Vol. 38, No. 1
March 2020

JOURNAL OF
RADIATION
EFFECTS
Research and Engineering

Testing Protective Relays and Power Generation Control Systems to HEMP

M.R. Rooney, W.M. Bollen, D. Fromme, G. Bohannon, M. Woerner, A. Walker, C. Anderson, and A. Mattei

This paper was presented at the 36th Annual HEART Conference
San Diego, CA, April 8–12, 2019.

Prepared by Amentum for the HEART Society under contract to NSWC Crane

JOURNAL OF RADIATION EFFECTS,
Research and Engineering
Vol. 38, No. 1, March 2020

TESTING PROTECTIVE RELAYS AND POWER GENERATION CONTROL SYSTEMS TO HEMP

M.R. Rooney
DTRA/J9NTS, Ft. Belvoir, VA

W.M. Bollen
SAIC, DTRA A&AS, Lorton, VA

D. Fromme, G. Bohannon, M. Woerner, A. Walker, and C. Anderson
SARA, Colorado Springs, CO

A. Mattei
Baylor University, Waco, TX

Abstract

During a high-altitude electromagnetic pulse (HEMP) event, large voltages and currents will couple to exposed electrical lines. Resulting impacts could occur not only to the large transmission-line infrastructures and components with which those lines interface, but also to the digital control system (DCS) protective relay equipment and its system-monitoring diagnostic lines. In addition, these currents and voltages will also couple to the DCS equipment that operate power generation plants (PGPs). This paper discusses HEMP survivability tests to both types of DCS equipment. This testing included both radiated (Military Standard [MIL-STD]-461, RS-105) and conducted (MIL-STD-188-125-1 pulsed-current injection [PCI]) testing. Testing was performed on the equipment mounted in both unprotected and HEMP-protected open-rack configurations. The basic, HEMP rack-level protection with no special-shielded enclosures is almost sufficient to protect many types of DCS equipment to the Department of Defense (DoD) HEMP threat levels. This type of straightforward protection is recommended for use by power companies to mitigate HEMP susceptibility of their DCS rack-mounted equipment. It is cost effective, but is not low risk per MIL-STD-188-125-1. The Defense Threat Reduction Agency (DTRA) is developing similar practical HEMP mitigation techniques for other power grid equipment.

Introduction

The Defense Threat Reduction Agency (DTRA) has ongoing research into the protection of the power grid in support of the Defense Critical Infrastructure [1] and the new Presidential Executive Order on electromagnetic pulse (EMP) [2]. Programs include the following: a) high-altitude electromagnetic pulse (HEMP) testing of protective relays and control systems (the focus of this paper); b) HEMP testing of a gas power generation plant (PGP); c) source region electromagnetic pulse (SREMP) assessment of effects on the power grid [3]; d) HEMP late-time tests on an active power grid [4]–[6]; e) HEMP late-time harmonic impact on electronics; f) islanding to protect specific sites from HEMP; g) the development of HEMP mitigation techniques for power grid equipment that is effective, but not as strict and costly as the low-risk hardening of Military Standard (MIL-STD)-188-125-1 [7]; and h) technical interchange with the power industry on HEMP protection and effects.

U.S. power grid equipment is susceptible to HEMP. HEMP consists of three components: E1, E2, and E3 as shown in Fig 1 (see next page). The vulnerability of the power grid to HEMP is unknown due to a lack of power grid test data and fundamental understanding. Only MIL-STD-188-125-1-hardened Department of Defense (DoD) facilities can operate through a HEMP event and/or a power grid failure (disconnect from the power grid and run on internal power).

Detailed HEMP effects on the power grid are not perfectly understood due to the variation in equipment and protection philosophy across the nation. Further, the complete understanding for the physics of the late-time HEMP, which is referred to as the magneto-hydrodynamic (MHD) E3 threat, requires more detailed models. Test data for HEMP effects on power grid equipment is lacking.

The focus of this paper is on the effect of HEMP E1 radiated and coupled currents on power grid equipment, especially digital control systems (DCSs). The DoD classified HEMP radiated threat is contained in MIL-STD-2169 [8] and is the basis for MIL-STD-188-125-1 test metrics. An unclassified E1 threat is given by RS-105 in MIL-STD-461 [9]. The testing in this paper focuses on using RS-105 for a radiated E1 threat. We used MIL-STD-188-125-1 pulsed-current injection (PCI)-specified levels for power and sensor/signal lines. These two tests form the basis to establish the susceptibility of the relevant electronics. These tests are defense-conservative, providing a high assurance of surviving a HEMP event.

Thus, the basic test methodology for all the DCS testing consisted of two tests. First, a transverse electromagnetic (TEM) bounded-wave transmission line (BWTL) was used to expose the electronics to an RS-105 radiated waveform. See Fig. 2 for the substation protective relay equipment test setup, which was similar to all DCS equipment testing. Second, PCI testing was used to expose DCS equipment electrical lines to a threat

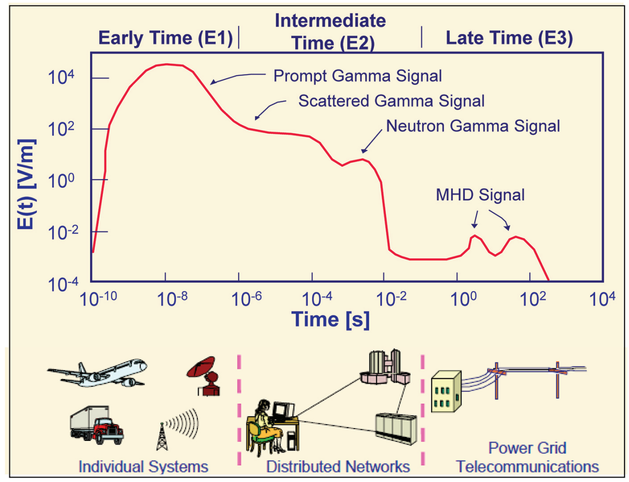

Figure 1. HEMP generic waveform.

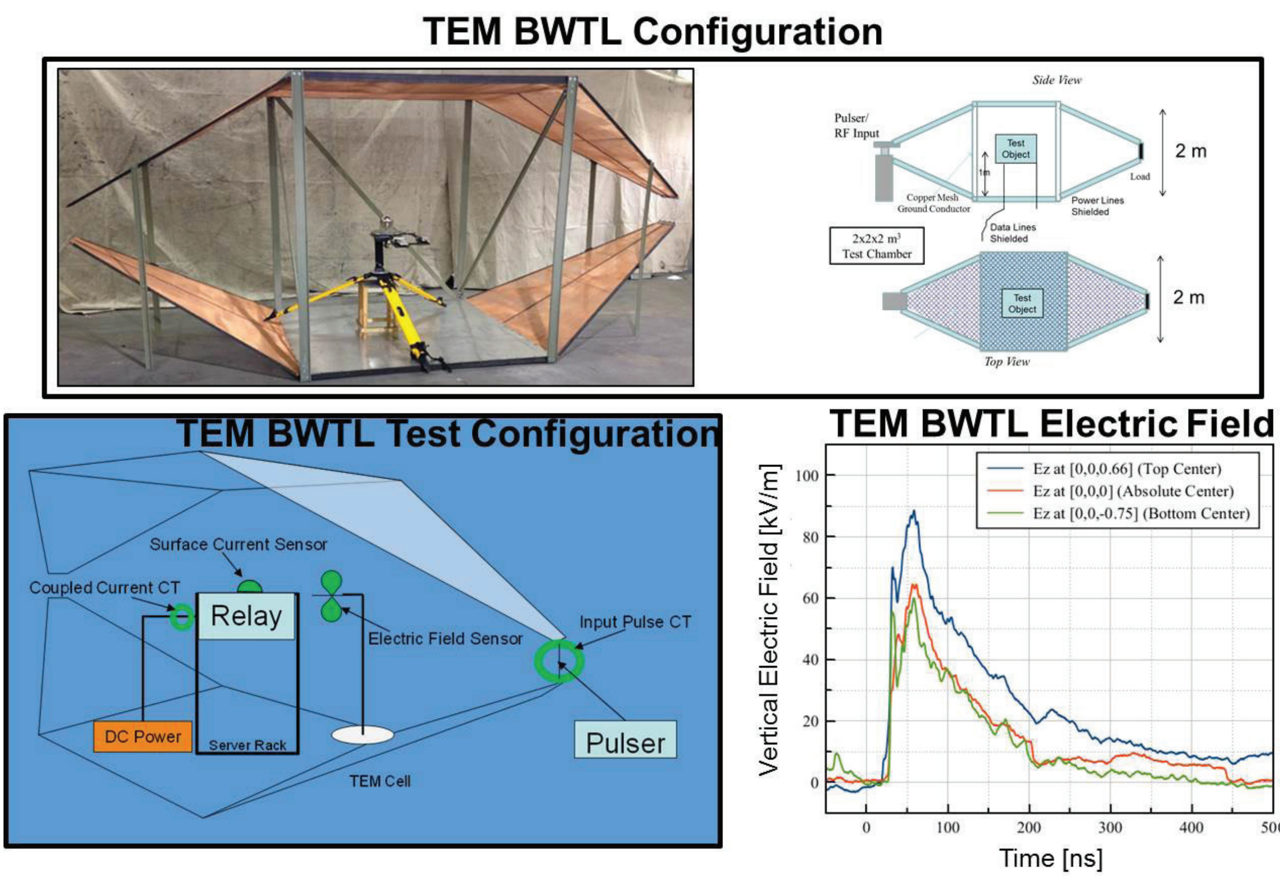

Figure 2. TEM BWTL for DCS protective relay testing.

JOURNAL OF RADIATION EFFECTS,
Research and Engineering
Vol. 38, No. 1, March 2020

current level derived from MIL-STD-188-125-1. Traditional MIL-STD-188-125-1 pulsers were used for this PCI testing. See Fig. 3.

Two types of PCI testing using MIL-STD-188-125-1 guidelines were performed: 1) power line PCI up to 2500 A wire-to-ground (WTG) and 5000 A common mode (CM), and 2) signal line PCI up to 5000/($N^{1/2}$) A WTG and 5000 A CM. (N is the number of conductors.) Per MIL-STD-188-125-1, WTG means the PCI is driven between a single wire and ground. CM means a bundle of wires is driven simultaneously. This is often done using an inductive coupler for the PCI test. In Fig. 3, calibration curves for the PCI pulsers are shown into a short circuit per MIL-STD-188-125-1. Since these pulsers have a 60-Ohm output impedance, actual delivered PCI current into the DCS equipment was less and has a much slower rise time due to the non-zero impedance of the DCS equipment inputs.

Mitigation of HEMP effects on the power grid are challenging for several reasons. The power grid is particularly sensitive to wide area threats such as HEMP. The power grid is a consortium of many independent companies, which will require national coordination. A low-risk approach like MIL-STD-188-125-1 will be expensive, and there is no national mandate to harden the power grid. Thus, we believe that the entire grid cannot be hardened in the foreseeable future. However, HEMP hardening of certain critical electronics is practical and described. DTRA is working on similar practical HEMP mitigation techniques to allow a more HEMP-robust national power grid.

DTRA is publishing technical reports, which will be available to the public for all of these DCS equipment tests.

Test Methodology and Equipment

The test methodology for the DCS equipment is

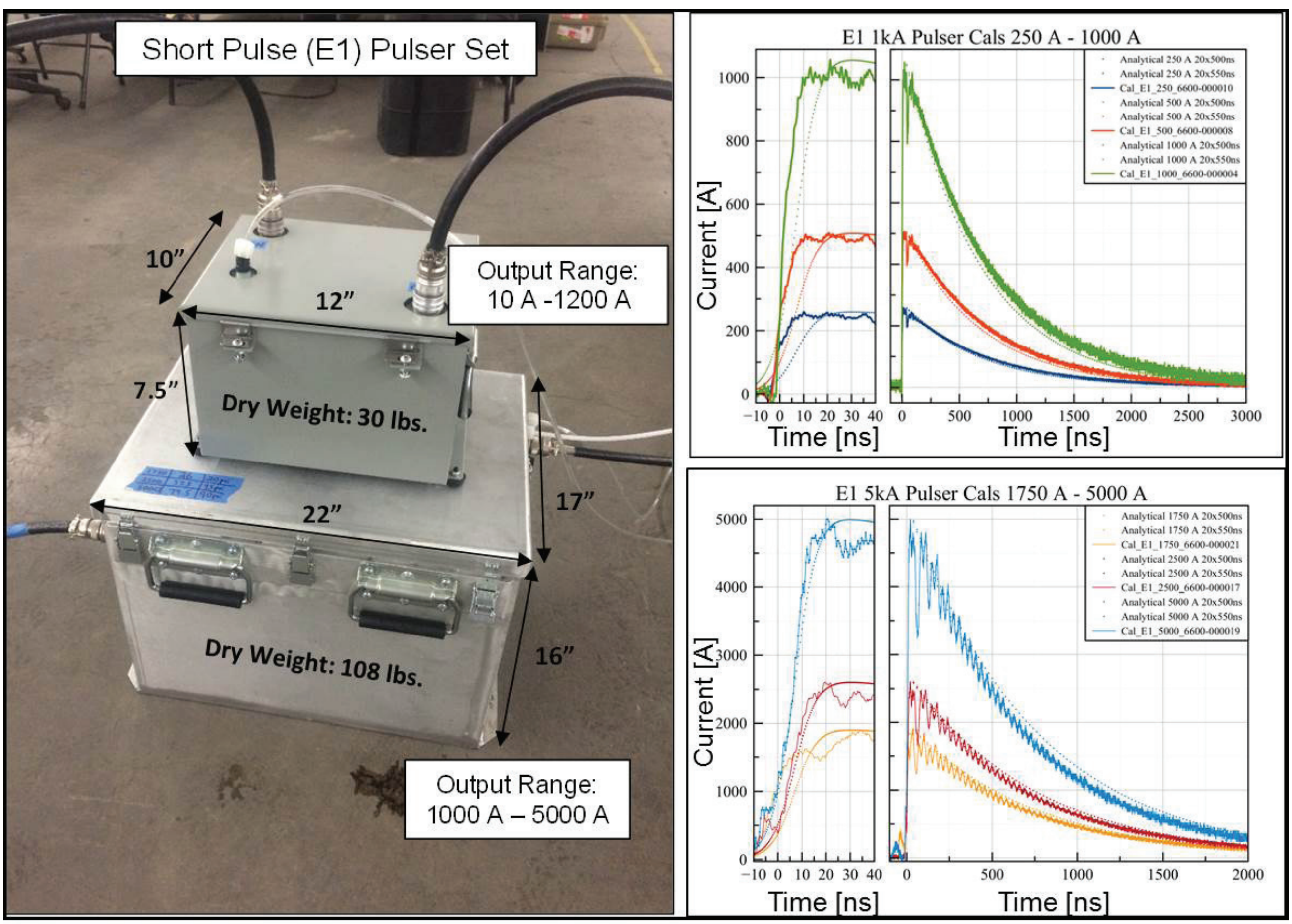

Figure 3. PCI HEMP E1 threat exposure using MIL-STD-188-125-1 App. B waveforms.

based on MIL-STD-188-125-1 PCI testing and MIL-STD-461, RS-105-radiated field requirements as previously mentioned. This testing focused on two types of DCS equipment: 1) substation digital protective relay (DPR) equipment [8] and 2) PGP industrial sensing and control equipment. This testing was performed on both a commercial-off-the-shelf (COTS), unprotected (nominal), open-rack configuration and a HEMP-protected, open-rack configuration (with no special electromagnetic shielding). This showed the susceptibility of the unprotected COTS configuration and demonstrated a basic, straightforward technique for protecting DCS equipment.

For DPR equipment, the test configuration simulated a substation DCS, rack-level (unprotected and protected) equipment installation using typical DPR model types. These model types were from three different manufacturers (two test samples/units each). These three types of DPR equipment are designated as follows: 1) Manufacturer A, Model-A (transmission level); 2) Manufacturer B, Model-B (distribution level); and 3) Manufacturer C, Model-C (Distribution Level). The type of substation they are used for is noted (transmission or distribution).

For PGP equipment, the test configuration simulated a PGP DCS, rack-level (unprotected and protected) equipment installation using typical PGP model types (one complete test model sample/unit plus additional test sample/unit modules for each model). These four types of PGP equipment are designated as follows: 1) Manufacturer A (same as DPR), Model-PGP-A; and 2) Manufacturers D–F, Model-PGP-D, -E, and –F. Testing on Model-PGP-A is complete and discussed. Testing on the other three PGP models is currently under way.

Hardening Methodology

Rack-level, EMP-protected, open-rack configuration using standard non-linear current overvoltage protection with PCI testing to MIL-STD-188-125-1 levels was used for both types of test equipment. This basic, open, rack-level, HEMP protection method used metal-oxide varistors (MOVs) and spark gaps, but no HEMP-shielded enclosures. This technique is shown to protect the DCS equipment tested to RS-105 levels and to be almost sufficient at the maximum MIL-STD-188-125-1 PCI threat levels. A clean/dirty protection interface is required for all wires (e.g., MOV wipe off). To some extent, the hardened rack can be considered to have two pieces: 1) "clean," which was the top of the rack, and 2) "dirty," which was the bottom of the rack where the protection interface was located. The protection interface separates the clean and dirty portions of the rack. In the hardening parlance, "clean" refers to the mitigation of HEMP coupling and "dirty" refers to the presence of HEMP-coupled currents. An MOV wipe off is where an MOV is used to short transient voltage spikes to ground. The protection interface was spatially isolated from the equipment (top) and located at the bottom of the rack. This prevented reradiation coupling from the dirty wires to the clean wires.

The protected configuration for the DPR configuration is shown in Fig. 4. A similar hardening approach was also used for the PGP equipment configuration; however, it included alternating current (AC) power MOVs and gas tube protection devices for the Ethernet lines as shown in Fig. 5 (see next page). If a completely full rack is to be protected, then this protection interface may need to be mounted outside the rack. For a collection of full racks, all required protection might be mounted in a spatially separate rack.

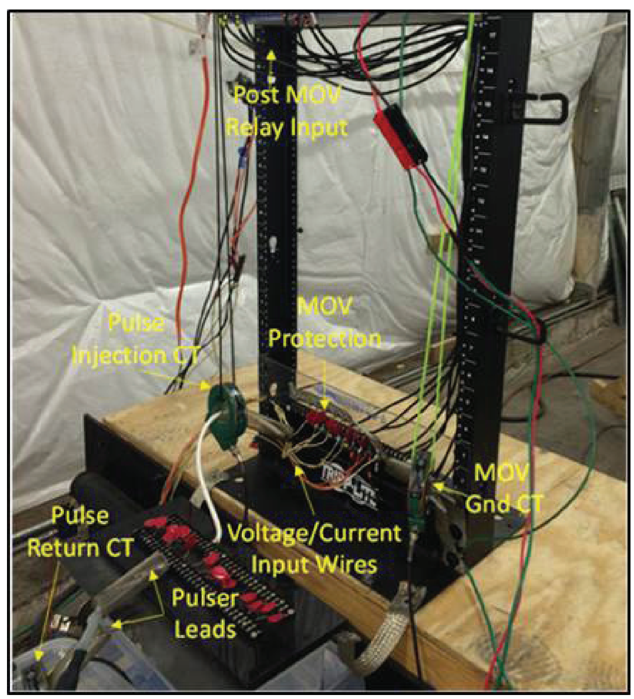

Figure 4. The EMP, open-rack-protected configuration for protective relays seen during PCI testing.

DPR Testing

DPR equipment is used throughout transmission and distribution power grids. This equipment controls and protects critical equipment from damage when it detects fault conditions. The DPR does this by sending control signals to isolate sections of the power grid. Fault conditions are identified by monitoring current and voltage metrics at various locations across the power grid. Comparison of these measured values against a set of equipment protection threshold values determines if a fault is present. Fault conditions are extinguished by active control (i.e., "tripping") circuit breakers or high-current relays in a coordinated fashion.

DPR Fault Detection

The DPRs that were tested had three types of fault detection algorithms: 1) time overcurrent (phase or ground current duration above threshold), 2) phase to phase (step distance), and 3) instantaneous overcurrent. For the protective relays tested, fault detection modes were defined as 1) time overcurrent (Model-A and Model-C), 2) phase to phase (step distance) (Model-A and Model-B), and 3) instantaneous overcurrent (Model-A and Model-B).

There are at least 10 different standardized time overcurrent characteristics: Five U.S. curves (Fig. 6, see next page) and five International Electrotechnical Commission (IEC) curves are typical. All three protective relays were programmed using an inverse time curve to detect AC power time overcurrent faults using the U.S. "very-inverse" curve shown to the left of Fig. 6 by a red arrow. This curve is further refined using "time dials" to scale the curve. Testing used time dials from 2.3 to 4.7, which is shown in the plot on the right in Fig. 6 (and highlighted by a red bar). The time delay to trip the output increases as the time dial value increases. The MIL-STD PCI and radiated test susceptibility results were not observed to be dependent on the time overcurrent settings.

Model-A step-distance uses the impedance calculated from voltage and current measurements and is capable of determining if the fault lies forward or reverse of the

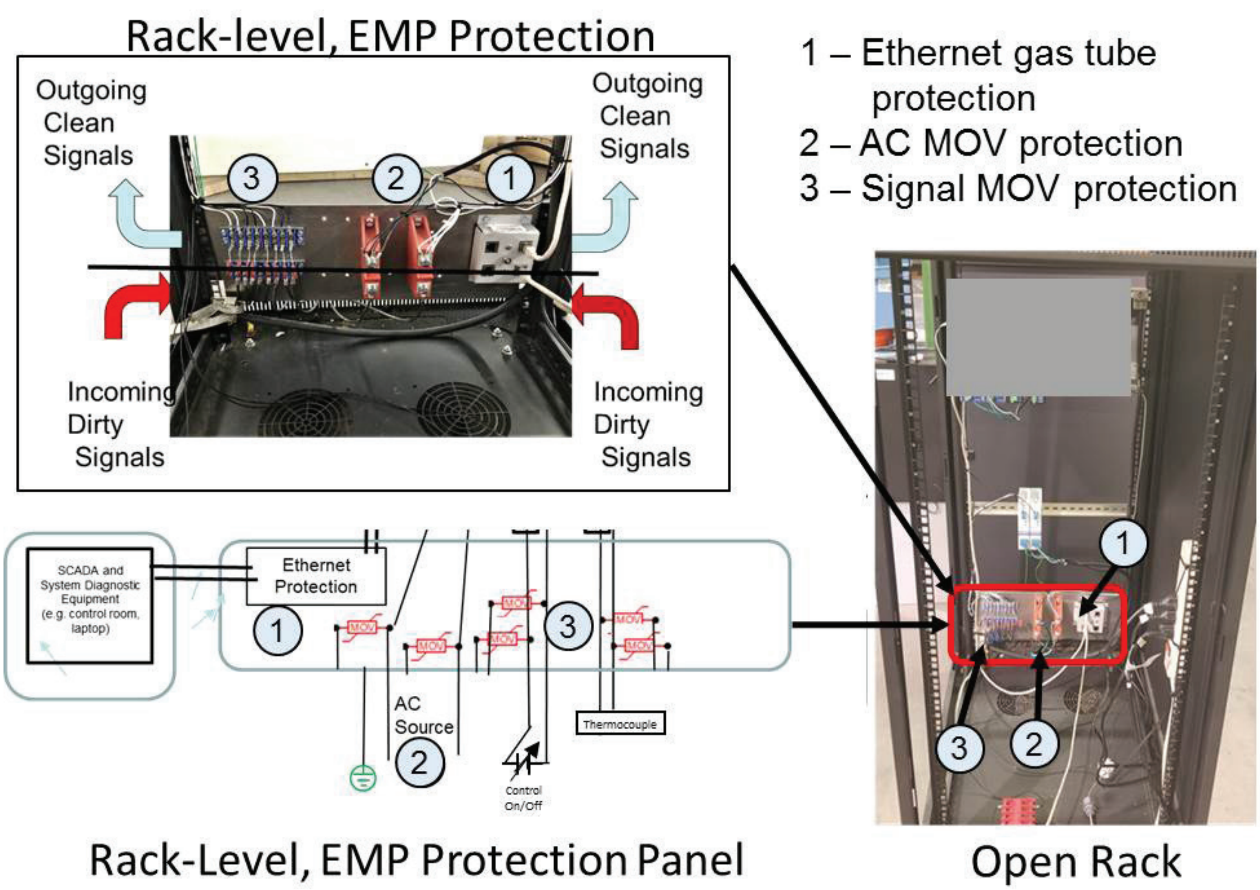

Figure 5. The EMP, open-rack-protected configuration for PGP.

zone of protection. Fault location is determined by comparing the calculated impedance with the known line impedance based on actual conductor parameters and line length. Model-A test units were configured for a three-zone protection scheme: Zone 1 monitored 90% of the line length and issued an "immediate" trip, Zone 2 monitored 125% of the line length (upstream) and issued a delayed 45-cycles trip to allow Zone 1 protection at the upstream substation to clear the fault, and Zone 3 monitored the line beyond the next downstream (reverse/step-down-side) substation and issued a delayed 90-cycles trip.

Instantaneous ground protection asserts (triggers) when the input current reaches a pre-determined threshold. When this threshold is reached, the protective relay will actuate its output contacts. The Model-A unit overcurrent threshold limits were set to 1,600 A. A calculation of three times the zero sequence current (3I0) was used for the symmetrical component calculation for the zero-sequence current. 3I0 is commonly used as the result of the ground current for an asymmetrical-faulted system. Thus, 3I0 compared to the threshold of 1,600 A. Instantaneous elements are typically used on transmission lines to protect 50–70% of the line.

The objective of the testing was to provide a baseline, empirically derived assessment of the HEMP E1 latching or damage susceptibility of typical DPR devices currently in use by the U.S. power grid. The transmission-level DPR was Manufacturer A, Model-A. The distribution or feeder–protection DPRs were Manufacturer B, Model-B and Manufacturer-C, Model-C. These will be referred to as Model-A, Model-B, and Model-C in the following discussion. A test to 1,100 V was performed on the three models to determine if non-linear protection was present, and only the Model-B input voltage terminals had a protection device.

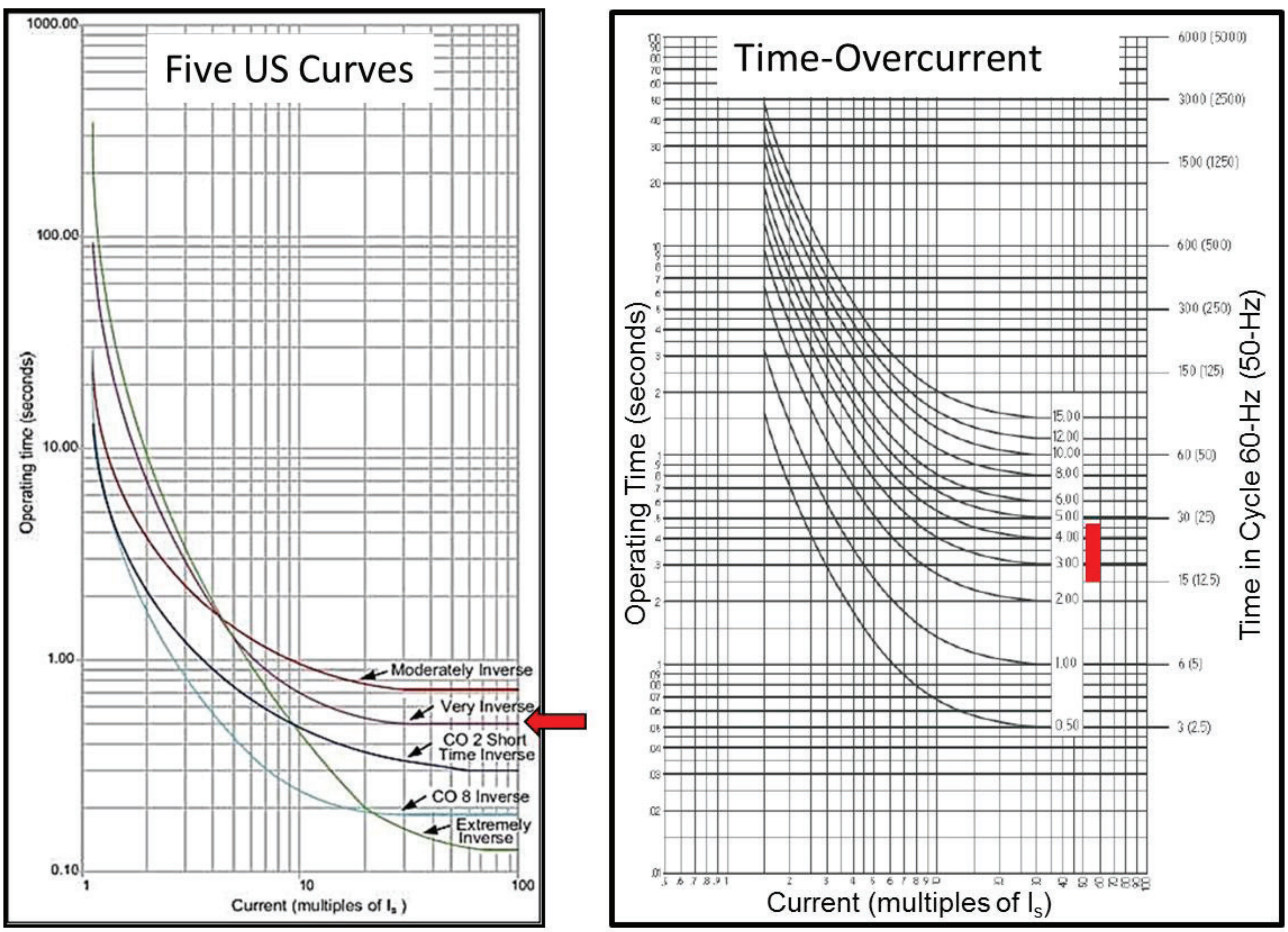

Figure 6. Time overcurrent curves.

JOURNAL OF RADIATION EFFECTS,
Research and Engineering
Vol. 38, No. 1, March 2020

Three sets of tests were conducted for each manufacture model mounted in an open-rack: 1) a nominal (as purchased), unprotected operational configuration was tested in a TEM BWTL; 2) a nominal, unprotected operational configuration was tested using MIL-STD-188-125-1 PCI levels; and 3) a HEMP-protected open-rack (using standard non-linear current overvoltage protection at the rack level, but no special shielding) was tested using MIL-STD-188-125-1 PCI levels. Before and after each test, functionality was checked. Testing was done as follows to minimize damage and to allow maximum data from two test samples/units: 1) TEM BWTL (radiated), 2) protected PCI (conducted), and 3) unprotected PCI (conducted).

For the TEM BWTL, only the unprotected configuration was tested. See Fig. 7. Only the direct current (DC) battery power line was connected since the sensor terminal wire immunity levels were established by PCI testing. The DPR equipment was tested before and after each exposure to ensure the pre-programmed settings were functioning properly. This was done using a Megger SMRT36 Protective Relay Test System. The test results are shown in Table 1. The Model-A and Model-C units had no response at the maximum TEM fields of 74–90 kV/m. Since there was no response, only one sample each was tested. One Model-B unit had a display latching upset at 74–90 kV/m, and the other Model-B unit tested did not upset.

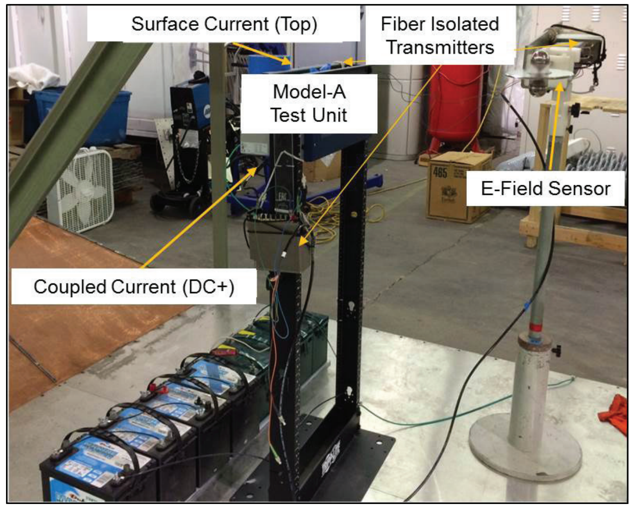

Figure 7. Unprotected-open-rack, protective relay test configuration.

Next, the DPR equipment was tested using PCI. Each DPR unit was tested before and after each PCI drive level to ensure the pre-programmed settings were functioning properly using a Megger SMRT36 Protective Relay Test

Table 1. Summary of the protective relay TEM BWTL test results (no protection).

Relay	Cablibration E Field	E Field	Surface Current	Coupled Current	Result
A SN: 305	3.3 kV/m	3.5 kV/m	27 A/m	1.5 A	Pass
	10 kV/m	13.5 kV/m	105 A/m	5.6 A	Pass
	36 kV/m	40 kV/m	310 A/m	9.7 A	Pass
	55 kV/m	70 kV/m	480 A/m	23 A	Pass
C SN: 177	3.3 kV/m	3.8 kV/m	26A/m	0.12 A	Pass
	10 kV/m	13 kV/m	93 A/m	0.3 A	Pass
	36 kV/m	40 kV/m	260A/m	1.5 A	Pass
	55 kV/m	70 kV/m	510 A/m	4.6 A	Pass
B SN: 696	3 kV/m	4 kV/m	15 A/m	2 A	Pass
	12 kV/m	16 kV/m	100 A/m	6 A	Pass
	43 kV/m	58kV/m	324 A/m	12 A	Pass
	74 kV/m	90 kV/m	525 A/m	50 A	Display
B SN: 500	74 kV/m	92 kV/m	398 A/m	48 A	Pass
Pass	=Unit Passed Test				
Display	=Loss of Display - No Other Functional Effects - Power Cycle Req'd				

System. The input current and voltages, and output relay contacts were monitored for damage or performance degradation during the PCI testing. Both an open-rack, HEMP-protected configuration and an unprotected configuration (nominal) were tested for all DPR equipment.

The PCI test configuration is shown in Fig. 8 with a close-up shown in Fig. 9. The test configuration was set up to emulate the actual use of protective relays in the power grid, which is shown generically in Fig. 10.

The Model-A and Model-B both had current and voltage input terminals. The Model-C had only current input terminals. As required, a resistive bridge was used to create both current and voltage inputs. Model-A tested four terminal types: 1) current phase source, 2) voltage phase source, 3) voltage neutral (common mode test), and 4) current phase load. Model-B tested four terminal types: 1) current phase source, 2) voltage phase source, 3) voltage neutral (only single point), and 4) current phase load. Model-C tested only two terminal types: 1) current phase source and 2) current phase load.

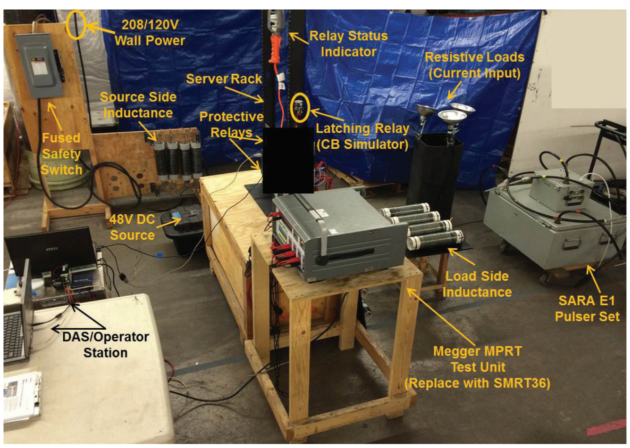

Figure 8. PCI test configuration.

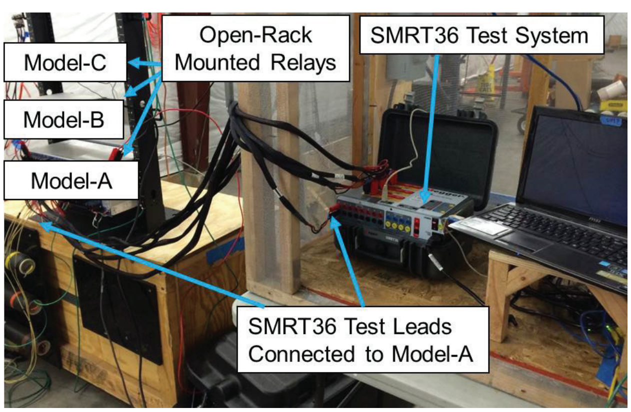

Figure 9. Close-up of the PCI test configuration showing the Megger SMRT36 protective relay test equipment.

In normal operation, DPR inputs consist of current transformers (CTs) and potential transformers (PTs) as shown in Fig. 10. During testing, inductors were used to isolate the various DPR inputs so PCI at each unit's terminals would not propagate elsewhere. Resistive loading was provided on the output terminal to provide a 1.5 A current for the current fault detection used by each model. A typical PCI test point configuration (without HEMP protection) is shown in Fig. 11 (see next page) for Model-B.

The summary results for PCI testing for all three DPR models are shown in Table 2 (see next page) with color coding based on observed effects. DPR equipment can be hardened to HEMP using a relatively straightforward hardening approach, as shown by the Table 2 results. This statement is based on the fact that, except for Model-B, all DPR equipment in a HEMP-protected rack survived with no upset or damage to the maximum MIL-STD-188-125-1 PCI threat level. Although Model-B failed, it had its damage threshold increased by over a factor of 5. The complete results of this test may be found in reference [10]. Thus, the basic HEMP-protection methodology described above is expected to significantly increase the survivability of DPR equipment in the power grid and provide a more HEMP-resistant power grid.

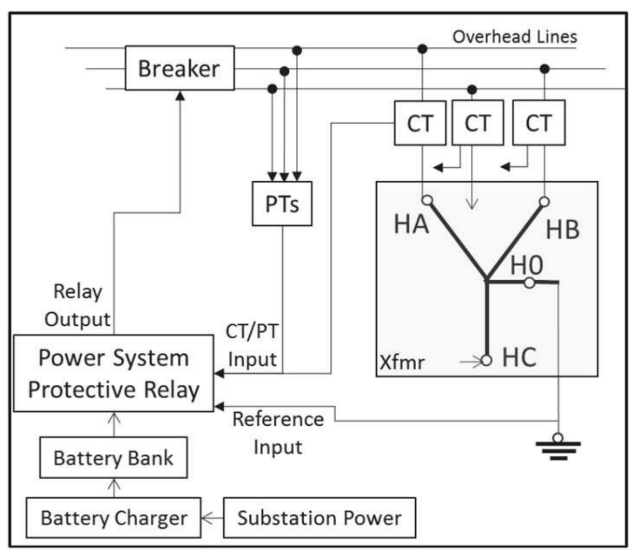

Figure 10. How protective relays are used typically in the power grid.

DPR Response Time

Although most of the testing reported in this paper focused on HEMP DPR susceptibility thresholds, an earlier investigation looked at the response time of the relays to a short, high-magnitude impulse when configured for instantaneous overcurrent tripping. This is important because typically equipment in the power grid responds in a few AC cycles. The question studied was "how do DPR units respond to fast transient pulses such as HEMP?" Clearly, HEMP pulses below the susceptibility levels discussed in this paper are expected to survive. However, modern DPR units utilize both hardware and software filtering. The impact of this filtering on the DPR response to short transient signals above their current fault level, but below their susceptibility level, was investigated.

The investigation tested a DPR (Manufacturer A) with a variable short PCI impulse. The DPR was monitored using 8 kHz data logging. The DPR threshold was monitored by the 50G element and, as such, configured for a non-directional, instantaneous overcurrent threshold. The current thresholds were set to 9.167 A (secondary current) and 2,200 A (primary current).

For an impulse current of 25 A secondary current (well above the 9.167 A threshold), there was no 50G DPR response observed for an impulse duration of ~4.125 ms (~0.25 cycles). However, the DPR unit reliably responded when the impulse duration was increased to 4.5 ms. See Fig. 12 (next page). Further, a 9.6 ms (>1/2 cycle) delay was observed before the DPR 50G element issued a trip

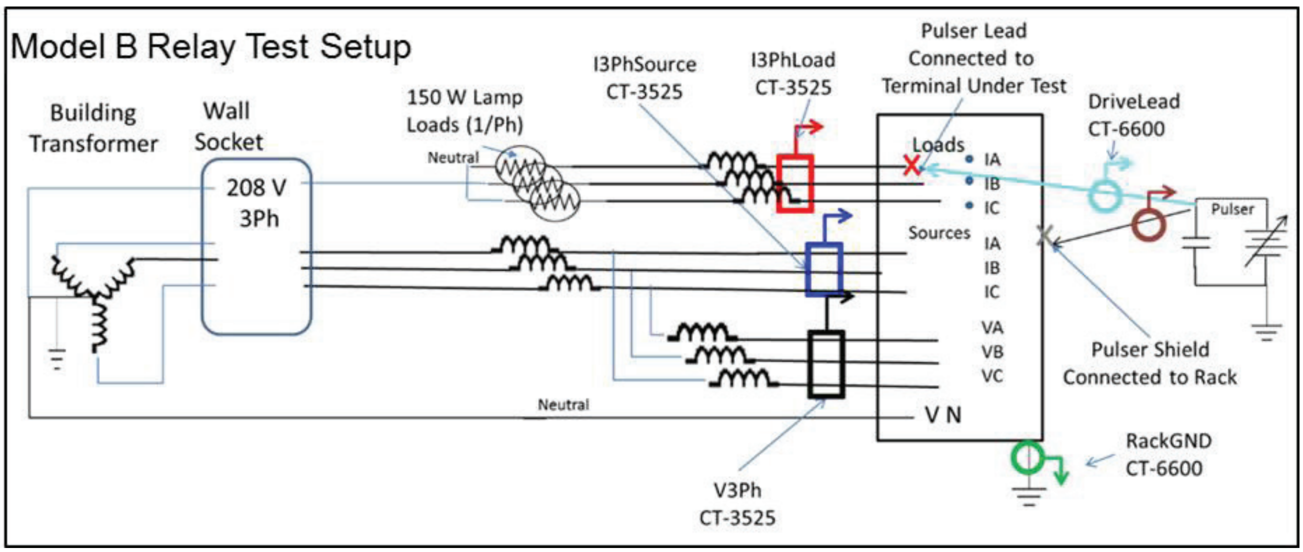

Figure 11. Typical PCI measurement points and injection connection for an unhardened DCS protective relay. (Note the inductive isolation.)

Table 2. Summary of PCI DPR test results showing the increased EMP survivability obtainable by straightforward hardening techniques.

			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
Unprotected PCI	A	305	Pass				N/A	Latch*	N/A	Arc*	Arc*	Arc*	Display*	Damage
		247	Pass				N/A	Arc*	N/A	Arc*	Arc*	Damage		
	B	500	Pass			Damage								
		696	Damaged in Protected Mode											
	C	177	Pass				N/A	Damage						
		341	Pass			Display	N/A	Pass	N/A	Display*	Display*	Display*	Display*	Display*
Protected PCI	A	247	N/A				Pass	N/A	Pass	N/A		Pass	Pass	Pass
	B	696					Pass		Pass			Pass	Pass	Damage
	C	341					Pass		Pass			Pass	Pass	Pass

	=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

command. This trip command would typically go to a gas circuit breaker (GCB). Therefore, the GCB would receive the command to open well after a short (e.g., HEMP) impulse event. Also, it is worth noting that a GCB also has a delayed response to a control signal. A GCB response delay is approximately a few cycles before it operates.

For a slightly higher impulse current of 25.1 A secondary current, the DPR reliably tripped for a shorter impulse duration of 0.23 cycles. Thus, the DPR 50G element response is related to both the impulse current peak and duration. No variation in the DPR response was observed for this testing. The DPR would always respond the same way every time. There were no ambiguous responses

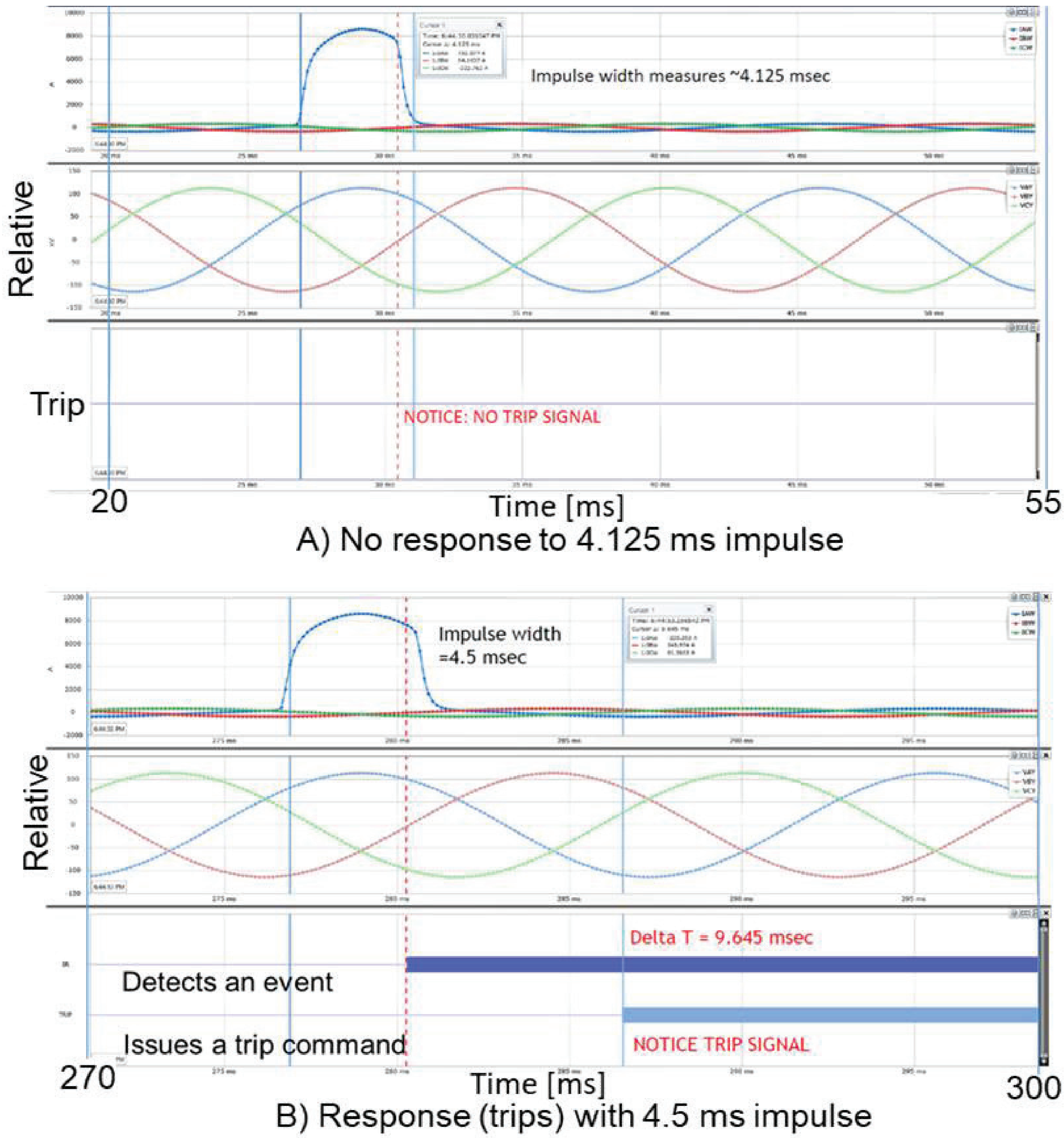

Figure 12. Model-A response to short impulses.

observed for the same conditions, i.e., "sometimes trip, sometimes not trip."

This response to transient signals is consistent with cosine filtering, which is done by the Model-A DPR. Thus, E1 (high frequency) is filtered out. Long impulses (~4 ms) are required to cause the DPR to trip. Note that E2 (in band to 60 Hz), will not be filtered. Further, MHD-E3, quasi DC current, will be filtered, but the current derivative may pass the filter along with MHD-E3 harmonics.

Although we tested the 50G element (non-directional overcurrent), in many cases a 67G element is used (directional overcurrent) with supervision by a 32GF element (forward ground). This more complex approach is only to inhibit false tripping. The testing showed that an unsupervised, non-directional, instantaneous overcurrent (50 G element) does not trip for short impulse currents. Thus, we expect the DPR to not trip even with these additional elements being present.

DCS PGP Testing

DCS PGP equipment is used to issue logical commands to control PGP system equipment. DCS PGP equipment uses processors to measure slow DC analog signals and faster digital status signals. The PGP equipment digitizes these signals and converts them to absolute units. The DCS PGP equipment then performs analysis. Lastly, the signals are concentrated and transmitted to a control computer, which issues local control signals and commands to the power plant.

DTRA is testing DCS PGP equipment and sensor inputs to HEMP. The sensor inputs for PGP equipment consist of the following modules: 1) digital sensors for PGP equipment (e.g., an on/off signal) and 2) DC analog sensors for PGP equipment (e.g., a thermal signal). The testing also includes all associated DC power supplies required to make the sensors operational. The Model-PGP-A modules are connected by a backplane. Only the Model-PGP-A results are discussed.

The susceptibility of DCS PGP equipment to HEMP has previously been unknown. The objective of the PGP testing was to provide a baseline, empirically derived determination of the HEMP E1 latching upset and damage susceptibility levels. The PGP equipment testing was done while the equipment was operating under simulated, realistic conditions. The PGP equipment is set up using relevant sensors while the testing occurs.

Three sets of tests were conducted for each PGP model (the same as with the DPR): 1) a nominal, unprotected open-rack operational configuration tested in a TEM BWTL; 2) a nominal, unprotected open-rack operational configuration tested with PCI testing to MIL-STD-188-125-1 levels; and 3) a HEMP-protected open-rack configuration using standard non-linear current overvoltage protection with PCI testing to MIL-STD-188-125-1 levels.

All Model-A-PGP equipment was tested in an open rack. The equipment was located at the rack top panel location. For the protected configuration, a HEMP-protection interface panel was mounted on the bottom of the rack as shown previously in Fig. 5 to provide spatial isolation. The unprotected test configuration of Model-PGP-A is shown in Fig. 13.

As shown in Fig. 13, the Model-PGP-A test object consists of the following modules: 1) the processor module, which has all of the communications and custom logic capabilities; 2) the power coupler module, which provides power for all modules installed in the backplane; 3) the digital module (optically isolated), which measures control signals (e.g., on/off) and has multiple inputs; and 4) the DC analog module,

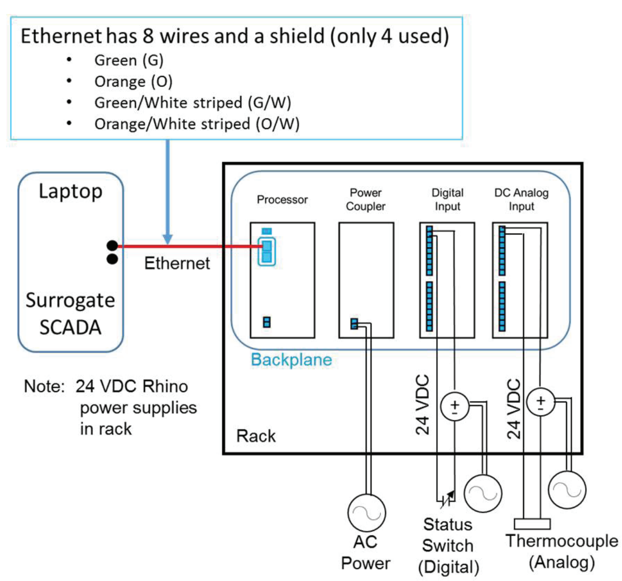

Figure 13. Model-PGP-A unprotected test configuration.

which measures sensor signals (e.g., thermistor) and has multiple inputs. A backplane connects all four modules.

For this test, the critical modules were the processor, the digital input, and the DC analog input. The digital input module monitored the state of a status switch (0 or 24 volts). The DC analog module monitored a thermocouple, which could be placed in a beaker of boiling water or removed. The sensors required DC power supplies to be operational.

Both sensors were located outside the rack. They were used to monitor the operation before, during, and after each HEMP exposure. For example, the thermocouple was placed in boiling water to get a reading. It was then removed from the water and allowed to come to room temperature so the change in the sensor response could be checked before exposure to HEMP. Next the Model-PGP-A unit was HEMP tested, and then the thermocouple placed back in the boiling water and removed again. These two measurements after testing were compared to an independent thermometer to confirm proper operation. This methodology results in two pulses where the HEMP impulse occurs between them.

Model-PGP-A equipment functionality was checked before, during, and after each HEMP exposure. The following procedure was used: 1) observation and validation of the functionality of the DC analog and digital inputs was performed; 2) verification of the processor module outputs was monitored by a comparison of the display screen echo and the known status and temperatures of the digital and analog modules; and 3) observation of equipment performance degradation, functional upset, and/or damage was monitored.

The free-field TEM BWTL testing used two orientations of the rack (front and side). An AC power line, a DC analog signal, and a digital signal line were connected outside the rack. Note that the line lengths were shorter than in a real installation; however, more realistic current levels were tested during the PCI testing which followed.

The Model-PGP-A rack was taller than the DPR rack and prevented the electric fields from exceeding 32 kV/m during the TEM BWTL testing. A picture of the test in the front configuration is shown in Fig. 14. No significant results were observed as shown in Table 3. A transient surge

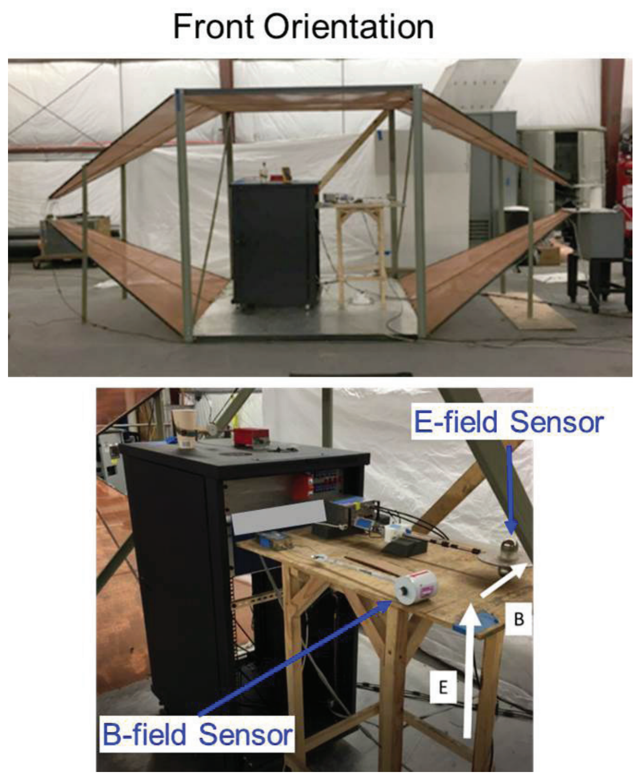

Figure 14. TEM BWTL test of the Model-PGP-A in the front orientation.

Table 3. Summary of Model-PGP-A free-field TEM BWTL test results.

Summary of Model PGP-A TEM Tests								
	Side Illumination				Front Illumination			
Component	6 kV/m	10 kV/m	20 kV/m	32 kV/m	6 kV/m	10 kV/m	20 kV/m	32 kV/m
Processor								
Power Coupler								
Digital Input								
DC Analog Input								
Rhino 24 VDC PS SN3207								
Rhino 24 VDC PS SN3215								
NLU = Non-Latching Upset				No Response				
PD = Permanent Damage				LU = Latching Upset Due to Paired Component Damage				

in the response of the DC analog module temperature sensor (a few seconds of an induced temperature signal) was noted, but it was well within the operating characteristics of the sensor. This response is shown in Fig. 15. Fig. 15 also shows how the pre-test and post-test thermal response check previously discussed was made on the DC analog module.

For PCI testing, the protected configuration was tested first due to a limited number of tests objects. The test points for the Model-PGP-A are shown in Table 4. The test point configuration for the protected rack is shown in Fig. 16.

During the Model-PGP-A PCI testing, there are two types of injections: 1) AC power, which drives black-and-white WTG and CM (ground is via rack) and 2) signal lines, which drive the Rhino power supply positive and

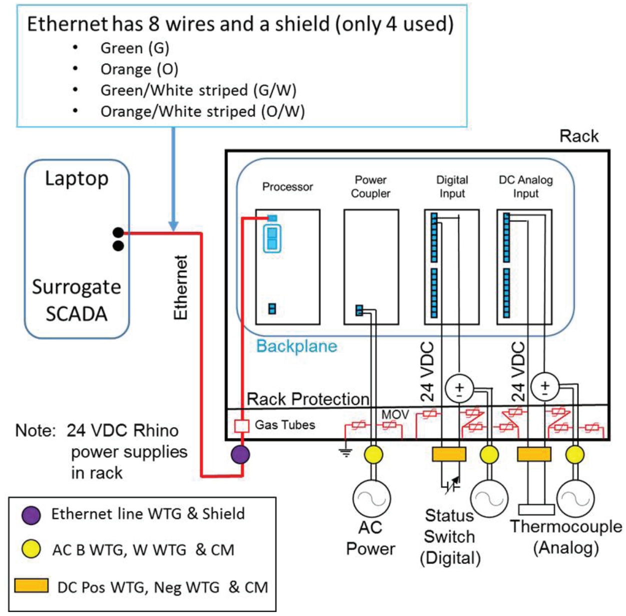

Figure 16. Protected rack Model-PGP-A PCI test point configuration.

Figure 15. The non-latching upset observed during TEM BWTL testing.

Table 4. Summary of Model-PGP-A PCI test points.

- Processor - Ethernet
- Power Coupler – AC power input
  - WTG black wire
  - WTG white wire
  - CM (black, white and ground)
- Digital Input
  - WTG positive input
  - WTG negative input
  - CM negative and positive input
- DC Analog input
  - WTG positive input
  - WTG negative input
  - CM negative and positive input
- Rhino 24 VDC power supply – AC input
  - Digital Input (SN-3207)
    - > WTG line (B)
    - > WTG neutral (W)
    - > CM (line, neutral)
  - DC Analog Input (UP:SN-8803/P:SN-3215)
    - > WTG line (B)
    - > WTG neutral (W)
    - > CM (line, neutral)
- Rhino 24 VDC power supply – DC output
  - Digital Input (SN-3207)
    - > WTG positive
    - > WTG negative
    - > CM (positive and negative)
  - DC Analog Input (SN-3215)
    - > WTG positive
    - > WTG negative
    - > CM (positive and negative)

negative outputs WTG and CM, and Ethernet lines WTG and shield to ground (CM for a shielded cable). However, PCI current can split between the DC power supplies and the PGP module inputs (digital and DC analog). The PCI return current is on rack (ground), but for the protected mode, this is through the MOV and spark gaps.

The unprotected (as purchased) PCI testing of the DCS PGP showed the equipment was susceptible to current levels about a factor of 3–10 less than MIL-STD-188-125-1 levels. As with the protective relays, a basic, open, rack-level, HEMP protection method using MOVs and spark gaps, but no special-shielded enclosures, is almost sufficient to protect the DCS Model-PGP-A unit and modules tested.

Once all four manufacturers' units are tested, a public release version of the results will be released to assist power companies in HEMP protecting their PGPs. The results of the Model-PGP-A PCI testing comparing protected and unprotected configurations are shown in Table 5 for AC modules, and in Table 6 (see next page) for signal line modules. In these tables, the numbers correspond to a measurement of the peak injected current vs. the column headings, which is the peak current of the PCI pulser into a short (per MIL-STD-188-125-1). Color coding is indicative of the equipment response. Current splitting can be seen to occur. Thus, collateral responses occur (PCI on one set of module inputs affects a second module). This is noted in the tables. Serial numbers of modules and DC power supplies are shown since more than one were tested.

Conclusions and Recommendations

A baseline HEMP survivability assessment of DPR equipment for three manufacturers and typical DPR models (two samples/units each) was performed. A baseline HEMP survivability assessment of DCS PGP models (one sample each plus additional modules) for four manufacturers and typical PGP models is planned. The first manufacturer's Model-PGP-A model unit testing has been completed.

Free-field, RS-105 testing in a TEM cell to 70 kV/m (30 kV/m for the Model-PGP-A) showed no latching or permanent damage.

Table 5. AC power PCI test summary for HEMP-protected and unprotected Model-PGP-A configurations.

PGP-A ACPower PCI Test Summary
(Cell numbers are measured amps at the input pin)

	Component	Wire	25A	50A	100A	200A	400A	800A	1600A	2500A	5000A
Unprotected Configuration	Power Coupler SN-0044	B	12	24	48	87	358	710			
		W	12	24	54	88	337	720			
		CM									
	Power Coupler SN-0116	W						**			
			No Currents measured above **Collateral Damage During Rhino SN-8803 Neutral Test								
	DC Analog Input SN-0033	B					*				
			No Currents measured above *Collateral Damage During Rhino SN-8803 Line test								
	Rhino 24 DC PS SN-8803 - AC	W	8	17	35	108, 118	180, 204	676, 676 **			
		B	6.3, 7.8	13, 18	32, 66	151, 214	224, 415 *				
		CM									
	Rhino 24 DC PS SN-3207 - AC	W									
		B	9	19	61	146	248,302				
		CM									
	Rhino 24 DC PS SN-8631 - AC	W	8.5	17	47	148	396	796			
		B	10	20	48	100	340	736			
		CM				286	521	915			
HEMP-Protected Configuration	Power Coupler SN-0001	W	12	23	50	72	136	250	265	270	
		B	13	31	36	62	127	224	250	323	
		CM				37	68	130			
	Rhino 24 DC PS SN-3207	W	7.4	16	34	65	132	248			
		B	8.3	10	16	32	54	93			
		CM				29	53	102			
	Rhino 24 DC PS SN-8804 (DCS AC inputs protected)	W							283	410	
		B							375	530	
		CM							116	170	370
	Rhino 24 DC PS SN-3215	W	7	15	28	64	118	228			
		B	11	11	27	32	49	87			
		CM				28	50	101			

NLU = Non-Latching Upset	No Response
PD = Permanent Damage	LU = Latching Upset Due to Paired Component Damage
Collateral Damage	Untested To Date
? = data not recorded	# = Arc shorts to ground

The unprotected (as purchased) PCI testing of the DPR units showed all tested manufacturer models were susceptible to latching and damage when exposed to HEMP, threat-level coupled currents (based on MIL-STD-188-125-1 PCI levels) injected on the wires running to the DPR units. The unprotected (as purchased) PCI testing of the DCS Model-PGP-A showed the equipment was susceptible to current levels about a factor of 3–10 less than MIL-STD-188-125-1 PCI levels.

The key finding of this work is that a basic, HEMP rack-level protection methodology with no special-shielded enclosures is *almost sufficient* to protect both types of DCS equipment in a low-risk manner. This protection method uses a clean/dirty protection interface for all wires (e.g., MOV wipe off) and the protection interface is spatially isolated (e.g., bottom of rack) from other electronics. Although this methodology does not provide the low-risk protection of MIL-STD-188-125-1, it should be adequate to significantly mitigate the risk of HEMP susceptibility for DCS rack-mounted equipment used by the power grid. This methodology is less expensive than what would be required to ensure low-risk survivability to MIL-STD-188-125-1. This HEMP-protection approach is recommended for use in typical substation and power plant installations.

PCI testing with short pulses (a few milliseconds) above the DPR fault current threshold and below the DPR susceptibility level were demonstrated to not trip the DPR. We believe this is due to hardware and software filtering of the DPR input signals. In this threat-level range,

Table 6. DC and digital analog PCI test result comparison for HEMP-protected and unprotected PGP configurations.

PGP-A Digital & DC Analog Input PCI Test Summary
(Cell numbers are measured amps at the input pin)

	Component	Wire	25A	50A	100A	200A	400A	800A	1600A	2500A	5000A
Unprotected Configuration	Processor SN-0001	G									
		O									
		G/W									
		O/W	12	20	>70	Audible arc					
		Shield	22	44	68	182	374	752			
	Digital Input SN-0010	Neg									
		Pos	1.4	4.7	11	29***	Damage to Rhino SN-8197 during digital test				
		CM									
	Rhino 24 DC PS SN-8197 - DC	Pos	3.2	13	25	180***					
		CM									
	Digital Input SN-0010 (Retest Rhino PS SN-8803 Protected)	Neg	6-4	10-7	15	~190					
		Pos									
		CM									
	Digital Input SN-0039	Neg	6	11	31	140	120#	710	Audible Arc starts at 140 A		
		Pos	4	10.6	17	29	120	190	Audible Arc at 29 A/Damage on 3rd 190 A		
		CM									
	DC Analog Input SN-0033	Neg									
		Pos	9.9	19	44	82	*				
		CM			Collateral Damage from AC injection on Rhino SN-8803						
	Rhino 24 DC PS SN-3207 - DC	Neg	8.6	17.6	39.2	78					
		Pos	3	13	25	180					
		CM									
HEMP-Protected Configuration	Processor SN-0001	G	22	43	86	178	352	636			
		O	20	47	84	172	351	589			
		G/W	22	46	84	176	350	620			
		O/W	21	44	86	171	348				
		Shield	20	20	40	87	171	338			
	Digital Input SN-0010	Pos	2.2	2.2	10.5	21	35	60	64	71	
		Neg	2.6	5	9.6	18	37	44	69, 70	77	
		CM				15	27	47			
	Rhino 24 DC PS SN-3207 - DC	Pos	2.2	2.2	8	21	35	60	150	267	
		Neg	2	4.9	8.9	16	31	40	83	**103**	
		CM				29	51	100			
	DC Analog Input SN-0404	Pos	3	6	13	21	47	87	91	**?**	
		Neg	2.5	5	12	22	50	99			
		CM				8	16	22			
	Rhino 24 DC PS SN-3215 - DC	Pos	~1	3	11	27	56	100	?	?	
		Neg	6	11.7	25	57	106	201	108		
		CM				28	53	100			

NLU = Non-Latching Upset	No Response
PD = Permanent Damage	LU = Latching Upset Due to Paired Component Damage
Collateral Damage	Untested To Date
? = data not recorded	# = Arc shorts to ground

impulses greater than about 4 ms are required to cause the DPR to trip, which is typically configured to send a command to open a GCB. Delay times before the GCB responds to the DPR trip command will be a few AC cycles.

DTRA is in the process of developing other power grid mitigation techniques in support of the EMP Executive Order. These techniques will be published and coordinated with the appropriate federal organizations (e.g., the Federal Energy Regulatory Commission [FERC]) and the power industry.

References

[1] *DoD Policy and Responsibilities for Critical Infrastructure*, DoDD 3020.40, 21 Sept. 2012.

[2] *Executive Order on Coordinating National Resilience to Electromagnetic Pulses*, 26 Mar. 2019.

[3] M. Rooney *et al.*, "DTRA operation independent spark overview: SREMP test on an operational transmission-distribution power substation and components at HERMES III," DTRA Tech. Rep. DTRA-TR-17-7, Oct. 2016 (controlled).

[4] M. Rooney *et al.*, "Phase-IV of the DTRA MIL-STD-188-125-1 MHD-E3 scoping tests overview of the tests at transmission line voltages and powers," presented at the *2012 HEART Conf.*, 12–16 Mar. 2012.

[5] D. Fromme, G. Edmiston, A. Walker, and M. Rooney, "MHD-E3 transmission level power grid test report: Part I – phase IV test description," DTRA Tech. Rep. DTRA-TR-15-46, 8 Jan. 2013.

[6] D. Fromme, G. Edmiston, A. Walker, and M. Rooney, "MHD-E3 transmission level power grid test report: Part II – phase IV test results," DTRA Tech. Rep. DTRA-TR-15-46, 8 Jan. 2013.

[7] *High-altitude Electromagnetic Pulse (HEMP) Protection for Ground-based C41 Facilities Performing Critical, Time-urgent Missions, Part 1 Fixed Facilities*, MIL-STD-188-125-1, 17 July 1998.

[8] *(U) High-Altitude Electromagnetic Pulse (HEMP) Environment*, MIL-STD 2169C, 30 Sept. 2012 (classified).

[9] *Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment*, MIL-STD-461F, 10 Dec. 2007.

[10] "Power system digital protective relay high-altitude electromagnetic pulse tests," DTRA Tech. Rep. DTRA-TR-18-72, 14 Feb. 2016.