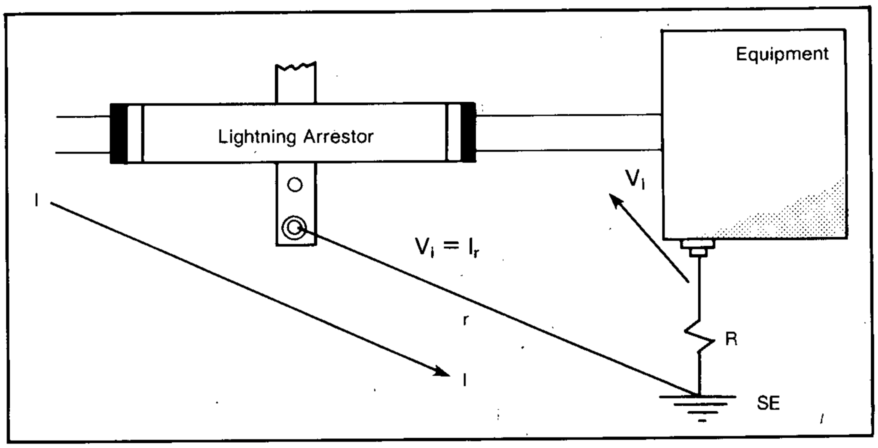

Figure 4. Star Point Grounding Connections.

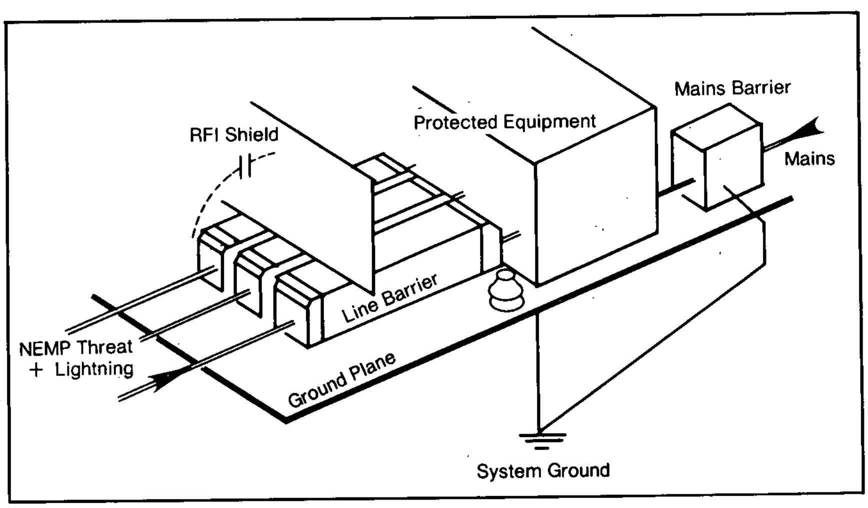

Figure 5. Grounding Constraints for Both EMP and Lightning Protection.

caused by high voltages; whereas, in a coastal or marsh terrain (low resistance), damage results from high circulating currents.

Because NEMP is a field effect, especially in the case of exoatmospheric bursts, the method of system coupling is largely radiated. All external wiring in a shielded location, and all internal wiring in an unshielded location will have induced currents and voltages due to direct radiation. The wavefronts will be extremely fast, and the resultant amplitude levels will depend upon the weapon yield and range of exposure. Table 3 summarizes these mechanisms.

GROUNDING AND LIGHTNING PROTECTION

Figure 3 shows how lightning activity can generate large, circulating ground currents. A proportion of the leader current will permeate across equipotential lines causing a high voltage to appear between buildings. Note that a direct strike is not necessary, and the storm only has to be close by for damage to occur. Clearly it is important to make sure that both locations have the same ground potential. The method for creating this equality is called star point grounding. The actual ground termination need only be large enough to dissipate the currents involved. Also it is important to note that the actual ground impedance need not be low since every potential will be relative to the star point. The star point method is shown in Figure 4. Here the user has some control over common mode potentials. Grounding topology is quite an involved topic; and the reader is directed to the bibliography for more rigorous treatments of the subject.

GROUNDING FOR EMP PROTECTION

Grounding to protect from EMP presents additional problems, apart from those associated with lightning protection. Stray capacitances become significant at higher frequencies, and proper care must be taken to reduce coupling between input and output wiring. To reduce common-mode voltage gradients, all barriers should be mounted on a ground plane. This ground plane should also be star-connected to the local ground. Figure 5 shows the differences and highlights the problems. It is assumed that the surges could be either EMP or lightning and that the actual "victim" equipment has been adequately shielded from EMP fields as discussed previously. Obviously in the case of EMP, the wiring down to ground will have high impedance, and there will exist a high voltage gradient from the chassis to the star connection during EMP activity. Provided that the equipment to be protected is on the same ground plane, then by the star point value rule, no common mode voltages will be generated. Ground loops will occur, however, between any adjacent grounded equipment. Therefore, it is important to treat each location as a separate problem with a common ground. Both mains and data lines should be fitted with EMP/lightning barriers.

CONCLUSION

An EMP barrier may not survive a thunderstorm because of the high currents, grounding considerations and long pulse times. Conversely a lightning barrier may not survive NEMP because of the very fast waveforms and resultant high frequency spectra. In its lifetime an EMP barrier and associated "victim" equipment (i.e., the equipment or system which must be protected) will undoubtedly be subject to lightning phenomena so it is important that it survive in a working state, through many storms, in readiness for a possible EMP threat. Finally it is possible to design a hybrid barrier which will survive both phenomena and which will protect the "victim" equipment effectively. ■

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