HIGH-ALTITUDE ELECTROMAGNETIC PULSE HARDENING PILOT PROJECTS

Status and Future Research

BACKGROUND

The detonation of a nuclear weapon at high altitude or in space can generate an intense electromagnetic pulse (referred to as a *high-altitude electromagnetic pulse* [HEMP]) that can propagate to the earth's surface and impact critical electrical equipment and systems. HEMP consists of three distinct components—E1 HEMP, E2 HEMP, and E3 HEMP—that are described by their distinct characteristics and time frames, as follows:

- The early time component (E1 HEMP) consists of an intense rapid-rise pulse on the order of tens of kV/m (up to 50 kV/m) with rise time of 2.5 nanoseconds. Principal impacts include disruption or damage of electronics.
- The intermediate time component (E2 HEMP) has an electric field pulse amplitude on the order of 0.1 kV/m and duration of 1 μsec to approximately 10 msec. E2 HEMP is similar to a nearby lightning strike where fields couple to conductors through the air. Because of the weakness of the E2 HEMP field, impacts to the bulk electric system are not expected [1].
- The late time component (E3 HEMP) is a very low-amplitude and low-frequency pulse. Amplitudes on the order of tens of mV/m (V/km) are possible with duration of one second to hundreds of seconds. The effects of E3 HEMP on the bulk power system are similar to those of a severe geomagnetic disturbance, where voltage collapse and transformer damage from additional hotspot heating are possible.

E1 HEMP is considered a unique threat to the power grid because of its large geographic footprint. The area affected is defined by the line of sight from the point of detonation out to the horizon; E1 HEMP can affect large geographic areas, but not all areas are affected equally. Figure 1, referred to as a *smile diagram*, illustrates how the incident electric field varies spatially when a notional 1-MT weapon is detonated 200 km above the central United States.

CONTENTS

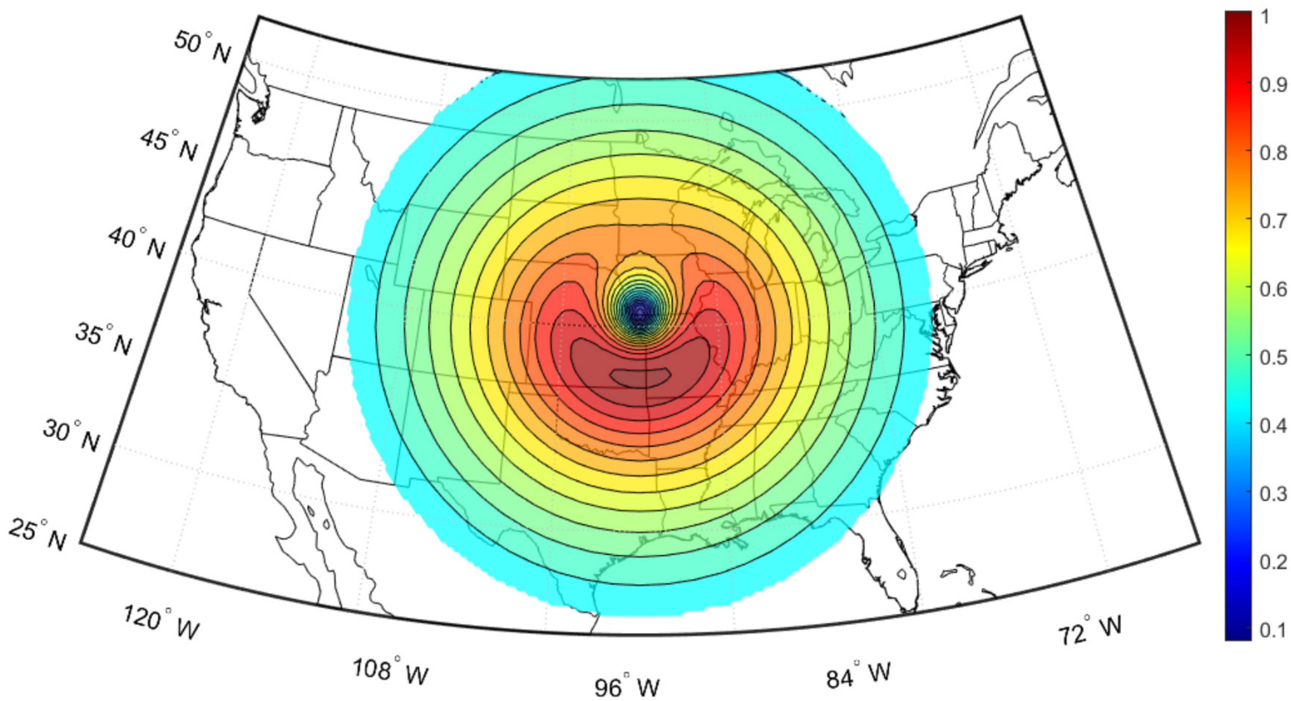

Figure 1. Example smile diagram illustrating how the peak electric field varies spatially over large areas

Another important feature of E1 HEMP is its waveshape and frequency content. Figure 2 depicts the IEC 50 kV/m E1 HEMP waveform [2] and its corresponding frequency content.

As shown in Figure 2, the IEC E1 HEMP waveform contains frequency components from direct current (dc) (0 Hz) to hundreds of MHz, with 99% of the energy contained within 10 kHz to approximately 100 MHz [2].

The incident E1 HEMP propagates to earth as a plane wave and can affect ground-based systems by directly illuminating components or systems (radiated threat) or by coupling to connected cables and generating voltage and current surges that can cause damage or disruption to connected devices (conducted threat), as illustrated in Figure 3.

On April 30, 2019, the Electric Power Research Institute (EPRI) released a final report [1] detailing the findings of a three-year research project that evaluated the impacts of HEMP on the bulk power system. The research, supported by more than 60 U.S. utilities, found that HEMP could cause damage or disruption of substation electronics, such as digital protective relays (DPRs), and that additional mitigation is needed. Several technologies and design enhancements to mitigate the observed impacts were also evaluated and tested as part of the research project. However, assessment of specific substation designs as well as testing and evaluation of E1 HEMP mitigations in actual substation environments were identified as important next steps for the electric utility industry.

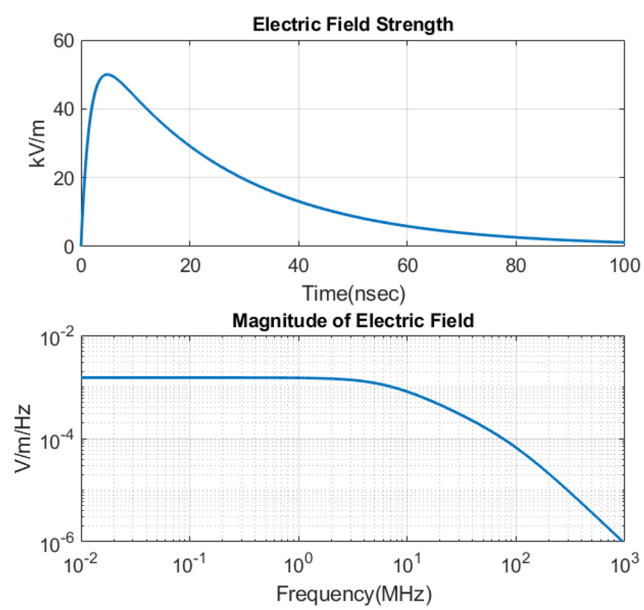

Figure 2. IEC 61000-2-9 waveform and its corresponding frequency content

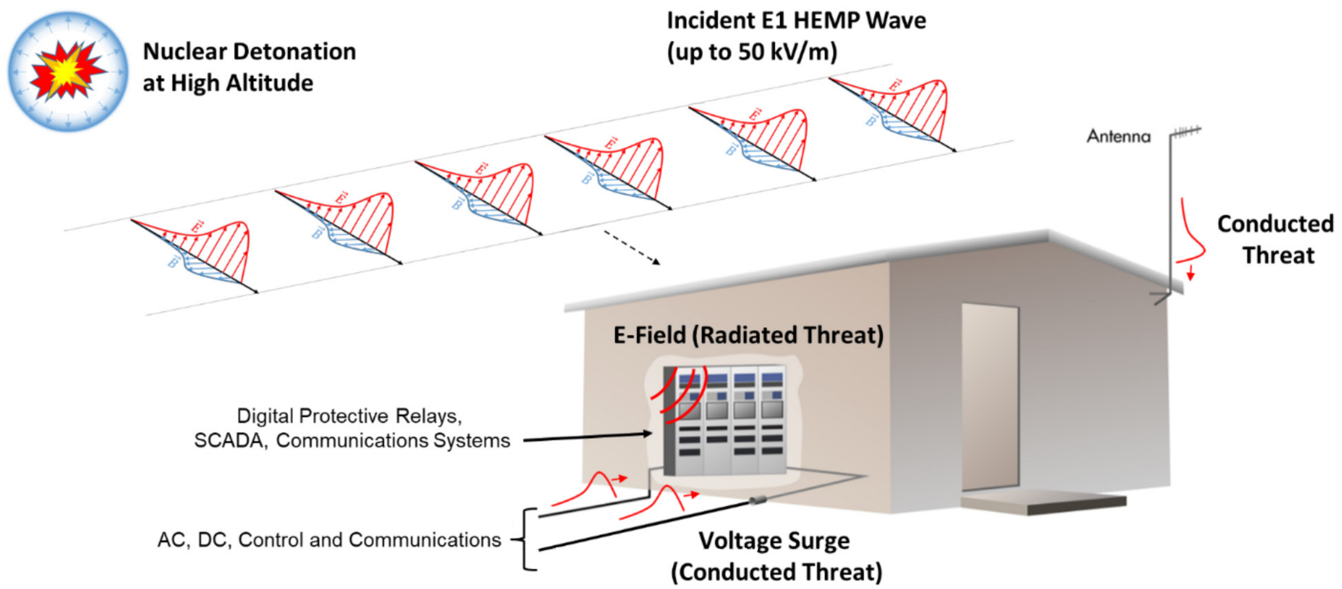

Figure 3. Illustration of the E1 HEMP threat to the electronics in a substation control building

The research also found that because of the weakness of the E2 HEMP field damage to the transmission system is not expected to occur. E3 HEMP alone was found to result in a regional blackout (multiple states), but immediate, widespread transformer damage due to hotspot heating from part-cycle saturation is not expected to occur to due to the short duration of the event. An evaluation of the combined impacts of E1 HEMP and E3 HEMP indicated that the inclusion of electronics damage from E1 HEMP could significantly degrade recovery efforts following a HEMP induced blackout. Thus, the need to improve the resiliency of substations against the effects of E1 HEMP was a key finding of the research, and led to a follow-on effort to pilot the installation of E1 HEMP mitigations in multiple substations across the United States.

SUBSTATION PILOT PROJECTS

Just prior to the release of the final report in April 2019, a project to harden substations against the effects of E1 HEMP was initiated [3]. Currently, E1 HEMP hardening pilot projects are ongoing in 19 substations across the contiguous United States. Additionally, an "observer" project began in July 2019 to provide a mechanism for sharing new information from these ongoing field trials with other utilities that are not currently installing EMP mitigations and to advance the state of the science with regard to E1 HEMP hardening and assessment [4].

The primary objectives of these follow-on research efforts are to:

- Assess the potential impacts of E1 HEMP on actual substation designs and develop design-based approaches for E1 HEMP mitigation.
- Identify potential unintended consequences with E1 HEMP hardening solutions, and develop engineering solutions to enhance reliability.
- Identify and/or develop maintenance processes and procedures for E1 HEMP mitigation designs.
- Provide realistic cost data to inform future decision-making.
- Create engineering guidance and tools for performing E1 HEMP assessments of substations and other medium-voltage and high-voltage infrastructure and guidance for developing mitigation designs.

The first step in each of the 19 pilot projects is an assessment of the specific substation design. As illustrated in Figure 4, each of the E1 HEMP assessments consists of the following:

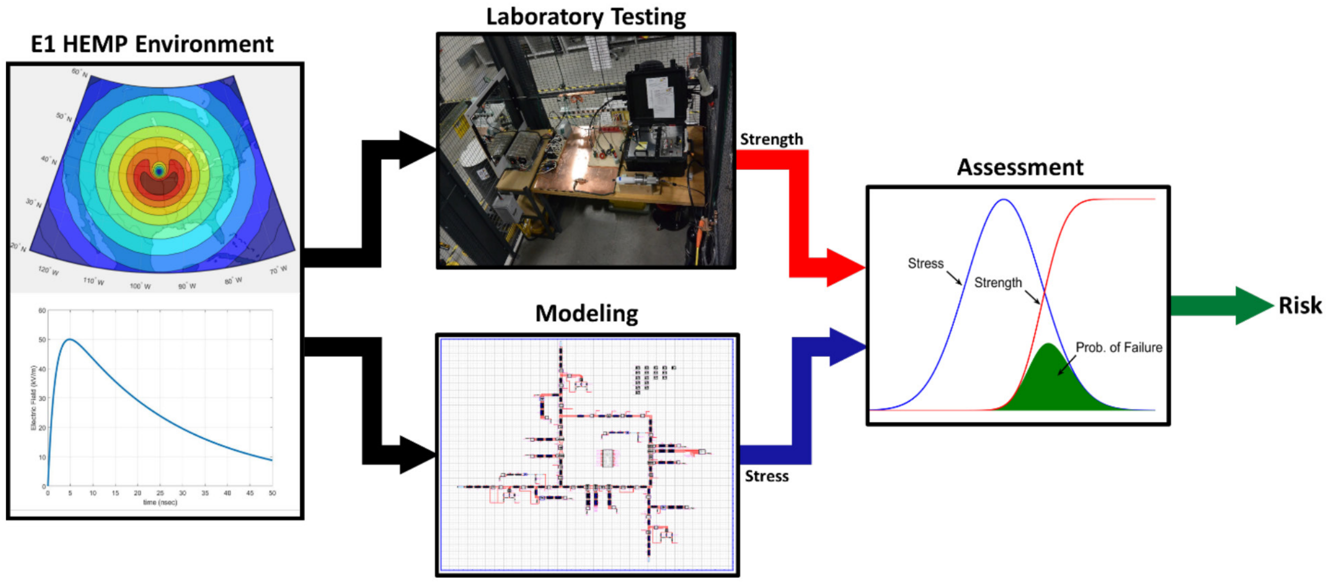

Figure 4. Workflow diagram of the E1 HEMP assessment process

- **Identification of a suitable E1 HEMP environment (E-field levels, waveform characteristics, and so on).** For these assessments, EPRI is using a combination of the IEC E1 HEMP threat environment [2] and a high-fidelity E1 HEMP environment supplied by Los Alamos National Laboratory [1]. EPRI is using 25 kV/m and 50 kV/m threat levels to provide boundaries of possible impacts.

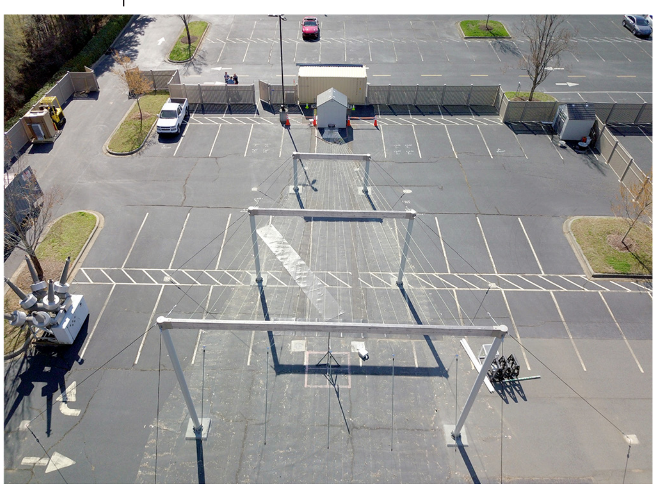

Figure 5. EPRI's outdoor MIL-STD-461G/RS105 test facility in Charlotte, North Carolina (Electronic devices, such as DPRs, are subjected to E1 HEMP pulses up to 50 kV/m to determine the level of insult that causes damage or disruption.)

- **Laboratory testing of electronic devices (DPRs, battery chargers, and so on) to determine the level of E1 HEMP insult that results in damage or disruption and shielding effectiveness testing to evaluate substation control building designs.** Testing to assess the device's resilience to conducted threats is performed using MIL-STD-188-125-1 [5] based direct injection methods. Radiated threat testing is performed using a guided wave simulator based on MIL-STD-461G/RS105 [6] (see Figure 5 for a photograph of EPRI's outdoor guided wave test facility). Also, shielding effectiveness testing of substation control buildings using an MIL-STD-188-125-1 approach is performed in the field to estimate the level of attenuated incident E-field that electronic equipment inside the control building might be exposed to during an attack.
- **Detailed modeling and simulation of the entire substation infrastructure to determine the voltage and current transients to which a given component (such as a DPR) could be exposed.** The modeling includes transmission and distribution lines, substation bus bars, instrument transformers, and control/signal cables. Coupling simulations are then performed to determine the resulting voltage and current transients that various components may be exposed to.

- **Deterministic and/or statistical approaches to assess the risk of equipment damage or disruption from the selected E1 HEMP threat environment.** This final step in the assessment involves comparing the level of electrical stress (voltage/current or E-field) as determined by modeling that the component or device could be exposed to with the strength of the equipment as determined by testing. When the stress exceeds the strength, impacts are expected to occur.

EPRI's work over the last several years has resulted in significant strides in advancing the state of the science with regard to E1 HEMP assessments. Prior studies by EPRI [1, 7] and others used generic circuit topologies of a single cable or a single overhead line to evaluate E1 HEMP impacts. EPRI's unique assessment capability now allows for the evaluation of entire substations in three dimensions [8] and includes the effects of E1 HEMP coupling to incoming transmission and distribution lines, substation bus bars, instrument transformers, control/signal cables, and DPRs. Although in the past only crude coupling approximations could be made, this robust assessment method allows detailed engineering studies to be performed, thus significantly improving the accuracy of assessments.

The results of the E1 HEMP assessment are used to determine the technology and/or design modifications that are necessary to mitigate the threat posed by E1 HEMP. In general, they include a combination of the following:

- Low-voltage surge protection devices and/or filters to protect analog inputs/outputs of DPRs and other electronic devices
- Fiberoptics-based communications and protection and control systems
- Shielded control/signal cables with cable shield grounded at each end of the cable
- Substation control house design modifications to enhance electromagnetic shielding properties
- Grounding/bonding enhancements to facilitate conduction of high-frequency signals

Once the specific mitigation options have been identified, the next step is to develop detailed engineering design packages that include equipment specifications, detailed engineering drawings, and installation guidelines.

Figure 6. The IEC 61850–based protection and control system hardened against E1 HEMP (Top: the full system deployed, which includes a shielded protection and control module in the substation control building and merging units housed in shielded enclosures inside circuit breaker control cabinets. The merging units and protective relays housed inside the shielded protection and control module are connected by fiberoptic cables. Middle: the protection and control module being tested up to 50 kV/m in EPRI's MIL-STD-461G/RS105 guided wave test facility in Charlotte. Bottom: the protection and control module deployed inside a substation control building.)

Last, laboratory and/or field testing is performed to evaluate the efficacy of the installed E1 HEMP mitigation design.

Project status varies between utilities. At the time of this update, 14 of the 19 pilot projects have completed the assessment phase and are in the E1 HEMP mitigation design phase, and 1 project, an IEC 61850–based hardening solution developed by CenterPoint Energy (Houston, Texas), is complete and currently in service [9].

The E1 HEMP hardening approach adopted by CenterPoint Energy is based on MIL-STD-188-125-1, and IEC 61000-5-10 and has been shown through extensive laboratory testing and assessment by EPRI to be resilient to both radiated and conducted threats from a 50-kV/m E1 HEMP environment [9]. An illustration of the complete system, photograph of the shielded protection and control module undergoing guided wave testing, and photograph of the final installation are shown in Figure 6.

ONGOING R&D AND NEXT STEPS

As these pilot projects continue, EPRI is advancing the state of the science with regard to E1 HEMP assessment and development of mitigation designs for substations and medium- and high-voltage infrastructure. Some of the highlights to date include developing additional E1 HEMP coupling models [8] and software tools (ECAT 3D), performing additional equipment testing to determine the response to E1 HEMP insults and evaluate mitigation options [10], and developing specific engineering guidance for improving the resilience of substations to the potential impacts of E1 HEMP [11]. Work will continue in these areas over the next 12–18 months.

EPRI began its HEMP R&D program by assessing the electric transmission system with particular emphasis on substations. However, HEMP does not discriminate, and it is well known that such an attack could affect other areas of the electric grid as well as other critical infrastructure sectors. Specific efforts underway to address these other areas include R&D to assess the potential impacts of E1 HEMP on telecommunications systems used in the bulk electric system [12]. This work began in early 2020 and will continue into 2022. Another ongoing effort in support of the U.S. Department of Energy is testing of generator instrumentation and control equipment that is critical to units used to perform system restoration—so-called *black-start units*—and assessing the power systems serving defense critical infrastructure.

Future EPRI R&D activities will include evaluating the effects of HEMP on distribution systems, end-use equipment, and additional generation technologies, including renewables.

SUMMARY

In collaboration with our member utilities and the U.S. government, EPRI is making significant progress in mitigating HEMP as a national security risk to the bulk electric system. EPRI will continue to provide periodic updates to the industry and the public as these projects progress.

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TECHNICAL CONTACT

Randy Horton, 571.312.0554, rhorton@epri.com

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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com