# Written Testimony

## Reliability Technical Conference

## Federal Energy Regulatory Commission

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*"The Potential for Long-Term and Large-Scale Disruptions to the Bulk–Power System"*

**June 22, 2017**

The Electric Power Research Institute (EPRI) conducts research and development relating to the generation, delivery, and use of electricity for the benefit of the public. An independent, non-profit organization, EPRI brings together its scientists and engineers, as well as experts from academia and industry, to help address challenges in electricity, including reliability, efficiency, affordability, health, safety, and the environment. EPRI's members represent approximately 90 percent of the electricity generated and delivered in the United States, and international participation extends to more than 30 countries.

The subject of today's testimony is EPRI's research efforts related to high-altitude electromagnetic pulse (HEMP) events.

## Background

The high-altitude detonation of a nuclear weapon can generate a large electromagnetic pulse (referred to as a high-altitude EMP or HEMP) that is comprised of three components: E1, E2 and E3. Depending on weapon yield and height of burst the resulting EMP can impact large geographic areas such as the size of an electrical interconnection. The early-time pulse, E1, refers to a nearly instantaneous (rise times are on the order of 2.5 nanoseconds or 2.5 billionths of a second) – large magnitude (50 kV/m) pulse that can result in damage to electronic components and electric infrastructure. The intermediate-time pulse or E2, refers to the short duration pulse which has characteristics similar to lightning although the magnitude of E2 is much lower (~ 0.1 kV/m) and the way in which it couples into electric infrastructure is different. The latter component, magnetohydrodynamic electromagnetic pulse (MHD-EMP) or E3 is similar to a severe GMD event, and can drive low frequency, geomagnetically-induced currents (GIC) in transmission lines and power transformers. However, the magnitude of E3 can be much higher than that of a severe GMD event, and the duration of E3 is much shorter lasting only a few minutes as compared with days in the case of a severe GMD event. As with severe GMD events, potential impacts from E3 range from voltage collapse to increased hotspot heating in bulk-power transformers.

**EPRI HEMP Research Project Description**

HEMP events are a growing concern in the energy business. While the industry has worked to develop effective responses to GMD, little definitive work has centered on the effects of a HEMP attack. Numerous constituencies are pressing to ensure the electric power system is more resilient to a large HEMP event, but technical information regarding the impacts of HEMP is inconsistent, and potential options to increase resilience through hardening and recovery are not well-defined. Some proposed approaches are high-cost and lack the technical basis to substantiate their viability. An additional concern is the potential for unintended consequences resulting from applying military-grade hardening measures. To address these issues, EPRI initiated a three-year research project in April 2016 with financial support from fifty-six electric utilities, to improve understanding of the potential impacts of HEMP on the bulk-power system and to develop cost-effective mitigation options.

As a part of this research project EPRI is collaborating closely with the U.S. Department of Energy (DOE), DOE National Laboratories, and the U.S. Department of Defense (DoD).

The EPRI EMP project is comprised of 7 tasks which are illustrated in Figure 1.

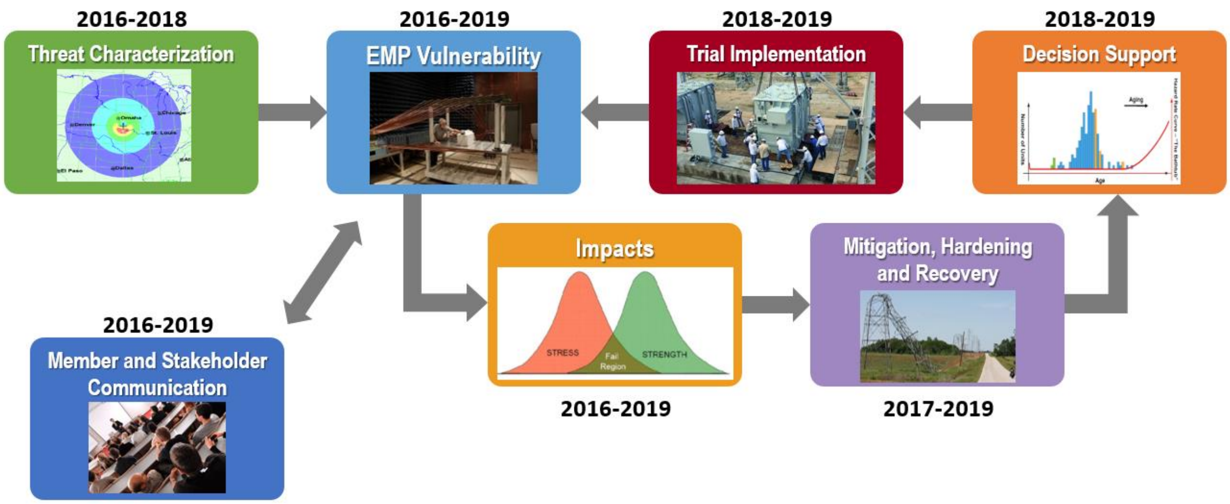


**Figure 1. EPRI's three-year HEMP research plan.**

Descriptions of each of the tasks are as follows:

*Task 1 – Threat Characterization*

The threat characterization task consists of:

- identifying the state of knowledge of unclassified HEMP research,
- identifying conservative (bounding) HEMP waveforms (magnitude, spatial and temporal characteristics, etc.) that can be used to assess the potential impacts on bulk-power system components, and
- investigating the physics of HEMP propagation and coupling to power system infrastructure.

As a part of this research, all three components of the HEMP environment are being evaluated, i.e., E1, E2, and E3.

In September 2016, EPRI released its first report[1] which is a compendium describing the state of knowledge of HEMP research that is relevant to the electric power industry as well as a suite of unclassified HEMP environments that can be used in power system assessments.

We are currently developing models to simulate coupling of E1/E2 pulses into transmission infrastructure and are performing an analysis of a transmission substation to determine impacts of E1/E2 on equipment. This work is described in more detail in a subsequent section (E1/E2 Assessment).

*Task 2 – EMP Vulnerability*

This task is identifying the vulnerability of transmission system and support assets (protection and control systems, communications, SCADA, cables, transformers, insulators, etc.) exposed to the HEMP threat defined in Task 1 by performing laboratory tests. This work is described in more detail in a subsequent section (E1/E2 Assessment).

*Task 3 – Impacts*

This task is assessing the potential impacts of a HEMP attack on the bulk-power system by combining the modeling results of Task 1 with the equipment testing results of Task 2. Assessment techniques, models and tools for assessing the impacts of a HEMP attack are also being developed.

The first of many studies has been completed, and will be described in more detail later in this testimony. A report[2] assessing the potential effects of E3 on U.S. bulk-power transformers was released in February 2017. A companion report assessing the potential impacts of E3 on the stability of the bulk-power system is expected to be finished by the third quarter of 2017.

The results of the first E1 threat assessment are expected by the end of the year.

*Task 4 – Mitigation, Hardening and Recovery*

This task is assessing various mitigation and hardening approaches that can be employed to reduce the impacts of HEMP on bulk-power system reliability. Potential unintended consequences of various mitigation and hardening strategies are being evaluated. Enhanced recovery procedures/plans are being developed.

As an initial step, we are developing interim guidance on hardening substations using information provided in relevant IEC and MIL standards. This is only a first step, and EPRI is

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[1] *High-Altitude Electromagnetic Pulse Effects on Bulk-Power Systems: State of Knowledge and Research Needs.* EPRI, Palo Alto, CA: 2016. 3002008999.

[2] *Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid: Geomagnetically Induced Current and Transformer Thermal Analysis.* EPRI, Palo Alto, CA:2017. 3002009001

not recommending that utilities harden to these standards. Future research efforts aim to develop cost-effective hardening and mitigation options that are relevant to the electric power industry. Interim guidance is expected to be completed and made available to project members by the third quarter of 2017.

*Task 5 – Decision Support*

This task is developing methodologies and tools to support risk-informed decisions regarding the implementation of HEMP hardening and mitigation measures. A framework for assessing the relative benefits of various hardening and mitigation approaches will be developed. Support tools designed to aid in decision making will be developed as a part of this task.

*Task 6 – Trial Implementation*

Once hardening measures have been identified, supporting member utilities will have the opportunity to evaluate the need to begin implementation on aspects of their systems. This task will develop a collection of leading industry practices with regards to HEMP mitigation and hardening. Applications of various assessment techniques and mitigation options will be catalogued, and the effectiveness and lessons learned will be communicated.

*Task 7 – Member and Stakeholder Communication*

An important aspect of this research project is communicating the results to our supporting members and stakeholders as appropriate. This task is developing communications to inform of the background and potential impacts of HEMP, and appropriately share new learning in a timely manner.

**E3 Assessment of the Continental U.S. Electric Grid**

GIC generated by E3 resulting from a HEMP attack can cause additional hotspot heating in windings and structural parts of bulk-power transformers. If heating is severe enough, it can cause damage to the transformer. The loss of hundreds of bulk-power transformers could create a situation where system recovery is not possible in a timely manner resulting in long-term blackout. Thus, one of the first steps in this three-year research project was to evaluate the potential impacts of E3 on bulk-power transformers.

Past research performed by Oak Ridge National Laboratories (ORNL) during the mid-late 1980's through early 1990's and again in the late 2000's evaluated the potential impacts of E3 on bulk-power transformers; however, the results of the research had conflicting conclusions. Earlier ORNL research[3] concluded that E3 would not result in significant damage to bulk-power transformers while a later research report[4] concluded that transformer damage was likely, and that up to 100 transformers could be damaged depending on the target location.

[3] Electromagnetic Pulse Research on Electric Power Systems: Program Summary and Recommendations. Oak Ridge National Laboratories, Oak Ridge, TN: 1993. ORNL-6708.
[4] Meta-R-321, The Late-Time (E3) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid. Metatech Corporation, January 2010.

The purpose of the EPRI study[5] was to determine, using advanced transformer models that were not available at the time of the ORNL research, if a significant number (hundreds) of bulk-power transformers would experience thermal damage from a single E3 event. More simply, the study sought to answer the question, "if a HEMP attack occurred, would there be enough bulk-power transformers left to facilitate system recovery?"

The fundamental approach to the EPRI study was similar to assessing the potential impact of a severe geomagnetic disturbance (GMD) event. First, the electric field environment necessary for calculating GIC flows was identified and a dc model of the interconnection-wide system was assembled. For this study, a publicly available E3 environment[6,7] with peak geoelectric field amplitude of 24 V/km along with a model of the Continental United States (CONUS) bulk electric system was used to calculate the GIC flows in the transmission system that would result from a single, high-altitude detonation over the CONUS. GIC calculations were then performed assuming the weapon was detonated over 11 different locations in the CONUS. The resulting time-series GIC flows were then used to compute the time-series hotspot temperature of each bulk-power system transformer included in the interconnection-wide assessment using physically-based transformer models. The maximum instantaneous hotspot temperatures were then evaluated against conservative temperature limits that were based on an assumed condition-based GIC susceptibility category of the entire transformer fleet. The number of transformers that were identified as exceeding the specified temperature limits were then combined with the probabilities of a given transformer being in one of the three specified categories to estimate the expected number of bulk-power transformers to be at potential risk of thermal damage. Additionally, the potential for thermal damage caused by circulating harmonic currents in the tertiary windings of large autotransformers was also evaluated.

The results of the EPRI study are provided in Table 1, and indicate that a significant number of transformers (hundreds to thousands) could experience GIC flows greater than the screening criteria presented in NERC TPL-007-1 (i.e. 75 Amps/phase), but only a small fraction of these transformers (3 to 14 depending on the target location evaluated) would be at potential risk of thermal damage.

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[5] *Magnetohydrodynamic Electromagnetic Pulse Assessment of the Continental U.S. Electric Grid: Geomagnetically Induced Current and Transformer Thermal Analysis*. EPRI, Palo Alto, CA: 2017. 3002009001.

[6] Oak Ridge National Laboratory, "Study to Assess the Effects of Magnetohydrodynamic Electromagnetic Pulse (HEMP) on Electric Power Systems – Phase I – Final Report," 1985.

[7] Oak Ridge National Laboratory, "Electromagnetic Pulse Research on Electric Power Systems: Program Summary and Recommendations," 1993.

**Table 1**
**Number of transformers experiencing peak instantaneous effective GIC flows ≥75 amps/phase and at risk of potential thermal damage**

| | | Total Number of Transformers Exceeding Temperature Limits Based on Assumed Condition-Based Geomagnetically Induced Current Susceptibility of Entire Transformer Fleet | | | |
|---|---|---|---|---|---|
| Target Location | Number of Transformers with $GIC_{eff}$ ≥75 Amps/Phase | Category I | Category II | Category III | Mixed Category (I: 36%, II: 25%, III: 39%) |
| 1 | 1897 | 0 | 2 | 22 | 9 |
| 2 | 1872 | 2 | 4 | 15 | 8 |
| 3 | 1938 | 1 | 4 | 22 | 10 |
| 4 | 1912 | 2 | 6 | 19 | 10 |
| 5 | 1812 | 0 | 5 | 21 | 9 |
| 6 | 2435 | 0 | 3 | 15 | 7 |
| 7 | 689 | 0 | 2 | 10 | 4 |
| 8 | 692 | 0 | 1 | 7 | 3 |
| 9 | 675 | 2 | 3 | 11 | 6 |
| 10 | 2382 | 1 | 4 | 23 | 10 |
| 11 | 1965 | 3 | 6 | 28 | 14 |

Additionally, the at-risk transformers were found to be geographically dispersed. The results of this study agree with earlier work performed by ORNL[8] which indicate that the failure of a large number (hundreds) of bulk-power transformers from E3 is unlikely.

The assessment results can be used to help quantify the overall risk of E3 impacting the bulk-power system (interconnection-level assessment), but they should not be interpreted to indicate E3 will not affect bulk-power reliability since the potential for widespread outages due to voltage collapse or the combined effects of E1, E2 and E3 are still being investigated. Additionally, because of the number of conservative assumptions that were required due to the lack of asset specific data, the results should not be used to inform investment decisions at individual utilities.

A companion study to the GIC and transformer thermal assessment, an analysis determining the potential for voltage collapse resulting from E3, is expected to be completed by the third quarter of 2017.

## E1/E2 Assessment

Although E3-related research is continuing, a significant focus of EPRI's research efforts in 2017 is related to assessing the E1/E2 threat, and developing the capability to evaluate the combined effects of E1, E2 and E3 simultaneously.

[8] Electromagnetic Pulse Research on Electric Power Systems: Program Summary and Recommendations. Oak Ridge National Laboratories, Oak Ridge, TN: 1993. ORNL-6708.

The E1 threat assessment process is illustrated in Figure 2, and is comprised of:

- performing testing of components to determine E1/E2 threshold levels, i.e., the levels at which damage or upset occur (Strength);
- modeling to determine the voltage and currents that components might be exposed during an event (Stress);
- analysis to determine the probability of damage or upset of a given component based on the strength of the component and the stress that it may be exposed during a HEMP event;
- assessing the impact of damage or upset of individual components or subsystems on the operation and performance of the overall bulk-power system.

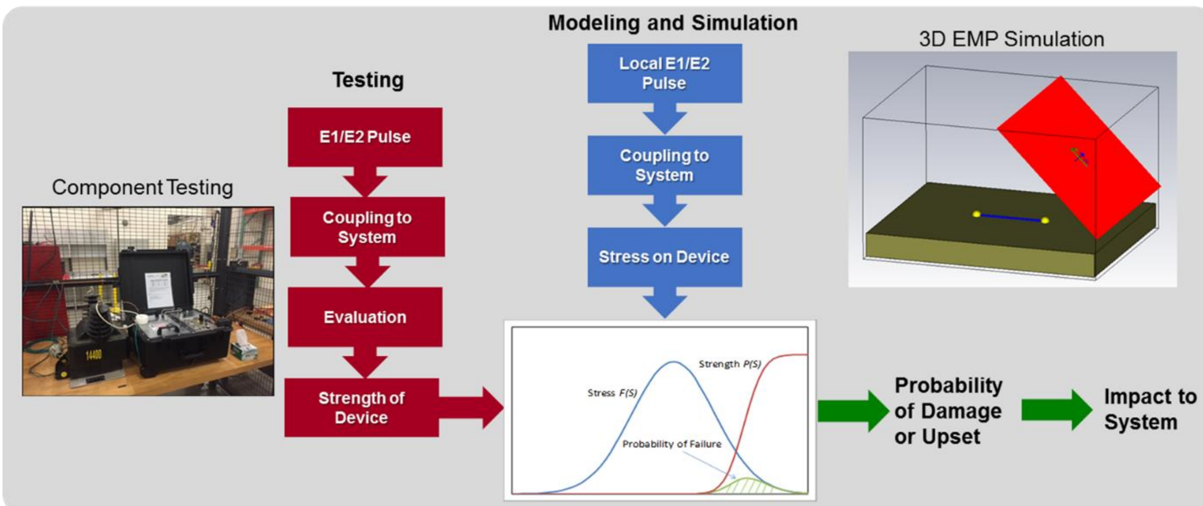


**Figure 2. Illustration of E1/E2 Assessment Process**

*Testing*

To facilitate high-volume EMP testing of components, EPRI is building two EMP test laboratories and updating our high-voltage test lab in Lenox, MA. In these laboratories, we will test systems and components by subjecting them to synthetic EMP pulses (E1). Equipment testing will include both radiated and conducted transients. Testing of protection and control (P&C) systems to determine impacts of E1 is initial priority. Testing is expected to begin by the second quarter of 2017 with initial results possible by the end of the year. In addition to performing tests internally, EPRI is also partnering with Sandia National Laboratory and Little Mountain Test Facility to perform additional E1 testing of P&C equipment. These projects are currently in progress.

*Modeling*

Models are being developed to simulate coupling of E1/E2 into transmission infrastructure (substation bus work, control cables, control houses, etc.). Additionally, work is underway to perform an analysis of a transmission substation to determine impacts of E1/E2 on equipment. Modeling results will also be used to inform equipment testing and mitigation efforts. Simulation work has begun, and will continue into 2018. EPRI is currently collaborating with Lawrence

Livermore National Laboratory (LLNL) and Los Alamos National Laboratory (LANL) to further research in this area.

An important component of this research is to develop tools that utilities can use to perform their own assessments. To that end, EPRI is developing software tools and modeling guidelines that can be used by utilities to simulate the coupling of an E1/E2 pulse into overhead and underground conductors and/or control cables to estimate the stress that equipment could potentially be subjected during a HEMP event. The beta version of the high-altitude electromagnetic pulse coupling application tool (HEMPCAT) for overhead lines has been made available to project members. Final version of the software tool is expected by the fourth quarter of 2017.

*Assessment*

We are in the early stages of evaluating potential methods of combining testing (strength) and modeling (stress) results in a statistical fashion to determine probability of damage or upset of an individual component or subsystem, e.g., a protective relay inside of a substation control house. Future research will develop methods of incorporating these results into a system-level E1/E2 assessment that can be used to initialize E3 studies so that the potential effects of E1/E2 (e.g., loss of protection and control at numerous transmission substations) can be included in E3 assessments and system recovery planning efforts. At the end of the research project we anticipate being able to evaluate the combined effects of E1, E2 and E3 on the bulk-power system.

**System Hardening and Recovery**

Efforts are currently underway to develop guidelines for hardening bulk-power systems against the effects of HEMP. Efforts to improve system restoration following an event will be initiated in 2018.

*E1/E2*

Guidance on hardening substation control houses per information provided in MIL-STD-188-125-1 and IEC SC-77 standards is currently being developed. Guidance will provide a listing of possible mitigation options as well as identify potential unintended consequences that require additional study. Initial guidance is expected to be made available by third quarter 2017. This initial guidance is for interim purposes only as ongoing research efforts aim to develop cost-effective hardening and mitigation solutions.

*E3*

Guidelines for hardening bulk-power systems against the potential effects of E3 are being developed. Guidance will provide a listing of possible mitigation options as well as identify potential unintended consequences that require additional study. This work is leveraging EPRI's geomagnetic disturbance (GMD) related research. Guidance is expected to be made available in third quarter of 2017.

**Concluding Remarks**

The potential impacts of HEMP are real; however, there are many open research questions that must be addressed. Additionally, guidance and tools necessary to perform assessments to determine impacts and investigate mitigation options are limited and not widely available. Evaluating the effects of such events on existing and future power grid infrastructure requires concrete, scientifically-based analysis. EPRI's research efforts, as well as others, seek to fill this knowledge gap. Once the true impacts are known, including the potential for unintended consequences, cost effective mitigation and/or recovery options can be developed and employed.

The recent E3 assessment of the US bulk-power transformer fleet is merely a first step in a series of studies aimed at informing the electric utility industry of the potential impacts of HEMP on the bulk-power system. Although the results of this assessment indicate that E3 from a single high-altitude detonation would have marginal effect on bulk-power transformers, the results should not be interpreted to indicate that HEMP will not affect bulk-power system reliability. More research is needed to determine the impacts of E1 on bulk-power system assets, and more importantly, the ability to accurately capture, through modeling and analysis, the synergistic effects of E1, E2 and E3 is needed to assess the true impact of HEMP on the grid and develop cost-effective mitigation options.

Lastly, this is a complex engineering problem, and building consensus and collaboration takes a great deal of time, effort and knowledge. EPRI is committed to developing science-based solutions to these difficult problems, and will continue to offer technical leadership and support to the electricity sector, public policymakers, and other stakeholders to enable safe, reliable, affordable, and environmentally responsible electricity.

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