

Control House and Relay Design Considerations for EMP Resiliency

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Abstract: In the evolving world of politics, the threat of an Electro Magnetic Pulse (EMP – nuclear or man-made) and its potential effect on the electric power grid has recently received much attention by government officials as well as the power industry. Specifically, an EMP event is identified as a low probability / high consequence event. There are several types of EMP events that pose this threat, specifically: Nuclear ElectroMagnetic Pulse (NEMP), including High-altitude ElectroMagnetic Pulse (HEMP), Non-Nuclear EMP (NNEMP), Radio Frequency Weapons (RFW), Lightning, and plasma waves (similar to Geo-Magnetic Disturbances - GMD).

Of particular concern for electronic equipment is what is defined as an E1 wave which is the leading edge of the EMP wave. The E1 wave with which the power industry is concerned emits an electric field with a fast rise time (about 1 nsec) with a significant radiated field strength – estimated at 50 kV/m. Such a pulse has been demonstrated to cause catastrophic damage to electrical and electronic equipment by either direct radiation or by coupling with conductive materials (e.g. field wiring and transmission lines) and conducting extremely high energy electrical pulses into those equipments. Such conductive materials include metal control houses, equipment enclosures and housings, and power and signal conductors (wires and cables) entering and exiting such equipment.

There are a number of mitigation strategies available to the utility industry including hardened control house designs with highly-conductive coatings, gasketed entry ways, application of shielded cable, shielded cable entry ways, and EM filtered air intakes. Additionally, application of process bus technologies enables the optical substation where all entries into the control house are fiber optic. Devices themselves can be hardened through the application of fast high-energy absorption devices.

EMP Overview

An Electro Magnetic Pulse (EMP) can best be described as an Electro-Magnetic Tsunami released as a result of the rapid release of a large amount of energy. The typical association of EMP is with the detonation of a nuclear device – resulting in what is known as a Nuclear EMP or NEMP. A NEMP event results in three different types of electro-magnetic waves with significantly different time horizons as shown in Figure 1 (from the Homeland Security document₁ on this topic). The first wave to be emitted is termed the E1 wave. This wave has a rise time of less than 1 nsec and an electric field strength of 50,000 V/m which is also the reference value in the IEC Generic Standard₂ on this topic. The follow-up wave, known as the E2 wave has the characteristics of lightning which is a wave front 1000 times slower than the E1 wave or around 1 µsec. The third wave resulting from a NEMP detonation is known as the E3 wave and is an almost DC wave of plasma that couples with power lines and looks much like the Coronal

Mass Ejection (CME) from the sun that results in almost DC coupling to power lines – similar to Geomagnetically Induced Currents (GIC).

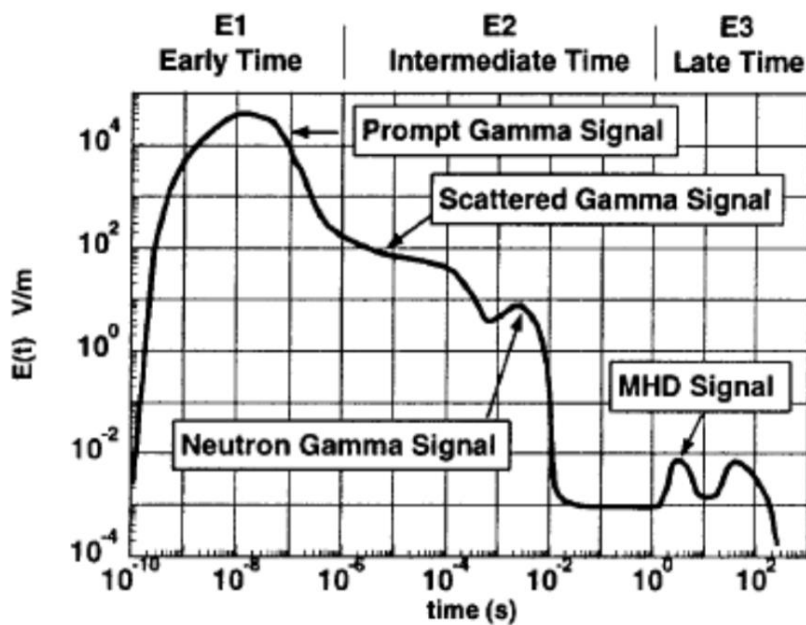


Figure 1
EMP Waveforms₂

The scenario of concern is the detonation of an atomic weapon at a high altitude. At a high altitude, the resulting “pulse” can effect a wide area. Such an event is a very low probability but extremely high impact,

In addition to a Nuclear EMP, Man-made EMP exists. With Man-made EMP, the focus is on generation of the E1 wave. In this paper, an E1 wave is generated in order to test the resiliency of power system equipment to the subject event. It should be noted that the Intelligent Electronic Devices (IEDs) on the power grid today are designed to withstand a lightning strike so the E2 wave is not a concern. Similar to NEMP, the Man-made (Non-nuclear EMP - NNEMP) starts with a source of stored energy which is then rapidly discharged through a tuned antenna. Design of the generator must take into account wave guide and antenna effects in order to optimize the E1 wave generation. A picture of an E1 pulse is shown in Figure 2. In order to perform these tests, a large Faraday Cage, (80’L x 40’W x 20’H in size) was used to contain the E1 pulse. The chamber was instrumented with multiple Tektronix 72504 Digital Oscilloscopes (25GHz instantaneous bandwidth on 4 simultaneous channels each) were used to connect to the D dot and B dot probes (for measurement of e-field and b-field respectively) in the chamber and as located inside the control house.

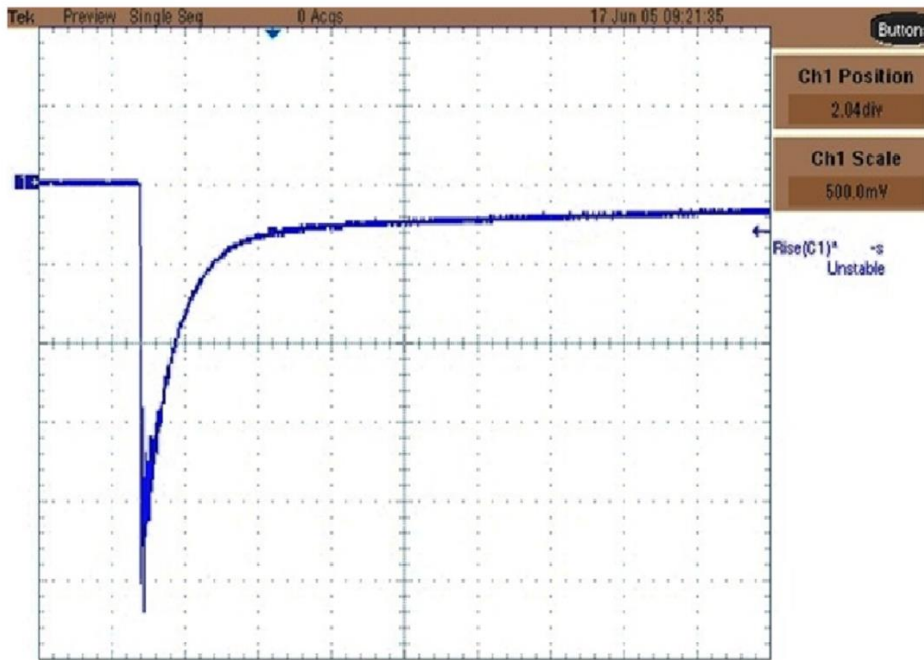


Figure 2
E1 Electric Field Wave Shape

Radiated vs. Conducted

Although the focus of the design criteria in this paper is on radiated EMP, conducted EMP from transmission lines is also possible. Measurement devices such as Current Transformers and Potential Transformers – due to parasitic capacitances – will conduct EMP into the terminals of an IED. Figure 3a and 3b (below) is a circuit model of a Capacitive Coupled Voltage Transformer (CCVT) and its associated frequency response. The plot only extends to 10kHz, however it can be seen in figure 3b that high frequency signal is still passed through to the relay, albeit, with about a 10x attenuation..

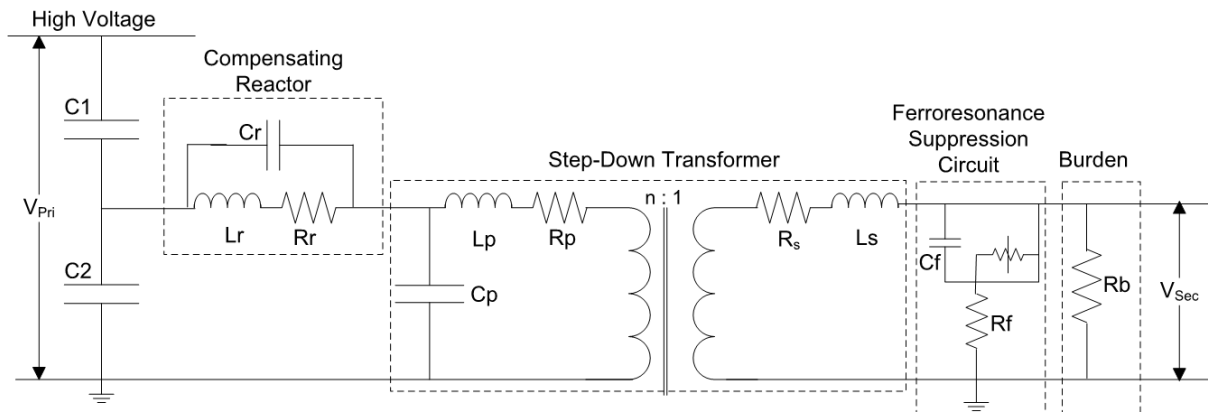


Figure 3a CCVT Model

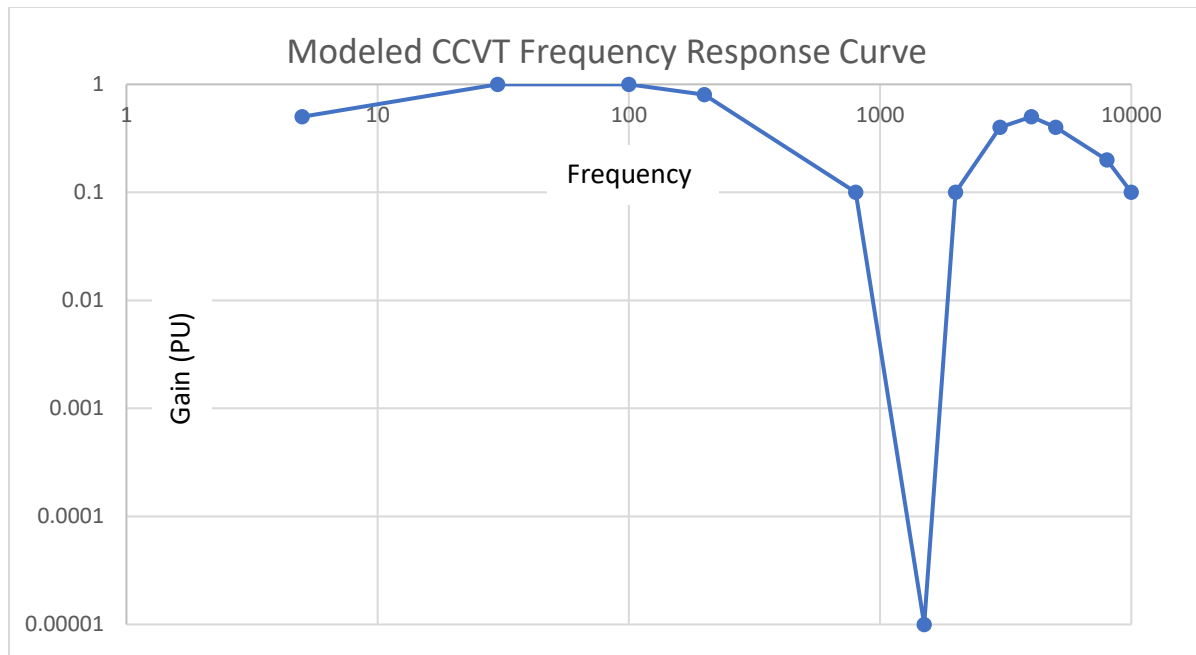


Figure 3b CCVT Frequency Response

General EMP Mitigation Techniques

One mitigation strategy for conducted EMP is the use of optical voltage and current sensors. These devices completely decouple the power line from the IEDs. High frequency signals may be modulated into light signals, however, when converted to an analog signal, the Anti Aliasing filter in the Merging Unit removes any of these frequencies.

Mitigation of EMP and other high level electromagnetic interference signals from the power grid is a decidedly non-trivial activity. It requires close attention to detail. The Faraday Cage, a continuous electrical shield which completely surrounds a device, room, building, etc., and has no apertures other than those absolutely necessary to bring power, signal, control and data into the shielded is most often used to protect high value electric and electronic devices and systems. It should be noted that a Faraday cage is only as good as its implementation and as such if not built correctly, or if cable penetrations are not installed meticulously, will probably leak.

A Faraday cage can be made from rolled and crimped steel, however, additional attenuation can be achieved through continuous welding of all seams in the cage. Even holes as small as 1/32 of an inch must be sealed. Particular care must be taken around doors and ventilation units. There is an excellent specification for the construction of honeycomb EMI filters found in MIL-STD-188-125₄ and MIL-Std-461₅.

Electrical lines entering a Faraday cage must be grounded and bypassed or otherwise filtered. This is a non-negotiable requirement. Where possible and practical, electronic equipment inside a Faraday cage should be battery powered. This is because it is not unusual for interference signals to be transmitted into a shielded enclosure by the grounding system.

The grounding system itself requires substantial attention. There are two schools of thought here. One states that the entire enclosure should have a single very low impedance ground (typically a wide copper strap of six inches or more in width) going to a welded or soldered connection to an underground grounding grid. Typical electrical practice uses a heavy wire loop buried four or five feet underground that surrounds the perimeter of the area to be protected. While this does provide signal attenuation to a certain extent, it is a “relatively” high impedance design and does not dissipate fast transients well. A better approach is to use a grid of two-inch-wide copper conductors on two foot centers, with each intersection Heliarc or cadwelded (a thermite based field welding technique). This design is common in data center construction. The Unit under Test was grounded at two corners.

Instrumentation is another area where close attention must be paid. It is generally agreed that the use of D dot probes are best for electric field measurements and B dot probes are best for magnetic field measurements. These probe designs are well described in the literature, but careful attention needs to be paid to the data reduction. A common mistake is to take the readings directly from the probes. In both cases, these probes are differential sensors and their outputs must be carefully integrated to produce an accurate answer.

It is frequently difficult to eliminate unwanted noise from fast transient measurements of high level signals, even when fiber optics are used. If noise is a problem, then the use of a noise channel which is a complete signal channel that has a termination instead of a probe on it, is used and the resulting signal is subtracted from the probe signal to produce a clean signal for display or further processing (such as integration).

Coaxial cable should be used with extreme caution as most coax leaks signals through its shields. The only form of coax that is largely immune to this is coax with a solid continuous outer shield, generally referred to as Heliax. While substantially more expensive and difficult to terminate, Heliax provides excellent noise free results. The use of double solid shields can lead to noise attenuation in excess of 120 dB, while a single solid shield will produce at least an 80dB reduction in noise.

IED Design Recommendations

Beyond normal electronic design for EMI protection, there are a several design practice e can be highlighted for the mitigation of EMP effects on IEDs.

High Power/Energy Transient Voltage Suppression (TVS) Diodes can be placed across vulnerable entry/exit points in an IED. A TVS diode features a very fast response and ultra-low clamping characteristics over traditional Metal Oxide Varistor (MOV) solutions. TVS diodes were designed to protect against voltage transient events, like lightning surge, switching transient, and Electrostatic Discharge and are somewhat useful in the protection of EMP events.

For an EMP event, because of the extreme induced peak voltages and currents, standard power TVS diodes, which only clamps a few hundred voltage, are not suitable to absorb the power/energy from an EMP event. There are, however, higher power/energy TVS diodes which are capable of clamping larger peak voltages which can be used on the AC current and voltage inputs and power supply inputs to prevent damage. Because of high reliability requirements for IEDs, it is recommended that high reliability TVS diodes be applied in this application.

Shielding and Grounding A metal enclosure of the IED components is recommended to provided shielding from radiated EMP. In addition to metal shielding, a adequate grounding and ground wiring with minimum ground impedance is proposed to reduce the common mode impedance. It is to be noted

that a flat braid ground wire has lower inductance than a solid copper wire and its use is a best practice in rack ground wiring.

Error-correcting Code (ECC) memory. In modern high-speed processor and memory electronic designs, a processor may run as fast as a few GHz frequency. The memory access speed can be as high as hundreds MHz frequency. A strong electric field from an EMP event may cause a bit error in such high-speed processing. Error-correcting Code memory technology can correct any single bit errors thereby providing improved immunity to the large electric fields emitted by an EMP event and subsequent processor lock-up and required re-boot.

Hardware vs. software watchdog. In the case where an EMP event does result in the latching of various logics in a processor and where no hardware damage occurs, a re-start of the processor may be able to clear the event and bring the IED back on line. The function to detect a latch-up is typically known as a Watchdog. If the Watchdog is not reset in a user-defined interval, it is designed to force a re-start of the system in an attempt to recover. It is strongly recommended that this function reside in Hardware so that a transient event cannot prevent a system re-start. The re-start should include power reset of the various modules of the IED.

IED Performance Criteria

When tested, an IED's performance can be classified into 3 categories:

Category 1: There were NO IED component failures and the IED continued to operate normally

Category 2: There were NO IED component failures, however, the IED locked-up and had to be reset

Category 3: There were component failures in the IED and normal operation was no longer possible.

Control House Design Criteria for IED Resiliency to EMP

For this test, two Control Houses were provided. One of these houses was a shielded design (See Figure 4); the other was identical except it was unshielded, providing a control sample. The shielded control house provided a six-sided, electrically-contiguous Faraday cage constructed of solid, highly conductive metals. Corner joints at floor, walls and ceiling were electrically bonded by continuous, mechanically-fastened, conductive brackets. Such corner joints can also be augmented with conductive paste, conductive gaskets or continuous welds, depending on the level of attenuation required. The resulting Faraday cage is generically referred to as the shield or shield layer. The typical control house (including this test model) will have multiple conductors entering and exiting, this necessitates that the shield be connected at one or more points to a low impedance earth ground. All conductors entering the test model were shielded cables whose shields were bonded to the house ground at the point of entry.



Figure 4 - Shielded Control House₃

The shielded control house was equipped with an RF personnel/equipment access door featuring continuous, 360° beryllium copper finger stock and a knife-blade door edge (see Figure 5). These blade-and-finger-stock RF seals can be single or double blade configurations, with the double blade configuration providing higher attenuation levels. The RF Door Frame was electrically bonded to the building shield which extends around its entire perimeter.

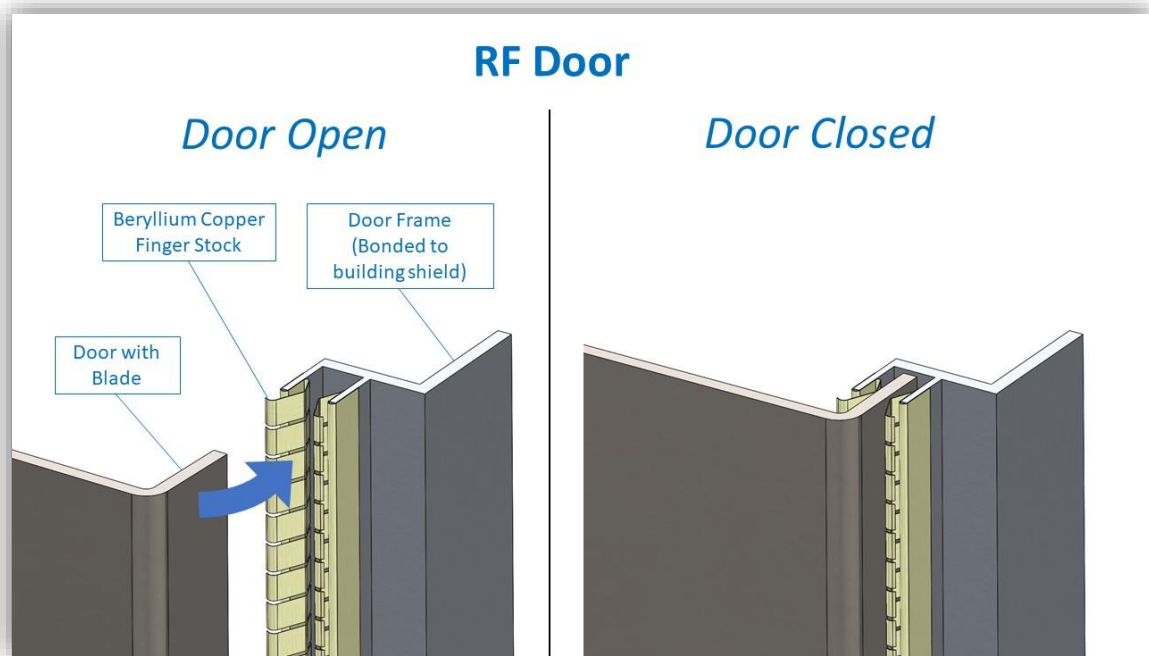


Figure 5 - RF Door with Beryllium Copper Finger Stock Gasketing₃

The shielded control house was also furnished with a typical fresh air intake, an air exhaust, and an HVAC unit, all of which require large penetrations through the shield layer. Such large airway penetrations are hardened against EMP by covering them with honeycomb vents (see Figure 6). A honeycomb vent consists of a conductive metallic frame bonded to the shield layer around its entire periphery. The airway itself is comprised of numerous hexagonal or other shape cells made of a conductive material and bonded to the frame. Each cell constitutes a waveguide whose maximum aperture dimension is $1/5$ or less the length of the cell. Greater Length/Width ratios can be employed for higher levels of attenuation (see references 4 and 5 for honeycomb filter construction).

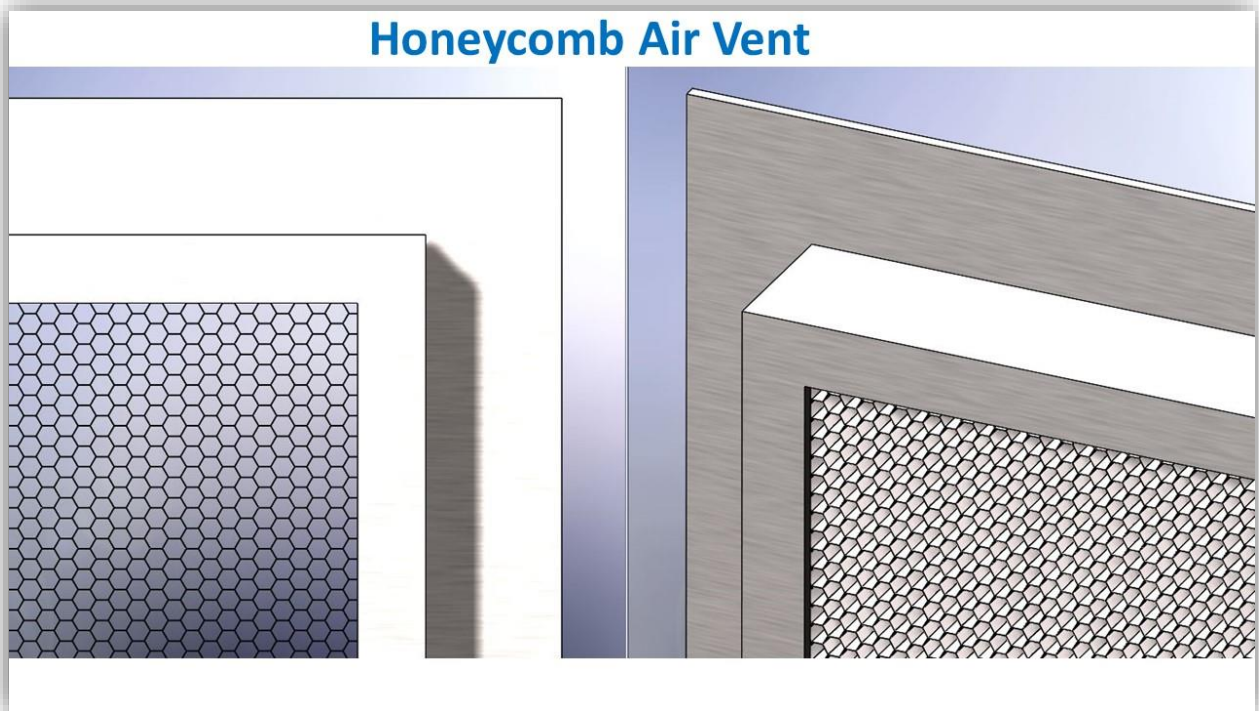


Figure 6 - Honeycomb Air Vent₃

The building shield addresses the atmospheric energy field. For conductors (wires and cables) entering or exiting the control house, special provisions need to be employed to prevent both radiated energy and conducted transients from being transmitted into the control house along these conductors. One method employed on the shielded control house was the use of shielded cables in conjunction with special conductor bulkhead feedthroughs (see Figure 7). These feedthroughs provide environmental sealing against moisture, air, dust and insect ingress; additionally, they possess features that connect the shields on incoming cabling to the shield layer of the control house. This provided a low impedance path to attenuate conducted transients from cable shielding directly to the building shield layer.

It is important to note that the foregoing discussion only addresses the electric field shielding issues. A true EMP pulse will have a large magnetic field component and failure to shield against that as well could result in destruction of equipment otherwise thought to be protected. Nuclear EMP standards call for 5000 Amp per meter magnetic field during testing. This is a very large value and must not be ignored.

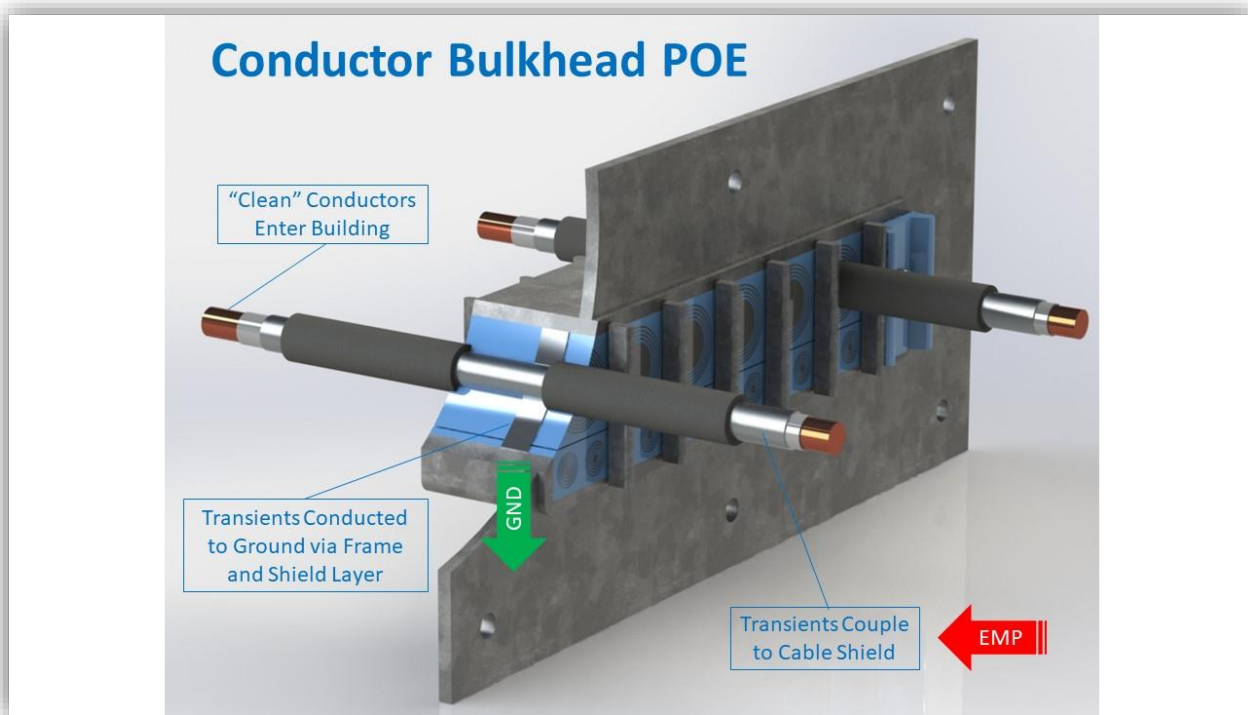


Figure 7 – Conductor Bulkhead Feedthrough₃

Test Set-up and Observations

The test set-up incorporated a range of IEDs including Electro Mechanical and Digital relays, GPS clock, Ethernet Switch, and SCADA RTUs. All devices were powered from a 120VDC power supply (10 – 12VDC batteries). The battery system was connected to ground via a resistive divider as exists in a typical substation to detect a battery ground. Analog inputs of Voltage and Current were provided from simple adjustable transformers (no electronics). All Digital Inputs and Digital Outputs were connected in Parallel and to a Lockout relay located outside of the control house. All wiring for this phase of testing was implemented using Shielded wire where the shield was grounded at both ends.

The test set-up can be seen in figure 8 where the test generator and antenna (seen to the left of the control house) is located at a calculated distance in order to bath the entire side of the control house with the EMP pulse. Since the test chamber is all metal, there are reflection off the walls that can be measured by the oscilloscopes. The external E and B field probes can be seen in the middle of the outside wall of the control house (figure 8). The internal probes are on the other side of the wall from the outside probes. All probes are connected to monitoring oscilloscopes through Helix coax cables.

The output pulse can be controlled in terms of rise time and magnitude with pulse rise times in the hundreds of Picoseconds. Figure 9 shows a frequency plot of the resultant e-field – outside (upper plot) and inside (lower plot) the control house – for a test pulse. The figure shows the frequency response for a 3 nsec test pulse with the primary energy centered around the 300 MHz range. Attenuation inside the control house was greater than 30 dB. There were no IED component failures nor did any of the IEDs lock-up – a Category 1 result.

It should be noted that independent of these test, other test facilities have performed radiated testing on IEDs and multiple vendor's devices have successfully passed the 50 kV/m test criteria with NO component failures and NO lock-ups – again, Category 1 results.



Figure 8 Test Generator and Control House in Test Chamber

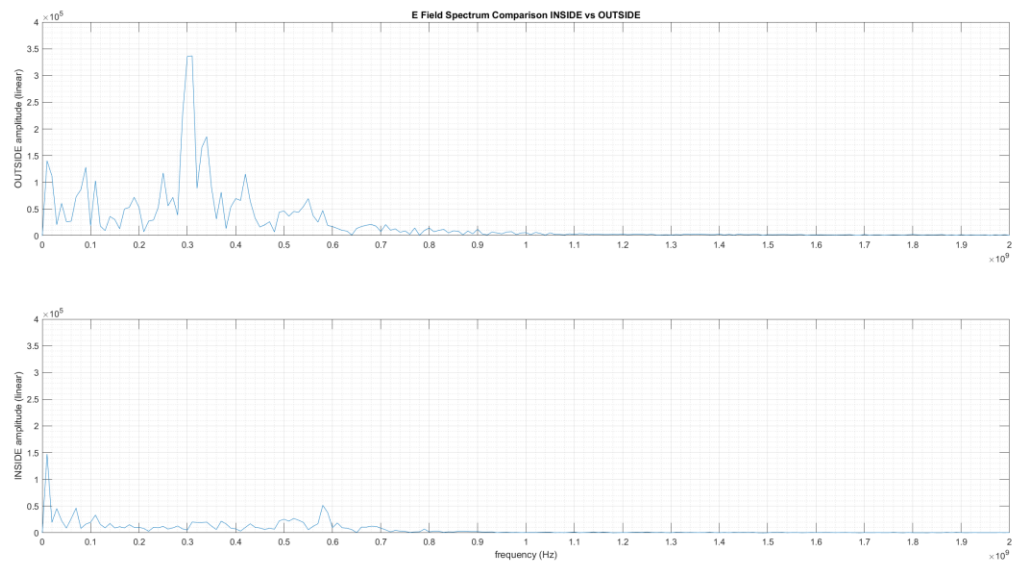


Figure 9 External vs. Internal Electric Field

Conclusions

The resiliency of the power grid to EMP events is critical to the continuance of society as we know it. There are numerous mitigation strategies and techniques that can be applied to achieve resiliency – such as IED design, shielding, and optical sensing. Utilities should start to develop a business strategy to address such as it clearly will become a requirement in the future. Testing in this area is ongoing.

References

1. STRATEGY FOR PROTECTING AND PREPARING THE HOMELAND AGAINST THREATS OF ELECTROMAGNETIC PULSE AND GEOMAGNETIC DISTURBANCES, US Department of Homeland Security, October 9, 2018; <https://www.hsdl.org/?view&did=817225>
2. IEC 61000-6-6 Electromagnetic Compatibility (EMC) Part 6-6 Generic Standards – HEMP Immunity for Indoor Equipment
3. EMP-Hardened Control House and related images © 2019 Trachte, LLC
4. MIL-STD-188/125, MILITARY STANDARD: HIGH-ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION FOR GROUND-BASED C4I FACILITIES PERFORMING CRITICAL, TIME-URGENT MISSIONS FOR COMMON LONG-HAUL/TACTICAL COMMUNICATIONS SYSTEMS (26 JUN 1990)
5. MIL-STD-461, MILITARY STANDARD: ELECTROMAGNETIC INTERFERENCE CHARACTERISTICS REQUIREMENTS FOR EQUIPMENT (31 JUL 1967)

Biographies

Roy Mao has a BS and MS in Electrical Engineering and is a Consulting Engineer with GE Grid Automation. He has 25+ years of hardware and electronic engineering in designing protection relay platforms, designing for reliability and electronic component engineering. Roy led architecture development for several new platform designs including protection relays, 61850 merging units, industrial Switches. Roy is a Professional Engineer of Ontario, Canada.

Harsh Vardhan is a lead application engineer with GE Grid Solutions, focusing on Digital Substation solutions for protection & control systems. Harsh has over 10 years of experience in the electric power industry. He holds a bachelor degree in electrical engineering and is a member of IEEE Power System Relaying & Control Committee.

Mark Adamiak has over 40 years of experience in the protection and control industry in both the utility (AEP) and manufacturing (GE) environments and has been involved in the creation of many IEEE and IEC standards. Mark is presently a consultant in the power industry and is involved in the protection of the utility industry from EMP. Mark is an IEEE Life Fellow and a member of the National Academy of Engineering.

Barry Howe is a Design Engineer at Trachte, LLC, and a serial innovator who brings visionary solutions to new product development challenges. With over four decades of design experience in a variety of industries, Barry has perfected an ability to consistently overdeliver while filling the gap between market need and engineering capability. He is driven by a love for pleasing his customer, whether that's the VP of R&D, an end user or an entire market sector. In every environment, from ambitious startup to Fortune 500 corporation, he has built a prolific legacy of innovation resulting in countless design awards and a string of domestic and international utility patents. When not busy engineering the next great thing, Barry enjoys flintknapping, archaeology and guitar.

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Notes from DHS document:

A draft executive order on coordinating national resilience to electromagnetic pulse incidents is currently being developed under the auspices of the National Security Council staff in coordination with Federal departments and agencies. Upon issuance, the executive order will obviously inform—and potentially alter—the Department's approach to the EMP-GMD threat that is articulated in this DHS Strategy.