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High-Altitude Electromagnetic Pulse and the Bulk Power System: Potential Impacts and Mitigation Strategies[1]

Primary Audience: Asset owners and operators of the United States bulk power system *(eei.com report provided through US InfraGard, not a product of Wapack Labs)*

Secondary Audience: Regulators, state and federal entities

Key Research Questions: This research sought to answer two key research questions: What are the potential impacts of a high-altitude electromagnetic pulse (HEMP) attack on the modern electric transmission system?

If impacts are of significant concern, what are possible mitigation options and potential costs and benefits of each?

Research Overview

Background: The detonation of a nuclear weapon at high altitude or in space (~30 km or more above the earth's surface) can generate an intense electromagnetic pulse (EMP) referred to as a high-altitude EMP or HEMP. HEMP can propagate to the earth and impact various ground-based technological systems such as the electric power grid. Depending on the height of the explosion above the earth's surface and the yield of the weapon, the resulting HEMP can be characterized by three hazard fields, denoted as E1 EMP, E2 EMP, and E3 EMP.

The International Electrotechnical Commission (IEC) defines the three HEMP hazard fields based on their distinct characteristics and time scales: The early time component (E1 EMP) consists of an intense, short-duration electromagnetic pulse characterized by a rise time of 2.5 nanoseconds and amplitude on the order of tens of kV/m (up to 50 kV/m at the most severe location on the ground).

The intermediate time component (E2 EMP) is considered an extension of E1 EMP and has an electric field pulse amplitude on the order of 0.1 kV/m and duration of one microsecond to approximately ten milliseconds.

The late time component (E3 EMP) is a very low frequency (below 1 Hz) pulse with amplitude on the order of tens of V/km with duration of one second to hundreds of seconds. E3 EMP is often compared with severe geomagnetic disturbance (GMD)

[1] http://www.eei.org/issuesandpolicy/cybersecurity/Documents/EPRI%20EMP%20Report%20-%20Grid%20Security%20-%20Key%20Messages.pdf

events; however, the intensity of E3 EMP can be orders of magnitude more severe, and E3 EMP is much shorter in duration than GMD events, which can last for several days.

Potential impacts of HEMP vary depending on the component (E1 EMP, E2 EMP, or E3 EMP) that is responsible for the resulting disruption or damage.

The geographic area exposed to varying levels of E1 EMP fields can be quite large, as the area of coverage is characterized by the line of sight from where the weapon is exploded to the horizon. For example, a detonation at 200 km can affect a circular area of on the order of 3 million square miles. However, not all areas included within the circular region experience the maximum electric field, and strength of the field falls off with distance from the ground zero location. The incident E1 EMP can couple to overhead lines and cables, exposing connected equipment to voltage and current surges (referred to as the conducted threat). The resulting E1 EMP can also radiate equipment directly (referred to as the radiated threat). Potential impacts from E1 EMP on the electric transmission system include disruption or damage of electronics such as digital protective relays (DPRs), communication systems, and supervisory control and data acquisition (SCADA) systems.

The characteristics of E2 EMP are often compared with nearby lightning strikes. However, it is important to understand that E2 EMP does not couple to overhead lines or cables in the more traditional sense of how lightning strikes a transmission tower or a conductor. Rather, E2 EMP couples to conductors through the air, like E1 EMP. This coupling mechanism is similar to how the field created by a nearby lightning strike couples to an overhead transmission line. Because the amplitude of the incident E2 EMP field is quite low (0.1 kV/m), impacts to the transmission system are not expected to occur.

E3 EMP induces low-frequency (quasi-dc) currents in transmission lines and transformers. The flow of these geomagnetically induced currents (GICs) in transformer windings can cause magnetic saturation of transformer cores, which causes transformers to generate harmonic currents, absorb significant quantities of reactive power, and experience additional hotspot heating in windings and structural parts. Potential impacts of E3 EMP on the bulk power system can include voltage collapse (regional blackout) and transformer damage due to additional hotspot heating.

When the EPRI EMP research project was launched, publicly available data on the HEMP threat, potential impacts of HEMP on the electric transmission system, and field-tested E1 EMP mitigation options specific to substations were limited. Additionally, there were differences between the findings of EMP research conducted during the 1980s through the early 1990s by the Department of Energy (DOE) and others and more recent findings communicated by the former Commission to Assess the Threat to the United States from Electromagnetic Pulse Attack (former EMP Commission). Because of these differences and the potential impacts that a HEMP attack could have on society, EPRI launched a three-year research project in April 2016 to provide electric utilities and other stakeholders with a technical basis for making more-informed decisions regarding the potential impacts of HEMP on the electric transmission system and potential options for mitigating possible impacts. By the conclusion of the project, the research was financially supported by more than 60 U.S. utilities.

Research Scope and Approach

The main goal of this research effort was to provide the electric utility industry and other stakeholders with an unclassified, technical basis for 1) assessing the potential impacts of a HEMP attack on the transmission system, and 2) hardening the system against those impacts, should any be found to be of significant concern. The research specifically focused on the electric transmission system (overhead transmission lines, substations, and switchyards), and did not consider the potential effects of HEMP on generation facilities, nuclear reactors, distribution systems, loads, or other key elements or infrastructure sectors.

An important aspect of this project was the close collaboration with various government entities that have extensive expertise and knowledge of the HEMP threat. Key collaborators included DOE, Lawrence Livermore National Laboratory (LLNL), Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), and the Defense Threat Reduction Agency (DTRA). EPRI, in close collaboration with the DOE, also developed a Joint Electromagnetic Pulse Resiliency Strategy that was published in July 2016.

To address the two fundamental research questions that were identified, the project was broken up into five research areas:

Environment and Modeling – Several conservative (bounding) unclassified HEMP environments for use in assessments were identified and/or obtained from the DOE and national labs, and software tools and methods for performing assessments were developed. All three hazard fields—E1 EMP, E2 EMP, and E3 EMP—were included in the environment and modeling research effort.

Testing – Extensive laboratory testing of DPRs was conducted to provide data on the levels of E1 EMP stress that could cause operational disruption of or damage to these devices. Testing included free field illumination testing per MIL-STD-461G/RS 105 to assess performance when subjected to radiated threats, and direct injection testing using a voltage impulse with waveform defined in MIL-STD-188-125-1 to assess performance when subjected to conducted voltage surges. Direct injection testing of instrument transformers such as a potential transformer and a capacitor coupled voltage transformers was also conducted to investigate propagation of voltage surges through these devices. Additionally, testing to evaluate potential mitigation options and shielding effectiveness of substation control houses was performed. Testing focused on E1 EMP impacts.

Assessment – Assessments using bounding HEMP environments were conducted to improve understanding of the potential impacts of a HEMP attack on the bulk power system. These assessments included E1 EMP, E2 EMP, E3 EMP, and the combined effects from E1 EMP and E3 EMP.

Mitigation, Hardening, and Recovery - Various mitigation and hardening approaches that could be employed to reduce the potential impacts of E1 EMP on DPRs were evaluated. Potential unintended consequences of various mitigation and hardening strategies were considered, and system recovery following a HEMP-induced blackout was explored.

Decision Support – A framework for supporting risk-informed decisions regarding the implementation of HEMP hardening and mitigation measures was developed.

Key Findings

Key findings from this research were as follows.

1. **E1 EMP**

Assessments using bounding E1 EMP environments showed that this hazard field has the potential to cause disruption or damage to DPRs over large areas such as an electrical interconnection. Potential damage to DPRs, assuming the nominal E1 EMP environment provided by LANL (up to 25 kV/m at the most severe location on the ground) was found to be moderate, whereas damage from the same environment but scaled so that the maximum peak field at the most severe location on the ground was 50 kV/m was found to be more severe. Based on the assumptions made in the assessments, it was estimated that approximately 5% of the transmission line terminals in a given interconnection could have a DPR that is disrupted or damaged by the nominal E1 EMP environment that was simulated, whereas approximately 15% could be impacted by the scaled (up to 50 kV/m at the most severe location on the ground) E1 EMP environment.

E1 EMP impacts alone were not found to cause immediate, interconnection-scale disruption or blackout of the power grid, but this finding is not conclusive due to uncertainties regarding how damaged DPRs might respond during an actual event (refer to Combined Effects of E1 EMP and E3 EMP below) or how potential E1 EMP damage to generator controls and other systems such as automatic generation control (AGC), not included as a part of this study, might affect the long-term operation of the grid. Additional research is needed to quantify and understand these uncertainties and how they might, in combination, affect the stability of the bulk power system.

Results from extensive modeling and laboratory testing of DPRs indicated that the following design options, when used in concert, could provide adequate mitigation of E1 EMP impacts up to the full IEC 61000-2-9 threat level of 50 kV/m:

- Shielded control/signal cables with proper grounding
- Low-voltage surge protection devices and/or filters
- Use of fiber optics based protection and control systems
- Modifications to substation control houses to enhance electromagnetic shielding properties
- Grounding/bonding enhancements

Additional supplies of DPRs and other critical assets could also be included as part of a mitigation strategy.

2. E2 EMP

Assessments evaluating the potential impacts of E2 EMP alone using the maximum threat level of 0.1 kV/m defined in IEC 61000-2-9 indicated that damage to the transmission system is not expected to occur. Thus, no specific mitigation options were identified as a part of this research

3. E3 EMP

E3 EMP alone was found to pose a threat to the operation and performance of the bulk power system. Assessment results indicated that a regional blackout (multiple states) is possible, but immediate, widespread transformer damage due to hotspot heating from part-cycle saturation is not expected to occur.

- Options for mitigating E3 EMP impacts were found to be like those that can be employed to protect against the effects of GMD events and include the following:
- Avoiding protection system misoperations by modifying protection and control schemes to be resilient to harmonics and system imbalance
- Blocking or reducing the flow of GICs
- Automatic removal of some shunt reactive power compensation devices, for example shunt reactors, and/or employing under-voltage load shedding (UVLS)
- Sparing of large power transformers and high-voltage circuit breakers

4. Combined Effects of E1 EMP and E3 EMP

Assessment of the combined effects of E1 EMP and E3 EMP showed that widespread E1 EMP impacts to DPRs, as they were modeled, did not significantly affect the outcome of the E3 EMP assessment results. This finding was based on testing and analysis that indicated that DPRs that are damaged by surges that propagate into the voltage inputs of the device would not result in the immediate disconnection of transmission lines, but rather would disable the DPRs such that they would no longer be able to perform their intended protection and control function. There is uncertainty with this assumption, as not all DPRs that are currently in use were tested, and testing of some DPRs indicated that control outputs could be damaged by voltage surges induced in unshielded control cables and could potentially result in circuit breaker tripping. Additionally, it is unknown how various DPRs across an interconnection would respond during an actual event. However, significant damage to DPRs and other controls from E1 EMP would be expected to degrade recovery efforts and longer-term viability of controlling system frequency due to potential damage to automatic generation control (AGC) and other ancillary functions. These latter effects could impact the long-term stability (voltage and/or frequency) of an area affected by the HEMP attack.

Recovery and Restoration

Until the transmission system is appropriately hardened against the potential impacts of E1 EMP, recovering from a HEMP-induced blackout may present operators with challenges that have not been experienced following previous blackouts from more traditional causes. These potential challenges are primarily related to unavailable, inoperable, or damaged equipment and impaired situational awareness capability that could occur as the result of E1 EMP related damage.

Predefined Transmission Operator step-by-step facility energization procedures currently in place may not be practical to implement following a HEMP event, due to the possibility of widespread unavailable, inoperable, or damaged equipment and impaired situational awareness. Thus, developing alternative plans that consider the potential impacts that HEMP, and in particular E1 EMP, can have on the transmission system may be worthwhile. Training on the differences between system recovery following a HEMP-induced blackout and one from a more traditional cause may also prove beneficial.

Because damage to large power transformers is expected to be minimal, recovery times following a HEMP-induced blackout would be expected to be commensurate with historical large-scale blackouts if robust E1 EMP protections are deployed such that E1 EMP impacts to equipment, situational awareness, SCADA, and other infrastructures that support power system restoration are minimal.

Why This Matters

A properly functioning electric grid is critical to national security and society, and its potential loss for an extended period (months or longer) could severely impact both. The findings of this research, which evaluated the potential effects on the electric transmission system only, indicate that if a HEMP attack occurred and the resulting fields were like the bounding E1 EMP, E2 EMP, and E3 EMP environments that were evaluated, impacts such as regional disruption or damage to DPRs and regional voltage collapse could be experienced. Research findings do not support the notion of blackouts encompassing the contiguous United States (CONUS) and lasting for many months to years. The technical basis for these findings and options for mitigating the potential impacts that were identified have been made available in this report so that the electric utility industry and other stakeholders can have the data necessary to make more informed decisions regarding the threat of a HEMP attack on the U.S. electric grid.

How to Apply Results

Through this research, options for hardening the electric transmission system against the potential impacts of E1 EMP have been identified, but additional research is needed to improve mitigation designs and understanding of the potential unintended consequences of E1 EMP hardening so that system reliability is not adversely affected. A collaborative research effort between EPRI and multiple utilities is currently underway to perform field evaluations of the various E1 EMP hardening options that were identified as part of this effort. Several options exist for mitigating E3 EMP impacts, and the industry has some limited experience with these since they can also be used to mitigate the potential impacts of severe GMD events

Although E3 EMP is not expected to cause immediate, widespread damage to large power transformers, it may be prudent to evaluate the number of transformer spares that are available to ensure that adequate replacements exist for the number of transformers that are identified as being at potential risk of damage. Transformer sparing philosophies for transformer banks comprised of single-phase units should consider that multiple phases of a transformer bank may be at risk of damage since all three phases of the transformer would be exposed to similar GIC levels.

Additionally, sparing of high-voltage circuit breakers may also be considered due to the uncertainty of their ability to interrupt currents which contain significant levels of GIC. Recovery plans and procedures designed to respond to widespread voltage collapse resulting from E3 EMP should consider the potential effects of E1 EMP on systems that are critical to grid restoration, such as protection and control, SCADA, and communications. The ability of E1 EMP to cause damage to these systems is a major concern since their loss can adversely affect system recovery efforts and timelines. Therefore, E1 EMP hardening of critical electronic systems within transmission control centers and substations along cranking paths may be considered higher priority. As information becomes available on E1 EMP impacts on generating units, distribution systems, and other facets of the electric power grid, assets in addition to those described in this report may also need to be considered in future mitigation plans.

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