Written Testimony

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"Hearing to examine the threat posed by electromagnetic pulse and policy options to protect energy infrastructure and to improve capabilities for adequate system restoration"

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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 electromagnetic pulse (EMP) events, including naturally occurring geomagnetic disturbances (GMD) as well as electromagnetic pulse (EMP) events, specifically high altitude EMP, or HEMP. EPRI has been researching GMD for many years with significant applications now implemented across the electric industry. Implications and solutions for EMP and HEMP are less understood. Much of the available information is not specifically applied to electric utilities, making it very difficult for utilities and regulators to understand effective options for protecting energy infrastructure. This testimony provides an overview of EPRI's research activities related to GMD, and a more detailed description of our EMP research efforts as we seek to better inform the issue with a firm technical basis for decision making.

GMD Research

During geomagnetic disturbance (GMD) events, magnetic field variations at the earth's surface drive low-frequency electric currents along transmission lines and through transformer windings to ground. These geomagnetically induced currents (GIC) cause half-cycle saturation of transformers leading to harmonic generation, increased reactive power losses, and heating of transformer windings and structural components. These effects are real, and have been observed in the past. For example, during the March 1989 geomagnetic storm, Hydro-Quebec experienced a blackout resulting from the effects of GMD-related harmonics, and a generator step-up unit (GSU) at Salem Nuclear Power Plant in New Jersey was damaged from resulting hotspot heating. Several other effects were observed in the United States and Canada, for example tripping of capacitor banks, but these did not result in any significant reliability impacts[1].

EPRI recognizes the potential impacts of severe GMD events, and has been involved in GMD-related research for nearly four decades[2]. Some of EPRI's research activities in this area include:

- developing sensors and a support network for measuring GIC;
- developing software tools, models and guidelines to assess the impacts of severe GMD events on the bulk-power system;
- improving the fidelity of existing models (e.g. earth conductivity);
- improving understanding of potential impacts of GMD events on bulk-power system components;
- evaluating mitigation options and their application; and
- supporting the development of benchmark GMD events used in assessments.

Because EPRI's research in the GMD area is expansive, only current activities will be addressed.

Geomagnetic Field Monitoring

EPRI currently has a research project underway to install three axis magnetometer sensors between existing magnetic observatories operated by the U.S. Geological Survey (USGS) to improve magnetic field resolution throughout the United States. Measurement data will be used to validate deep earth conductivity models, and improve understanding of local geological factors that can affect the geoelectric field induction process.

SUNBURST Network

The EPRI SUNBURST network is both an organized method for measuring geomagnetically induced currents (GICs) and a source of data for continuing research studying the cause, effects and mitigation of GIC impacts on electrical power systems. While the primary focus of this research is operating the monitoring network, the data collected in this project will be used for feedback into new prediction models that will serve as advance warnings, that is, the NASA Solar Shield project. The SUNBURST project also supports an annual event where relevant scientists from the field of solar phenomena/space weather come together to discuss common issues and concerns related to GICs.

The SUNBURST network consists of a consortium of member utilities where near-real-time continuous monitoring of the GIC flowing in the neutral of large power transformers is performed. Over the last decade, EPRI has accumulated a body of data and experience about correlations between space weather and GIC flows in the grid.

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[1] North American Electric Reliability Corporation (NERC), March 13, 1989 Geomagnetic Disturbance: www.nerc.com/files/1989-quebec-disturbance.pdf

[2] *Investigation of Geomagnetically Induced Currents in the Proposed Winnipeg-Dulluth-Twin Cities 500 kV Transmission Line.* EPRI, Palo Alto, CA: 1981. EL-1949

New GIC Sensor

One of the limitations of measuring GIC using current technology (e.g. SUNBURST) is that the monitoring location must be the neutral of the transformer. Depending on the type of transformer, e.g. an autotransformer, a neutral connected GIC node may not provide the observability necessary to determine the GIC flows that could affect power system operation. To fill this gap, EPRI has recently developed a sensor that is capable of measuring GIC flows in energized conductors. Measurement of GIC in energized AC (alternating current) transmission lines and transformer windings improves observability of the behavior and effects of GIC on the bulk-power system. In addition, GIC flows through interconnections and in some cases, remote transformers can be measured directly. This will lead to developing more effective network boundary models, and closer representation of actual GIC conditions when assessing impact to transformers.

Current Research in Grid Operations & Planning Area

Harmonics studies are an integral part of any GMD vulnerability assessment, and as such, are a key component of related reliability and planning assessments and associated regulatory requirements, e.g. NERC TPL-007-1 standard. However, commercially-available software tools or industry guidelines necessary to perform such assessments are limited. To fill this gap, EPRI is developing an open source software tool that can be used to perform GMD-related harmonics studies. Additionally, guidelines for performing assessments to determine the potential impacts of GMD-related harmonics on the bulk-power system are being developed.

EMP Research

Electromagnetic pulse (EMP) attacks and geomagnetic disturbance (GMD) events are often discussed together when evaluating potential impacts on the bulk-power system and approaches for improving system resiliency. While both events are considered high-impact low-frequency (HILF) events (along with physical attacks, severe storms, earthquakes, and other similar events), there are very important differences that should be considered when evaluating resiliency improvement priorities and investment decisions.

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 geographical 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 simply E3 is similar to a severe GMD event, and can drive low frequency, geomagnetically-induced currents (GIC) in transmission lines and power transformers. However, there are two key differences between E3 and GMD. First, E3 from a single high-altitude detonation would not generate planetary-scale effects like a severe GMD event can. Secondly, the magnitude and duration of E3 are significantly different. The magnitude of E3 can be much higher than that of a severe GMD event; however, 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.

EMP 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 is inconsistent and 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. To fill this gap, EPRI initiated a three-year research project in April 2016, currently with financial support from fifty-six electric utilities, to improve understanding of the potential impacts of HEMP on the bulk-power system and develop cost-effective mitigation options. The financial support of EPRI's members demonstrates the importance to them of providing scientific and technical analysis of this issue for the benefit of the public.

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

The EPRI EMP project is comprised of 7 tasks which are as follows.

<u>Task 1 –HEMP Threat Characterization</u>

As a part of the threat characterization task, we are:

- identifying the state of knowledge of unclassified HEMP research,
- identifying conservative (bounding) HEMP waveforms (magnitude, spatial and time dependent 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[3] associated with this task which is a compendium describing the state of knowledge of HEMP research that is relevant to the electric

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

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 into transmission infrastructure (substation bus work, control cables, control houses, etc.) and are performing 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 working with Lawrence Livermore National Laboratory (LLNL) to further research in this area.

Additionally, 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 pulse into overhead and underground conductors and/or control cables. The beta version of the overhead conductor coupling tool is expected to be finished by the fourth quarter of 2017.

<u>Task 2 – Electric Infrastructure EMP Vulnerability</u>

This task is identifying the vulnerability of transmission systems and support assets (protection and control systems, communications, SCADA, cables, transformers, insulators, etc.) exposed to the HEMP threat defined in Task 1 – HEMP Threat Characterization by performing laboratory tests. To facilitate high-volume EMP testing of components, EPRI is building two EMP test labs and updating our high-voltage test lab in Lenox, MA to 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.

<u>Task 3 – Electric Infrastructure Impacts</u>

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[4] 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.

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

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, EPRI is developing interim guidance on hardening substations using information provided in relevant IEC[5] and military standards. This is only a first step, and EPRI is not recommending utilities harden to these standards. Future research efforts aim to develop cost-effective hardening and mitigation solutions that are relevant to electric power infrastructure. Interim guidance is expected to be completed and made available to project members by the third quarter of 2017.

Task 5 – Risk-based 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 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 – Project 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.

February, 2017 Report: 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 an environment where system recovery is not possible in a timely manner resulting in long-term

[5] IEC is the International Electrotechnology Commission – an international standards organization

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 late 2000's evaluated the potential impacts of E3 on bulk-power transformers; however, the results of the ORNL research had conflicting conclusions. Earlier ORNL research[6] concluded that E3 would not result in significant damage to bulk-power transformers while a later research report[7] concluded that transformer damage was likely, and that up to 100 transformers could be damaged depending on the target location.

The purpose of the EPRI study was to determine, using advanced transformer models that were not available at the time of the ORNL research, whether or not 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 that adopted by the North American Electric Reliability Corporation (NERC) to assess the potential impacts of severe geomagnetic disturbance (GMD) events on bulk-power transformers. First, the electric field environment necessary for calculating GIC flows was identified and a direct current model of the interconnection-wide system was assembled. For this study, a publicly available E3 environment along with a model of the United States 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 continental United States (CONUS). GIC calculations were then performed assuming weapon detonation over 11 separate 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 EPRI study found that although a significant number of transformers (hundreds to thousands) could experience GIC flows greater than the 75 amps/phase screening criteria adopted from NERC TPL-007-1, only a small number (3 to 14 depending on the target location evaluated) of these transformers were found to be at potential risk of thermal damage. In addition, the at-risk transformers were found to be geographically dispersed.

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

[7] 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 results of this study agree with earlier work performed by ORNL 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 synergistic 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. Future research will be aimed at improving the assessment process to include the synergistic effects of E1, E2 and E3.

Concluding Remarks

The potential impacts of GMD and HEMP are real; however, evaluating the effects of such events on existing and future power grid infrastructure requires concrete, scientifically-based analysis. Once the true impacts are known, including the potential unintended consequences of mitigation options, 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 as indicating 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.

EPRI is committed to developing science-based solutions to these difficult problems, and offers technical leadership and support to the electricity sector, public policymakers, and other stakeholders to enable safe, reliable, affordable, and environmentally responsible electricity to the people of the United States.