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Electromagnetic Black Sky Responses of Power and Control Equipment

Performed for the Electric Infrastructure Security Council

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List of Acronyms

Acronym	Title
A	Amperes
A/m	Ampere per meter
AC	Alternating Current
C4I	Command, Control, Coimmunications, Intelligence
CDF	Cumulative Distribution Function
CT/CVT/CCVT	Current Transformer/Capacitive Voltage Transformer/Couple Capacitor Voltage Transformer
dB / dBm	Decibel / decibel = 10 log P1/1 milliwatt
DC	Direct Current
DTRA	Defense Threat Reduction Agency
E1	Short Pulse – Early Time HEMP Environment from MIL-STD-188-125-1
E2	Intermediate Pulse - HEMP Environment from MIL-STD-188-125-1
E3	Long Pulse - HEMP Environment from MIL-STD-188-125-1
EMC	Electromagnetic Compatibility
EMI/IEMI	Electromagnetic Interference / Internal Electromagnetic Interference
FMECA/FMEA	Failure Mode Effects and Criticality Analysis / Analysis
FWHM	Full Width at Half Maximum
GCB	Gas Circuit Breaker
GIC	Geomagnetic Induced Currents
GMD	Geomagnetic Disturbance
GSU	Generator Step Up Transformer
HEMP	High Altitude Electromagnetic Pulse
Hz	Frequency in Cycles per second kHz,MHz,GHz - kilo (1E3),mega(1E6),Giga Hertz(1E9
HV	high voltage
IPB	Iso Phase Bus
LA	Lightning Arrester
MHD	magnetohydrodynamic
msec,nsec,s	milliseconds (1e-3 seconds), nanosecond (1e-9 seconds),seconds
MIL-HDBK-423	"High-Altitude Electromagnetic Pulse (HEMP) Protection for Fixed and Transportable Ground-Based C4I Facilities, Volume 1, Fixed Facilities, " May 15, 1993.
MIL-STD-188-125-1	"High-Altitude Electromagnetic Pulse (HEMP) Protection for Ground Based C4I Facilities Performing Critical, Time Urgent Missions, Part I, Fixed Facilities", dated 17 July 1998, with Change Notice 1, dated 7 April 2005.
MIL-STD-464	"Electromagnetic Environmental Effects Requirements for Systems ", dated 1 December, 2010.
MOV	Metal Oxide Varistor (Surge Protector)
NERC	National Energy Regulatory Commission
OEM	Original Equipment Manufacturer
ORNL	Oak Ridge National Laboratory
PCI	Pulse Current Injection
PDF	Probability Density Function
POE	Point of Entry
PT	Potential Transformer
RF	Radio Frequency
SE	Shielding Effectiveness
TEM	Transverse Electromagnetic (Test Cell)
UPS	Uninterruptible Power Supply
V /m	Volts per meter
VAC	Volts - Alternating Current
VAR	Volt Ampere Reactive

List of Units

Quantity	**Symbol**	**Units**	**Abbrev.**
Current	I	Amperes	(A)
Electric Field	E	Volts/Meter	(V/m)
Frequency	F	Hertz	(Hz)
Length		Feet	(ft, ')
Length		Inches	(in, ")
Magnetic Field	H	Amps/Meter	(A/m)
Magnetic Induction	B	Tesla	(T)
Power	P	Watts	(W)
Relative Power	P	Decibels with respect to milliwatts	(dBm)
Decibels			(dB)
Voltage	V	Volts	(V)
Relative Voltage	V	Decibels with respect to microvolts*	dB(uV)
Resistance	R	Ohms	(W)

* *dB(uV) =dBm + 107. Vpeak for 0dBm = 316mV. Vpeak for 100W = 100V.*

EXECUTIVE SUMMARY

This report attempts to survey the responses of electric power system equipment and controls to two Electromagnetic Black Sky threats; High Altitude Electromagnetic Pulse (HEMP) and Geomagnetic Disturbance (GMD). HEMP E3 and GMD both produce induced Geomagnetic Induced Currents (GIC). In addition, HEMP produces faster upper atmospheric, plasma-induced E1 and E2 pulses that can directly couple to conductors. Both HEMP and GMD have caused power system upset and failures. The study is intended to identify equipment that is particularly sensitive to pulsed threats within the power gird.

Detailed component response discussions consist of probabilities of the occurrence of any non-normal behavior as a function of stress (voltage or current). Unwanted component responses can be characterized as one of three categories: 1. Upset – a non-normal state which recovers without any permanent effects and with no operator intervention required, 2. Latching Upset – a non-normal state which requires an operator intervention or power interruption to recover, and 3. Damage – a non-normal state which is due to permanent damage or degradation outside of the normal operating range requiring replacement of a component to allow normal operation. The latter is the type of response of most interest in this effort.

These electromagnetic fields and the currents and voltages induced on conductors into and within electronics and electrical equipment provide for a stress to strength comparison. The impact of induced currents was tested using Pulsed Current Injectors (PCI) with 50-60 Ω, 3000-5000 Amperes peak, and 150 to 300 kV open circuit voltage, and direct radiation impacts were tested using Transverse Electromagnetic (TEM) field simulators. The strength – the level at which the component suffers degradation or damage – can be measured in simulators and bench tests but statistical damage data on large power equipment and even on auxiliary equipment is not common.

This survey included equipment and components common in power generation plants and transmission substations. The equipment was organized into 5 groups of equipment, uses specific data when this data exists, and categorizes these groups into generic risk categories. It is intended to help power grid owners/operators in identifying and targeting areas where additional effort is required (while avoiding wasted effort) to achieve improved resilience of the power grid as a whole. Note: This study focused only on power system equipment. It is well known from previous studies that computer-based control systems (e.g. SCADA) are vulnerable to both radiated and conducted E1 pulses.

Important to Note: this study (and all others on this subject, to date, with the exception of actual HEMP tests conducted in the early 1960's) is, by necessity, reductionist – it examines individual electric grid components in isolation, and how they respond to specific components of a HEMP pulse. In reality, all of the components are functioning in an interconnected grid, and would be exposed to E1, E2, and E3 in succession during a real HEMP event. Specifically regarding EHV transformers, the impact of E3 could be amplified if relay protection is compromised by the E1 pulse, which could direct higher levels of E3 currents through some transformers if, for example, significant numbers of transmission lines are tripped offline by damaged relays. PTs, CTs, GCBs, and LAs could also experience adverse effects due to the rapid succession of the E1, E2, and E3 pulses. A fuller accounting of the entire HEMP spectrum and the effects on a fully-connected grid should/will be explored in future studies to better determine the expected impact of these compounding effects. In the meantime, conservative engineering judgement is recommended to help ensure the best protection for electric grid components for the full HEMP spectrum.

Summary of Initial Findings

a. Control Equipment consists of relays, and sensor inputs to transmitters / computers. EMP conducted-current tests of relays have been performed by DTRA. Six representative digital relays (2 copies each of three relays) were tested for TEM and PCI stress in both protected and unprotected modes. In the TEM tests, only one relay suffered a minor Upset in its display, even without protection (which for radiated fields would be EM shielding surrounding the relay). For the PCI tests, five of six samples tested in the unprotected mode were permanently Damaged at some level of stress. The sixth suffered a Latching Upset. In the protected mode (Simple non-linear MOV protection properly mounted and isolated from the equipment), the relays demonstrated a significant improvement in their responses: only one of the six relays tested suffered a minor Upset to its display when MOV protection was used. Two representative electromechanical relays were also tested, and suffered no Upsets, up to maximum stress levels, in an unprotected mode.

b. Substation battery chargers for the remote-control systems were also tested. The representative battery charger was Damaged at the maximum stress level, but suffered only minor Upset at lower stress levels. The representative battery charger tested has built in non-linear protection. It is believed that isolating this protection would likely improve the effectiveness of the protection. This work and retest is planned for later this year.

c. At power generation plants, the high voltage side of Generator Step-Up (GSU) transformers, are most likely unaffected by HEMP E1 or E2, but can be affected by HEMP E3 or GMD if connected to long lines. The GSU is directly affected (for both HEMP E3 and GMD) by resulting harmonics and VAR, and the GSUs harmonics can introduce sub-synchronous resonances in generators and turbines, possibly causing permanent damage. Because HEMP E3 is short-lived (a short 10-second pulse followed by a second pulse lasting for approximately 2 - 4 minutes, see Figure 6), and GSU's are full transformers rather than autotransformers (and therefore do not have tertiary windings), thermal impacts on GSUs are likely limited to local hot spots. Bulk heating is less of a HEMP E3 concern, though it does become a concern for longer GMD events.

d. Several generation plant Distributed Control Systems were surveyed. Although direct tests were beyond the scope of this study, wired connections (ethernet, CAT) represent a vulnerability for both radiated and conductive stress and should be shielded and filtered.

e. For generator excitation systems, based on the systems reviewed (but not tested), the available data suggest that rated strength for both E1 radiated and conductive stress could cause damage or upset, and should be shielded and/or filtered. E3/GMD is not expected to be problematic.

f. Generating plant sensors include temperature, pressure, speed, position, optical, and mass flow sensors among others. Because plant sensors and transmitters are not connected to long lines, E3/GIC stress/strength/mitigation has been determined not to be a concern. For HEMP E1, wireless, battery powered sensors and transmitters are minimally affected by the HEMP E1 radiated stress because 1) they are out of band of the of HEMP, being 2.4GHz and above 802.11 devices and 2) their size is less than λ/2 at 1GHz, and are minimally affected by the HEMP E1 conducted stress because there are no attached signal or power wires. Wired sensors and transmitters should be tested for HEMP E1 impacts, but this was beyond the scope of this study.

g. At transmission substations, the high-voltage interface of power components – EHV Transformers, Potential Transformers (PTs), Current Transformers (CTs), Gas Circuit Breakers (GCBs) and Lightning Arrestors (LAs) – are the least likely to fail due to E1, E2, or E3. These results are not generated by system or component level HEMP related tests. Rather, for the E1 threat, the estimate is based on the peak leakage voltage past / through the LA which is then compared to the lightning and other slower breakdown thresholds. An arc on the outside of a bushing is the most likely E1-related problem and is a recoverable event and thus does not represent the damage event of interest in this survey. LAs could, however, be at risk of damage on the low-voltage side for E1, E2, or E3 pulses. The E3/GIC assessments for EHV transformer manufacturers are based on calculations of the bulk heating which itself is not likely of concern for HEMP E3 (a short 10-second pulse followed by a second pulse lasting for approximately 2 - 4 minutes, see Figure 6), but does contribute to accelerated aging and the failures associated with that for long GMD/GIC events. That said, detailed analysis of hot spots in structural elements and especially tertiary windings in autotransformers were not investigated in this study and remain an area of concern for E3. The low voltage side of CTs, PTs, and GCBs represent the biggest unknown based on complexity of the control wiring, and a complete lack of data (to date).

Methodology: Testing and Research/Extrapolation used (and compared/contrasted) the U.S. Military Standard (MIL-STD) and the International Electrotechnical Commission (IEC) Standards.

The primary threats (including all three time domains: E1, E2, and E3) acknowledged by the MIL-STD and IEC 61000 have been compared and are similar; tests and test techniques are also similar; but the *methodology for relating the equipment level data and the system hardness differ substantially.*

a. The peak fields, currents and voltages are within 50% / factor of 2 for the two standards (50 kV/m, 3000-5000 Amps peak, and 150 to 300 kV open circuit voltage). Importantly, of all the 78 individual components reviewed, only DoD or DOE have actually tested to levels approaching required MIL-STD or high IEC 61000-4-25 HEMP levels. ***Equipment vendors do not typically certify for the HEMP resilience of their equipment.***

b. Simulators with comparable characteristics (Pulsed Current Injectors (PCI) with 50-60 Ω, 3000-5000 Amperes peak, and 150 to 300 kV open circuit voltage, and Transverse Electromagnetic

(TEM) field simulators) are required by both standards in the HEMP related tests.

c. Both standards acknowledge the effects of shielding and conducted penetration attenuation.

d. The approaches, however, are quite different. The MIL-STD requires their verification by test (traceability), while there is no released system level verification requirement or traceability for the IEC standard. The authors characterize the MIL-STD as a system level top down approach, and the IEC approach as a bottom up building block approach. MIL-STD-188-125-1 is based on system level testing while IEC 61000 assumes a system protection concept characterized by three attenuations: for fields (H, E), and conducted current. There is clearly a need for an authority to unify the stress (determined by the shielding level provided and verified by the utility) and the component strengths (determined by the vendors and PCI/TEM) tests into a verified, protected system for Black Sky resilience.

e. In addition to the equipment survey results, the comparison suggested some other inputs for the Black Sky critical facilities. Experience with military systems led to the system level testing approach suggested in the MIL-STD-188-125-1. The global shield (system level, top down protection approach noted in d. above) required by the military standard makes system testing more cost effective by limiting the penetrations and requiring measured residuals behind this protection, but the final test is a live system test. This is of course very difficult (to impossible) for large power plants operating at high voltage. Continuing hardness maintenance and surveillance/monitoring insure the protections have not been compromised by changes. Some attempt to adapt the verification and hardness surveillance approaches from the MIL standard for the civilian power sector would provide a more traceable hardening protocol than the equipment level testing to an assumed system hardening concept of IEC 61000. However there remains a need for an agreement between the specifications used by the vendors (the hardening concept in IEC 61000) and the actual (traceable) shielding and attenuation in order to provide a traceable system hardness statement for Black Start Systems under Black Sky conditions.

1. INTRODUCTION

The survey starts with a quick introduction to the scope, objectives, and general approach of the report. This includes a quick overview of two of the most relevant commercial standards, and some of the military standards, including the types and levels of tests. The major features of the five categories and their critical hardening components are surveyed in Section 3. For each component group, Sections 4 and 5 describe the expected stresses and strengths. Where available, strengths are based on specific measurements rather than analysis. Each survey ends with an assessment of mitigation techniques which could be employed to limit the stress and thus improve the sub-system hardness. The system hardness, of course, is the compendium of the subsystems and equipment hardness. Relevant data sheets, references, and vendor details are included where possible.

1.1. Scope and Objectives

This report constitutes an initial attempt to compile an overview of the hardness of components which are critical to the US Grid. This report includes:

The technical objectives and approach to the work**.** This includes a short discussion of the qualitative approximation to the detailed probability density functions which are typically not available, and the overview of the grid systems which were surveyed.

A brief overview of the grid and identification of the major groups of components.

A description of each electric grid system component (Component) analyzed, including the characteristics of the Component that may make it sensitive to E1/E3.

A qualitative evaluation of the risk that a Component is subject to upset, degradation, or irrecoverable damage from E1/E.

If there is an assessment that damage from E1/E3 could result in failure of the Component, a description of possible failure mechanism (decision tree block).

An evaluation and description of the consequence of the Component's failure on adjacent power system devices and local grid facility (generator, substation).

A bibliography of source information.

1.2. Overall Approach

The ultimate goal was to obtain a stress to strength comparison for each component of the suggested list of subsystems and components shown in Table 1. The components included both power handling components, sensors, and control/communications critical to the operation of the grid. These were placed in groups that could be treated together, based on the SARA team’s initial assessment of the technologies involved. The smart meters were eliminated to limit the scope. As the work progressed these categories resolved into two major groups: the transmission and sub-transmission substation group, and the generating station group. Each of these were divided into subsections on the sensors, controls (computers and communications), actuators (switches), and power components (transformers). The mapping between the original component list and the report sections is shown in the bottom section of the Table. The strength of the equipment in these assemblies is determined by the design, protection, and inherent strength of the interface components to transient voltages and currents.

Table 1: Summary of Components of Interest to Power System Susceptibility.

###	Subject	Known	Data Availability ???	Likely	Data Other Stress	Limited Data
1	Digital Relays	DTRA	PCI Information - DTRA			
2			Radiation Response - DTRA HERMES			
3			Extensive Hands On Experience			
4	Potential/Current Transformers	DTRA	High Side Known for E1 and E3	Prob	Signal Side for E1	
5			Low side Known for E3			
6	Boiler Pressure and Temperature			Prob	Generic Data	
7	Generator Excitation Systems			Prob	Generic Data	
8	RTUs for SCADA			X	Generic Data	
9	Electronic Terminal Equipment for			X	Generic Data	
10	Power Plant Distributed Control Systems			X		
11	Smart Meters					X
12	Large Power Transformers				See Line 14	
13	Generator Step-up transformers (GSU)				See Line 14	
14	Transmission to distribution transformers	DTRA	E1 and E3 Tests and TestBeds			

Known Data is typically controlled by the sponsor and in the case of DTRA is marked For Official Use Only. Use of Specific Data and References will have to be cleared with the sponsor.

Generic Data includes

1.) Actual Transient specifications (in the Lightning/ faster regime (<100 nsec risetime)

2.) Existing Literature on the specific subject

No Known commercial systems have 100% testing as required by MIL-STD 118-125-1

Subject		Report Section	
Digital Relays			Chapter 4 Substation Equipment
		4.1	Lightning Arrestors
		4.2	Substation PTs and CTs
Potential/Current Transformers		4.3	Substation Controls - Relays and Battery Charger
		4.4	Substation Switches and Actuators
Boiler Pressure and Temperature Trnasducers			Cahpter 5 Substation Equipment
Generator Excitation Systems		5.1	Sensors and Transmitters
RTUs for SCADA		5.2	Distributed Control Systems
Electronic Terminal Equipment for		5.3	Generator Excitation Systems
Power Plant Distributed Control Systems		5.4	GSUs
Smart Meters		5.5	Supporting Systems
Large Power Transformers			
Generator Step-up transformers (GSU)			
Transmission to distribution transformers			

Typical stresses will be discussed and are based on several sources including two common commercial specifications (IEC 61000 and IEEE C62) and a series of military standards which specify test techniques and levels for critical military systems with time critical missions. The latter obviously provide the highest level of hardness but require higher levels of hardening which correlates to cost. Stress is the predicted/expected voltages and currents to which the component is subjected. This is then compared against the strength of that component, often derived from datasheets with similar stresses. Since comparison of each and every component's strength to its stress (especially in complex systems such as substations, power plants or even subsystems, relays, RTUs and excitation systems) is not possible, the comparisons are done at the major interfaces identified in the system block diagram. A version of Failure Mode Effects Analysis, and Failure Mode Effects and Criticality Analysis (FMEA or FMECA - see Section 2.2) is sometimes used to discuss this process. The response at the interface determines the stress propagated downstream and thus the response of the system is described by a decision tree type structure. A sample part of such a fault/response tree dealing only with the lightning arrester and relay responses is shown in Figure 1.

In each decision block voltage, current energy or power related responses are considered and their effect on the sub-system, system and following (downstream) interfaces is decided. Even for relatively simple subsystems like a transformer the block is treated as mainly the interface and simplified and this is the area where experiment and expertise is most required. The role of uncertainty is also important since it can represent the most likely response. Every component in a complex control system cannot possibly be included so the analysis is always lacking in hard data.

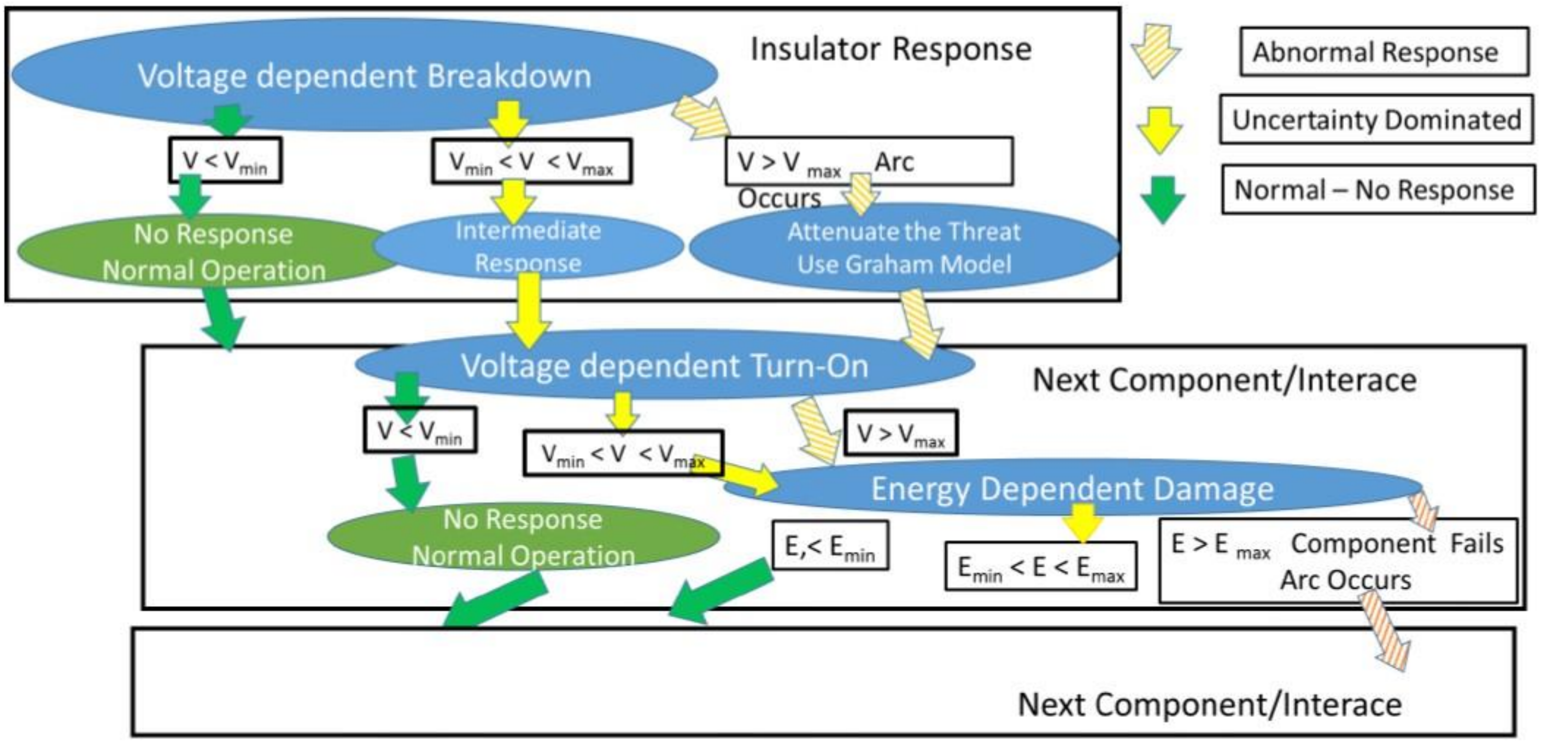

Figure 1: Simple Decision Tree Segment from Interface Block Diagram.

2. BACKGROUND

This report focuses on the effects of electromagnetic related Black Sky events, specifically HEMP and GMD, on power equipment and controls. Black Sky hazards are events that could severely impact the electric grid, cause wide area multistate blackouts, equipment damage, and likely cause communication systems to fail. If the power grid failure points include major transformer or control nexuses the electric grid restoration time for a Black Sky hazard could be weeks or months, rather than the few days after a typical hurricane or ice storm. Black Sky hazards include cyber-attacks, coordinated physical attacks on key grid components, high-altitude electromagnetic pulse (HEMP), severe solar storms (Geomagnetic Disturbances -GMD), extreme terrestrial weather, and catastrophic earthquakes. This discussion attempts to summarize actual data related to the probabilities of significant abnormal responses in grid control and power handling components to HEMP and GMD related Black Sky Hazards.

2.1. History

Over the time since the early 1950's many studies of the effect of HEMP on the power grid have been conducted. Most of the interest in and measurements of electromagnetic weapon effects in the atmosphere occurred near the end of the atmospheric tests and matured during the underground test era and in laboratory simulators. Since the EMP response is an atmospheric effect the underground tests and simulators produce only an approximation of the expected environment and there is great reliance on numerical simulations especially for the stresses. Detailed responses consist of probabilities (based on comparisons of stress to strength) of the occurrence of any non-normal behavior and are typically characterized as one of three categories: 1. Upset – a non-normal state which recovers without any permanent effects and no operator intervention required, 2.) Latch or Latching Upset – a non-normal state which requires an operator intervention or power interruption to recover, and 3.) Damage – a non-normal state which is due to permanent damage or degradation outside of the normal operating range requiring replacement of a component to allow normal operation.

More recent interest in GMD events has resulted in several studies of the possible effects of the Geomagnetically induced currents (GIC) due to GMD.

Both HEMP and GIC have examples of power system upset and failures. GMD/GIC effects include increased Volt Ampere Reactive (VAR) flow, system voltage fluctuations, generation of harmonics, protective relay misoperation, and transformer related heating. HEMP failures result mainly from the 1960-1970 era US and USSR atmospheric and underground tests, and have included street light failures, power line insulators damaged, generator failures, and communications lines failing. Unfortunately, since the understanding of the HEMP coupling and the diagnostics were limited, the details of currents and voltages are not available and worse, the technologies and materials have changed significantly since that time. Thus, due to the technology changes and the lack of recent testing (post 1960's) the current grid assessments vary from effects that are possible but not necessarily catastrophic to apocalyptic predictions. The critical technical issue is the probability/confidence and distribution of these effects.

The electromagnetic fields from a nuclear detonation are a result of the high energy radiation interacting with the atmosphere and are grouped into three time domains (designated E1 - Short, E2 - Intermediate, and E3 - Long) based on the types of interactions with the atmosphere. The latter E3 shares many features with the fields from a geomagnetic storm (although typically larger in amplitude than GIC). An excellent reference which discusses the generation of HEMP and the effects of yield, height of burst, propagation and reflection at the earth's surface can be found in "The Early-Time (E1) High Altitude Electromagnetic Pulse (HEMP) and its impact on the U.S. Power Grid" META-R-320 prepared for Oak Ridge National Laboratory(ORNL).

Systems cannot be tested by just subjecting them to the electric and magnetic fields present from a high altitude burst because the US and most of the world no longer conduct such tests. Many control and diagnostic systems have matured significantly since the last atmospheric tests (1960's) and the effects measurements on atmospheric tests were limited. Underground testing which continued into the 1990's provided some information but suffered from some severe limitations in the area of power systems (limited volume and lengths and the effects due to walls in test tunnels in underground testing). Simulators are difficult to construct due to not only the difficulty of simulating the radiation of a nuclear detonation without the blast and shock but the: 1.) physical extent of the systems, 2.) geographical distribution of the fields, and 3.) risk to other systems. In the mid-1960s the complete theory (as now accepted) of E1 HEMP was developed, independently by William Karzas and Richard Latter, and Conrad Longmire. The resulting complex computer codes describing the electromagnetic propagation and atmospheric interactions (air chemistry) allow the fields to be calculated and to be used to calculate the coupled voltages and currents for long lines exposed to an atmospheric burst. Much of this work has been spearheaded by the Department of Defense. Primarily the Defense Nuclear Agency (DNA) now the Defense Threat Reduction Agency (DTRA) and the Department of Energy (Oak Ridge National Laboratory – DOE/ORNL). The result is that the present-day testing consists of local field excitations (TEM cell exposures) of small equipment and pulsed current injection (PCI) on any conductors which would be exposed to fields, using fields and currents from these codes.

Both military and commercial standards address the strength of equipment and how to test / measure / estimate the strength, and how to analyze the resulting data. They also suggest test levels which depend on the nature of the Point-of-Entry (POE). The following sections describe some details of the approach used to assess risk to components of the power system, including probability of effect, threats (stresses), and standards (primarily strength related).

2.2. Probability of Effect

The probability of the failure of a component is related to the ratio of the stress at the component input terminal to the strength of the component at that point of entry (whether it is a chip, a bushing or a breakdown in an insulator. The classic ideal probability density function or distribution is a Gaussian given by:

$$f_x(x) = \frac{1}{\sqrt{2\pi\sigma_x^2}} e^{-(x-\mu_x)^2/2\sigma_x^2}$$

which is plotted in Figure 2, along with its integral the Cumulative Distribution Function (CDF).

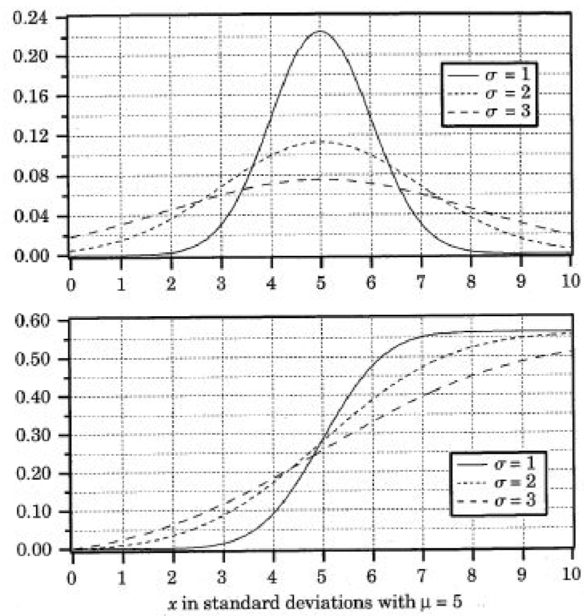

Figure 2. Probability (Top) and Cumulative Density Function (Bottom).

This approach results from a large amount of data. When only a small amount of data is available or little to no failure data is represented, that data can present a much less clear picture of the cumulative probability of an effect. It is important to clearly identify the approach used to deal with this important aspect of real data. In Figure 3 some typical sample data from a Pulse Current Injection Test (PCI) using MIL-STD-188-125-1 protocols is presented in a format attempting to identify or allow some definition of the CDF. Ten tests ranging from 25 to 2500 Amps were planned on each sample. Testing stopped when a sample was damaged. Each test was rated as Pass (No Effect), Fail, or Upset (latching or transient). Failures are represented as a value of 1, and "No Effect" is shown as a 0. Upsets are often indicators of incipient failure and certainly are not "No Effect" thus they are shown as 0.5 (transient) or 0.75 (latching). Dashed colored curves are data and black/gray solid curves are "Gaussians" chosen to represent this data. The center black curve is a Gaussian using the mean and standard deviation of the four failure data points. The failure rate appears to be ~80% which corresponds to the 4 out of 5 failures experienced in the sample, but this is a statistical artifact related to the standard deviation (STD) of the four samples. The fifth sample is not treated in this calculation. The treatment of the non-failing sample is an important aspect of the cumulative damage discussion. In addition two of the four failing samples (representing two of the three manufacturers) fail below 400 suggesting maybe all three "samples" grouped as relays are not that similar.

The left hand gray curve uses the mean and STD of these two samples and the right gray curve uses the mean and STD for the two samples from the third manufacturer. Of course, confidence for two sample statistics are poor. This example is designed to highlight the issues of extremely limited data. A comprehensive discussion of this is beyond the scope of this report. Often the data we have available fits into the case represented by the poor statistics, or worse is from related but not HEMP or GIC specific tests.

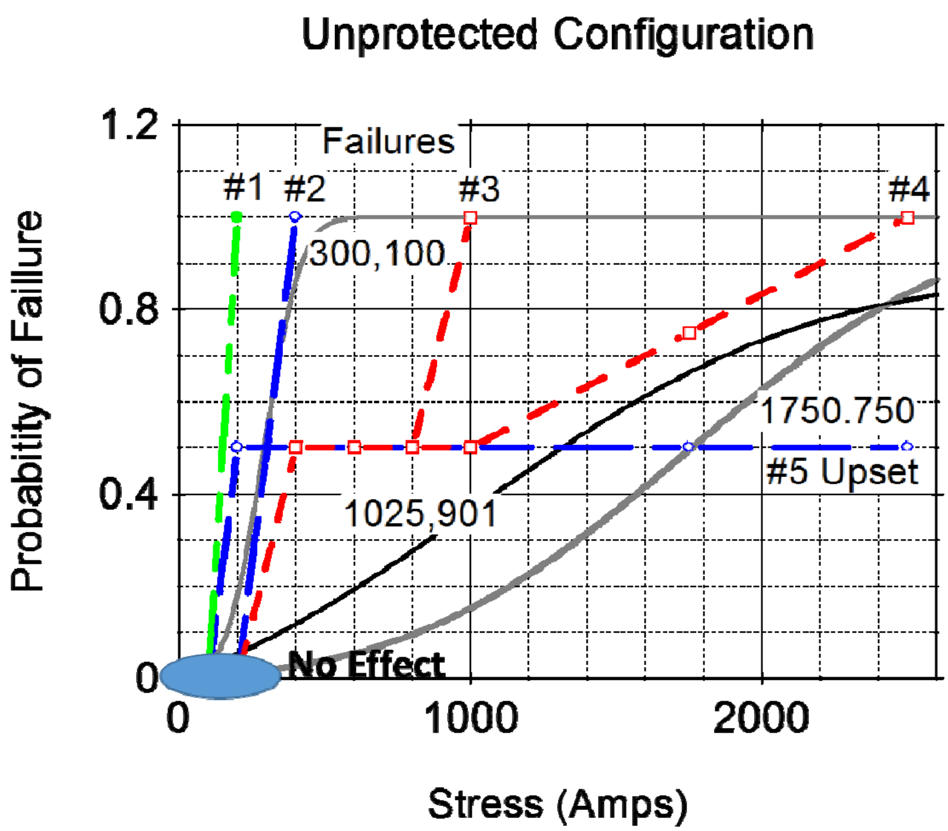

Figure 3. Simulated Limited Data Sets for Failure.

The civil aviation industry tends to use a combination of FMEA and Fault Tree Analysis in accordance with SAE ARP4761 instead of FMECA.

FMECA may be performed at the functional or lower level. Functional FMECA considers the effects of failure at the functional block level, such as a substation, transformer, switch, sensor (CT, PT) relay or controller/battery charger etc. Functional FMEAs can be performed much earlier, and may help to better structure the complete risk assessment and provide other type of insight in mitigation options.

This report utilizes a very limited FMECA–like analysis which follows the conducted transient through a functional block diagram and modifies the threat as it propagates through this path.

Ground rules and assumptions are:

- Standardized block diagram with identification of critical interfaces such as Black Start and stresses (Voltage, Energy, Current)
- Sources for failure rate and failure mode data (the subject of the majority of the rest of this report)
- Fault detection coverage that system built-in test will realize
- Criteria/Severity Levels to be considered (damage, safety, maintenance, etc.)

Next, the systems and subsystems would be depicted in functional block diagrams. Reliability block diagrams or fault trees are usually constructed at the same time. These diagrams are used to trace power flow at different levels of system hierarchy, identify critical paths and interfaces, and identify the higher level effects of lower level failures.

Failure mode assessment for most EMP related threats is qualitative due to limited samples as will be readily obvious as the individual parts/assemblies are discussed in later sections. For our qualitative assessment, probability is loosely based on data, but can suffer as noted earlier from limited tests and the necessity to use related (lightning, ESD, and other) data.

2.3. Standards (Threats and Test Requirements)

Defense hardening efforts have evolved and are codified in three specifications designed for fixed/mobile ground based facilities (MIL-STD-188-125-1/2), aircraft (MIL-STD-3023), and ships (MIL-STD-4023), as well as the generic immunities called out in MIL-STD-461 RS-105 and CS-116, and MIL-STD-464. Commercial standards, some specific to HEMP, are codified by IEC (61000 series). IEEE has a series of surge related standards, the C62 series, 62.11, 62.41.1, 62.41.2, 62.45, 62.62, and 62.72. 62.41.1, and 62.45 address switching induced and lightning surges but acknowledges "Surges associated with nuclear electromagnetic pulse (NEMP) and electrostatic discharges (ESD) involve rise times on the order of a few nanoseconds, requiring instrumentation of different characteristics from those discussed here." Thus, the majority of the directly HEMP related stress (testing levels) are based on IEC 61000 and MIL-STD-188-125-1. The MIL-STD has three time domains labelled Short, Intermediate and Long (E1, E2, E3).

The IEC has several publications related to HEMP, including IEC 61000-1-3, 61000-2-9, 61000-2-10, 61000-2-11, which describe the EMP environments. Testing of HEMP protective devices is described in the 61000 series 4-20, 4-23, 4-24, 4-25, and 4-32. Installation and mitigation guidelines for distributed infrastructure are described in 61000-5-8, and 5-9. Some of the 4-25 tests are based in turn on IEEE 61000-4-4, and some of the levels and rationalizations are based on ORNL studies that correlated BIL tests to HEMP done in the 1980's and 1990's, such as the paper by Miller [12].

Table 2. IEC Standards related to HEMP.

Military Standards		
MIL-STD-2169	Fields	Not Available
MIL-STD-464C	Fields	Refers to IEC 61000 but shows only highest level.
	Testing	Refers to EMI Tests and Stress levels in MIL-STD-461 CS115,116 and RS105
MIL-STD-188-125-1	Field Attenuation, Testing	A Performance Specification for Critical Fixed Ground Based Facilities with Critical Missions - includes Hardening Methods and Test Requirements
MIL-STD-3023	Field Attenuation, Testing	Performance Specification for Aircraft
MIL-STD-4023	Field Attenuation, Testing	Performance Specification for Ships
MIL-HDBK 423	Background for Standards	Methods, Suggestions and Protocols for Measurements, Installation, Mitigation
IEC 61000 Standards		
61000-1-3	General	HEMP Effects on Systems
61000-2-9,10,11	EM Environment	Radiated, Conducted, Classification of Environments
61000-4-4,23,24,25,33	Testing and Measuring	Radiated, Conducted, Immunity Simulator Compendium
61000-5-3,4,5,6,7,8,9	Installation and Mitigation	Concepts, Radiated, Conducted, External EM Influences, System Level Susceptibility Assessments for HEMP and HPEM
61000-6-6	Generic Standard	Immunity Tests

HEMP is due to the interaction of an exo-atmospheric or high-altitude radiation output from a nuclear detonation with the upper atmosphere. The HEMP threat is a broad band Electromagnetic field which is incident on the surface of the earth and whose fields couples to conductors (both long and short) and can have direct effects on electronic circuit cards and equipment. As noted earlier MIL-STD-464C and MIL-STD-188-125-1 deal specifically with HEMP and testing. These two references provide both descriptions of the threats (Electromagnetic fields), the derived threats (voltages and currents), the tests, simulators and recommended pass-fail criteria for these threats. IEC 61000 has several publications which cover the same time domains and technical areas, but allow for various levels of protection where the military specifications tend to assume that the asset is critical, consists of an EM shield and must survive. This implies the large margins and substantial (100%) testing necessary for a time-critical national defense system. The military standards have no lower levels of protection, but might be a good model for the Black Start portions of the grid. IEC-61000 in general uses 8 concepts (labelled 1,1A,2,2A,3,4,5,6 see following discussion) which vary from no shielding and no conducted penetration protection, to 80 dB of Electric and Magnetic field shielding and 80 dB of conducted attenuation.

2.3.1. HEMP Field Threat

The early time (E1) pulse is due to the prompt gamma environment of the nuclear detonation interacting with the upper atmosphere. The military standard which specifies this field is not available but an available version was developed by the IEC in 61000-2-9 and is shown in MIL-

STD-464C, Figure 4. The frequency domain equivalent is shown in Figure 5.

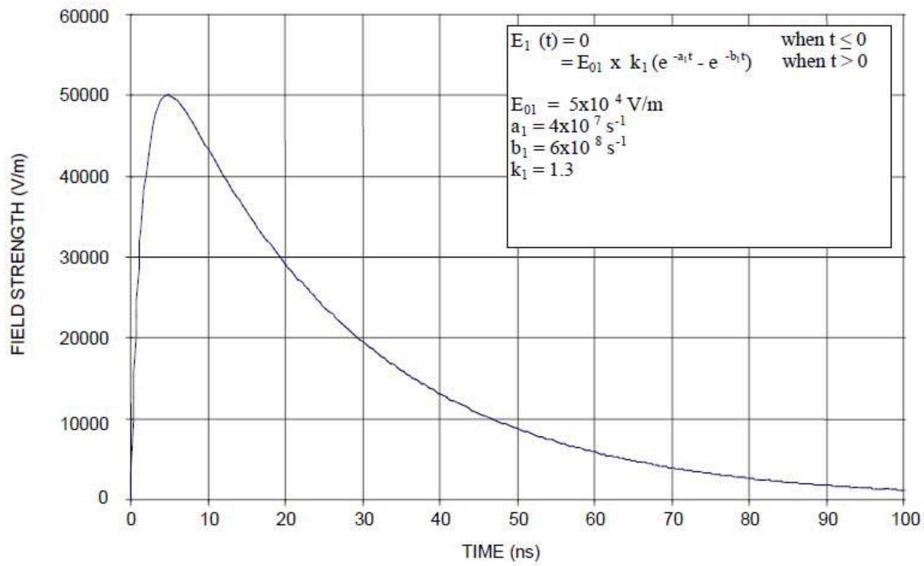

Figure 4: MIL-STD 464C (IEC 61000-2-9) HEMP Electric Field.

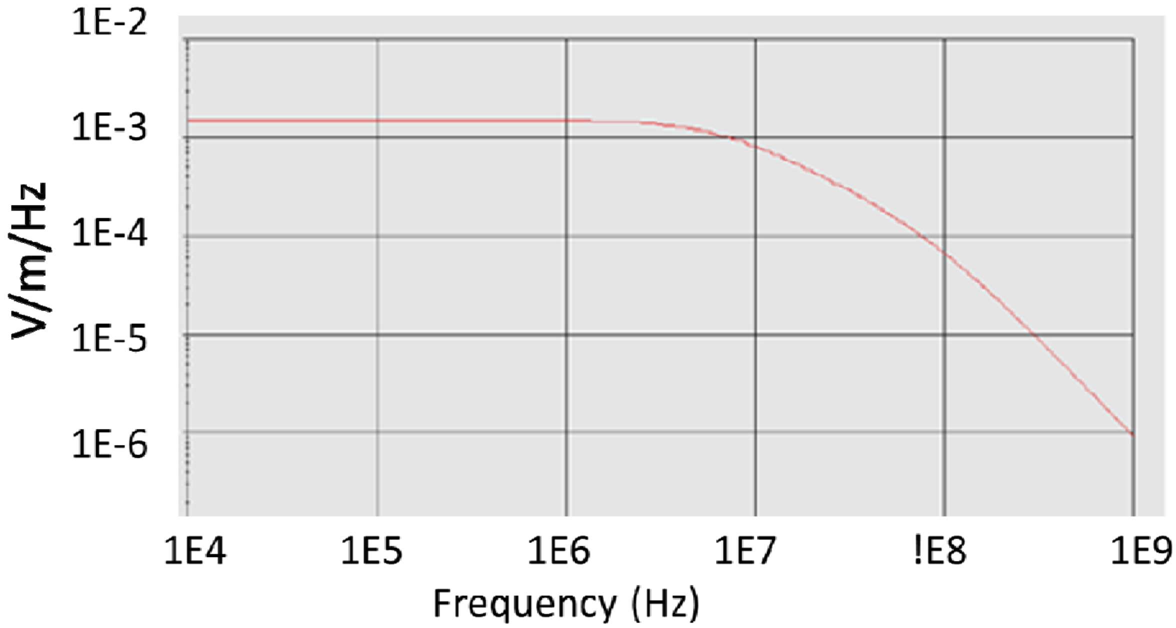

Figure 5: MIL-STD-464C (IEC 61000-2-9) Frequency Domain HEMP Electric Field.

The E1 field can be simulated in a Transverse Electromagnetic Field (TEM) Simulator, with a voltage pulse similar to the time history of Figure 4. An alternate specification of the same double exponential waveform is provided in Table 3.

Table 3: Source Specifications from Various Standards.

Fields		E(kV/m)	Risetime τ (nsec)	Full Width at Half-Maximum (nsec)
464C		50	5	25
61000-2-9		References 464C		

A time history of the composite waveform (E1, E2, and E3) is shown in Figure 6 from MIL-STD-464C. E2 and E3 fields are very small (10's of V/m) thus there are no **direct** field effects from E2 or E3.

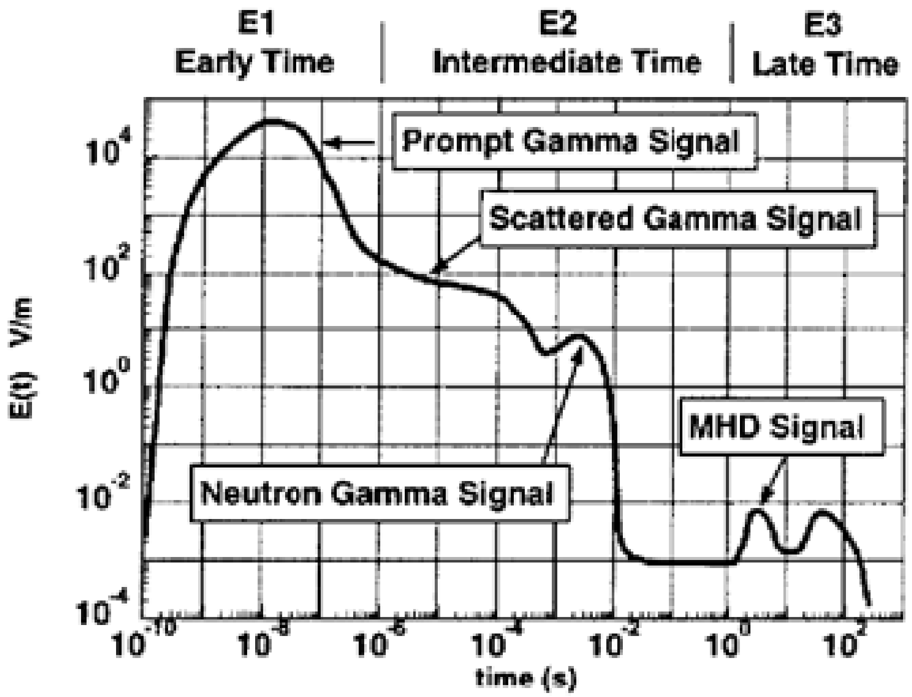

Figure 6: Composite EMP waveform from MIL-STD-464C.

The GMD threat is similar in time domain to the E3 threat but of slightly lower amplitude and much longer duration (hours or days but with amplitude variations). It presents no direct field effects. The conducted currents will be discussed in the following sub-section.

The approach to specifying the shielding in the MIL-STD-188-125-1 approach is a frequency dependent insertion loss measurement (see Appendix A of the MIL-STD and Figure 7). IEC-61000 in general uses 8 concepts (labelled 1,1A,2,2A,3,4,5,6 see below) which vary from no shielding and no conducted penetration protection, to 80 dB of Electric and Magnetic field shielding and 80 dB of conducted attenuation.

The hardness concepts are defined in IEC-61000-2-11:

- Concept 1: Above-ground wooden, brick or concrete block building or structure with large windows and doors without rebar or other explicit shielding. Lack or presence of conducted lightning protection (overvoltage protection without filtering) defines sub-concepts 1A and 1B, respectively.
- Concept 2: Above-ground concrete building or structure with rebar or buried brick or concrete building or structure. Lack or presence of conducted lightning protection (overvoltage protection without filtering) defines sub-concepts 2A and 2B, respectively.

- Concept 3: Shielded enclosure with minimal RF shielding effectiveness. Typical equipment box with small apertures. Nominal lightning overvoltage and EMI conducted penetration protection (filtering).
- Concept 4: Shielded enclosure with modest RF shielding effectiveness and good bonding at all POEs. Nominal lightning overvoltage and EMI conducted penetration protection (filtering).
- Concept 5: Shielded enclosure with good RF shielding effectiveness and POE protection (overvoltage and filtering).
- Concept 6: Shielded enclosure with high-quality RF shielding and POE protection (overvoltage and filtering).

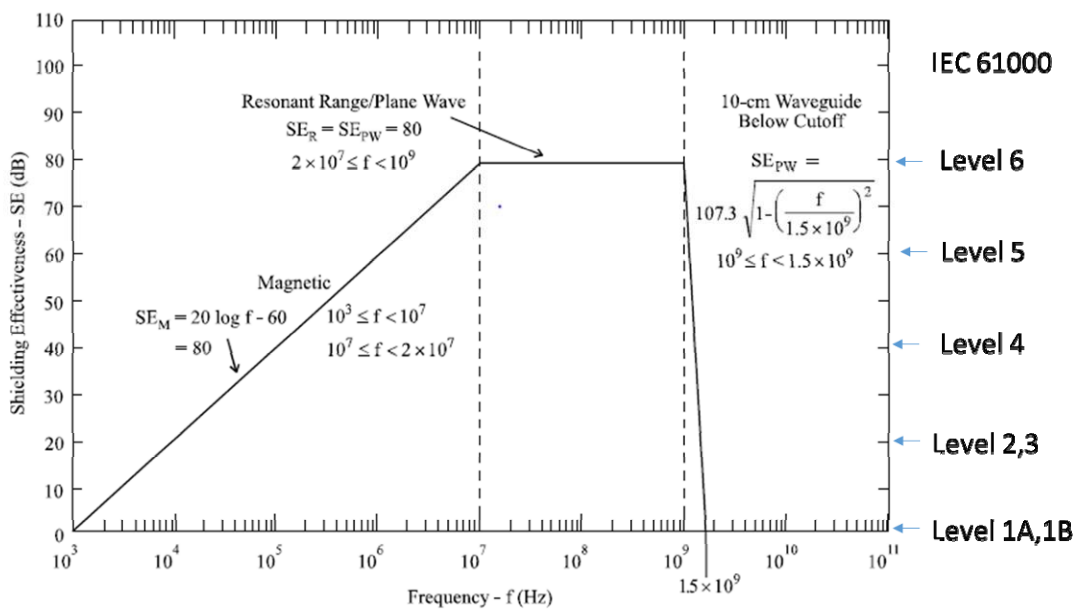

Figure 7: Frequency Dependent Shielding Requirement (MIL-STD-188-125-1).

2.3.2. Conducted Threats

In addition to the direct effects of the field any interfaces which are connected to either long or short lines, antennas, or other conductors will experience coupled currents which can be substantial. These levels have been published in several MIL-STDs, and are summarized in MIL-STD-188-125-1 for Fixed Ground-Based Critical facilities. These currents are grouped in the same time groups as the field – E1, E2, and E3. The primary circuit level threat are the coupled currents and voltages.

The E1 voltages can reach levels of tens to hundreds of kilovolts open circuit and thousands of amps short circuit. The E1 pulsed test source (from MIL-STD-188-125-1) is specified as a 60 Ohm source impedance, 300 kV open circuit voltage pulser, which produces a 20 nsec risetime (τ_r), 500-550 nsec Full Width at Half Maximum (FWHM) 5000 Amp pulse into a short circuit. The EC 10 and 11 immunity tests in 61000-4-25 require a pulser source of 25/500 nsec, at 50 Ω for levels of 1,4,8,16, and 25 kV (20-500 A) short circuit current; and a pulser of 10/100 nsec, at 50 Ω for levels of 20,40,80,120, and 160 kV (400-3200 A). A series of other EC tests EC1-6 and 7-9 are described in 61000-4-25 with other waveforms and substantially reduced requirements in Table 8 p 31 of 61000-6-6. The EC1-6 sources are 3, 10, 30 MHz damped sine waves of 2 - 80 A with open circuit voltage of 100-4000 Volts (50 Ω). The EC7-EC9 sources are described as 5/50 ns 4-16 kV open circuit voltage (50 Ω) with a reference of 61000-4-4. And a 25/500 ns, 25 kV, 500 A source for EC 10 to a 10/100 ns waveform at 160 kV, 3200 Amp source for EC11. These comparisons are highlighted in Table 4.

The E2 pulse couples well to long lines and large vertical towers/conductors. The MIL-STD-188-125-1 E2 simulator pulse is specified as a 10 Ohm source impedance, 2.5 kV open circuit voltage, which produces a 1.5 μsec risetime (τ_r), 3-5 msec Full Width at Half Maximum (FWHM) 250 Amp pulse into a short circuit. IEC 61000-4-25 IC1-3(X) specify four levels of 1-4,000 Volts, 40 Ω, (25-100 A) 10/700 μsec for its waveform. The “X” level is a special level also mentioned in 61000-4-5 the basic standard.

The E3 pulse couples well to long lines (power, communications, and buried conductors). The MIL-STD-188-125-1 E3 pulse is specified as a 5 Ohm source impedance, 2.5 kV open circuit voltage, which produces a 200 msec risetime (τ_r), 20-25 sec Full Width at Half Maximum (FWHM) 1000 Amp pulse into a short circuit. These currents produce secondary threats to transformers and equipment in the form of harmonics due to half-cycle saturation, hot-spot heating in windings and other metal structural members VAR currents in grounded transformer coils, and increases in vibration and noise levels. These single pulse threats do not result in significant heating risks but may present other threats specifically related to peak current which is higher than benchmark currents noted in GIC studies by factors approaching 5X. A major threat of GIC related events is the thermal heating, and the VAR/harmonic current effects which may result in widespread relay-based responses.

FERC Order 779 issued May 16, 2013 required the North American Electric Reliability Corporation (NERC) to develop standards to address risks to reliability caused by GMDs in two stages. Stage 1 included operating procedures, and stage 2 assessments of operating performance. Project 2013-03 (Geomagnetic Disturbance Mitigation) described TPL-007-1, a new Reliability Standard to specifically address the Stage 2 directives in Order No. 779. This dealt with thermal heating typical of GIC from a geomagnetic source (longer lived) rather than a nuclear HEMP. These effects will be discussed in the transformer sections.

Table 4: Conducted Current Pulser Requirements / Specifications

Source Specs		Concept	Risetime τ (nsec)	Full Width at Half-Maximum (nsec)	Impedance (Ω)	Current (Amps)	Voltage (kVolts)
MIL-STD-188-125-1							
	E1	Std	20	500-550	60	2500/5000	150-300
	E2	Std	1500	2-3 msec	10	250	2.5
	E3	Std	1-2 sec	20-25 sec	5	1000	5
IEC							
	61000-4-25	EC1-6	Damped Sine @ 3,10,30 MHz		50	20-80	0.1-4
		EC7-9	5	50	50	80-320	4-16
		EC10	25	500	50	500	25
		EC11	10	100	50	3200	160

*IEC 61000-4-25 Required Immunity Test Levels - Fields/Conducted Currents in 61000-2-11/6-6

Table 5 provides a sample and comparison for IEC and MIL-STD-464/188-125-1 of the field and measurement specifications.

Table 5. Derivative Threats from Various Standards. 61000-2-11 not 4-25 or 6-6.

IEC 61000-2-11		Concept	E Atten	H atten	Conducted I Atten	E* (kV/m)	H* (A/m)	Common Mode Early Time Ic Elevated**	Common Mode Early Time Ic Buried
	ET	1A/1B	0	0	0/20	50	133	4000/400	500/50
		2A/2B/3	20	20	0/20/40	5	13.3	4000/400/40	500/50/5
		4	40	40	40	0.5	1.33	40	5
		5	60	60	60	0.05	0.13	4	0.5
		6	80	80	80	0.005	0.013	0.4	0.05
						* = 2.5/25 nsec		L< 3 km	L> 3 km
	IT	1A/1B				100	0.27	200/20	400/40
		2A/2B/3				10	0.08	200/20/2	400/40/4
		4				1	8.E-03	2	4
		5				0.1	8.E-04	2	4
		6				0.01	8.E-05	2	4
								L~ 100 km Grounded Power	L~ 100 km TelCom
	LT	1A/1B				4.E-05		333	
		2A/2B/3				4.E-05			
		4				4.E-05			
		5				4.E-05			
		6				4.E-05			
								**< 1% peaks >	
MIL-STD-188-125-1						MIL-STD 464			
	E1	Frequency Dependent SE						2500/5000	800/√N
	E2	Frequency Dependent SE						250	
	E3							1000	
		ET=Early Time = E1			IT=Intermediate Time = E2				

3. POWER SYSTEMS AND SUBSYSTEMS OVERVIEW

Two major categories of facilities are surveyed, generating plants and transmission substations.

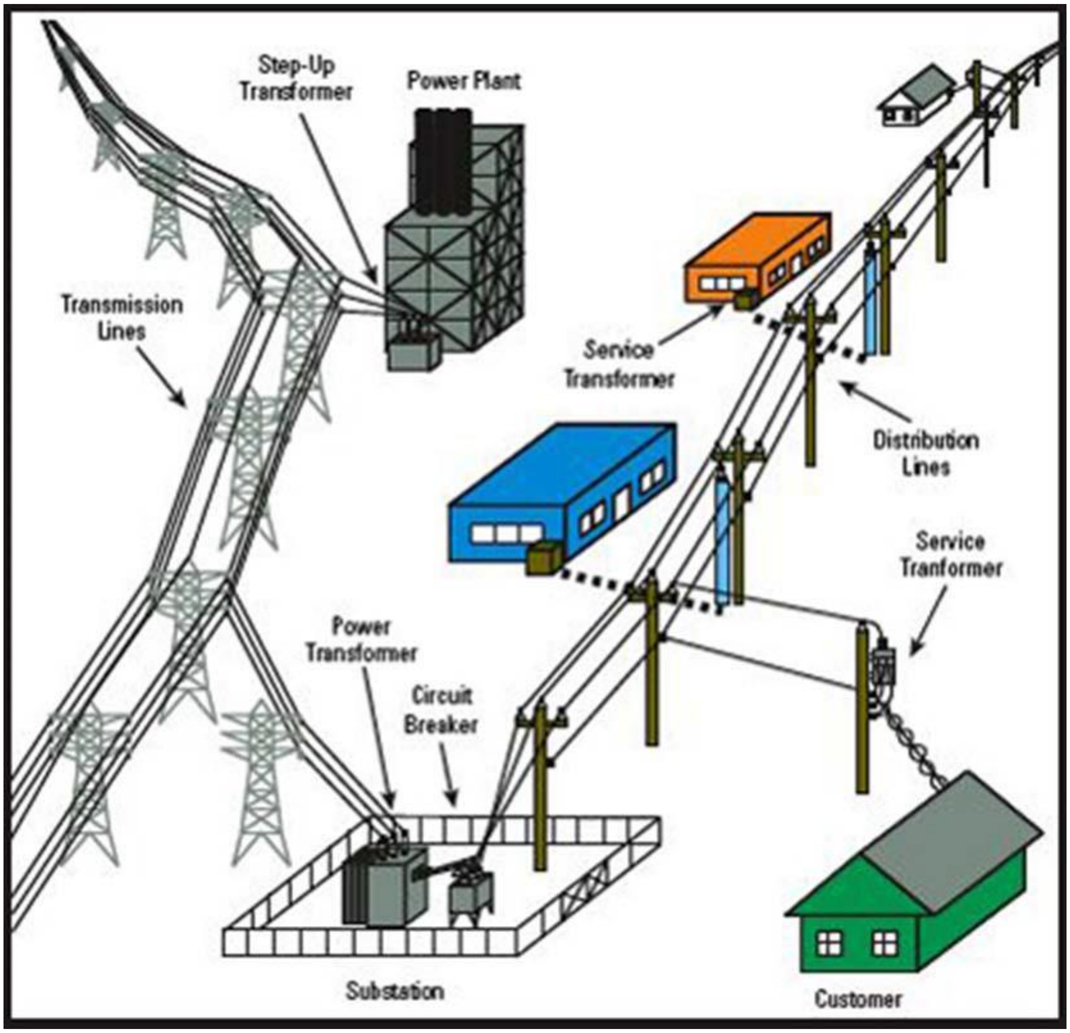

Figure 8: Power System Overview.

3.1. Substations

A generic block diagram of a typical Substation is shown in Figure 9 and an example is shown in Figure 10.

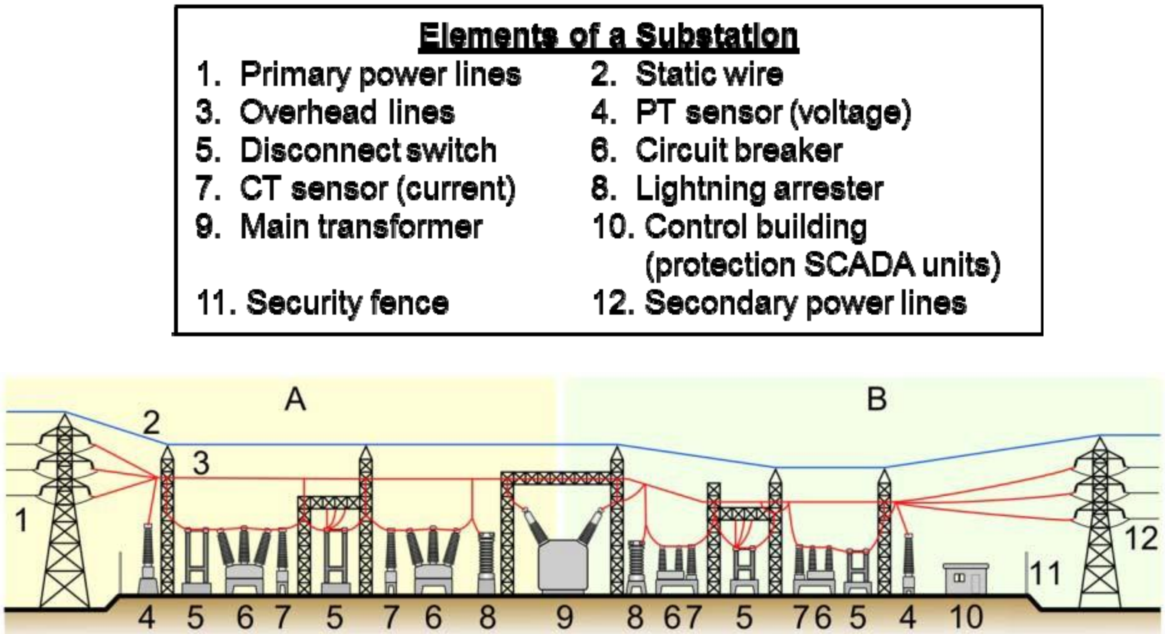

Figure 9: Elements of a Substation

Figure 10: Substation to Distribution.

3.2. Generating Stations

A generic block diagram of a generating station is shown in Figure 11.

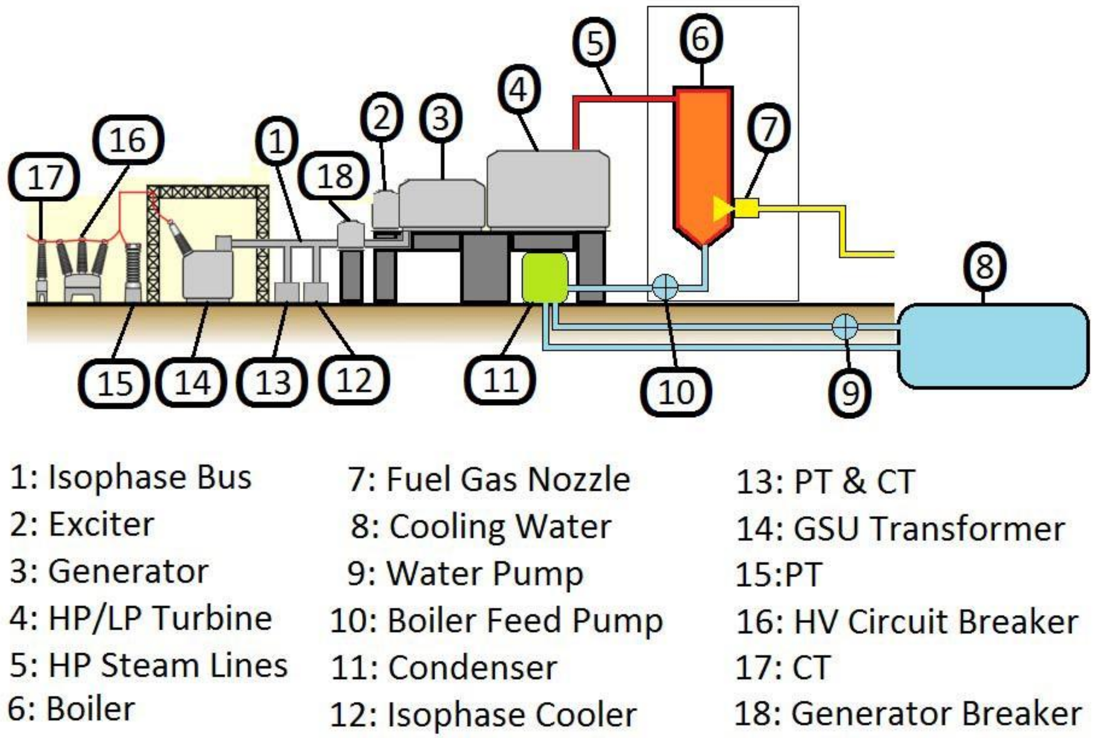

Figure 11: Typical Steam Turbine Generating Station.

The Generating Station is connected to the high voltage switchyard via its generator step-up (GSU) transformer (see Figure 12-Figure 14). This transformer is typically a grounded-wye / delta configuration, with the delta on the generator side. While the GSU / substation will have nearby lightning arresters for protection, the grounded-wye configuration on the transmission grid network side of the transformer provides a path for the DC currents associated with E3.

Figure 12: GSU Dead End Tower Leading to Switchyard.

The GSU is connected to the generator via an isolated phase bus and a generator breaker. Designing for electromagnetic immunity has been common for many years in the vicinity of the isolated phase bus (also called the isophase bus, or IPB - see Figure 13). The IPB is a set of hard tubing buswork contained within isolation tubing. This tubing functions to shield the area from the electromagnetic fields created by the thousands of amperes of current that flow from the generator to the GSU. Additionally, the tubing provides a means for a cooling system for the buswork and to protect the surrounding area from thermal damage associated with high bus temperatures.

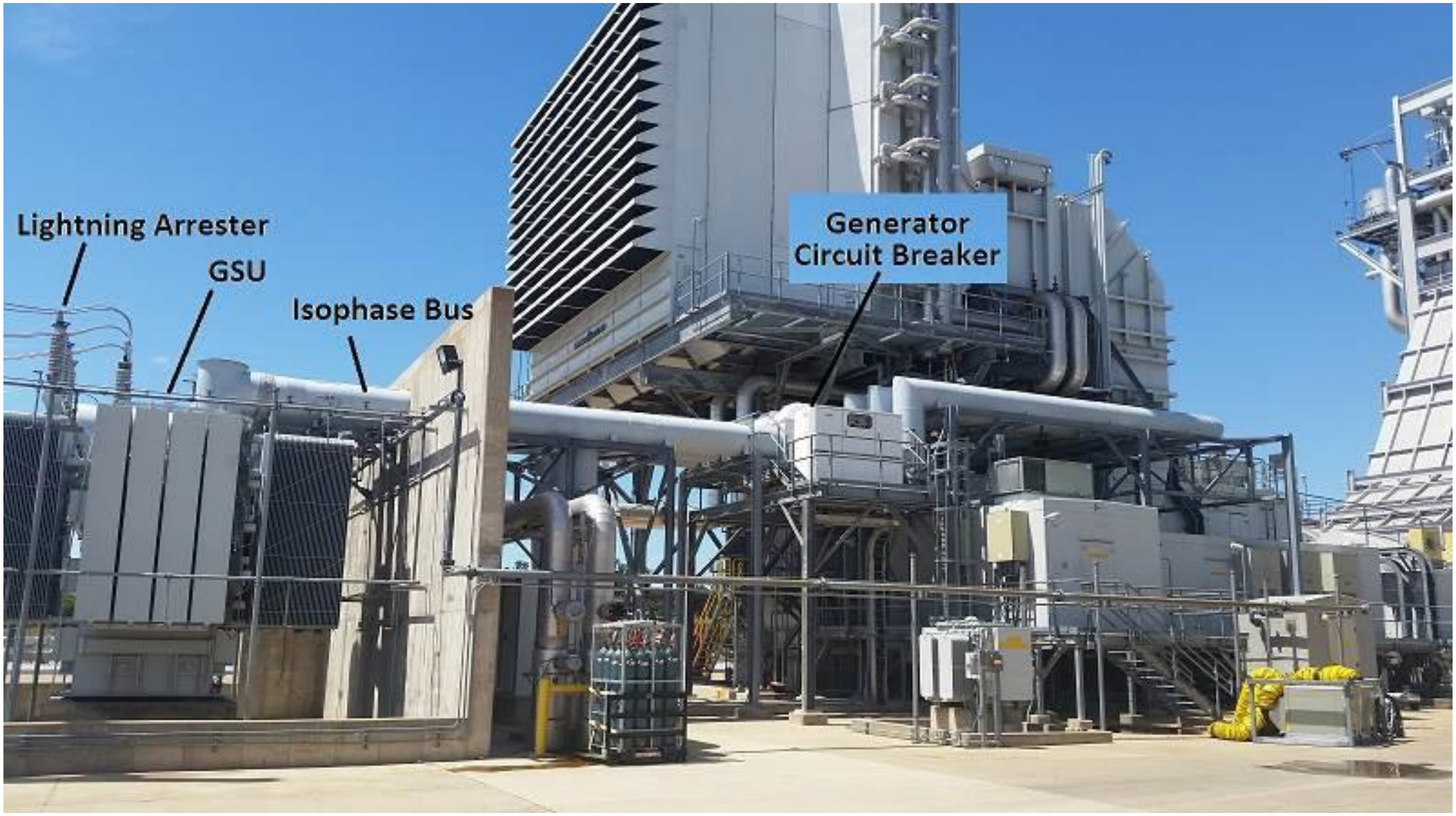

Figure 13: Transmission to IPB, Left to Right.

LAs, GSU, IPB, IPB PTs taps (to right of wall behind cannisters), IBP chiller. Taken from opposite side relative to Figure 13.

It is common practice to avoid running cables near the IPB unless necessary. It is also common practice within generating plants to route control and signal cable through grounded aluminum cable trays at 90 degrees from power busses. These cables and trays are in use throughout the plant and connect the plant infrastructure to the plant control system. These cables are often shielded, but that shield is grounded at only one end.

Figure 14: Isophase Bus and Cable Trays.

Note cables oriented 90 degrees from Isophase Bus.

Figure 15: Isophase bus (top) and PTs access.

Figure 16: Generating Plant Cooling Towers and Water Treatment Skid.

3.2.1. Power Plant Controls

Generating plant controls can be separated in to several distinct areas:

Turbine controls represent one segment of control in the plant. The turbine controls provide the specific operating parameters for the combustion turbines and steam turbines. These are typically provided by the generator system manufacturer for their equipment. There are instances where third parties have displaced the Original Equipment Manufacturers (OEM) controls with other control equipment.

A large segment of the plant controls represents the Balance of Plant (BOP). The BOP system is typically called the Distributed Control System (DCS). The DCS will tie to the turbine controls and support the controlling of supporting systems (water, fuel, air, pumps, cooling, etc.). The DCS may interact with another group of controls which are typically independent systems such as water treatment, skids (a preassembled platform with a complete subsystem that is fully contained and controlled), compressor stations, etc.

The third group consists of the smaller independent sub-systems typically provided in complete packages such as skids. These systems are provided simple commands such as start/stop or discrete values to achieve a specific set point.

The plant distributed control system (DCS) has a hierarchical structure where electromagnetic hardening between communicating devices increases as the distance from the control room increases (Figure 17).

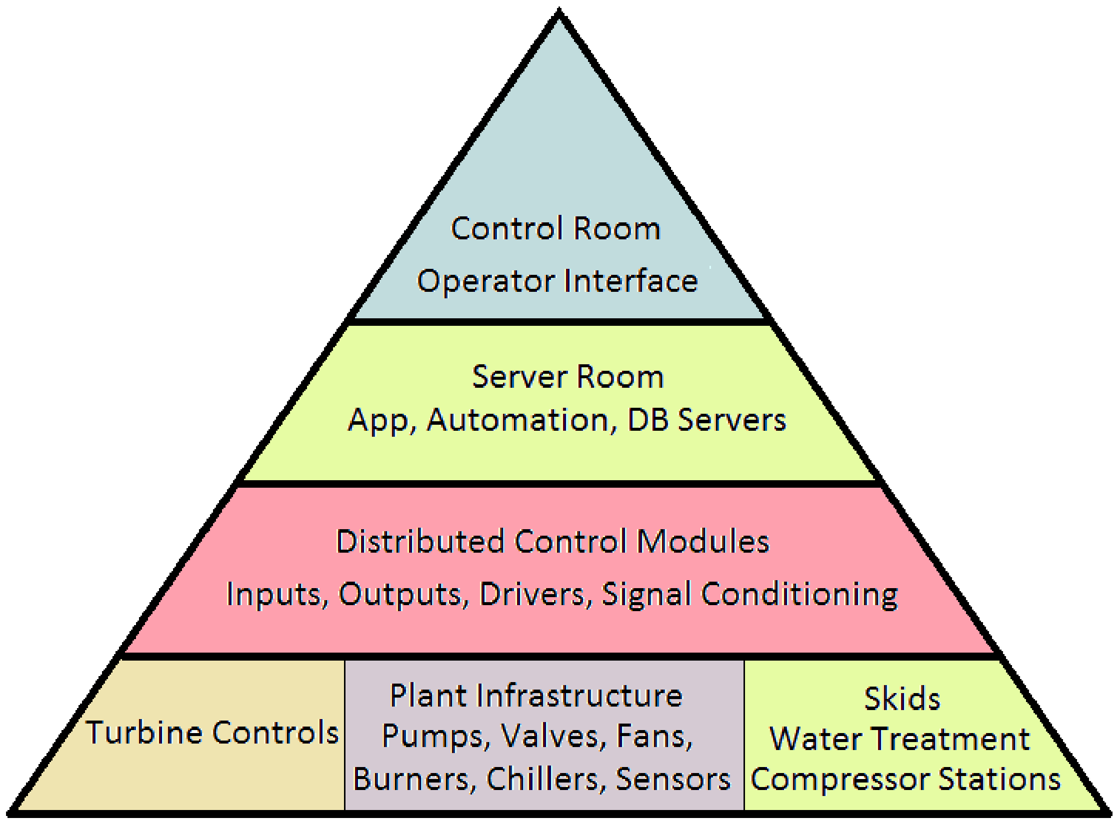

Figure 17: Hierarchy of DCS Network.

At the top levels of the DCS hierarchy, it is not uncommon for installations to use unshielded twisted pair (CAT5 or CAT6) cabling for connections between the operator interface console and the network hardware associated with the servers (though some will likely use shielded cable). Likewise, the servers may be interconnected via cabling that is unshielded, since the length of the runs will likely be short.

For connections between the server room and the distributed control modules, these are typically shielded twisted pair Ethernet or fiber optic cable. While fiber optic cable is the preference for communications interconnection, the media converter that transitions from fiber to copper frequently becomes a source for a point of failure.

At the lowest level of the DCS structure is the interconnection between sensors and actuators and the input/output modules for the control system. These signals represent a variety of voltage or current levels, and EMC cabling standards dictate shielded cable with a ground tied at one end of the cable. This standard helps increase power frequency (50-60 Hz) noise immunity for the cable runs within the plant, some of which can reach hundreds of feet in length, but does not provide a good RF shield.

The typical DCS system will have hundreds of inputs. A few basic locations for some of the monitored parameters that are sent to a DCS are shown in Figure 18.

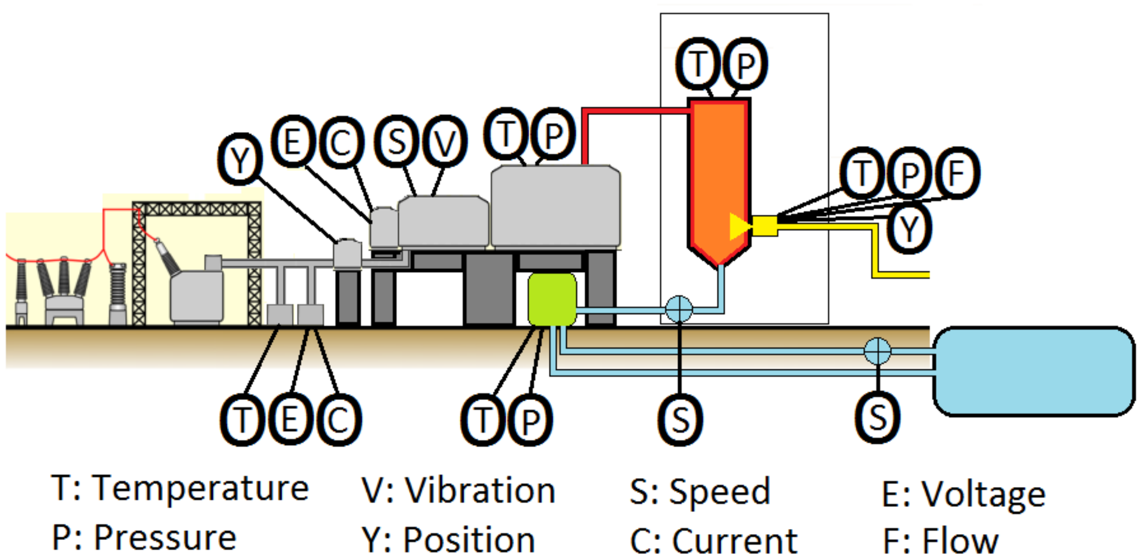

Figure 18: Selected Plant Sensors.

The plant DCS will monitor every system within the plant, to a much deeper level than is shown in Figure 18. In general, though, these are the types of inputs that a control system requires to operate the plant.

The strength of the equipment in these assemblies is determined by the design, protection, and inherent strength of the interface components to transient voltages and currents. To begin to address the details of these strengths the components were broken into five groups, summarized in Table 1. These include:

- Relays
- Sensors/Transducers
- Generator Excitation Systems
- Control System Electronics

- Power Transformers

Within these five groups, fourteen generic components were identified in Table 1. The following sections address each group and its components.

3.2.2. 1st Tier Black Sky Cranking Path Power Plants

Large hydroelectric power houses are examples of 1st Tier Black Sky Cranking Path power plants because of their simplicity, superior load following capability, and uninterruptable supply in the form of water behind the dam with its minimal dependence on the grid or infrastructure for delivery [22]. An on-line survey of such plants indicate that they conform to Concept 2B of IEC 61000-2-11 with the building and lightning arrestors providing 20dB of attenuation/shielding. However, as noted before the shielding and conducted attenuation should be verified by test, rather than inspection in order to provide high confidence. The primary difference in philosophies between the MIL-STD-188-125-1 and IEC approach is the Shielding Effectiveness (SE) in the MIL-STD is assessed by measurement rather than a survey based assessment.

In the brief on-site survey of steam turbine power system, the generator plants are also Concept 2A/B to Concept 3. The plants are metal buildings, with the generator on a steel-reinforced concrete base. There are external lightning protection devices on the water cooling towers as well.

While these superficial surveys suggest hope that some power plants contain elements of the IEC 2 “protection concept”, we know of none verified by test. So either the stress must remain at the full MIL-STD-188-125-1 levels or the IEC equivalent, or the shielding and attenuation of the protection concept needs to be verified in order to provide high confidence. Older unshielded brick, block or unreinforced concrete power plants are assumed to take the full brunt of MIL-STD-188-125-1.

3.3. Power System Component Immunity Preview

Based on this survey, many power system components meet the various IEC 61000 EMC immunity standards and the related/derivative standards like IEC 61000-4-11 for voltage sag and interruption (e.g. due to E3/GIC, see Table 6), and EN 61326-1 (sensors, including both fast burst 5/20ns bursts based on IEC 61000-4-4 and AC power quality from IEC 61000-4-11; see Table 7).

Table 6: Voltage Sag Levels and Durations Described by IEC 61000-4-11.

Dip level (%)	Dip duration (periods)
0	0.5*
	1
40	5
	10
70	25
	50

Table 7: EN61326-1 Electrical equipment for measurement, control and laboratory use.

Item	Port	Phenomenon	Basic Standard	Test Value	Performance
1	Enclosure	Electrostatic discharge (ESD) EM Radiated Field Radiated power frequency magnetic field	EN61000-4-2 EN61000-4-3 EN61000-4-8	4 kV / 8 kV contact / air 80 MHz - 1 GHz 10V/m 1.4 - 2.0 GHz 3V/m 2.0 - 2.7 GHz 1V/m 30 A/m	B A A
2	AC Power (Including protective Earth)	Fast Transient Burst Surge Conducted RF Voltage Dips Voltage Interruptions	EN61000-4-4 EN61000-4-5 EN61000-4-6 EN61000-4-11 EN61000-4-11	2.0 kV 2.0 kV Line to Earth 1.0 kV Line to Line 3 V rms 1 kHz 80% AM modulation 30% for 500 ms, 60% for 200 ms 100% for 20 ms 100% for 5 s	B B B A C B C
3	DC Power (Including protective Earth)	Fast Transient Burst Surge Conducted RF	EN61000-4-4 EN61000-4-5 EN61000-4-6	2.0kV 2.0 kV Line to Earth 1.0 kV Line to Line 3 V rms 1 kHz 80% AM modulation	B B B A
4	I/O Signal / Control (Including lines connected to functional Earth port)	Fast Transient Burst Surge Conducted RF	EN61000-4-4 EN61000-4-5 EN61000-4-6	1.0 kV (ports > 3m) 1.0 kV Line to Earth (ports > 30m) 3 V rms 1 kHz 80% AM modulation (ports > 3m)	B B A
5	I/O Signal / Control Connected directly to power supply network	Fast Transient Burst Surge Conducted RF	EN61000-4-4 EN61000-4-5 EN61000-4-6	2.0 kV 01.0 kV Line to Earth 0.5 kV Line to Line 3 V rms 1 kHz 80% AM modulation	B B B A

**Performance A=operate-through; B=performance self-recovers after test; C=performance recovers after operator reset.*

4. SUBSTATION EQUIPMENT

4.1. Lightning Arresters

Most substations (either transmission or generating plant output substation) are protected by lightning arrestors on the overhead lines. The data sheets specify the clamping voltage, typically with risetimes in the >~1μs range. DTRA tests have shown LAs clamp the E1 current pulse but faster risetime pulses leak larger pulses into the downstream chain. So, a typical threat into the primary side of a CT, PT, or GCB is reduced to roughly <2X of the LA rating after several hundred nanoseconds as shown in Figure 19 [5], with an overshoot of several – ten nanosecond duration rings. Assuming all LAs function similarly for the E1 and that the installed LAs were designed to protect the downstream equipment, including the GCBs, CTs, PTs and switches should experience a long line stress on their primaries that doesn't exceed other transients such as switching transients or their design criterion.

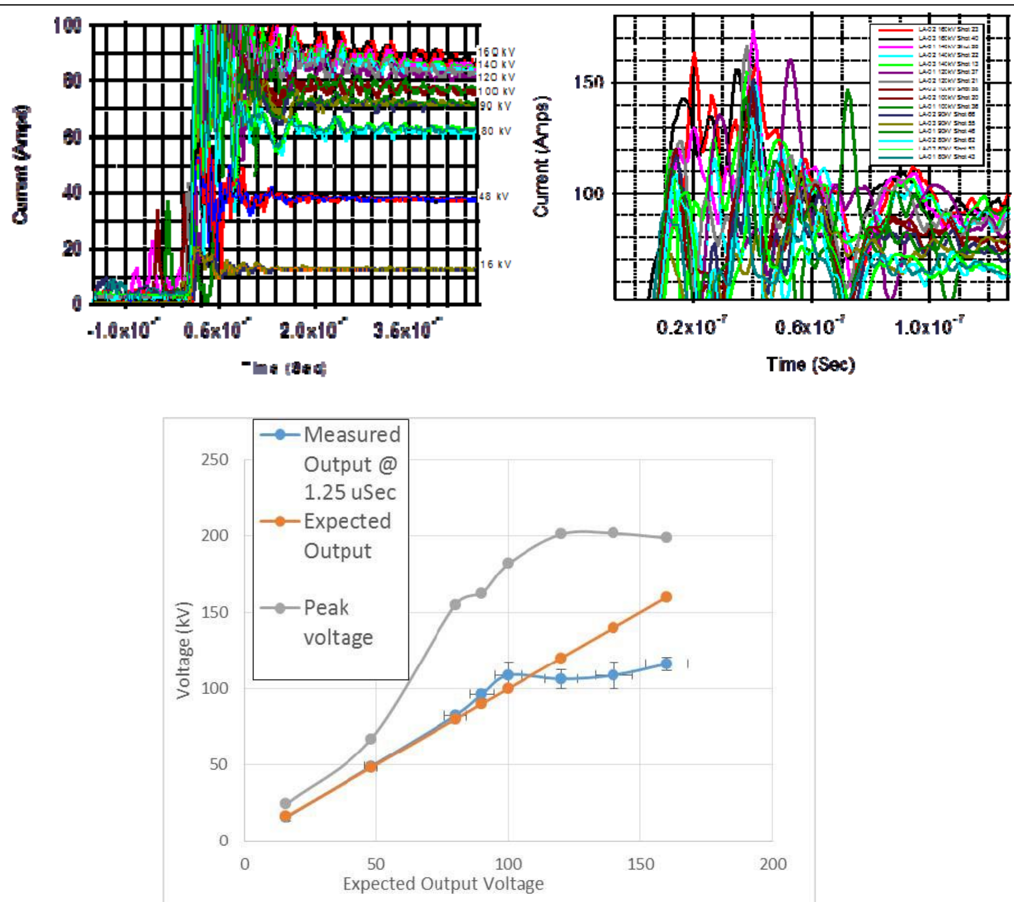

Figure 19: Leakage and Clamping Voltage – Poly 69 kV LA.

4.2. Substation Sensors - PTs and CTs

In this assessment, we are concerned with instrument transformers (PTs and CTs) down to substation level voltages of 34kV and above (see Table 8), which are connected to the grid control systems and which will experience high stress because they directly measure high voltage transmission or distribution lines outdoors.

Table 8: Grid Voltage Ranges [13].

Power Line Classification	Voltage Range [kV]	Purpose
Ultra High Voltage (UHV)	> 765	High Voltage Transmission > 765 kV
Extra High Voltage (EHV)	345, 500, 765	High Voltage Transmission
High Voltage (HV)	115, 138, 161, 230	
Medium Voltage (MV)	34, 46, 69	Subtransmission
Low Voltage (LV)	< 34	Distribution for residential or small commercial customers, and utilities

Source: U.S. Department of Energy, Office of Electricity Delivery and Energy Reliability

In the surveyed power system, CT's are typically located inside the tank of power transformers (mounted on the bushings), and they are also bushing-mounted on most circuit breakers (externally). External, standalone CT's are primarily used for revenue metering, like at a power plant or a customer site. The bushing CT's on transformers or breakers are usually installed with a stack of 2 or 3 CT's per bushing. One will go to primary protective relaying, one will go to backup protective relaying, and one may go to a panel meter (non-revenue) or be treated as a spare.

The difference between metering and relaying CT's is that metering CT's are highly accurate over a lower linear range, whereas relaying is less accurate but has a wider range. For relaying CT's, the utility is interested in the fault current magnitude, so, for example, if the utility is using a 150:5 CT for metering (and high accuracy on the 0-150 amp range), they may be using a 1200:5 CT for relaying, because the utility wants to capture the peak fault current with reasonable accuracy. Distribution and transmission CT's are in the range of 50A to 3000A primary current (the surveyed system has 3000:5 CT's connected near high fault current areas, such as near power plants). In what follows, we will concern only with CTs > 50A going to protective relays.

4.2.1. PT and CT Stresses

HEMP E1 Radiated Stress: The stress for PTs and CTs is expected to be dominated by the E1 conducted currents and voltages. The fields on the PTs and CTs is the full HEMP field and therefore is ~50 kV/m with a risetime of 5 nsec and FWHM of 25 nsec. The metallic structure surrounding PTs and CTs suggests little or no contribution to voltage on conductors from local field coupling (see Figure 20). Of course, the bushings are insulators providing the normally oil filled conductive connection from the sensor at the high voltage line to the secondary side of the sensors which are in a grounded metal enclosure.

Figure 20: Typical CT (Left) / PT (Right).

HEMP E1 Conducted Stress: The primaries of CTs and PTs within a substation should be protected at minimum by lighting arrestors (LA) on the transmission lines coming into the facility. The upper bound of the stress at the sensors is the E1 leakage noted in the previous section. For the secondaries, the stress will be coupled onto instrument cables leading from the PTs or CTs to the relays. Because these cables are often outside, may be 100's of feet long, either raised or in poorly shielded trenches, the expected current would be the full 5000/2500 Amp coupled current or the maximum concept 1A currents. The danger for the PT or CT as a result would be breakdown and arcing because of the induced voltages reflected off the secondary and wiring in the base of the PT/CT.

HEMP E3/GIC Conducted Stress: Since PTs measure long line signals directly, they may experience effects of the quasi-DC bias due to E3/GIC if connected in a line-ground configuration. Based on MIL-STD-188-125-1 injected pulse characteristics and pulser characteristic ([3] Table I and Table B-II), the peak quasi-DC bias voltage at the PT is about 5kV for 20s if the PT is in a line-ground configuration. This is because typical inductive PT primary resistances are >100Ω, compared to only 5Ω for the E3 Norton equivalent source, so the E3 source impedance dominates, i.e. 1000A x 5Ω = 5000V. For capacitively coupled voltage transformers (CCVTs), the DC blocking capacitors obtain the same result. This voltage is the primary stress expected at the PT high voltage side.

Based on MIL-STD-188-125, the CT stress may be 1000A DC for 20s if they are measuring HV phases that support E3, i.e. on a grounded-wye transformer. As a result, these CTs may themselves saturate and introduce harmonics and errors into the relay data stream. CTs downstream of transformers will pick up both wye transformer harmonics as well as generate their own, which will be transmitted to protective relays. This harmonic stress exists in addition to the voltage at the primary side of the CT.

4.2.2. PT and CT Strengths

HEMP E1 Radiated Strength: There is no known radiated test data for PTs and CTs. Since the stress for instrument transformers is dominated by E1 conducted, this lack of strength data is not surprising.

HEMP E1 Conducted Strength: For PTs and CTs the primary fault mode is assumed to be arcing / breakdown of the insulation on the high voltage side of the probe. For PT and CT primaries, the accepted strength for voltage is 2 x BIL if the BIL full wave 1.2/50μs lightning impulse test has been applied to the primary[1]. Typically, most voltage ratings are higher for shorter faster pulses, and this was demonstrated in [12], and is cited in IEC 61000-4-25 [10].

Most CTs and PTs reviewed conformed to the IEEE Standard C57.13, Requirements for Instrument Transformers [17]. The BILs for CTs and PTs required by C57.13 are repeated in Table 9 below. Based on this and the 2xBIL result, outdoor PTs and CTs above 34kV have expected primary E1 strength of greater than 400kV, as shown in Table 10. Thus, voltage breakdown at the primary interface is not expected to be an issue.

For CT secondaries, IEEE Standard C57.13 requires a 3500V 1-minute open-circuit strength, and recommends protection above 3500V for safety. The protection devices for CTs are not specified, but they are likely slow relative to E1 (varistors *or* spark gaps are called out in the standard). C57.13 does not specify a strength for PT secondaries. Therefore, the E1 strength of both PT and CT secondaries is unknown.

[1] For windowed CTs, the BIL test is performed as a high voltage dielectric test, with a foil electrode lined around the inside of the CT window and with the output windings grounded a full wave impulse is applied to the foil lining.

Table 9: IEEE Standard C57.13 Table 2 showing BIL vs Nominal Voltage Requirements.

Maximum system voltage (kV)	Nominal system voltage (kV)	BIL and full-wave crest (kV)[b]	Chopped wave minimum time to crest flashover (kV) and (us)		Power frequency applied voltage test (kV rms)	Wet 60 Hz 10 s withstand (kV rms) [c]	Minimum creepage distance for Light Pollution (mm) and (in)	
0.66	0.6	10	12	—	4	—	—	—
1.20	1.2	30	36	1.50	10	6[d]	—	—
2.75	2.4	45	54	1.50	15	13[d]	—	—
5.60	5.0	60	69	1.50	19	20[d]	—	—
9.52	8.7	75	88	1.60	26	24[d]	—	—
15.5	15	95	110	1.80	34	30[d]	—	—
15.5	15	110	130	2.00	34	34	279	11
25.5	25	125	145	2.25	40	36[d]	381	15
25.5	25	150	175	3.00	50	50	432	17
36.5	34.5	200	230	3.00	70	70	660	26
48.3	46	250	290	3.00	95	95	890	35
72.5	69	350	400	3.00	140	140	1220	48
123	115	450	520	3.00	185	185	1680	66
123	115	550	630	3.00	230	230	2010	79
145	138	650	750	3.00	275	275	2340	92
170	161	750	865	3.00	325	315	2900	114
245	230	900	1035	3.00	395	350	3560	140
245	230	1050	1210	3.00	460	445	4320	170
362	345	1300	1500	3.00	575		5210	205
550	500	1675	1925	3.00	750		8080	318
550	500	1800	2070	3.00	800		8080	318
800	765	2050	2360	3.00	920		11200	442

Table 10: Expected Primary E1 Cond Strength.

PT or CT Nom Voltage (kV)	Primary E1 Breakdown 2xBIL (kV)
0.6	20
1.2	60
2.4	90
5	120
8.7	150
15	190
15	220
25	250
25	300
34.5	400
46	500
69	700
115	900
115	1100
138	1300
161	1500
230	1800
230	2100
345	2600
500	3350
500	3600
765	4100

HEMP E3/GIC Conducted Strength: A literature search turned up no reported damage to PTs or CTs as a result of E3/GIC. In fact, PTs and CTs as inputs to sophisticated relay control algorithms are often cited as inputs to improvements in grid stability following GIC.

The CT E3 strength is calculated from the thermal current rating by derating it after the method in IEEE Std. C57.13 which multiplies by the sqrt(t_{rating}/20s), where t_{rating} is usually 1s and 20s is the FWHM of the E3 pulse. The survey of MV and HV CTs from GE show that their strength is greater than the E3 1000A for most MV and HV sensors. For CTs whose nominal rating is below 50A, this analysis indicates the strength can be as low as 200A for a 10A, 36kV metering/relaying CT. But these lower current CTs are *not* used in long lines, so consequently will not see the E3 threat.

For MV and HV PTs in a line-to-ground configuration, the E3 strength is assumed to be the maximum rated voltage of the device, which is greater than nominal voltage. At a minimum, it will be 34kV for the transmission line class of instruments considered in this section.

Strength Summary for PTs and CTs: The strength survey for powerline sensors is summarized in Table 11. Direct HEMP test data is not available. However, where possible it is calculated from EMC immunity data cited in the component data sheet. The table columns are as follows:

- Manufacturer: Component manufacturer.
- Component: Gives model number and description.
- E3/GIC Strength: Strength relative to voltage sags/harmonics, inferred from component data sheet EMC specs.
- Min E1 Cond Strength: The primary voltage holdoff appears to be sufficient to suggest that breakdown at this interface is unlikely. However, the secondaries are not typically protected and are subject to the full coupled current and voltage of the E1 field.
- Mitigation: Suggested in the following section.

Table 11: Powerline Sensors Strength Summary.

Inst Transformer Type	**Manu.**	**Component**	**E3/GIC Strength**	**Min E1 Cond Strength**
MV CT, Distribution	GE	Model CTW7-150-T100/200 36.5kV, 150kV BIL, 10-600A (metering and relaying)	>1kA for 50:5 models and above (1s Thermal Current Rating/sqrt(20s))	300kV Primary (2xBIL). Secondary unknown.
HV CT, Transmission, Outdoors	GE	IEC Oil Filled & SF6 Gas Current Transformers 72.5-126kV	15 to 19kA	700 to 1100kV (2*BIL). Secondary unknown.
HV CT, Transmission, Outdoors	GE	IEC Oil Filled & SF6 Gas Current Transformers 145kV-252kV	15 to 24kA	1300 to 2100kV (2*BIL. Secondary unknown.
HV CT, Transmission, Outdoors	GE	IEC Oil Filled & SF6 Gas Current Transformers 363kV-550kV	24kA	2350 to 3350kV (2*BIL). Secondary unknown.
MV CT, Distribution, Relaying	GE	Model CTWH7-150-T200 36.5kV, 150kV BIL, 800-3000A (metering and relaying)	>2.5kA (1s Thermal Current Rating/sqrt(20s))	300kV Primary (2xBIL). Secondary unknown.
MV CT, Distribution, Outdoors, Relaying	GE	Model JKW-150 & JKW-200 25kV to 34.5kV, 150kV to 200kV BIL, 25-3000A (outdoor, relays)	>1kA for 50/100:5 models and above (1s Thermal Current Rating/sqrt(20s))	>500kV Primary (2xBIL). Secondary unknown.
MV CT, Distribution, Outdoors, Relaying	GE	Model JKW-250 & JKW-350 46kV to 69kV, 250kV to 350kV BIL, 25-3000A (outdoor, relays)	>1kA for 50/100:5 models and above (1s Thermal Current Rating/sqrt(20s))	>500kV Primary (2xBIL). Secondary unknown.
HV CVT, Transmission, Outdoors	GE	IEC/IEEE Capacitive & Coupling Capacitor Voltage Transformers (CVT & CCVT) 72.5kV - 1100kV (350kV - 2500kV BIL)	NA Line-Line, Hard Line-Gnd (Capacitive > 10nF)	700 to 5000kV (2*BIL) on Primary Only. Secondary unknown.
MV PT, Distribution, Relaying, Indoors	GE	Models PT7-2-150 & PT7-2-200 150-200kV BIL, 24000-34500V	NA Line-Line, Max Rated Voltage if in Line-Gnd Config	300 to 400kV (2*BIL) on Primary Only. Secondary unknown.
MV PT, Distribution, Relaying, Indoors	GE	Model PT7-1-150 150-200kV BIL, 15240-34500V	NA Line-Line, Max Rated Voltage if in Line-Gnd Config	300 to 400kV (2*BIL) on Primary Only. Secondary unknown.
MV PT, Distribution, Outdoors, Relaying	GE	Models JVS & JVT 150-350kV BIL, 24000-69000V	NA Line-Line, Max Rated Voltage if in Line-Gnd Config	300 to 700kV (2*BIL) on Primary Only. Secondary unknown.

4.2.3. Mitigation Assessment for PTs and CTs

HEMP E1 Radiated: The metallic structure surrounding PTs and CTs suggests little or no contribution to voltage on conductors from local field coupling. Therefore, shielding or field mitigation is not considered further in this section.

HEMP E1 Conducted: Based on the stress vs. strength survey mitigation to limit damage on the primaries for MV and HV PTs and CTs against HEMP E1 does not appear necessary and is low priority for medium or high voltage IEEE C57.13 qualified PTs and CTs. *The strength of secondaries to common mode HEMP E1, however, should be determined by test and possibly protection in the form of MOVs / filtering near the secondary terminals will be needed as a result.*

HEMP E3/GIC: Based on the stress vs. strength survey, it is expected the primaries of MV and HV PTs will be immune to E3, while MV and HV CTs will be immune for CTs rated above 50A, which is the typical rating for CTs used in protective relaying.

4.2.4. PT and CT Summary

Table 12, highest priority mitigation for MV and HV powerline sensors, is to test the secondaries for immunity, or add protection such as MOVs.

Table 12: PT and CT Mitigation Summary.

Inst Trans (Application Outdoor, Relaying, >34.5kV, IEEE C57-13)	Stress	Mitigation
CT	HEMP E1 Conducted	Test or add protection to secondary.
CT	HEMP E1 Radiated	NA
CT (>=50A)	HEMP E3/GIC	Not needed for IEEE C57-13 CTs
PT	HEMP E1 Conducted	Test or add protection to secondary.
PT	HEMP E1 Radiated	NA
PT	HEMP E3/GIC	Not needed for IEEE C57-13 PTs

4.3. Substation Controls – Relays and Battery Charger

Protective relays are not directly connected to transmission lines and transformers, but rather through potential transformers (PTs) and current transformers (CTs) that step down grid voltages and currents to 120 volt, 5 amp levels suitable for input relays (i.e., computers). While relaying CTs and PTs provide inputs, relay outputs actuate trip coils and close coils. Finally, modern relays are powered by batteries, which in turn are charged by a battery charger.

In our survey (see Figure 21 through Figure 23) the cabling between the PTs, CTs, trip coils, and relays is unshielded. CTs are typically wired with 4-conductor #10 cable. Trip coils are typically 12-conductor #12 cable. Close coils are also wired with 12-conductor #12 cable. All are unshielded. CT/PT wires start in a junction box at the device, run through flexible conduit to the ground, and then through PVC conduit for 'some distance' (it varies) until it hits the main cable trough that runs back to the control house. The main cable trough in a substation is a concrete U-shape with heavy steel plate covers. This trough goes to the control house and then there are vertical steel channels/troughs on the outside of the house where the cables run up the side of the house to the ceiling cable tray inside and then over to the relay panel, and they drop down to the panel. Runs varied, but were usually between 100 and 400 feet, with 450 feet the longest. Equipment grounding of PTs, CTs, breakers, cabinets, etc. is done via a copper (copperweld) cable strapped to the case, run down the stand, and tied to the substation ground grid. Grounding of the signal cables occurs in the control house at the PT junction board or at the relaying panel.

The relay battery chargers are connected to low voltage mains inside the facility. The AC power runs back to the step-down transformer will typically exceed the restricted length of 5m.

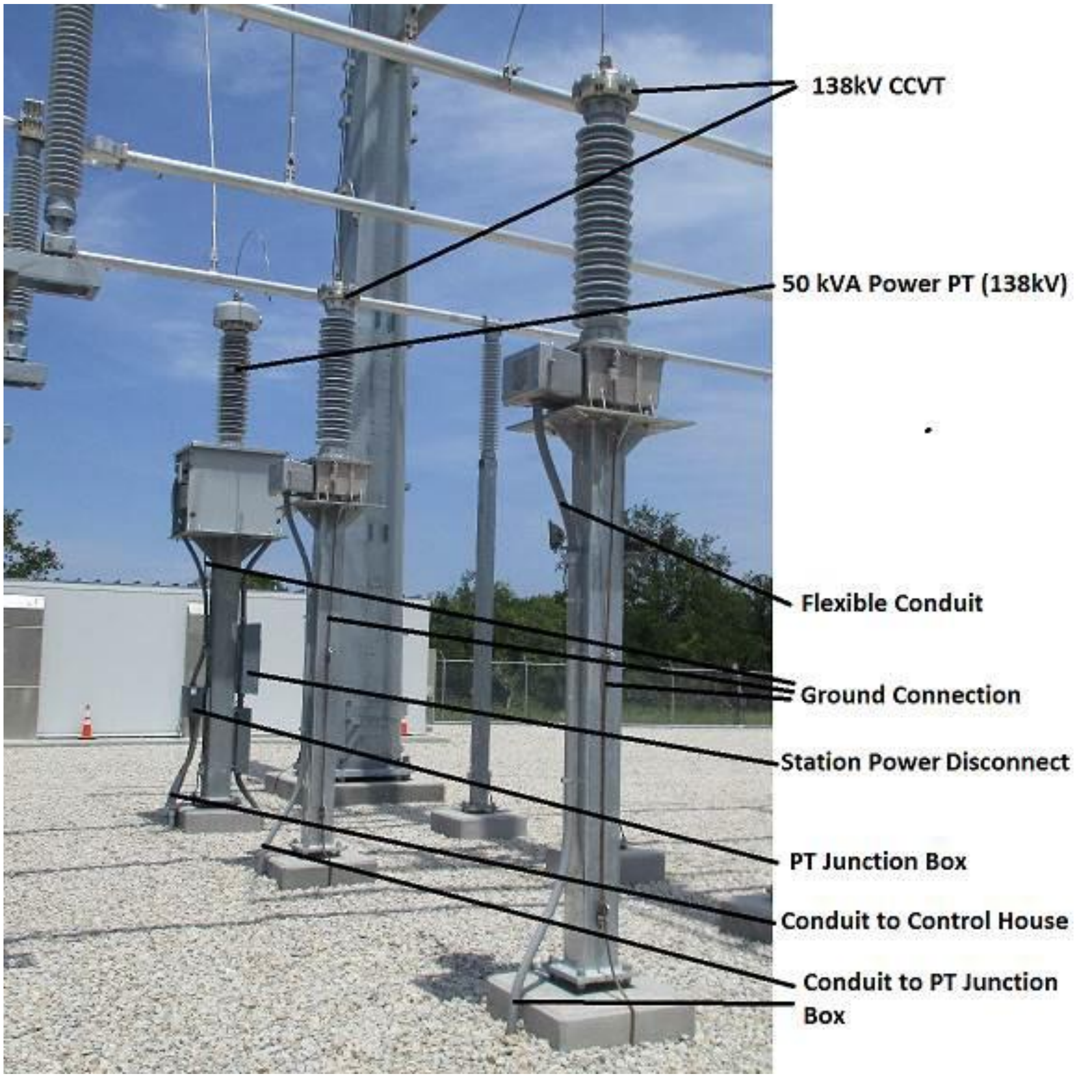

Figure 21: PT and CCVTs at typical substation.

Figure 22: Close up of ground strap with lightning counter.

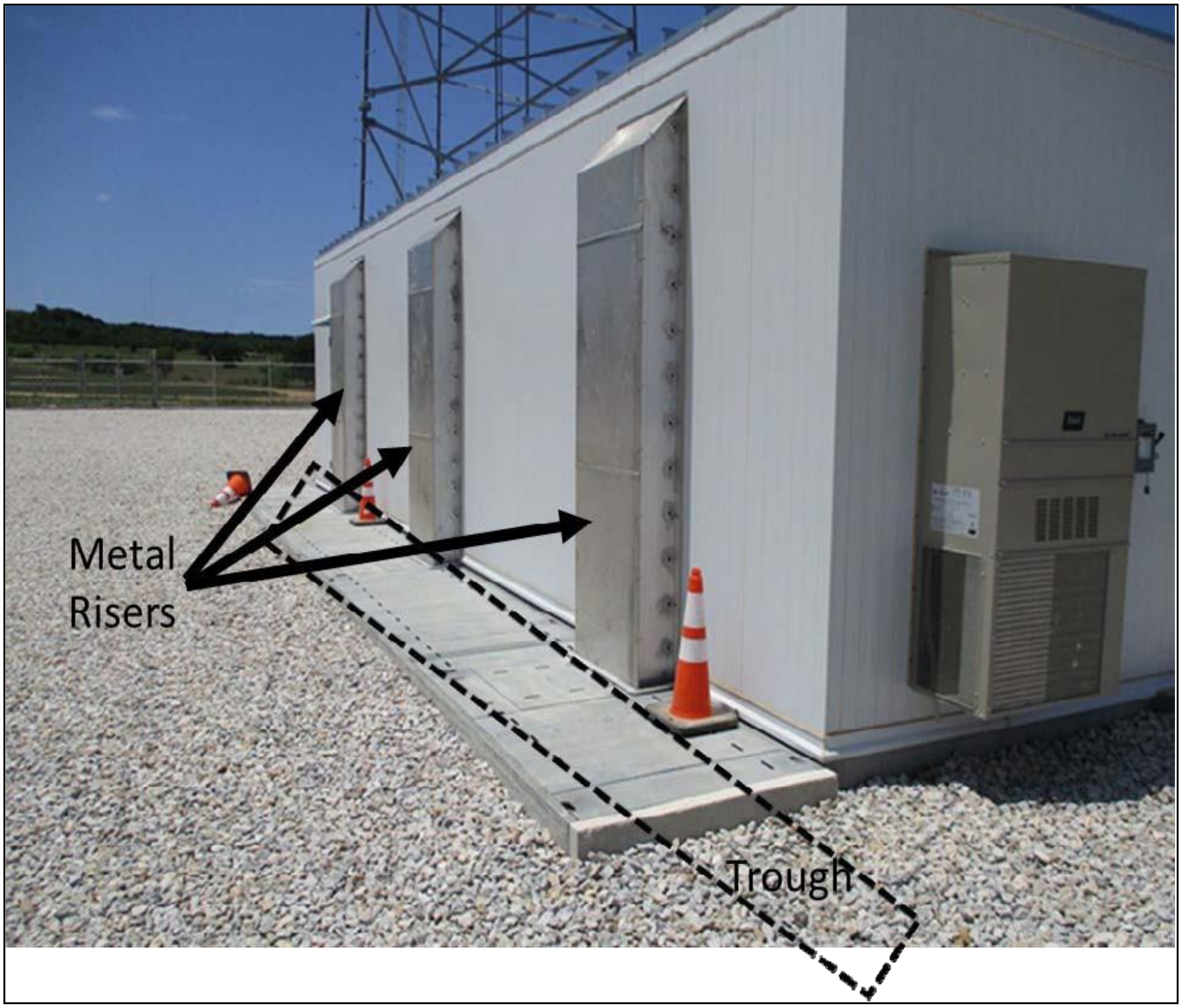

Figure 23. Example of Trough and Metal Risers into Control House.

4.3.1. Relay and Charger Stresses

HEMP E1 Radiated Stress: The E1 radiated stress is 50 kV/m for a relay and battery charger inside a generic unverified substation control building. If the building SE and POE protection residuals are measured and verified by the methods of MIL-STD-188-125-1 Appendices A and B, then this level would be reduced accordingly. For an IEC Protection Concept 2B, this would be 20dB or 5 kV/m.

HEMP E1 Conducted Stress: Based on these above cabling descriptions, for relay signal inputs, the baseline stress is the MIL-STD-188-125 E1 5000A common mode, and max 5000A/sqrt(N), 500A) wire to ground, per Table I of the MIL standard; for power inputs its 5000A common mode and 2500A wire to ground.

For battery chargers, because of the unrestricted length of AC power runs inside the control building, the E1 stress will be 5000A common mode and 2500A wire to ground for the AC power inputs. If the control building SE and POE protection residuals are measured by the methods of MIL-STD-188-125-1 Appendices A and B, then these levels would be reduced accordingly. For example, if the building is demonstrated to meet Protection Concept 2B, then the stress would be reduced by 20dB or 500A.

HEMP E3/GIC Conducted Stress: E3/GIC effects are twofold: harmonic distortion of power voltages, CT harmonics, and DC voltage sag. The harmonic distortion signals may be transmitted by CTs and PTs to the relay inputs for processing, but this should be an anticipated condition. Both effects will be transmitted to the battery charger. The DC bias is expected to be low current (milliamps) for ac power ports at low voltage equipment such as the chargers [10].

4.3.2. Relay and Charger Strengths

Relays themselves typically have protection for lightning-coupled stresses using proprietary, solid state circuitry having various time dependent clamping and leakage characteristics that are similar to, but not specifically intended for, EMP/E1 protection. The equipment has protection specified by IEC and IEEE specifications: IEC 60255-22-5:2008, IEC 60255-22-1:2007, IEC 61000-4-5:2005, and IEEE C37.90-1-2002. The latter covers a similar frequency range but with a different test approach than Appendix B of MIL-STD-188-125-1. A comparison of the test results of some of the typical equipment using MIL-STD type tests would allow direct comparison of results and prepare for discussions of the applicability of existing commercial specifications.

HEMP E1 Radiated Strength: - Digital Relays

Reference [1] reports on the laboratory radiated and PCI tests of three models of digital protection relay manufacturers using the MIL-STD 188-125-1 HEMP pulse with 20ns risetime and 500ns FWHM. Testing was performed on two samples each of three relay models in 2014-2015. The following table summarizes the radiated test TEM cell test results described therein. Only one effect was observed from the TEM cell exposures which were conducted with only the relay supply power lines connected. The Basler BE1-11f (serial number 696) upset at ~70 kV/m. This upset was probably due to the coupling to the power cabling, rather than direct coupling to the electronics, but this supposition cannot be confirmed from the existing tests. Table 13 summarizes the results.

Table 13: Relay Radiated Susceptibility Test.

			TEM Cell Calibration E-Field Levels			
Configuration	Relay	S/N	3-3.3 kV/m	10-12 kV/m	36-43 kV/m	55-74 kV/m
TEM Cell	SEL-421	305	Pass	Pass	Pass	Pass
		247	Test Not Planned			
	Basler	500				Pass
		696	Pass	Pass	Pass	Display
	Siemens	177	Pass	Pass	Pass	Pass
		341	Test Not Planned			
	=Test Not Performed					
Pass	=Unit Passed Test					
Display	=Loss of Display - No Other Functional Effects - Power Cycle Req'd					

For some relays, e.g. SEL, the manufacturers claim that with judicious location of their relays in hardened cases, IEC 61000-6-6 [8] can be met.

HEMP E1 Conducted Strength- Digital Relays:

In the SARA relay tests reported in reference [1], PCI tests were performed on the voltage and current sensor terminals on each of the relays. The relays were tested with and without MOV protection (Littlefuse V20E130P were used). All three models survived with the protection at up to 1750A peak E1 pulse. However, without MOV protection, one model failed at ~200 A, only one model survived up to 1000A peak E1 and it suffered a latching upset at 400 A. Results are shown in Table 14. It's noteworthy that all relays with the exception of the Basler BE1-11F were certified to the IEC 61000-4-4 E1-like EFT burst with 2kV signal and 4kV power peak voltages.

HEMP E3/GIC Conducted Strength: Digital Relays

All relays surveyed have been tested against voltage dips/sags and extremely fast transient bursts with the exception of the Basler BE1-11F which also does not include the IEC 61000-4-4 E1-like EFT burst. The EFT burst is superimposed on the power supply mains voltage similar to the E3/GIC harmonics, but with a much higher voltage in the range of from 2-4kV. The power supply voltage ranges in all case allow for >16% of supply over/undervoltage, greater than the expected stress.

Table 14: Relay PCI E1 Test Results.

			PCI Drive Levels											
Configuration	Relay	S/N	25 A	50 A	100 A	200 A	250 A	400 A	500 A	600 A	800 A	1000 A	1750 A	2500 A
Nominal PCI	SEL-421	305	Pass				N/A	Latch*	N/A	Arc*	Arc*	Arc*	Display*	Damage
		247	Pass				N/A	Arc*	N/A	Arc*	Arc*	Damage		
	Basler	500	Pass			Damage								
		696	Damaged in Protected Mode											
	Siemens	177	Pass				N/A	Damage						
		341	Pass			Display	N/A	Pass	N/A	Display*	Display*	Display*	Display*	Display*
Protected PCI	SEL-421	247	N/A				Pass	N/A	Pass	N/A		Pass	Pass	Pass
	Basler	696					Pass		Pass			Pass	Pass	Damage
	Siemens	341					Pass		Pass			Pass	Pass	Pass

(grey)	=Test Not Performed
Pass	=Unit Passed Test
Arc*	=Visual/Audible Arcing Occurred - No Other Functional Effects
Display	=Loss of Display - No Other Functional Effects - Power Cycle Req'd
Latch	=Latching Functional Upset - Power Cycle Req'd
Damage	=Unit Damaged
*	=Arc Observed in Addition to Upset or Damage

<u>HEMP E1 Conducted Strength:</u> Electromechanical Relays

In general, Electromechanical Relays are less susceptible to upset/damage than digital relays. Electromechanical relays (see Figure 24) that were tested up to 8kV Voc in [6] showed no damage. Assuming IEC test standards were followed with a pulser source impedance of 50 ohms, I_{sc} would have been 8000/50= 160A. This is shy of the 500A derived above based on MIL-STD-188-125 with 20dB attenuation, but does satisfy the IEC test standard.

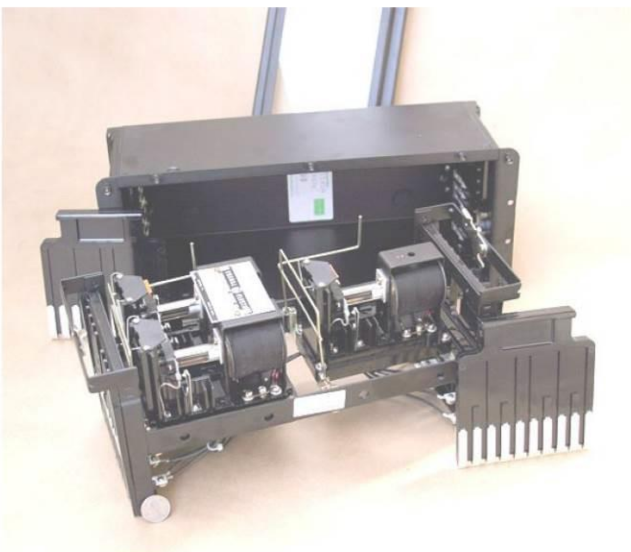

Figure 7-8. GE-PJC electromechanical overcurrent relay.

Figure 7-9. GE-GCX electromechanical distance relay.

Figure 24: Electromechanical Relays tested in [6] up to 8kV showed no failures.

<u>HEMP E1 Conducted Strength:</u> Battery Charger

In April 2017 SARA conducted E1 PCI tests under simulated normal operating conditions on a Hindle Power Incorporated AT30 Battery Charger, a typical substation battery charger.

The unit survived to 2000A; at 2250A a crowbar resistor became damaged. Results of the test are shown in Table 15.

Table 15: AT30 Battery Charger PCI Test Results.

Shot No.	Drive Level	Injection		Pre-Test	Post-Test	Effects/Notes
		Location	Type	Status	Status	
0001-0021	Calibrations					
0022-0025	Ambient					
0026	250	AC Input PhA	WTG	Nominal	Nominal	No Effects
0027	250	AC Input PhB	WTG	Nominal	Nominal	No Effects
0028	250	AC Input PhC	WTG	Nominal	Nominal	No Effects
0029	250	AC Input	CM	Nominal	Nominal	No Effects
0030	500	AC Input	CM	Nominal	Nominal	No Effects
0031	500	AC Input PhA	WTG	Nominal	Nominal	No Effects
0032	500	AC Input PhB	WTG	Nominal	Nominal	No Effects
0033	500	AC Input PhC	WTG	Nominal	Nominal	No Effects
0034	750	AC Input	CM	Nominal	Nominal	*Self Recovered Momentary Upset
0035	750	AC Input PhA	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0036	750	AC Input PhB	WTG	Nominal	Nominal	BAD DATA - Pulser Pre-fire
0037	750	AC Input PhB	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0038	750	AC Input PhC	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0039	1000	AC Input	CM	Nominal	Nominal	*Self Recovered Momentary Upset
0040	1000	AC Input	CM	Nominal	Nominal	*Self Recovered Momentary Upset
0041	1000	Radiative CAL Drive		Nominal	Nominal	No Effects
0042	1000	Case Drive		Nominal	Nominal	No Effects
0043	1000	AC Input PhA	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0044	1000	AC Input PhB	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0045	1000	AC Input PhC	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0046	1250	AC Input PhA	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0047	1250	AC Input PhB	WTG	Nominal	Nominal	No Effects
0048	1250	AC Input PhC	WTG	Nominal	Nominal	No Effects
0049	1250	AC Input	CM	Nominal	Nominal	No Effects
0050	1500	AC Input	CM	Nominal	Nominal	*Self Recovered Momentary Upset
0051	1500	AC Input PhA	WTG	Nominal	Nominal	No Effects
0052	1500	AC Input PhB	WTG	Nominal	Nominal	No Effects
0053	1500	AC Input PhC	WTG	Nominal	Nominal	No Effects
0054	1750	AC Input	CM	Nominal	Nominal	**Self Recovered Momentary Upset
0055	1750	AC Input PhA	WTG	Nominal	Nominal	No Effects
0056	1750	AC Input PhB	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0057	1750	AC Input PhC	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0058	2000	AC Input	CM	Nominal	Nominal	*Self Recovered Momentary Upset
0059	2000	AC Input PhA	WTG	Nominal	Nominal	No Effects
0060	2000	AC Input PhB	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0061	2000	AC Input PhC	WTG	Nominal	Nominal	*Self Recovered Momentary Upset
0062	2250	AC Input PhA	WTG	Nominal	Nominal	***Crowbar Resistor Catastrophic Failure

4.3.3. Strength Summary – Relays and Battery Charger

The strength survey for relays is summarized in Table 16. The table columns are as follows:

- Manufacturer: Component manufacturer.
- Component: Gives model number and description.
- E1 Rad Strength: E1 TEM or Radiated test strength.
- E3/GIC Strength: Strength relative to voltage sags/harmonics, inferred from component data sheet EMC specs.
- Min E1 Cond Strength: Component expected to survive up to stated level.

- Max E1 Cond Strength: Component will fail above this level.
- Mitigation: Priority mitigation to survive stress.
- HEMP Test References: Report numbers where available.
- EMC Immunity References: Applicable IEC, IEEE, EN EMC references from data sheets.

HEMP test data is only available for a very few devices, especially for E1. However, the mitigation for digital relays is inferred from the SARA tests to apply to all digital relays.

Table 16: Relay Strength Survey.

Manufacturer	Component	E1 Rad Strength	E3/GIC Strength	Min E1 Cond Strength	Max E1 Cond Strength	Mitigation	HEMP Test References	EMC Immunity References
Quadramho	Quadramho Solid State Distance Relays					MOVs in shielded enclosure		
SEL	SEL 311L		Hard, based on >16% PS over/under voltage. >4kV fast burst.	Fast Pulse (5ns/50ns): 3.2kV (64A)		MOVs in shielded enclosure	Meta-R-320	Surge Withstand Capability Immunity: IEC 60255-22-1:2007, 1kV peak differential Mode. IEC 60255-11:2008 Power supply Immmunity for Relays. IEC 61000-4-4:2011 Severity Level: 4 (4 kV on power supply)
SEL	SEL 751		Hard, based on >36% PS over/under voltage. >4kV fast burst.			MOVs in shielded enclosure		Surge Withstand Capability Immunity: IEC 61000-4-4:2011/IEC 60255-26:2013, 4kV @5kHz, 2kV on comm.
SEL	SEL 751A		Hard, based on >36% PS over/under voltage. >4kV fast burst.			MOVs in shielded enclosure		Surge Withstand Capability Immunity: IEC 61000-4-4:2011/IEC 60255-26:2013, 4kV @5kHz, 2kV on comm.
SEL	SEL-351 Directional Overcurrent		Hard, based on >16% PS over/under voltage. >4kV fast burst. 100ms interruption.			MOVs in shielded enclosure		Surge Withstand IEC 60255-22-1:2007 1kV peak differential mode. IEC 61000-4-4:2004 Fast Burst Immunity. IEC 60255-11:2008 Power Supply dips for Relays.
SEL	SEL-501 Relay Type		Hard, based on>36% PS over/under voltage. >4k Fast Burst			MOVs in shielded enclosure		IEC 60801-4:1988 Level 4 (4 kV on power supply, 2 kV on inputs and outputs) Fast Transient Burst grandfathered into 61000-4-4
SEL	SEL-501-2 Phase and Ground Overcurrent		Hard, based on >36% PS over/under voltage. >4k Fast Burst			MOVs in shielded enclosure		IEC 60801-4:1988 Level 4 (4 kV on power supply, 2 kV on inputs and outputs) Fast Transient Burst grandfathered into 61000-4-4
SEL	SEL-501-2 Relay Two Phase Overcurrent		Hard, based on >36% PS over/under voltage. >4k Fast Burst			MOVs in shielded enclosure		IEC 60801-4:1988 Level 4 (4 kV on power supply, 2 kV on inputs and outputs) Fast Transient Burst grandfathered into 61000-4-4
GE	GE MFAC 34 Relay Differential High Impedance Three Phase and Ground Fault Protection		Electromechanical, assumed hard.					
GE	GE MVAJ 21 Relay High Burden		Electromechanical, assumed hard.					
GE	GE-GCX Electromechanical overcurrent relay		Electromechanical, assumed hard.	Fast Pulse: 8kV (160A)			Meta-R-320	
GE	GE-PJC Electromechanical overcurrent relay		Electromechanical, assumed hard.	Fast Pulse: 8kV (160A)			Meta-R-320	
SEL	SEL 421	>50kV/m	Hard, based on>25% PS over/under voltage. >5kV fast burst.	800A	1000A	MOVs in shielded enclosure	DTRA-TR-16-90	IEC 61000-4-4:2011 4kV@5kHz. IEC 60255-11:2008 Power supply dips for Relays
Basler	BE1-11f	>50kV/m	May be vulnerable to harmonics. No burst. >20% PS over/under voltage.	100A	200A	MOVs in shielded enclosure	DTRA-TR-16-90	EN 61000-4-11: Voltage Dips and Interrupts
Siemens	SIPROTEC 7SJ600	>50kV/m	Hard, based on >15% PS over/under voltage. 2kV fast burst.	200A	400A	MOVs in shielded enclosure	DTRA-TR-16-90	IEC 255-22-4 and IEC 1000-4-4, class III, 2 kV, 5/50 ns, 5 kHz, burst length 15 ms.
Hindle Power Incorporated	AT30 Battery Charger			2000A	2250A	MOVs in shielded enclosure	Walker et al: DTRA-TR-16-XX, AT-30	SWC (oscillatory surge) requirements of ANSI C37.90; transient suppression levels for category B in IEEE Std. 28/ANSI C62.1.

4.3.4. Mitigation Assessment – Relays and Battery Chargers

HEMP E1 Radiated: Based on the stress vs. strength survey, relays are hard to damage due to the very highest levels of the E1 field inside a facility, and no additional mitigation is required.

HEMP E1 Conducted: Based on the stress vs. strength survey, the recommended damage mitigation for digital relays against HEMP E1 currents is to add protective MOVs within properly shielded enclosure to the CT and PT inputs of the relay. MOVs must be selected dependent on the expected commercially applicable maximum input voltages of the relay sensors, including abnormal transients.

HEMP E3/GIC: Based on the stress vs. strength survey it is expected that standard power supply tolerances and immunity tests indicate adequate margin over damage for the very small effects which may be propagated to the LV mains power for the relays surveyed.

4.3.5. Summary – Relays and Battery Chargers

As summarized in Table 1, highest priority mitigation for relays is providing MOVs in shielded packages on CT and PT inputs.

Table 17: Relay Mitigation Summary

Component	Stress	High Priority Mitigation
Digital Relay	HEMP E1 Conducted	MOVs in shielded package on all signal inputs
Digital Relay	HEMP E1 Radiated	Low priority
Digital Relay	HEMP E3/GIC	Low priority
Analog Relay	HEMP E1 Conducted	Low priority
Analog Relay	HEMP E1 Radiated	Low priority
Analog Relay	HEMP E3/GIC	Low priority
Battery Charger	HEMP E1 Conducted	MOVs or filters on power inputs.
Battery Charger	HEMP E1 Radiated	Low priority
Battery Charger	HEMP E3/GIC	Low priority

4.4. Substation Switches and Actuators

At the time of this report no known PCI tests of a gas circuit breaker (GCB) have been conducted. The ABB 72 PM 31-42 is rated at 72 kV at continuous current of 1200 Amps shown in Figure 25 has been in several DTRA tests but has not been directly subjected to HEMP PCI or Field testing. Review of the typical control cable lengths, and protection in the GCB suggests that the full threat 500A/2500A would be applied to these wires in a MIL-STD-188-125-1 test, there is no strength data available and this makes some data a critical part of a HEMP assessment.

Figure 25. GCB (Left) with GCB Control Panel.

4.5. Power Transformers

At the time of this report no known PCI tests of a Transmission level transformer have been conducted. The DTRA testbed contains two 69kV primary transformers with distribution level secondaries of 480 VAC and 2.4 kVAC. One is shown in Figure 26 with the station class lightning arresters. Some tests are planned by DTRA. Based on the lightning arrestor leakage voltages this is not considered a high risk, but no full threat data exists.

Figure 26. 69 kV Transformer with Lightning Arresters.

5. GENERATING STATION EQUIPMENT

5.1. Expected Stress Survey

E1 radiated stress: As noted earlier, in the absence of a verifiable shielding for the fields and attenuation for conductors which are located outside the buildings a 50 kV/m field is the baseline field in both standards. If the building SE and POE protection residuals are tested and verified by the methods of MIL-STD-188-125-1 Appendices A and B, then this level would be reduced accordingly. For an IEC Protection Concept 2B, this would be 20dB or 5 kV/m. While this field would vary for equipment in the interior of the buildings it is doubtful if any of the above ground buildings would achieve the concept 4 level of 40 dB which would reduce the field to 500 V/m.

E1 conducted stress: The baseline stress is the MIL-STD-188-125 E1 5000A common mode, and max(5000A/sqrt(N), 500A) wire to ground, per Table I of the MIL standard; for power inputs its 5000A common mode and 2500A wire to ground. If the building SE and POE protection residuals are measured by the methods of MIL-STD-188-125-1 Appendices A and B, then these levels would be reduced accordingly. For example, if the building is tested and verified to meet IEC 61000-2-11 Protection Concept 2B, then the stress would be reduced by 20dB or 500A.

HEMP E3/GIC Conducted Stress: 200A for 100s to 1000A for 20s for E3. GIC is many minutes long. The GSU is directly affected, by resulting harmonics and VAR, and the GSUs harmonics can introduce sub-synchronous resonances in generators and turbines. Intrasite lines are not affected so plant Distribute Control System (DCS) transducers, transmitters, controls, and computers are not directly affected by E3/GIC since they are not connected to long lines.

5.2. Sensors and Transmitters

Generating plant sensors include temperature, pressure, speed, position, optical, and mass flow sensors among others. The plant controls include their interconnecting wiring, transmitters, receivers, and servo/control modules which automate the power plant. Despite the large installed base of direct wired sensors, the trend is toward using either wired or unwired transmitters that connect to the actual sensor. Transmitters save time and money in installation, improve measurement reliability, reduce maintenance and increase uptime. A transmitter converts the mV signal from a resistive temperature transducer (RTD) or thermocouple (T/C) or pressure transducer to a common 4-20mA signal, or to a digital fieldbus output such as HART, Foundation Fieldbus, Profibus PA in the case of a smart transmitter, or one of the proprietary instrument protocols. Both the digital and analog outputs are transmitted over a twisted pair wire for a considerable distance. Smart transmitters incorporate remote calibration, advanced diagnostics and built-in control capabilities. Some are capable of wireless operation. A survey of sensors used in a modern fossil-fuel based steam plant are shown in Table 18.

Table 18. Pressure Sensors/transmitters.

Type	Manufacturer	Model or Series
Pressure	Foxboro	I/A (IDP / IGP)
Pressure	Siemens	Sitrans
Pressure	Emerson	Rosemount 3051
Pressure	ABB	2600T
Pressure	GE	UNIK 5000, PTXPRESS
Vibration	Siemens	SIPLUS CMS
Vibration	Emerson	CSI Series
Vibration	ABB	WiMon100
Vibration	GE (Bently Nevada)	990 Series
Temperature	Foxboro	Model RTT20 Temperature Transmitter (HART or 4-20)
Temperature	Rosemount (Fisher, Emerson)	3144P Temperature Transmitter
Temperature	Rosemount (Fisher, Emerson)	648 Wireless Temperature Transmitter (Battery Powered)
Temperature	ABB	TTF300 Field-mount temperature transmitter
Speed Sensors/Controllers	Honeywell	Boiler feed/condensate pumps scoop tube fluid coupling (oil clutch) speed control
Speed Sensors/Controllers	Honeywell	Turbine speed probes, geartooth (hall effect)
Arc Flash CB	ABB	Opto arc sensor (code for 4160 panels)
Arc Flash CB	Westinghouse	Opto arc sensor (code for 4160 panels)
Standalone Batch Controller for Progressive Water RO system	Allen-Bradley	PLC

Because plant sensors and transmitters are not connected to long lines, E3/GIC stress/strength/mitigation has been eliminated from further discussion.

5.2.1. Battery Powered Wireless Sensors/Transmitters Strength

In SARA's plant survey, one of the installations used wireless sensors on the lignite coal feed system, with line of sight signaling. Wireless use is growing as operators get more comfortable with it; it is beginning to be used in some of the critical loops, with triple redundancy. However other operators surveyed are reluctant to use wireless because of reflections and multipaths and issues with getting power to the devices.

HEMP E1 Radiated Strength: Wireless, battery powered sensors such as the ABB WiMon100 vibration/temperature transducer/transmitter shown in Figure 27 are minimally affected by the HEMP E1 radiated stress because 1) they are out of band of the of HEMP, being 2.4GHz and above 802.11 devices and 2) their size is less than λ/2 at 1GHz.

HEMP E1 Conducted Strength: Wireless, battery powered sensors are minimally affected by the HEMP E1 conducted stress because there are no attached signal or power wires.

HEMP E3/GIC Conducted Strength: Plant transducers are not affected by E3/GIC since they are not connected to long lines.

Figure 27: Example of wireless, battery powered generating plant transducer.

Approx. 4” long threaded directly into boiler. (ABB WinMon100 Wireless Vibration and Temperature Sensor).

5.2.2. Battery Powered Wireless Sensors/Transmitters Mitigation

No mitigation is believed to be required for wireless battery powered transducers. However, there is limited direct data to provide confidence.

5.2.3. Wired Sensors/Transmitters Strength Survey

An example of a wired sensor transmitter is shown in Figure 28: Example of wired DIN-powered generating plant transducer. Transmitter wires for such devices examined in this survey typically had aluminized Mylar shielding and sometimes low-coverage overbraid. However, the shielding is designed to eliminate powerline low frequency noise but not RF, i.e. E1 frequencies, and is only terminated at one end, so no E1 threat reduction can generally be assigned to the shield.

The CSI 9330 interfaces with existing plant monitoring systems while continuously monitoring critical machinery.

Figure 28: Example of wired DIN-powered generating plant transducer.

Emerson, 0.9 in x 3.9 in x 4.5 in.

<u>HEMP E1 Radiated Strength:</u> Most sensor transmitter/transducers surveyed have been tested to EN/IEC 61000-6-2 which has an rms 10V/m strength from 80-1000MHz.

<u>HEMP E1 Conducted Strength</u>: EN/IEC 61000-6-2 tested sensor transmitter/transducers have been tested against the 5/50ns IEC 61000-4-4 fast transient at 1kV, 2kV, and 2kV for signal, DC, and AC ports, respectively.

HEMP E3/GIC Conducted Strength: Plant transducers are not affected by E3/GIC since they are not connected to long lines.

5.2.4. Wired Sensors/Transmitters Mitigation Assessment

The surveyed sensors with their immunities are shown in Table 19. Because of the relatively low immunities and high currents even for Protection Concept 2B, a component level test program should be undertaken, starting with samples of the most common components (similar to the relay tests), to provide actual test data supporting or refuting these conclusions.

HEMP E1 Radiated: Power-on test components to E1 radiated at 50kV/m. If the plant has been tested and verified to a higher-level IEC protection concept, the test levels can be lowered accordingly. For example, for Concept Level 2B, the components may be tested to 5kV/m, to achieve the IEC 99% threat level.

HEMP E1 Conducted: Power-on test using the E1 waveform at 5000A common mode, and max(5000A/sqrt(N), 500A) wire to ground, per Table I of the MIL standard; for power inputs use 5000A common mode and 2500A wire to ground would provide some baseline data for an assessment of sensors. If the building SE and POE protection residuals are verified by the methods of MIL-STD-188-125-1 Appendices A and B, then these levels would be reduced accordingly. For example, if the building is tested and verified to meet IEC 61000-2-11 Protection Concept 2B, then the stress would be reduced by 20dB or 500A, to achieve the IEC 99% threat level.

HEMP E3/GIC Conducted: No mitigation is required.

Table 19. Sensors/Transmitters Survey Results.

Type	Manufacturer	Component	E1 Rad Strength	Min E1 Cond Strength	EMC Refs
Pressure	ABB	2600T	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	NAMUR 21 Recommendations
Pressure	Emerson	Rosemount 3051	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61326, IEEE C62.41.2-2002 Surge 6 kV crest (1.2/50 us) and 6kV Crest/500A Ring Wave (0.5 us – 100 kHz) for Loc Cat B (in building but not outlets, e.g. service panels)
Pressure	Foxboro	I/A (IDP / IGP)	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61326-1, IEC 61000-4-2 through 4-5, 4-4 5/50ns bursts of 1kV sig 2kV pwr
Pressure	GE	UNIK 5000, PTXPRESS	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61000-6-2:2005 incl. 61000-4-4 EFT, 4-5 Surge, 4-11 Dips and Sags
Pressure	Siemens	Sitrans P DSIII Series	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61326/A1 1998 but no specifics
Pressure	Siemens	Sitrans P ZD Series	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61326/A1 1998 but no specifics
Temp	ABB	TTF300 Field-mount temperature transmitter	10 V/m 80-1000MHz	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	

Table 19. Sensors/Transmitters Survey Results.

Type	Manufacturer	Component	E1 Rad Strength	Min E1 Cond Strength	EMC Refs
Temp	E+H Omnigrad	S TMT162R	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61326
Temp	Foxboro	Model RTT20 Temperature Transmitter (HART or 4-20)	30 V/m Peak 26-1000 MHz if metal housing option	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	Datasheet states RFI. Manual states "The RTT20 complies with the requirements of the European EMC Directive 89/336/EEC." which includes 5/50 EFT and 1.25/50 surge (ref Ott, "Electromagnetic Compatibility Engineering", Section 14.3.)
Temp	Rosemount (Emerson, Fisher)	3144P Temperature Transmitter	30 V/m 80-1000MHz	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	IEC 61000-4-3, 30 V/m 80-1000MHz, IEC 61326 2006
Temp	Rosemount (Emerson, Fisher)	648 Wireless Temperature Transmitter (Battery Powered)	Inherently Hard, out of band, no wires.	Inherently Hard, out of band, no wires.	
Vibration	ABB	WiMon100 Combined sensor/wireless transmitter (Battery powered)	Inherently Hard. Out of band.	Inherently Hard. No wires.	ETSI EN 300 328 v.1.7.1, EN 301 489-1 v.1.9.2, EN 301 489-17 v.2.2.1. No wires - thread in, battery powered.
Vibration	Emerson	CSI 9330 Vibration Transmitter	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61000-4-2 thru 4-8. Industrial level 10V\/m

Table 19. Sensors/Transmitters Survey Results.

Type	Manufacturer	Component	E1 Rad Strength	Min E1 Cond Strength	EMC Refs
Vibration	Emerson	CSI 9420 Wireless Vibration Transmitter	Inherently Hard. Out of band.	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61326-1 (Power and sensor wires)
Vibration	GE (Bently Nevada)	990 Series	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61000-6-2 Immunity for Industrial Environments
Vibration	Siemens	SIPLUS CMS SM1281 SIMATIC S7-1200 4 IEPE VIBRATION CHANNELS	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61000-6-2: incl. 61000-4-4 EFT, 4-5 Surge, 4-11 Dips and Sags
Vibration	Siemens	SIPLUS CMS2000	10V/m	5/50ns IEC 61000-4-4 fast transient at 1kV/20A, 2kV/40A, and 2kV/40A for signal, DC, and AC ports, resp	EN 61000-6-2 incl. 61000-4-4 EFT, 4-5 Surge, 4-11 Dips and Sags

5.3. Distributed Control Systems (DCS)

There are several popular manufacturers of complete distributed control systems. Manufacturers and product model lines include:

- Emerson Ovation & Delta V
- Siemens T3000
- GE Mark VI & Mark Vie
- Group Schneider / Foxboro Infusion I/A
- ABB / Bailey
- GE Bently-Nevada

These systems encompass the upper levels of the DCS hierarchy. The lowest level (sensors) may be filled with compatible equipment from different manufacturers, but the upper levels (operator interface, application servers, and control interface modules) will typically be from a single platform. Protection of the DCS includes the AC power system, the DC power system, communications infrastructure, and the direct wiring from sensors/actuators to input modules.

Central to the DCS are the harnesses comprising the communications physical layer.

<u>Ethernet</u>: In the steam plants surveyed, Ethernet cables ran in separate conduit from A/C signals, but Ethernet sometimes ran in DC trays. Ethernet was mostly in its own conduit which is not always metallic - sometimes PVC conduit is used. RJ-45 surge protectors were not typical. Where possible optical fiber is used on long runs but there is still susceptibility of the actual switches and media converters. From a HEMP perspective optical fiber is recommended wherever possible.

<u>Sensor installation including cabling/wiring</u>: For direct-wired sensor installation, sensors typically use standard 4-20 mA loops with 0-1 volt signals. Newer installations typically use 22 gauge wire that is double-shielded with the wires wrapped in a foil, and the foil is overbraided by a ground shield. The ground shield is grounded at a copper bus at the DCS I/O cabinet that is separate from the DCS ground bus, called the "Vertical Ground Bus". The ground buses are then tied together by 1/0 or 2/0 cable, and then tied to the plant ground grid. Grounding at the I/O device panel and tying from there to the ground grid is general practice. There may be 25 I/O panels distributed around the plant, but common practice is to ground sensors at the I/O panel, with the goal always being to eliminate possibilities for ground loops.

Detailed protection measures for protection of DCS circuits are given in [9], the EPRO handbook, Section IV-C. As the Smart Grid becomes more prevalent, control systems will become more distributed and use internet protocols or industrial automation standards. The overall approach to maximizing the hardness of such DCS is to reduce coupling and add protection, based on the measures in [9].

Recommended hardening/mitigation measures per [9]:

- Wired Comm Links
  - Install optical fiber between routers
  - Install shielded CAT cable between routers, for example L-COM TRD855DSZ
  - For COTS routers, install Ethernet surge protection such as the Transtector 1101 series
  - Enclose routers in hardened racks
  - Filter power to routers
- Wireless Comm Links
  - Front-door protection: Short range wired comm links such as Wi-Fi, Bluetooth and Zigbee use the ISM bands above 900MHz; many are at 2.4GHz and above. This is at the high end of most HEMP standards so isn't expected to be much of a problem. Front-door coupling due to IEMI would be more severe.
  - Filter power to sensor transmitters
  - Use battery powered sensor transmitters

5.3.1. Strength Survey

HEMP E1 Radiated: Of the surveyed equipment, only the GE Power Systems SPEEDTRONIC Mark VI Turbine Control System gave specific EMC certifications; others merely claimed CE marking. Assuming GE Power Systems SPEEDTRONIC is representative, the radiated immunity is 10V/m.

HEMP E1 Conducted: Of the surveyed equipment, only the GE Power Systems SPEEDTRONIC Mark VI Turbine Control System gave specific EMC certifications; others merely claimed CE marking. A valid CE Marking affixed to a product indicates that it complies with the relevant European 'New Approach' product safety Directives. Assuming GE Power Systems SPEEDTRONIC is representative, the conducted immunity is (5ns/50ns) at 4kV.

5.3.2. Mitigation Assessment

The surveyed DCS components have low strength relative to high stress, even for Protection Concept 2B. Therefore, a component level test program should be undertaken, starting with samples of the most common components (similar to the relay tests), to provide actual test data supporting or refuting these conclusions.

HEMP E1 Radiated: Power-on test components to E1 radiated at 50kV/m. If the plant has been tested and verified to a higher-level IEC protection concept, the test levels can be lowered accordingly. For example, for Concept Level 2B, the components may be tested to 5kV/m, to achieve the IEC 99% threat level.

HEMP E1 Conducted: Power-on test using the E1 waveform at 5000A common mode, and max(5000A/sqrt(N), 500A) wire to ground, per Table I of the MIL standard; for power inputs use 5000A common mode and 2500A wire to ground. If the building SE and POE protection residuals are verified by the methods of MIL-STD-188-125-1 Appendices A and B, then the test levels are to be reduced accordingly. For example, if the building is tested and verified to meet IEC 61000-2-11 Protection Concept 2B, then the stress would be reduced by 20dB or 500A, to achieve the IEC 99% threat level.

HEMP E3/GIC Conducted: No mitigation is required.

5.4. Generator Excitation Systems

An exciter system provides the source for DC current in the rotor winding of the generator. As this current flows through the rotor field winding, a sinusoidally distributed flux is established in the air gap. As the generator's shaft is rotated, this rotating flux will induce a voltage in the stator windings of the generator. The amount of field winding excitation required is dependent upon machine speed, the load required, and the load's power factor. There are several different types of excitation systems. Two of the most commonly used are the DC Exciter system and the Static Excitation system.

DC Exciter

Older generators may have a DC Exciter system, which is a small DC generator system that is driven by either the generator's main shaft or by a separate motor. The DC Exciter is typically composed of three devices – a pilot exciter, an automatic voltage regulator (AVR), and a main exciter. A control system or rheostat will vary the field winding current of the smaller pilot exciter, which then sends current to the AVR. The output of the AVR is then used to control the field winding current of the main exciter. This main exciter then sends DC current to the generator rotor field windings via slip rings.

The preference is typically to have the exciter system driven by the main shaft of the generator so that any interference from external disturbances is minimized.

Static Exciter

The Static Excitation system is used in modern power generation plants. In a static excitation system, a three-phase circuit is taken from the output of the generator, run through a step-down transformer, and then rectified to DC via a set of silicon controlled rectifiers (SCR's). Like the DC Exciter, brushes are used to pass the DC current to the rotor field windings. The solid-state nature of the excitation system allows for a fast response and accurate control of the generator.

To start the field in the generator, an alternative dc source such as a station battery is used for field flashing.

Various Manufacturers of Static Exciter Systems include:

- Emerson Ovation excitation systems
- General Electric EX2100e Generator excitation system
- Mitsubishi (MEPPI) Thyristor system
- ABB UNITROL excitation systems
- Siemens SPPA-E3000 Static Excitation System (SES)

It is common for the above manufacturers to offer retrofits to convert older DC exciter systems to the newer static exciter systems. Some also offer upgrades to the conventional AVR system.

5.4.1. Strength Survey

HEMP E1 Radiated: Of the surveyed equipment, only components of the ABB UNITROL Static Excitation Systems gave specific EMC certifications based on EN 61000-2-6 which in turn cites IEC 61000-4-3. Assuming this is representative, the radiated immunity for exciters is not expected to exceed 10V/m. Based on the very limited stress survey, above ground plants were expected to have at most 40 dB of attenuation resulting in 500 V/m stress which suggests a possible problem. On the other hand, the frequency response of the exciter systems is related to AC frequencies and the E1 field is 100's of nsec.

HEMP E1 Conducted: Of the surveyed equipment, only components of the ABB UNITROL Static Excitation Systems gave specific EMC certifications based on EN 61000-2-6 which in turn cites IEC 61000-4-4. Assuming this is representative, the conducted immunity is (5ns/50ns) at 1kV for signal inputs, and 2kV for power inputs. Again, the very limited assessment of the plant attenuation for conducted transients would suggest possible conducted transients exceeding the 40 A short circuit current expected at 2 kV. The excitation systems are not isolated from the outgoing power but are in fact derived from it so significant coupling is expected.

5.4.2. Mitigation Assessment

The surveyed exciter systems have low strength relative to high stress, even for Protection Concept 2B. Therefore, a baseline component level test program should be undertaken, starting with samples of the most common components (similar to the relay tests), to provide actual test data supporting or refuting these conclusions. Since the coupling is also poorly defined a better assessment of the coupled signal would also contribute to a better overall assessment.

HEMP E1 Radiated: Power-on test components to E1 radiated at 50kV/m. If the plant has been tested and verified to a higher-level IEC protection concept, the test levels can be lowered accordingly. For example, for Concept Level 2B, the components may be tested to 5kV/m, to achieve the IEC 99% threat level.

HEMP E1 Conducted: Power-on test using the E1 waveform at 5000A common mode, and max(5000A/sqrt(N), 500A) wire to ground, per Table I of the MIL standard; for power inputs use 5000A common mode and 2500A wire to ground. If the building SE and POE protection residuals are verified by the methods of MIL-STD-188-125-1 Appendices A and B, then the test levels are to be reduced accordingly. For example, if the building is tested and verified to meet IEC 61000-2-11 Protection Concept 2B, then the stress would be reduced by 20dB or 500A, to achieve the IEC 99% threat level.

HEMP E3/GIC Conducted: No mitigation is required.

5.5. GSUs

As mentioned in Section 4, HEMP E1 stress at transmission level transformers is mostly mitigated by transmission line lightning arrestors. SARA's report [5] has lightning arrester E1 test data to confirm this. The remainder of this section will therefore focus on E3/GIC. Based on SARA tests conducted at INL [15], and National Electrical Reliability Council's (NERC) process for assessing GMD and transformers in particular, it will be seen that in general mitigation is typically needed for GSUs.

The generating station is connected to the high voltage switchyard via its GSU (see Figure 13 and Figure 14). This transformer is typically a grounded-wye / delta configuration, with the delta on the generator side. While the GSU / substation will have nearby lightning arresters for protection, the grounded-wye configuration on the transmission grid network side of the transformer provides a path for the DC currents associated with HEMP E3/GIC.

The primary impact of HEMP E3/GIC on large power transformers is a result of the DC current that flows through wye-grounded transformer windings. This geomagnetically-induced current (GIC) results in an offset of the AC sinusoidal flux resulting in asymmetric or half-cycle saturation. Half-cycle saturation results in a number of known effects:

- Hot spot heating of transformer windings due to harmonics and stray flux;
- Hot spot heating of non-current carrying transformer metallic members due to stray flux;
- Harmonics;
- Increase in reactive power absorption; and
- Increase in vibration and noise level.

In the surveyed system, all transformers are delta on the generator side, grounded wye on the grid side. Most are 138kV grid side, but some are 345kV grid. No DC detection equipment was installed on the surveyed GSU's. There is a neutral CT designed for AC current measurement which does not register DC current. There are no special GIC reduction devices for E3/GIC installed. During an E3/GIC event, it may be possible to saturate the transformer due to the DC ground current. That would result in increased harmonics and transformer heating. The only protection against heating is a thermal cutoff in the transformer, triggered by a 90C rise above ambient temperature (so if ambient is 22C, then the transformer will trip offline when top oil hits 112C). There is no specific harmonic detection/protection on the GSU's. The closest they have is imbalance detection – the system will tolerate a 3%-5% phase imbalance and will trip above that. This phase difference may induce harmonics in the transformer, or likewise, harmonics in the transformer could conceivably induce a phase difference in current in the generator, but this is not expected to damage the transformer; the phase imbalance detection is primarily for generator protection and is mitigated by the as-mentioned phase imbalance trip.

The NERC TPL-007 requires a Geomagnetic Disturbance (GMD) Vulnerability Assessment of the system to determine its ability to withstand a benchmark GMD Event without causing voltage collapse (see Figure 29). It also requires a transformer thermal assessment of high-side, wye grounded Bulk Electric System (BES) transformers connected at 200kV or higher where effective GIC ≥ 75 A per phase. The effective 75 A per phase is a conservative screening criterion: it's based on conservative thermal models; the peak hot spot temperature of 150°C is well below IEEE Std C57.91 recommended limits; it's applicable to single-phase and three-limb, three-phase transformers. Susceptibility assessment is on a transformer-by-transformer basis, due to the fact that in many cases GSUs are individual designs for the power plant.

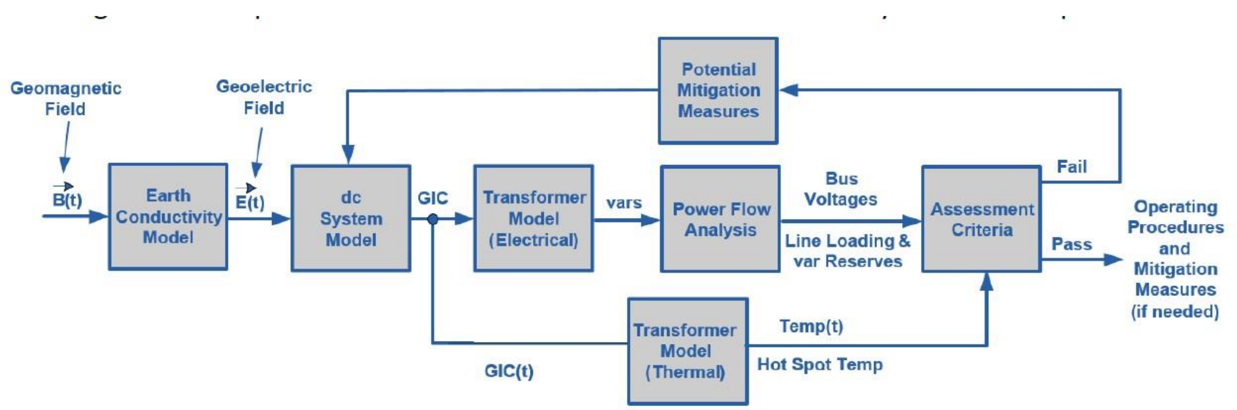

Figure 29: GMD Vulnerability Assessment Process.

5.5.1. Expected HEMP E3/GIC Stress Survey - GSUs

The E3 test standard from [3] Table I is ideally 1000A for 20s but is allowed to be as low as 200A for 100s. The NERC Benchmark GMD is shown in Figure 30. As can be seen, the duration of the peaks in the Benchmark GMD exceed the longest E3 pulse. The amplitudes calculated for the GMD however depend on the transmission system geometry, latitude, and the local conductivity profile of the soil which means the strength calculated by the utility operator during assessment may be much lower or much greater than the simple E3 prescription. But at least for the example in Appendix B of [27], common mode currents up to -762.45A (254.15A/phase) are predicted for systems located at latitude of about 34 degrees, which only uses 1/10th of the source GMD fields based on the scaling prescribed in Table 2 of [23]. A similar calculation assuming a transmission facility in the far north would therefore yield 7624.5A common mode (2541.5A/phase), all other things being equal.

Therefore, in general the overall Benchmark GMD waveform is typically much worse from a peak X FWHM perspective than E3, but since it's done on a case-by-case basis, the GIC stress should be clearly identified as the higher of the two specs up to 100 seconds.

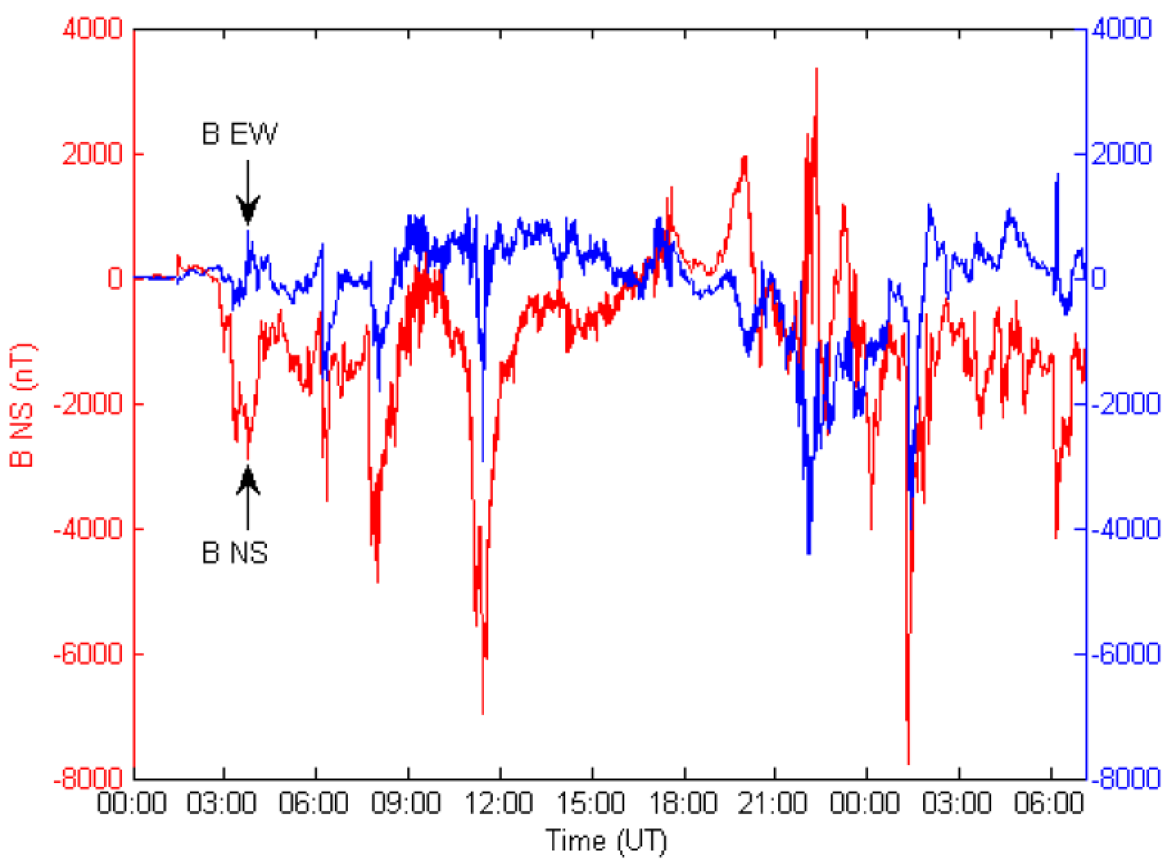

Figure 30: Benchmark GMD Fields. Red B NS (North-South), Blue B EW (East-West)

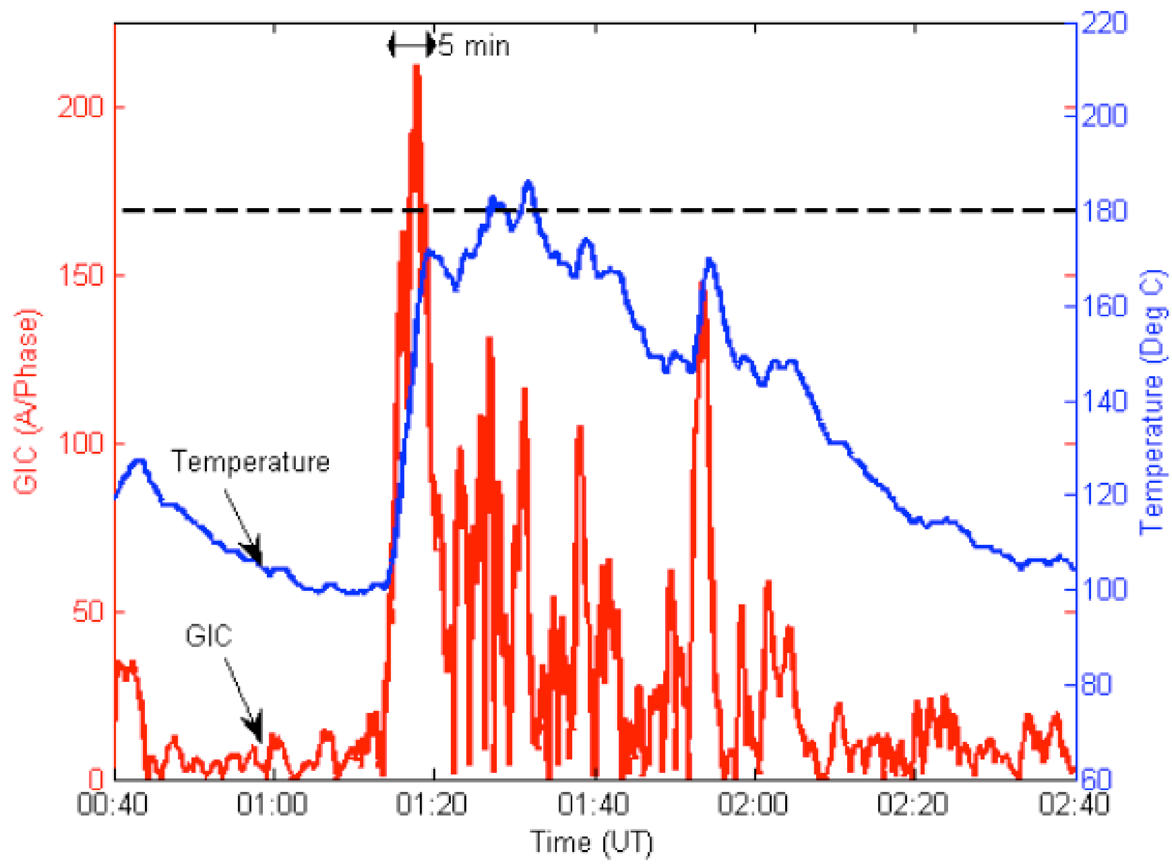

Figure 31: Close-up of Metallic Hot Spot Temperature Assuming a Full Load.

5.5.2. Expected HEMP E3/GIC Strength Survey - GSUs

Harmonic Limits: The standard "accepted" harmonic limits are taken from IEEE 519-1992 standard which are scaled based upon voltage class. The maximum limits under this standard are shown below in Figure 32. The allowable levels decrease as the Point of Common Coupling (PCC) voltage level increases, and since the duration of the individual MHD-E3 injections are short, the applicable limits in Table 11.1 of IEEE 519-1992 may be exceeded by up to 50%. This means that 3.75% and 2.25% are the applicable limits for V_{THD} and individual harmonics (respectively) at the 138 kV level. Also, it means that 7.5% and 4.5% (respectively) are the applicable limits for V_{THD} and individual harmonics at the 13.8 kV level.

FOR HARMONIC CONTROL IN ELECTRIC POWER SYSTEMS IEEE Std 519-1992

The limits listed in Table 11.1 should be used as system design values for the "worst case" for normal operation (conditions lasting longer than one hour). For shorter periods, during start-ups or unusual conditions, the limits may be exceeded by 50%.

Table 11.1
Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion THD (%)
69 kV and below	3.0	5.0
69.001 kV through 161 kV	1.5	2.5
161.001 kV and above	1.0	1.5

NOTE: High-voltage systems can have up to 2.0% THD where the cause is an HVDC terminal that will attenuate by the time it is tapped for a user.

Figure 32. IEEE 519-1992 Voltage Distortion Limits.

Thermal Limits: Calculate the transformer response using method found in the 2013 NERC application guide entitled "Application Guide: Computing Geomagnetically-Induced Current in the Bulk-Power System" [27]. If the Amperes/Phase is greater than 75 A, then use the Table 1 from NERC TPL-007-1 [23] (repeated below as Table 20) to determine the worst-case transformer hot spot value. If this exceeds the maximum transformer oil temperature limit of 200C (per IEEE C57-91, repeated in Table 21), then further refinements to the thermal assessment are done either based on transformer manufacturer GIC capability curves (see [28] for an example by AEP on a 750kV transformer), or more detailed thermal analysis.

Table 20: Upper Bound of Peak Metallic Hot Spot Temperatures

Effective GIC (A/phase)	Metallic hot spot Temperature (°C)	Effective GIC(A/phase)	Metallic hot spot Temperature (°C)
0	80	100	182
10	107	110	186
20	128	120	190
30	139	130	193
40	148	140	204
50	157	150	213
60	169	160	221
70	170	170	230
75	172	180	234
80	175	190	241
90	179	200	247

Calculated for the Benchmark GMD Event (from [23]) and Compared to IEEE C57-91: 2011.

Table 21: IEEE C57-91 Maximum Transformer Temperature Limits.

	Normal life expectancy loading	Planned loading beyond nameplate rating	Long-time emergency loading	Short-time emergency loading
Insulated conductor hottest-spot temperature °C	120	130	140	180
Other metallic hot-spot temperature (in contact and not in contact with insulation), °C	140	150	160	200
Top-oil temperature °C	105	110	110	110

5.5.3. Mitigation Assessment – GSUs

Figure 33 shows a time history of the second harmonic (in %) in the top trace and the 2nd and 4th harmonics as a function of drive current in the lower two traces.

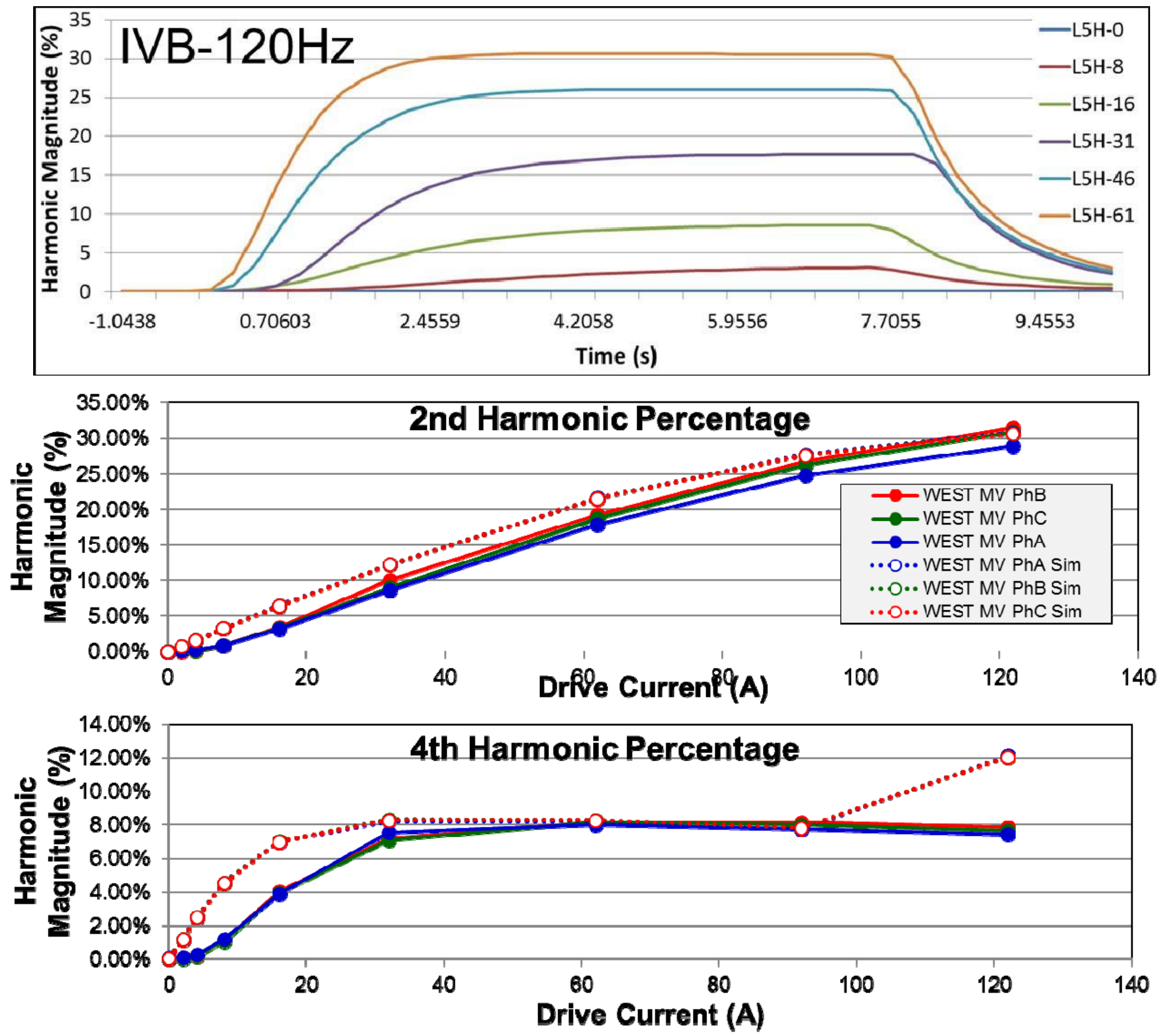

Figure 33. Measured Harmonic Data from DTRA E3 Tests.

This far exceeds the limits of IEEE 519-1992 shown in Figure 32. Based on these test results, the general response of the grid during Quasi-DC current injection was the development as expected of a large reactive current. The apparent load to the utility increased from ~1.8 MVA to in excess of 7 MVA during the current injection in the driven loop. The saturating transformers produce >150 kW of harmonic power that travels in both directions, towards the utility and towards the loads. These currents were not identified and acted upon by the standard power system protection elements. Power drawn into and out of the test transformers identified up to 600 kW of "missing power." When integrated over the injection period, the missing power consists of MJs of energy.

Thermal Vulnerability: Based on the example calculations in the EPRI study "Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental US Electric Grid", February 2017, the single shot E3 conclusion was "However, of the hundreds to thousands of transformers that were then evaluated in more detail by performing a time domain thermal analysis, only a small number of them were found to be at potential risk of thermal damage". Solar storms can last significantly longer (although at lower currents) and could possibly represent a larger threat to the transformer fleet. Longer time frames allow implementation of the first three of the following mitigation procedures,

Per [29], mitigating measures can take one of the following forms:

- Reassignment of VAR resources,
- System reconfiguration, normally by bringing key circuits in and out of service,
- Load rejection,
- Using GIC reduction devices (GRDs) on static VAR compensator (SVC) transformers to ensure they can provide reactive support during any event, and
- Using GIC reduction devices to maintain transformer currents below an arbitrary threshold (independent of GIC "waveshape") or to ensure that key transformers remain in service during any event.

It should be noted that a GRD on a GSU transformer would not prevent a generator from tripping on unbalance or negative sequence protection. Usage of GRDs should always be conditional to the results of system suitability studies (protection impact and failure modes) as well as functional requirements. Additionally, the application of GRDs must consider the failure of a GRD as a valid contingency. The mitigating measures are then reinserted into the GMD assessment model to demonstrate improvement.

Indirect Detection and Mitigation Using Protective Relaying: Commercial transformer differential protective relays have the capability to alert system operators to the presence of harmful harmonics due to E3 or GIC, or once harmonics reach a potentially damaging level, to trip GSUs offline. For example, the SEL-487E relay is able to calculate percentages of the second, fourth, and fifth harmonics for the operate current. The operating current is a phasor sum of the high- and low-side winding currents, phase-shift compensated and adjusted to a per-unit basis adjusted for transformer MVA rating, the CT ratio, and the transformer ratio. Logic in the relay can be used to compare the instantaneous harmonic percentage calculation with a pre-determined pickup value, and if that threshold is met, to begin a logic timer. Should the value stay above the threshold for the duration of the timer, i.e. longer that a typical inrush current, a status bit would be set and passed via SCADA to a system operator, or the bit may be used to trigger some other output. These protective relays normally have harmonic restraint or harmonic blocking settings that are used to prevent tripping during transformer energization inrush. Inrush events are typically brief, only lasting up to a second or two. An E3 or GIC timer value would be longer, and different thresholds could be signaled to notify of different levels of harmonic activity. Other relay models allow for the calculation of total harmonic distortion (THD), and this value may be used in a similar manner as described above. It is important to note, of course, that the relay must be protected from E1, to unsure that it can function to provide such E3 protection during an actual HEMP event.

In all cases, CTs themselves may be subject to saturation and develop their own harmonics due to DC currents, so this must be accounted for in the detection scheme. Certain types of CTs such as double-core, Hall effect, or Rogowski coils are less susceptible to saturation.

<u>Direct Detection and Mitigation Using GIC Reduction Devices</u>

One example of a GRD is the neutral blocking device known as the SolidGround from EMPRIMUS/ABB. DTRA tested this GRD at Idaho National Labs and the results showed that it blocked simulated GIC successfully by capacitively blocking the ground currents to nearby grounded transformers without disturbing normal grid operation [31]. These results were reported at the 2013 Minnesota Power Systems Conference [32]. Figure 34-Figure 35 are excerpted from [32] and provide an overview of the technology. There is one documented installation of the SolidGround device on the ATC Wisconsin Grid on a 345kV/300MVA transformer [33].

Concerns relating to the use of capacitive neutral blocking devices were summarized in [36]:

1. Over voltages can cause surge protection devices to fail
2. Neutral insulation coordination must be evaluated
3. Potential for series resonance and ferro-resonance must be evaluated
4. Blocking device impedance cancellation could increase neutral ground currents
5. GIC could be redirected to other transformers

EMPRIMUS performed studies pertaining to these concerns and the results were presented in [37]. The first four were demonstrated to be of minor concern. The mitigation for the fifth was suggested to be installing neutral blocking devices on all transformers. The DTRA report [31] observed that re-routed blocked current was 50% of its original level.

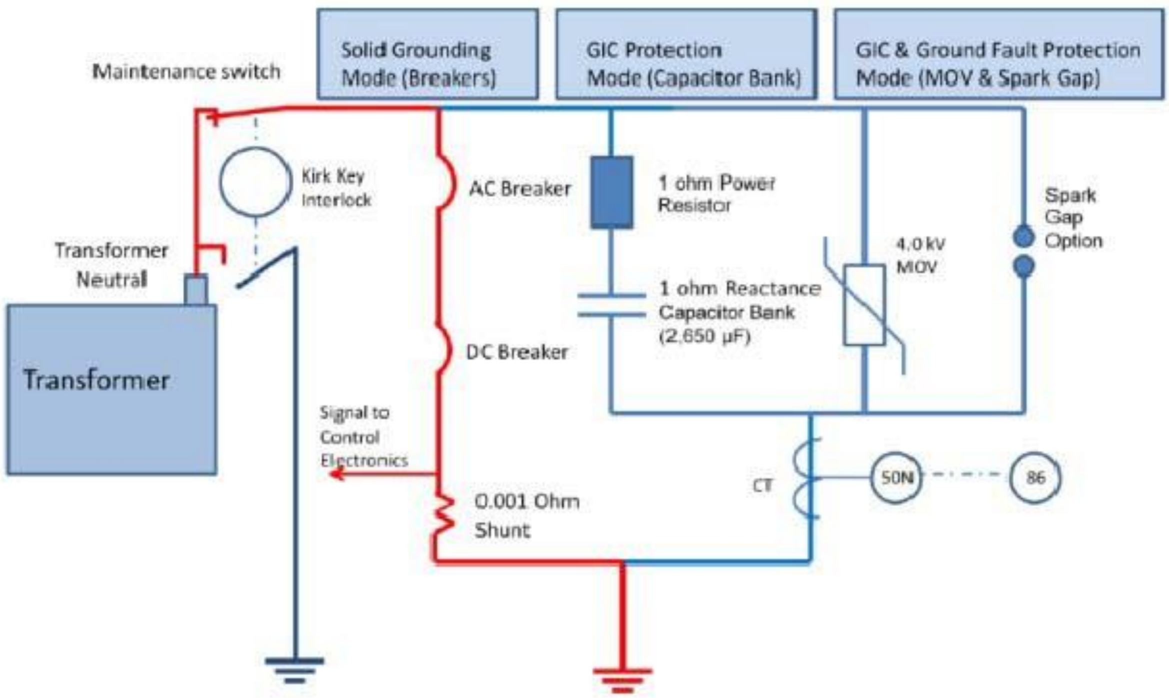

Figure 34: SolidGround System Overview [32].

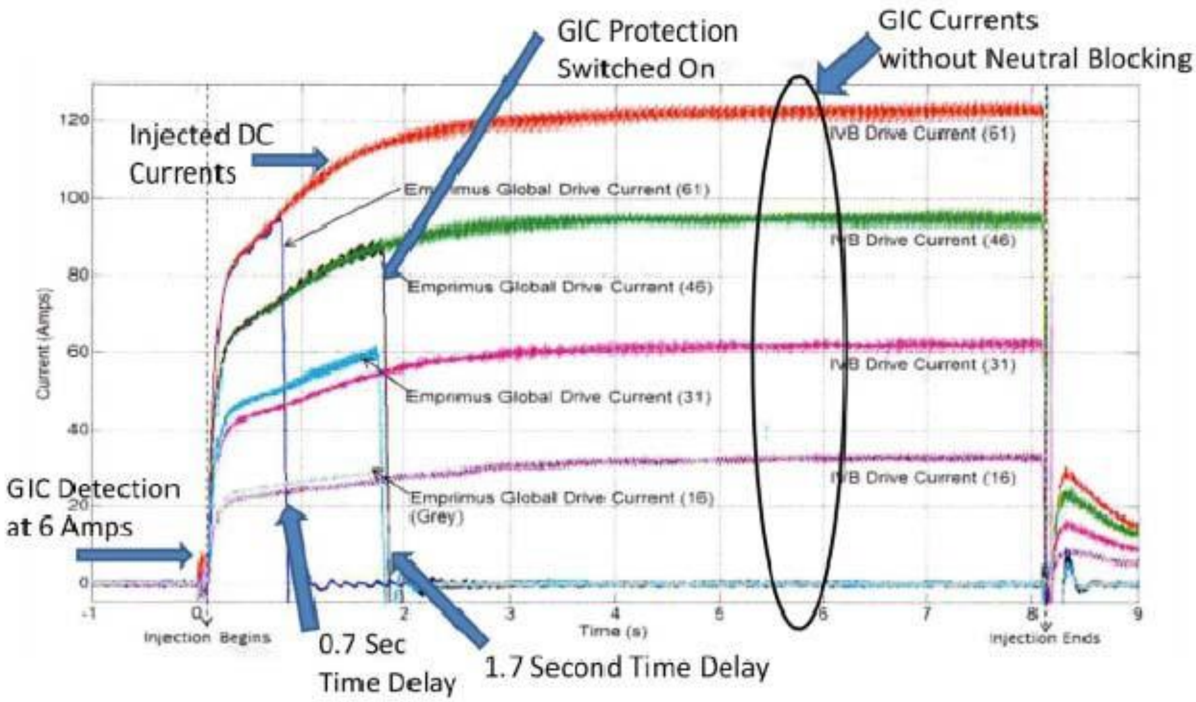

Figure 35: SolidGround Neutral Blocking Live Grid Test Results [32].

5.6. Supporting Systems

While this section has so far concentrated on the components directly involved with generation, there are important supporting systems that must maintain operability after a HEMP or GMD. These include

- Air Conditioning
- Cooling
- Water Treatment (for steam plants)
- Fuel delivery
- Radios

While we will not address these systems or their components specifically, it’s evident from our plant surveys that they have exposed unprotected cables which exceed the MIL-STD-188-125-1 restricted length limit of 5m and therefore would require test and verification at the full 5000A to be considered Black Sky compliant. An example of this is evident in Figure 16 with the exposed vertical cable runs on the chillers. Our conclusions are that these support systems are at greater risk from coupled currents on POEs than power components. Their loss would pose as great a risk to post-event operation and recovery as the long line threats to the primary transmission component. *Therefore they should be shielded/filtered/treated and most importantly tested similarly.*

6. CONCLUSIONS

The authors of this survey do not believe that these results represent the final answer to the issues associated with hardening of the commercial grid to the EM Black Sky threats represented by HEMP and GMD induced GIC. The results not only identify some equipment which seems particularly sensitive to pulsed threats on the power and signal cables but has identified an important difference in the approaches used to identify the tests which are required to certify equipment/systems especially for critical first line equipment such as the Black Sky restart systems.

The survey identified major weaknesses and by association suggested strengths of the grid to these threats. The limitations imposed by the statistics of existing data were discussed, along with a comparison of the HEMP related portions of the IEC 61000 series of standards with the military standard MIL-STD-188-125-1 for fixed ground based facilities with time critical missions. A survey of equipment associated with generating stations and transmission substations was conducted and existing responses / tests associated with both the field and conducted currents on this equipment was collected.

The primary threats (including all three time domains: E1, E2, and E3) acknowledged by the MIL-STD and IEC 61000 have been compared and are similar; tests and test techniques are also similar; but the *methodology for relating the equipment level data and the system hardness differ substantially.*

a. The peak fields, currents and voltages are within 50% / factor of 2 for the two standards (50 kV/m, 3000-5000 Amps peak, and 150 to 300 kV open circuit voltage). Importantly, of all the 78 individual components reviewed, only DoD or DOE have actually tested to levels approaching required MIL-STD or high IEC 61000-4-25 HEMP levels. ***Equipment vendors do not typically certify for the HEMP resilience of their equipment.***

b. Simulators with comparable characteristics (Pulsed Current Injectors (PCI) with 50-60 Ω, 3000-5000 Amperes peak, and 150 to 300 kV open circuit voltage, and Transverse Electromagnetic (TEM) field simulators) are required by both standards in the HEMP related tests.

c. Both standards acknowledge the effects of shielding and conducted penetration attenuation.

d. The approaches, however, are quite different. The MIL-STD requires their verification by test (traceability), while there is no released system level verification requirement or traceability for the IEC standard. The authors characterize the MIL-STD as a system level top down approach, and the IEC approach as a bottom up building block approach. MIL-STD-188-125-1 is based on system level testing while IEC 61000 assumes a system protection concept characterized by three attenuations: for fields (H, E), and conducted current. There is clearly a need for an authority to unify the stress (determined by the shielding level provided and verified by the utility) and the component strengths (determined by the vendors and PCI/TEM) tests into a verified, protected system for Black Sky resilience.

e. In addition to the equipment survey results, the comparison suggested some other inputs for the

Black Sky critical facilities. Experience with military systems led to the system level testing approach suggested in the MIL-STD-188-125-1. The global shield (system level, top down protection approach noted in d. above) required by the military standard makes system testing more cost effective by limiting the penetrations and requiring measured residuals behind this protection, but the final test is a live system test. This is of course very difficult (to impossible) for large power plants operating at high voltage. Continuing hardness maintenance and surveillance/monitoring insure the protections have not been compromised by changes. Some attempt to adapt the verification and hardness surveillance approaches from the MIL standard for the civilian power sector would provide a more traceable hardening protocol than the equipment level testing to an assumed system hardening concept of IEC 61000. However there remains a need for an agreement between the specifications used by the vendors (the hardening concept in IEC 61000) and the actual (traceable) shielding and attenuation in order to provide a traceable system hardness statement for Black Start Systems under Black Sky conditions.

Summary of Initial Findings

a. Control Equipment consists of relays, and sensor inputs to transmitters / computers. EMP conducted-current tests of relays have been performed by DTRA. Six representative digital relays (2 copies each of three relays) were tested for TEM and PCI stress in both protected and unprotected modes. In the TEM tests, only one relay suffered a minor Upset in its display, even without protection (which for radiated fields would be EM shielding surrounding the relay). For the PCI tests, five of six samples tested in the unprotected mode were permanently Damaged at some level of stress. The sixth suffered a Latching Upset. In the protected mode (Simple non-linear MOV protection properly mounted and isolated from the equipment), the relays demonstrated a significant improvement in their responses: only one of the six relays tested suffered a minor Upset to its display when MOV protection was used. Two representative electromechanical relays were also tested, and suffered no Upsets, up to maximum stress levels, in an unprotected mode.

b. Substation battery chargers for the remote-control systems were also tested. The representative battery charger was Damaged at the maximum stress level, but suffered only minor Upset at lower stress levels. The representative battery charger tested has built in non-linear protection. It is believed that isolating this protection would likely improve the effectiveness of the protection. This work and retest is planned for later this year.

c. At power generation plants, the high voltage side of Generator Step-Up (GSU) transformers, are most likely unaffected by HEMP E1 or E2, but can be affected by HEMP E3 or GMD if connected to long lines. The GSU is directly affected (for both HEMP E3 and GMD) by resulting harmonics and VAR, and the GSUs harmonics can introduce sub-synchronous resonances in generators and turbines, possibly causing permanent damage. Because HEMP E3 is short-lived (a short 10-second pulse followed by a second pulse lasting for approximately 2 - 4 minutes, see Figure 6), and GSU's are full transformers rather than autotransformers (and therefore do not have tertiary windings), thermal impacts on GSUs are likely limited to local hot spots. Bulk heating is less of a HEMP E3 concern, though it does become a concern for longer GMD events.

d. Several generation plant Distributed Control Systems were surveyed. Although direct tests were beyond the scope of this study, wired connections (ethernet, CAT) represent a vulnerability for both radiated and conductive stress and should be shielded and filtered.

e. For generator excitation systems, based on the systems reviewed (but not tested), the available data suggest that rated strength for both E1 radiated and conductive stress could cause damage or upset, and should be shielded and/or filtered. E3/GMD is not expected to be problematic.

f. Generating plant sensors include temperature, pressure, speed, position, optical, and mass flow sensors among others. Because plant sensors and transmitters are not connected to long lines, E3/GIC stress/strength/mitigation has been determined not to be a concern. For HEMP E1, wireless, battery powered sensors and transmitters are minimally affected by the HEMP E1 radiated stress because 1) they are out of band of the of HEMP, being 2.4GHz and above 802.11 devices and 2) their size is less than $\lambda/2$ at 1GHz, and are minimally affected by the HEMP E1 conducted stress because there are no attached signal or power wires. Wired sensors and transmitters should be tested for HEMP E1 impacts, but this was beyond the scope of this study.

g. At transmission substations, the high-voltage interface of power components – EHV Transformers, Potential Transformers (PTs), Current Transformers (CTs), Gas Circuit Breakers (GCBs) and Lightning Arrestors (LAs) – are the least likely to fail due to E1, E2, or E3. These results are not generated by system or component level HEMP related tests. Rather, for the E1 threat, the estimate is based on the peak leakage voltage past / through the LA which is then compared to the lightning and other slower breakdown thresholds. An arc on the outside of a bushing is the most likely E1-related problem and is a recoverable event and thus does not represent the damage event of interest in this survey. LAs could, however, be at risk of damage on the low-voltage side for E1, E2, or E3 pulses. The E3/GIC assessments for EHV transformer manufacturers are based on calculations of the bulk heating which itself is not likely of concern for HEMP E3 (a short 10-second pulse followed by a second pulse lasting for approximately 2 - 4 minutes, see Figure 6), but does contribute to accelerated aging and the failures associated with that for long GMD/GIC events. That said, detailed analysis of hot spots in structural elements and especially tertiary windings in autotransformers were not investigated in this study and remain an area of concern for E3. The low voltage side of CTs, PTs, and GCBs represent the biggest unknown based on complexity of the control wiring, and a complete lack of data (to date).

Important to Note: this study (and all others on this subject, to date, with the exception of actual HEMP tests conducted in the early 1960's) is, by necessity, reductionist – it examines individual electric grid components in isolation, and how they respond to specific components of a HEMP pulse. In reality, all of the components are functioning in an interconnected grid, and would be exposed to E1, E2, and E3 in succession during a real HEMP event. Specifically regarding EHV transformers, the impact of E3 could be amplified if relay protection is compromised by the E1 pulse, which could direct higher levels of E3 currents through some transformers if, for example, significant numbers of transmission lines are tripped offline by damaged relays. PTs, CTs, GCBs, and LAs could also experience adverse effects due to the rapid succession of the E1, E2, and E3 pulses. A fuller accounting of the entire HEMP spectrum and the effects on a fully-connected grid should/will be explored in future studies to better determine the expected impact of these compounding effects. In the meantime, conservative engineering judgement is recommended to help ensure the best protection for electric grid components for the full HEMP spectrum.

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