EMP/HEMP Filters: Electronics assembly-level solution in the battle against intentional EMI and electronic warfare

Abstract

The world's most critical systems, including banking, transportation, energy, and government, now run on sophisticated digital systems and data centers, that leverage the vast networking infrastructure available in most modern countries. This critical infrastructure is increasingly vulnerable to disruption, and even destruction, from high levels of electromagnetic interference, which may be caused by natural phenomenon, or the result of malicious intent. Though it may be impossible to predict both intentional and unintentional electromagnetic interference, it is not impractical to protect against it. A new class of electrical filters, electromagnetic pulse (EMP) and high altitude EMP (HEMP) filters, are designed to suppress the EMI onslaught from nuclear strike level events, and lesser forms of EMI. Unlike other EMP/HEMP protection systems, EMP/HEMP filters are able to be installed to protect specific electronics and electrical systems, and not just provide general protection at the facility level. This type of targeted protection may be the solution for many susceptible electrical systems, from commercial, industrial, government, and military that may otherwise remain unprotected.

Introduction

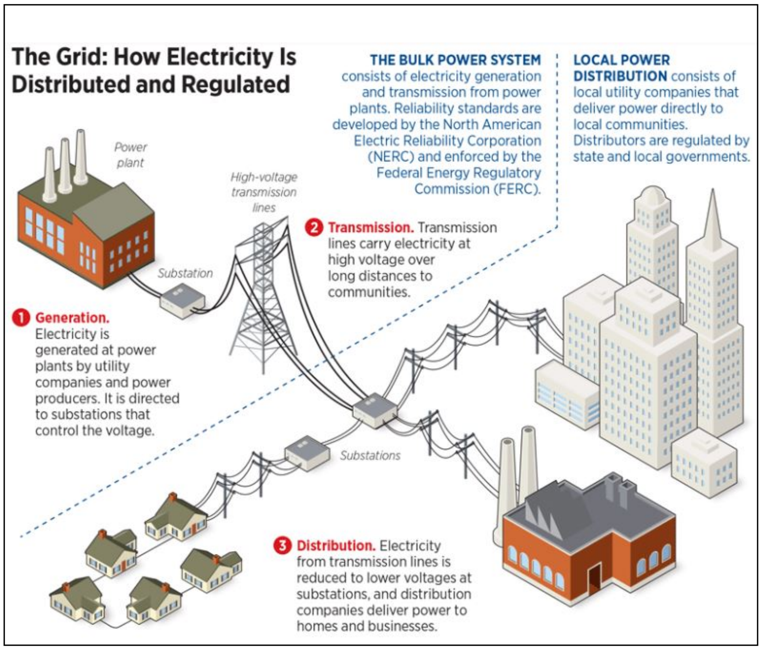
On October 9, 2018 the Department of Homeland Security (DHS) announced the release of the Strategy for Protecting and Preparing the Homeland against Threats from Electromagnetic Pulse (EMP) and Geomagnetic Disturbance (GMD). The Strategy lays out an approach to protect critical infrastructure and prepare to respond and recover from potentially catastrophic electromagnetic incidents. The strategy also reflects a consensus assessment of the EMP threat posed. Electromagnetic incidents caused by an intentional EMP attack or naturally-occurring GMD events could cause serious damage to critical infrastructure, including the electrical grid, communications equipment, and transportation capabilities. The Strategy addresses 3 main goals:

1. Improve risk awareness of electromagnetic threats and hazards
2. Enhance capabilities to protect critical infrastructure from the impact of an electromagnetic incident
3. Promote effective electromagnetic-incident response and recovery efforts

Spectrum Control has developed capabilities to effectively support DHS Strategy Goal 2.

As more critical applications are being deployed in networked systems and using the internet/cloud, virtually all organizations are now susceptible to disruption, and even destruction, of their essential systems and information from IEMI threats, including EMP/HEMP. The typical EMC standards that apply to data centers, computers, monitoring/sensing, and control electronics generally aren't adequate to protect against the types of energy induced in sensitive systems from EMP/HEMPs and IEMI technology.

Unlike most commercially available EMI filters, EMP/HEMP Filters are specifically designed to counter the conducted emissions from High Power Electromagnetics (HPEM), unintentionally, or intentionally, induced into the power line of a protected system. Subsequently, EMP/HEMP filters must tackle very different energy levels, waveforms, and frequencies than EMC filters, and understanding of these differences is critical in understanding the protection they provide. This white paper aims to describe HPEM threats to modern electronics, the differences between EMC and EMP/HEMP protection, and details regarding recently available EMP/HEMP Filter technology.



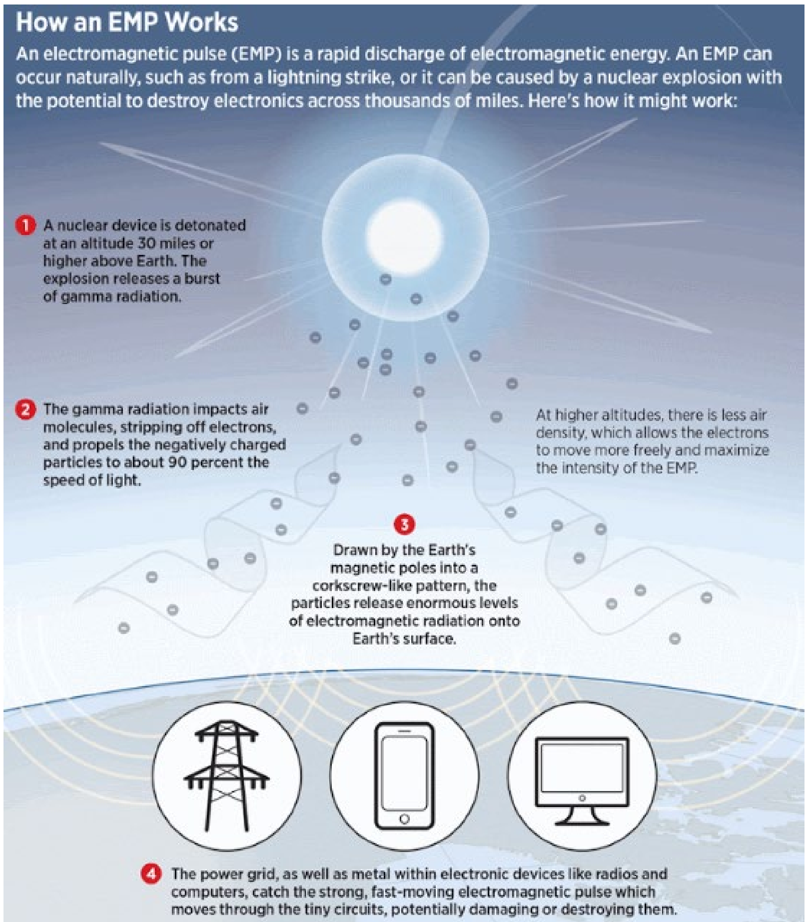
NOTE: FERC regulation does not include Texas.

An overview of common electrical distribution networks
Source: The Heritage Foundation Research

EMI, EMP, HEMP, HPEM, HIRF, GMS/GMD, CME, and Electromagnetic Threats

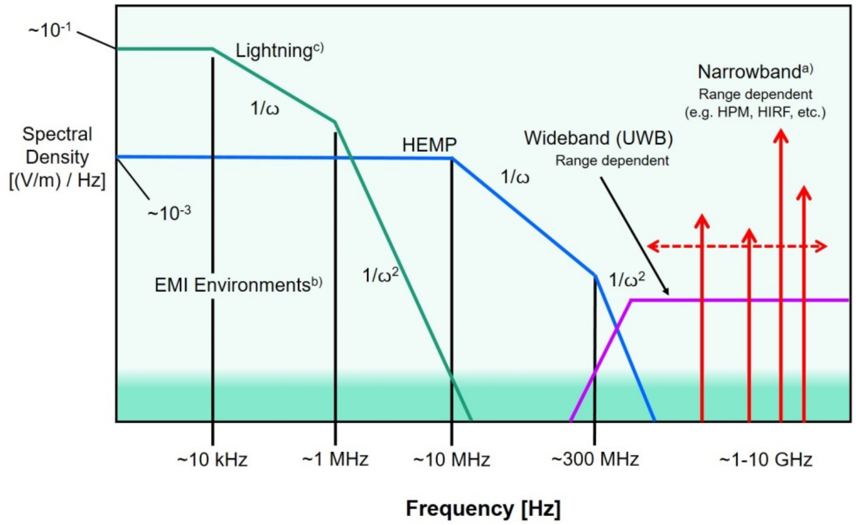
All electronics and electrical equipment are composed of electrical conductors within the devices and equipment themselves, and many additionally include conductors that connect the devices and equipment to peripherals or power sources. These conductors, regardless of size, all conduct electromagnetic energy (EME) that travels by, converting some of the EME from free space waves to conduct electricity (electrons). Depending on the size, shape, conductor composition, nearby conductors, nearby dielectrics, and nearby magnetic materials the amount and frequency of the EME conducted varies. However, common among all electrical equipment and electronics, the electrical design only accounts for the specified amount and type of electrical energy, with some margin for error and safety, and the addition of electrical energy can cause components within the electrical and electronic systems to behave different than intended, fail from a wide variety of electrical failure modes, or overheat and experience derated performance or destruction.

The EME otherwise not desired for electronics operation is called electromagnetic interference (EMI), and can be generated by unintentional, intentional, or natural means. To which degree and what type of electronics are affected by EMI depends on the power, frequency, time domain behavior, and pattern of the EMI, as well as the design and composition of the electronics and their interconnect. The common Electromagnetic Compliance (EMC) standards and regulation are designed, in part, to mitigate Unintentional EMI (UEMI) emissions from regulated electronics and to provide standards that enable electronic manufacturers to design devices to survive, to some degree, reasonable EMI exposure. There are also standards that account for common natural events that produce EMI, such as lighting storms and strikes.



EMP/HEMP overview
Source: The Heritage Foundation Research

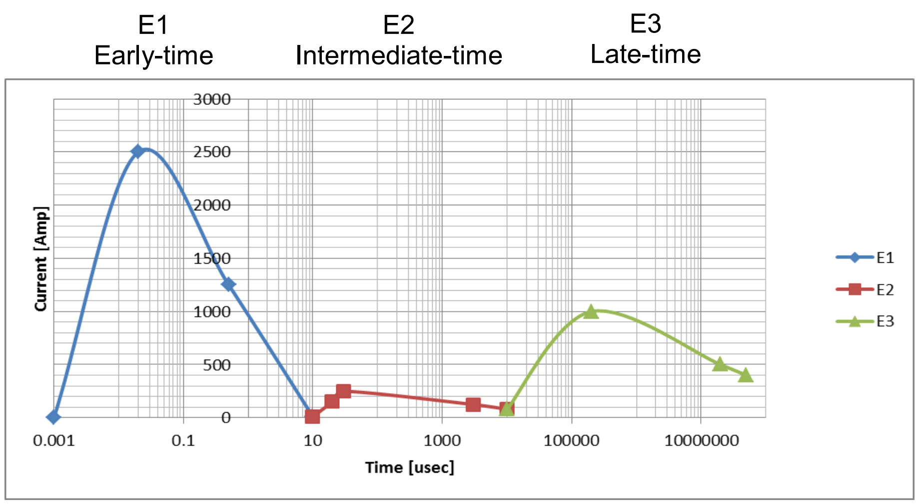
The most concerning type of EMI to critical infrastructure is high energy and short time duration discharges, known as High Power Electromagnetics (HPEM). Of these, Electromagnetic Pulses (EMP) type EMI is of the most concern, with a special classification denoted to an EMP created by detonating a nuclear weapon tens of miles, or more, above earth's atmosphere, High-altitude EMP (HEMP). Naturally occurring EMI from space weather and earth weather, such as Coronal Mass Ejections and Geomagnetic Storms/Geomagnetic Disturbances (GMS/GMD), can also create significant enough EMI to also be concerning to critical systems in similar ways as EMP/HEMPs are.



a) Narrow band extending from ~0.5 to ~5 Ghz
b) Not necessarily HPEM
c) Significant spectral components up to ~10 MHz depending on range and application

After the initial gamma ray expulsion occurs during a nuclear explosion, the earth's atmosphere reacts to the radiation, and generates additional EMP response. The complex response of HEMP has been documented experimentally, and is described as having three components, dubbed E1, E2, and E3. The HEMP components exhibit different time, frequency, and total energy responses, which may affect electronics and electrical systems in various ways.

EMP Pulse Configuration



Generally, the high energy and shorter time of duration events produce EMI with high frequency components, which are able to induce electrical response in smaller conductors, such as computers, communications, and portable electronics. Longer time frame events--where the total energy of the EMI is spread out over a longer time period--are more dangerous to larger electrical systems and electrical infrastructure, such as building electricity and the electrical grid. Hence, HEMP events and natural disturbances that cause similar EMI are of the most concern, as they exhibit a response that has both fast and slow components, which can adversely affect virtually all electronics and electrical systems, and is also challenging to protect against.

EMP Verses GMD Characteristics

Attribute	EMP	GMD
Cause	Adversarial threat	Natural hazard
Warning	Strategic: unknown Tactical: none to several minutes	Strategic: 18 to 72 hours Tactical: 20 to 45 minutes
Effects	E1: high peak – quick rise time E2: medium peak field E3: low peak field, but quicker rise time and higher field than for GMD (possibly 3 times higher)	No comparable E1 wave forms No comparable E2 wave forms E3: low peak field – fluctuating magnitude and directions
Duration	E1: less than a 1 microsecond E2: less than 10 millisecond E3 blast: ~10 seconds E3 heave: ~1 – 2 minutes	No comparable E1 wave forms No comparable E2 wave forms E3: hours
Equipment at Risk	E1: telecommunications, electronics, and control systems, relays, lightning arrestors E2: lightning – power lines and tower structures – "flashover," telecommunications, electronics, control systems, transformers E3: transformers and protective relays – long run transmissions and communication – generator step-up transformers	E3: transformers and protective relays – long haul transmission and communication – generator step-up transformers
Footprint	Regional to continental depending on height of burst	Regional to worldwide, depending upon magnitude
Geographic Variability	Can maximize coverage for E1 or E3 E3: intensity increases at the lower latitudes and as distance from ground zero is decreased or as yield is increased	E3: intensity increases near large bodies of water and generally at higher latitudes although events have seen in southern latitudes

Source: DOE Electromagnetic Pulse Resilience Action Plan

HEMP events affect a massive area, hundreds to thousands of miles radius from the epicenter, which makes the threat of HEMP an international concern. However, there are more targeted methods of IEMI, including High Power Microwave (HPM), High Power RF (HPRF), and High Power Millimeter-wave (HPMMW), which involve the use of directed EME. Jamming radar, GPS, cellular, WiFi, and emergency/military communications is a well-known uses of HPM/HPRF, but there is also now HPEM directed energy weapons that are powerful and directional enough to reach specific targets and do more damage than merely suppression or spoofing. These HPEM threats can be of a wide range of power levels and frequencies, and may even have the ability to change the characteristics of the EME they produce to affect distinct electrical systems or electrical devices. Though harder to protect against, some of the methods of protecting against HEMP can also mitigate other IEMI threats.

How Critical Electronics are Commonly Protected from EMI and HEMP

The amount of protection electrical systems or electronics require from HEMP and IEMI depend on several factors, including the natural EMI resilience of the system, the enclosure/installation shielding dynamics, and what current HEMP/EMI protections are already used. Military, space, aviation, government, and automobile organizations have already established regulations and standards that require some level of immunity to HEMP and HPEM threats, space and aviation systems are generally require the most stringent protections, as aircraft at higher altitudes are subjected to less attenuated GMD/GMS and space weather.

Nevertheless, these standards often focus on facility-level and larger electrical systems, and outside of military specifications (MIL-SPEC) specifically regarding HEMP, there have only in the past few years come IEC and other standards governing HEMP and HPEM immunity of critical systems and equipment [7,8]. Also outside of the military and government installations, HEMP and IEMI immunity protection is strictly optional, though the impact of a successful HEMP or IEMI attack against a datacenter, internet/cellular communications and networking, or autonomous driving system in a car or semi-trailer could be devastating in costs and loss of life [9]. As modern society becomes more dependent on smart and connected systems, such as the Internet of Things (IoT) or Industry 4.0, the potential impact of HEMP and IEMI threats will only grow with older systems becoming vulnerable due to upgrades and newer systems innately vulnerable due to their electronic and network communications capability.

Susceptibility Level of Electronic Equipment based on EMI Regulations and Standards	
Electronics Equipment at Risk from IEMI and HEMP	*Power Levels (V/m)*
Aircraft	7,200
Military Equipment	200
Automobiles	100
Network and Telephone Equipment	10
IT Equipment	10
Medical Equipment	10

Source: HEMP/IEMI Update: The Threat and Concerns Presented to IEEE EMC Society Chicago Meeting November 18, 2015

At Risk Electronics System/Equipment Type	**Risks and Risk Level**		
	E3 or GMS	*E1/E2*	*IEMI*
Hand-held and personal	None	Medium	High
Aircraft, ship, or vehicle	None	Medium	High
Control systems, SCADA	Low	High	High
Data-center equipment	Low	High	High
Communications networking and data lines	High	High	High
Electrical power grid	High	High	High

Source: HEMP/IEMI Update: The Threat and Concerns Presented to IEEE EMC Society Chicago Meeting November 18, 2015

Recognizing this danger, and how more military and government operations are relying on commercial equipment and civilian systems, the Department of Homeland Security (DHS) has released guidelines for protecting and restoring critical equipment and facilities susceptible to EMP [10]. The guidelines present four levels of consideration, depending on cost and how long the equipment and facility services can remain inoperable after an EMP event. The first level of protection recommends shielding and unplugging unprotected electrical systems and equipment, which would only apply to non-critical equipment.

The second level, for equipment that can be down for hours after an EMP event, describes the use of EMP rated surge protection devices (SPDs) with 1 nanosecond or faster response time and ferrites on electrical and electronic cabling. Shielding is highly recommended for facilities, rooms, and racks as it is considered more cost effective than hardening every piece of electronics. However, data and power cables that penetrate the shielding barrier will require additional EMP protection. For more essential systems that can only allowed to be down for minutes, the DHS recommends the use of EMP protection standards, such as IEC SC 77C and ITU EMP standards, and for the shielding to provide a minimum of 30-80 dB of protection to 10 GHz. For equipment outside of shielded areas, it is recommended to have SPDs for each piece of equipment.

Lastly, level four describes equipment that can, at most, be down for a few seconds. The DHS recommends the use of MIL-STD-188-125-1 and MIL-HDBK-423 for EMP protection for facilities, with greater than 80 dB of hardening through 10 GHz. As a note, the DHS recommendations don't mention MIL-STD-188-125-2, which describes EMP/HEMP protection for critical portable systems, which include systems that are not installed as part of a facility and otherwise shielding and protected as part of MIL-STD-188-125-1 requirements.

Department of Homeland Security EMP Protection Levels for Equipment & Facilities

Level 1 **Low $s**	Use procedures and "low cost" best practices to mitigate EMP effects. Unplug power and data lines into spare/backup equipment. Turn off equipment that cannot be unplugged and that is not immediately needed for mission support. Store one week of food, water, and critical supplies for personnel. Wrap spare electronics with aluminum foil or put in Faraday containers. Have backup power that is not connected to the grid (generators, solar panel, etc.) with one week of onsite fuel (propane/diesel). Use GETS, WPS, and TSP services; join SHARES if applicable.
Level 2 **Hours**	In addition to Level 1, use EMP rated surge protection devices (SPDs) on power cords, antenna and data cables and have EMP protected back-up power. Use SPDs (one nanosecond or better response time) to protect critical equipment. Use true online/double-conversion uninterruptible power supplies (UPS). Use fiber optic cables (with no metal); otherwise used shielded cables and ferrites/SPDs. Shielded racks/rooms and/or facilities may be more cost effective than hardening numerous cables. Use EMP protected HF radio voice/email if need long-haul nets. Suppress EMP fires.
Level 3 **Minutes**	In addition to Level 2, use civil EMP protection standards (like IEC SC 77C). Use EMP shielded racks/rooms and/or facilities to protect critical computers, data centers, phone switches, industrial and substation controls and other electronics. Shielding should be 30-80 dB of protection through 10 GHz. Use SPDs to protect equipment outside of shielded areas. Can use single-door EMP-safe entryways. Use ITU and IEC EMP standards for design guidance and testing. Have 30 days of back-up power with on-site fuel (or via assured service agreement with EMP resilient refuelers). Use EMP protected HF radio and satellite voice/data nets if need long-range links to support missions
Level 4 **Seconds**	Use military EMP Standards (MIL-STD-188-125-1 and MIL-HDBK-423, and 80+ dB hardening through 10 GHz. Use EMP/RFW shielding in rooms, racks, and/or buildings to protect critical equipment. Use EMP STDs to protect equipment outside of shielded areas. Use EMP protected double-door entryways. Have 30+ days of supplies and EMP protected back-up power (to include on-site fuel) for critical systems. Don't rely on commercial Internet, telephone, satellite, or radio nets that are not EMP protected for communications. Use EMP protected fiber, satellite, and radio links and services

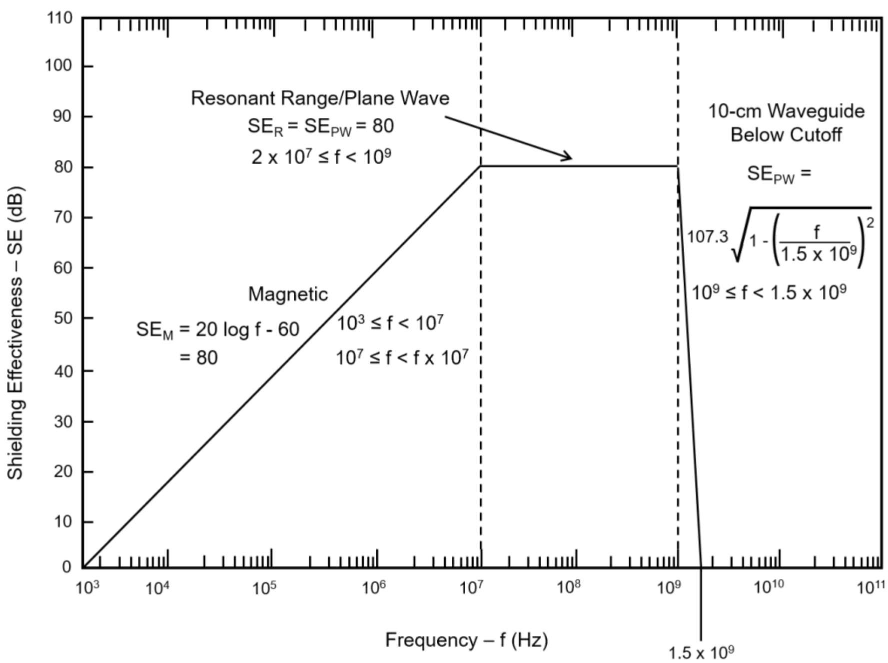
Source: US DHS EMP Protection and Restoration Guidelines for Equipment and Facilities

The DHS recommendations suggest using IEC and MIL standards for EMP protection, and the use of ferrites and surge protectors on power lines and data cables. However, ferrites and surge protectors don't generally offer substantial protection against fast transients, such as E1 waveforms. Where surge protectors typically force a disconnection, or high impedance, state when experiencing high voltages and currents, ferrites use magnetic permeability to create a filtering affect with the highest levels of attenuation in the megahertz frequencies. Hence, very fast surge protectors are necessary to be useful at all against fast transients, but are not ideal for equipment that needs to remain operational or would suffer from a hard cut-off from power.

Though, a surge protector could help mitigate damage from E3 waveforms, as most surge protectors are designed around protecting against EMI events such as lightning strikes and the E3 waveform and lightning strike waveforms are somewhat similar. Ferrites do provide suppression--not against higher frequency fast transients--and may not provide the adequate attenuation across the full frequency spectrum necessary for EMP/HEMP hardening.

What is actually required is a suppressive device with substantial attenuation from several megahertz to 10 GHz, where the majority of EMP/HEMP conducted energy is concentrated. This is where EMP/HEMP Filters are valuable, as they have the capability of being added, in-line, to individual electronics, assemblies, or equipment racks to provide a power line protected again E1, E2, and even E3 pulses according to MIL-STD-188-125-1/2. As EMP/HEMP Filters can be made for either DC or AC power, these EMP suppression systems can also be used with transportable systems (anything not integrated into a facility) such as land-mobile vehicles, aircraft, mobile shelters, mobile power sources, and provide levels of protection to AC and DC distributed power systems for sensitive electronics.

Minimum HMP Shielding Effectiveness Chart



Source: MIL-STD-188-125-2 Appendix A

It is important to distinguish EMP/HEMP Filters from EMI/EMC Filters commonly used in industrial and consumer applications. Though some EMI/EMC Filters could provide some suppression against E1, E2, and E3 waveforms, they generally aren't rated for the power levels or fast transients in the E1 and E2 waveforms, and generally don't have the necessary level of suppression to help meet MIL-STD-188-125-1/2 requirements of over 80 dB of attenuation from 10 MHz to 10 GHz for point-of-entry (POE) HEMP protection (See MIL-STD-188-125-2 Section 5.7.1).

EMP/HEMP Filter Function and Performance Requirements

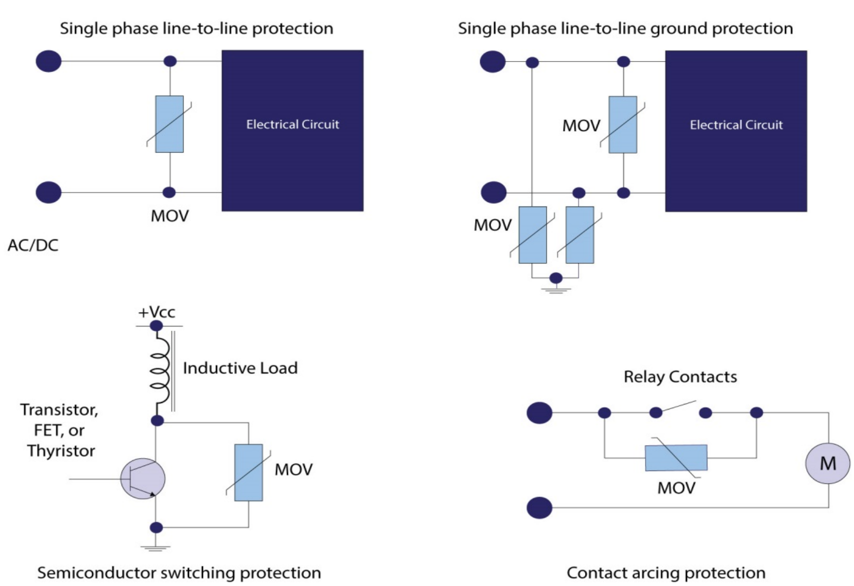
A true EMP/HEMP Filter is designed to work within a HEMP shielding system to provide in-line suppression to the power line of HEMP waveforms with mission critical equipment (MCE) without disrupting the operation of the MCE. For equipment that would suffer from the hard shut-off behavior of a surge protector/arrester, but still requires HEMP waveform suppression, EMP/HEMP Filters provide protection while allowing desired DC and AC power signals to pass through. Due to the substantial power levels and frequency range of HEMP energy, a EMP/HEMP Filter also needs to be robust enough to absorb the potentially destructive overshoot voltage.

EMP/HEMP Filter Function

An EMP/HEMP Filter includes a suppression circuit that enters a high off-state impedance, virtually transparent to the downline circuits, during normal operation. In case of a voltage overshoot that exceeds the switching voltage, the filter suppression circuitry switches to a very low impedance, high attenuation mode that shorts the excessive voltage and absorbs the excess energy within the filter. As long as the high voltage exposure continues, a EMP/HEMP filter is designed to maintain suppression until the voltage drops to a safe level below the switching voltage.

The high impedance suppression function of a EMP/HEMP filter is enabled by the use of a Metal Oxide Varistor (MOV), which is a type of voltage-dependent and non-linear resistor (VDR), or variable resistor. When a MOV is exposed to voltage that exceeds its breakdown voltage, the MOV impedance drops from its normal high impedance state to a low impedance state. In an EMP/HEMP Filter, the MOV is a short between the power line and a discharge resistor, which is how the excess voltage is absorbed. The main conducting region of a MOV acts like a dielectric below the clamping voltage, which allows the varistor to act like a capacitor rather than a resistor. In AC circuits, the capacitance affects the body resistance of the MOV in the non-conducting leakage region of its current/voltage (IV) characteristic. This means that when exposed to higher frequency AC, RF, and microwave frequencies, the MOV’s leakage resistance drops as a function of frequency, thus enabling very high attenuation at higher frequencies.

Common Electrical Protection Circuits Using MOV



EMP/HEMP Filter Key Performance Characteristics and Requirements

Key Performance Parameters

- Insertion loss (attenuation) *Frequency Dependent
- Operating voltage
- Switching voltage
- Current max
- Leakage current
- Dielectric withstand voltage
- Operating temperature
- Temperature rise
- MIL-STD-188-125 – filter residual let through (pass through current)

There are several requirements for EMP/HEMP filters to meet MIL-STD-188-125-1/2 requirements that exceed IEC HEMP filter requirements, and are based on decades of evaluation of experimental data taken during HEMP events. The most important criteria for the EMP/HEMP Filter is to survive and provide adequate suppression during EMP/HEMP events. This requires having adequate attenuation (insertion loss) at the necessary voltage levels to protect the downstream equipment, and the power handling capability to maintain adequate function and survive an EMP/HEMP event without degrading. And, otherwise, the EMP/HEMP Filter shouldn't impact the MCE's operation.

These requirements translate to a filter with an attenuation that meets with the MIL-STD-188-125-2 minimum shielding effectiveness requirement for POE protection devices, operation voltage and current specs that provide adequate power to the MCE, pass through current specifications that meet the MIL-STD-188-125 residual let through current requirements, and a device that can withstand the voltage transient spikes of an E1, E2, and E3 pulse without exceeding the filter's operating temperature.

Moreover, MIL-STD-188-125-2 section 5.7.1 describes the physical design of an electrical POE protective device, including enclosure and shielding considerations. It is important to note that if the enclosure or shielding of the MCE provides less attenuation than the EMP/HEMP Filter, than the shielding will be the weakest link in transient suppression, and the EMP/HEMP Filter will only be able to suppress the transient signals carried on the power lines, which may be the primary concern in some cases, depending on the power line and shielding dynamics.

EMP/HEMP Filter Testing (MIL-STD-188-125-2 & MIL-STD-220)

MIL-STD-188-125-2 indicates that an electrical POE protective device must undergo Pulsed Current Injection (PCI) testing according to MIL-STD-188-125-2 Appendix B. The exact requirements for the PCI testing depend on the intended use of the EMP/HEMP Filter. These type of filters can be usefully classified and tested as "Power Line LLPM" PCI requirements, of which Table B-IV in MIL-STD-188-12-2 Appendix defines the requirements for peak short-circuit current, source impedance, rise time, FWHM, and acceptance test resistance. Though there are several ways of testing and determining attenuation value, MIL-STD-220C describes the US military preferred method.

Conclusion

Though the US Military has been aware and has standards and regulations of EMP/IEMI protection, industrial, commercial, and civil electrical systems and equipment is largely unprotected. This is especially alarming as the threat from IEMI and HPEM weapons is only increasing as the technology for IEMI devices becomes more readily accessible and compact, while legacy systems important to societal function are increasing becoming electrified and rely on networked communications. Moreover, many organizational leaders are unaware of the magnitude of threat that EMP/IEMI weapons pose, and may also not be aware of EMP/HEMP mitigation technologies, such as EMP/HEMP Filters. Ideally, critical networking, communications, control, monitoring, civil, municipal, emergency response, and public safety will eventually all become protected from the dangers of EMP/IEMI prior to a catastrophic occurrence that makes it apparent that the cost of such protections is much less than the unfortunate inevitabilities without them.

Glossary

Acronym	Description	Acronym	Description
A	Ampere	**IEC**	International Electrotechnical Commission
AC	Alternating Current	**Hz**	Hertz
B	Magnetic Field Component	**IEMI**	Intentional Electromagnetic Interference
CME	Coronal Mass Ejection	**kA**	Kiloampere
dB	Decibel	**KHz**	Kilohertz
DC	Direct Current	**LLPM**	Long-line Protection Module
DHS	Department of Homeland Security	**LVD**	Low Voltage Differential
DWV	Dielectric Withstanding Voltage	**mA**	Milliampere
E	Electric Field Component	**MCE**	Mission Critical Equipment
E1	Early Time HEMP Pulse	**MHz**	Megahertz
E2	Intermediate Time HEMP Pulse	**MIL-HDBK**	Military Handbook
E3	Slow Time HEMP Pulse	**MIL-PRF**	Military Performance Specification
EM	Electromagnetic	**MIL-SPEC**	Military Specification
EMC	Electromagnetic Compliance	**MIL-STD**	Military Standard
EMI	Electromagnetic Interference	**MOV**	Metal Oxide Veristor
EMP	Electromagnetic Pulse	**Ms**	Millisecond
EMSEC	Emanations Security	**Ns**	Nanosecond
ESA	Electric Surge Arrestor	**nT**	Nanotesla
GHz	Gigahertz	**PCI**	Pulse Current Injection
GIC	Geomagnetic Induced Current	**POE**	Point of Entry
GMD	Geomagnetic Disturbance	**RF**	Radio Frequency
GMS	Geomagnetic Storm	**S/m**	Siemens/m
HEMP	High-altitude Electromagnetic Pulse	**SNR**	Signal-to-noise Ratio
HIRF	High Intensity Radio Frequency	**SPD**	Second
HPEM	High Power Electromagnetics	**Us**	Microsecond
HPM	High Power Microwave	**UL**	Underwriters Laboratories
HPMMW	High Power Millimeter-wave	**V**	Volt

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