Estimating the Cost of Protecting the U.S. Electric Grid from Electromagnetic Pulse

Foundation for Resilient Societies

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Last Revised: September 2020

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List of Acronyms

AC	Alternating Current
CCTV	Closed Circuit Television
DC	Direct Current
DoD	Department of Defense
DOE	Department of Energy
EHV	Extra High-voltage
EMP	Electromagnetic Pulse
FERC	Federal Energy Regulatory Commission
GIC	Geomagnetically Induced Current
GMD	Geomagnetic Disturbance
GSU	Generator Step-up (transformer)
HEMP	High-altitude Electromagnetic Pulse
HILF	High Impact Low Frequency
HV	High Voltage
HVDC	High-voltage Direct Current
kV	Kilovolt
MOV	Metal Oxide Varistor
MW	Megawatts
PLC	Programmable Logic Controller
RTU	Remote Terminal Unit
SCADA	Supervisory Control and Data Acquisition
SVC	Static Var Compensators
SEL	Schweitzer Engineering Laboratories
SQL	Sequential Query Language
UPS	Uninterruptible Power Supply
VOLL	Value of Lost Load

Executive Summary

The prospective cost and benefits of protecting the U.S. electric grid from electromagnetic pulse (EMP) have been largely missing from public discourse, despite many government reports and Congressional testimonies conveying the risk America faces from both high-altitude electromagnetic pulse (HEMP) attack and geomagnetic disturbance (GMD).[*] This report provides for public policy consideration a transparent, bottom-up cost estimate of HEMP and GMD protection. Our estimates are approximate, absent previous experience in protecting electric grids from EMP on a continent-wide scale, and should be refined by further engineering and economic study.

To estimate the cost of EMP protection, we developed a database of key electric grid facilities, including generation plants, substations, and control rooms. The database allowed us to estimate counts for each facility type and components within facilities. We then estimated EMP protection costs for each facility and component based on these drivers:

- For generation plants: megawatt capacity, technology, and grid connection voltage
- For substations: high-side transformer voltage and number of circuits when available
- For control rooms: entity type (generation dispatch, transmission operator, reliability coordinator, etc.) and generation capacity or peak load controlled

Our data sources for per-facility and per-component protection costs include:

- For generation plants: construction costs for plant electrical and electronic equipment published by the U.S. Energy Information Administration (EIA)
- For substations: equipment cost surveys and interviews with industry vendors
- For control rooms: Congressional testimony and cost experience of large utilities.

To produce our EMP protection cost estimates, we relied on simple mathematical calculations. First, we multiplied the counts of facilities and components by per-unit protection costs. We then aggregated the per-facility cost estimates by state, protection type, and facility category, and then for the United States as a whole. We calculated per-capita protection costs by dividing protection costs by population statistics obtained from the U.S. Census Bureau. We calculated potential increases in electricity billings by comparing protection costs to billing data obtained from the U.S Energy Information Agency (EIA).

Key findings are:

- Our estimated cost to protect the bulk power system portion of the U.S. electric grid from HEMP pulses caused by nuclear detonations and also from GMD caused by solar storms is on the order of $25.5 billion annually, comparable to other important societal expenditures.
- The vast majority of this cost—98%—would be for E1 protection against HEMP E1 while only 2% of the costs would be for HEMP E3 protection and concurrent GMD protection.
- Among grid facilities, generation plants would be the costliest to protect, accounting for 70% of estimated costs, followed by substations accounting for an estimated 29% of costs. Control rooms would be a minor portion of the total, accounting for 1% of costs.
- On a per capita basis, EMP protection could cost $79 per year.
- As a percent of electricity billings, EMP protection could add 7% to average electricity rates.
- EMP protection could avoid trillions in lost GDP and save millions of American lives.

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[*] Throughout this report, the term “electromagnetic pulse” or “EMP” refers to both HEMP and GMD.

1. Introduction

The U.S. electric grid is the keystone infrastructure upon which all other critical infrastructures depend. Unfortunately, the U.S. electric grid is vulnerable to EMP from manmade sources as an act of war and naturally occurring GMD from solar phenomena.

Both manmade and natural EMP can damage key grid components and generate wide-area blackouts, leaving portions of the grid unrestorable for an extended period.[1] This study postulates a level of EMP protection that would enable prompt restoration of the electric grid following a HEMP or extreme GMD event. Qualitatively, the goal for our assumed level of protection is that HEMP or GMD should not cause widespread, long-lasting outages.

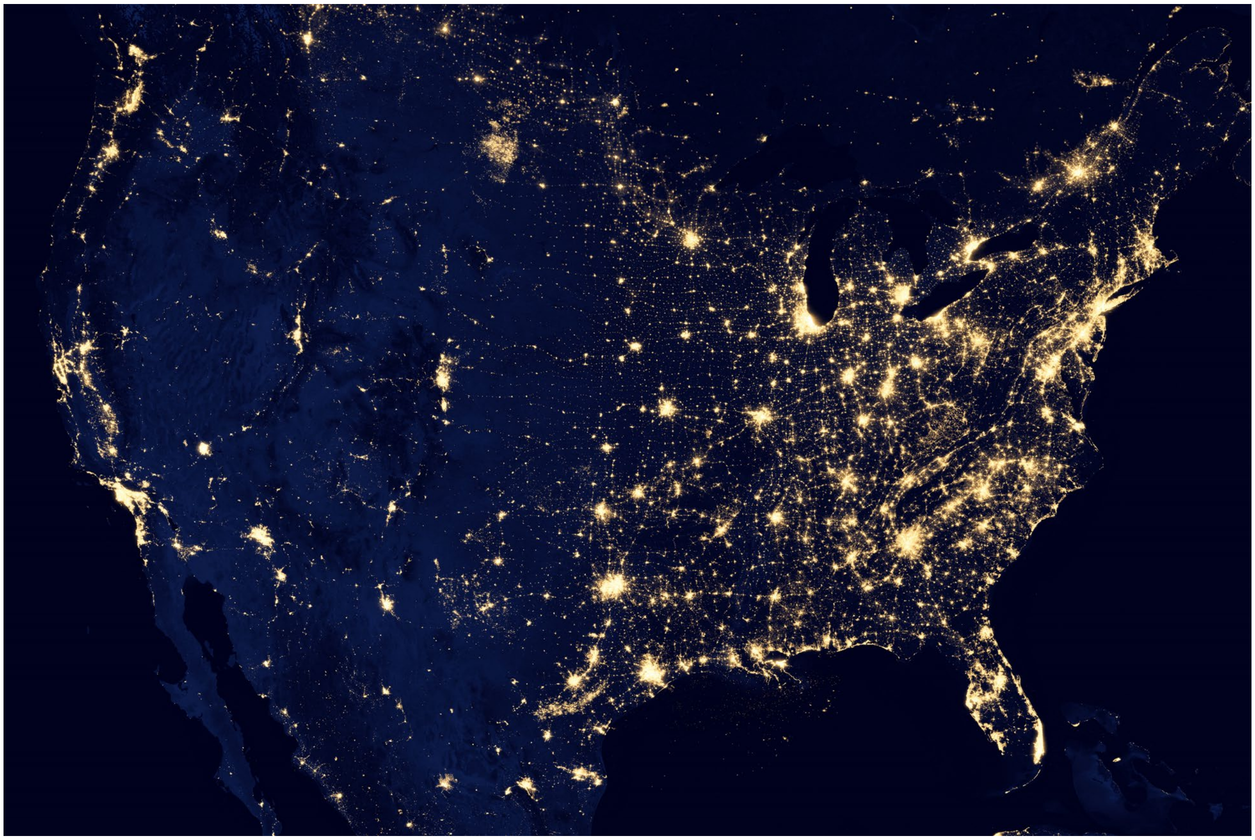

Figure 1: United States at Night. Composite image showing the extent of the U.S. electric grid—the world's largest integrated machine—by the expanse of electric lights. Few societal undertakings would match the scope and importance of protecting America's electric grid from the existential threat of EMP. Photo credit: NASA/NOAA

Serious policy debate on hardening the grid requires an assessment of both the grid's vulnerabilities and costs of protection. While the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack published several assessments of electric grid vulnerability, no rigorous and publicly available assessment of the costs of EMP protection has been produced. This report makes two significant contributions towards that end:

1) We establish a transparent methodology for estimating costs of EMP protection—determining the categories and numbers of grid facilities and components to be protected and multiplying by the per-facility or per-component cost. This framework can be iterated as understanding of vulnerabilities, protections, and protection costs improves.
2) We propose initial cost estimates for hardening the U.S. electric grid from electromagnetic threats; policymakers can use these estimates to budget for more detailed cost studies or to implement actual EMP protections.

Electromagnetic Pulse Threats

Electromagnetic pulse threats arise from intense pulses of electromagnetic radiation over a wide range of frequencies. This report is concerned with two threats that can produce wide-area effects: HEMP and GMD.

High-Altitude Electromagnetic Pulse

HEMP results from the detonation of a nuclear weapon at high-altitude (between 40 and 400 kilometers above the surface of the earth). HEMP is composed of several distinct pulses termed E1, E2, and E3. Gamma radiation from the nuclear detonation ionizes the atmosphere. Interaction of electrons released from ionization with the earth's magnetic field creates the fast acting E1 pulse. Gamma radiation, released from delayed reactions that follow the initial burst, creates the E2 pulse via a similar mechanism.[2] Finally, the explosion's deflection of the Earth's magnetic field generates the slower acting E3 pulse, also termed the magnetohydrodynamic (MHD) pulse.[3]

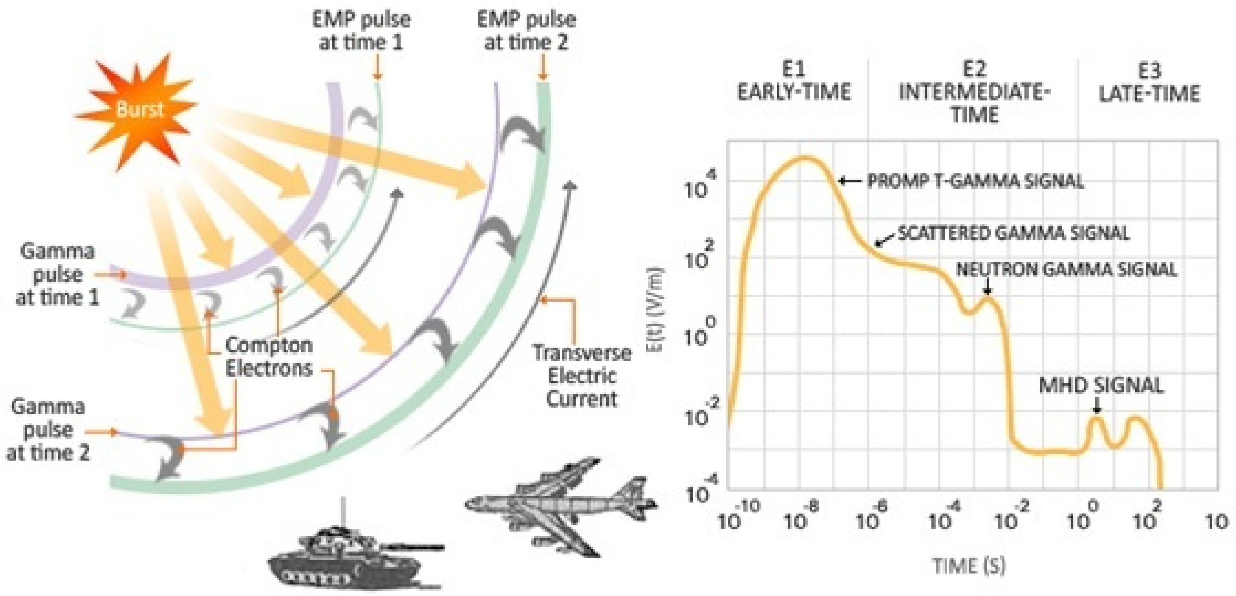

Figure 2: Production of High-altitude Electromagnetic Pulse. A nuclear weapon detonating in the upper atmosphere produces a series of electromagnetic pulses starting at approximately one pico-second after the burst and extending for several minutes. These pulses can cause failures in equipment with electrical systems, both aloft and on the ground. Photo credit: Defense Threat Reduction Agency

The E1 pulse has the greatest peak power and is particularly damaging to the microprocessors common in digital electronics, which are designed to operate at low power. The effect of the E2 pulse is similar to lightning. Much of the U.S. electric grid is already hardened against lightning; therefore, this report addresses the E2 pulse in lesser detail. The E3 pulse has a lower peak power but a longer duration, leading to a larger amount of energy deposition. The slower E3 pulse couples to very long conductors, such as overhead transmission lines, and induces a quasi-DC power flow that can damage systems designed to operate under AC conditions.[3] [4]

Atmospheric nuclear tests conducted during the Cold War era provided data on HEMP effects. In 1962, the United States conducted Operation Fishbowl, a series of high-altitude nuclear tests over the Pacific Ocean. Starfish Prime, one of the tests conducted during that operation, produced effects on the Hawaiian grid 800 miles from ground zero. The HEMP reportedly blew fuses for thirty strings of electrical street lights and tripped numerous substation circuit breakers.[2] This same year, the Soviet Union conducted its own high-altitude tests over Kazakhstan, which resulted in electrical fires and direct damage to diesel generators, electrical substations, and communication lines.[5] Since these Cold War-era tests, the grid has evolved and widely employs digital controls, which are more susceptible to malfunction and damage under E1 HEMP conditions.[6]

Geomagnetic Disturbance

Geomagnetic disturbance is caused by solar storms that deflect the Earth's magnetic field. Charged particles in coronal mass ejections warp the magnetic field, inducing electric currents in conductors on the Earth's surface. The effect of GMD is similar to the effect of the E3 component of HEMP, but typically generates a weaker electric field that persists for a longer time.[7]

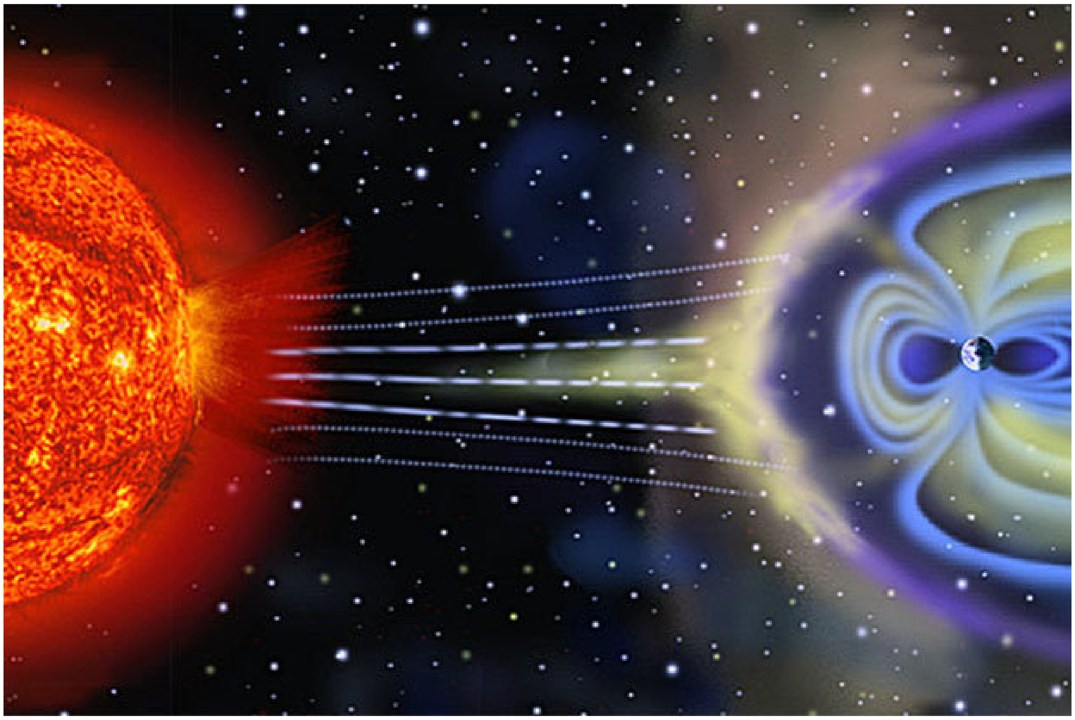

Figure 3: Coronal Mass Ejection from the Sun Causing a Geomagnetic Disturbance on Earth. Charged particles emitted from sun impinge on earth's magnetic field, causing its disturbance. As the magnetic field shifts, current is induced in long conductors on the earth's surface. Graphic credit: NASA.

The Carrington Event of 1859 provided initial experience with the effects of GMD on long conductors in telegraph lines. This intense solar storm created a visible aura borealis as far south as the Caribbean. The GMD produced by the storm created arcs in equipment, disrupted communications, and at times even permitted telegraph operation without connection to a power source. [7] [8]

The solar storm of March 1989 was less intense than the Carrington Event, but precipitated a cascading collapse of the Quebec power system and damage to extra high-voltage (EHV) transformers in the United States. Failure of the Quebec system was initiated by relays sensing effects of the GMD and tripping seven static VAR compensators (SVCs) in Canada as a protective measure. The loss of multiple SVCs over a short period created a loss of reactive power and a substantial voltage drop, ultimately leading to system collapse.[9] A generator-step up (GSU) transformer at the Salem Nuclear Power Plant was severely damaged during the storm due to overheating. Several other large GSUs failed soon after the storm, possibly because of degradation caused by the event.[7]

Current Status of EMP Threats

A long-term, wide-area power outage is an existential threat to the United States. Power grids are complex networks susceptible to cascading collapse; failure of a small percentage of components can cause partial or even complete collapse of the network. The conclusions of a power-flow study produced by the Federal Energy Regulation Commission (FERC) provide a poignant example: loss of various combinations of only nine key substations—out of a network of 55,000—could blackout the entire U.S. grid for weeks or months.[10] Both HEMP and GMD pose risks of concurrent component failures across this wide, complex network.

Geomagnetic disturbance represents a chronic risk to the U.S. electric grid. Although GMD events have caused geographically widespread outages without long-term blackouts, no modern electric grid has ever been subjected to an event as intense as the 1859 Carrington storm. A Carrington-class event could be an order of magnitude more intense than the March 1989 storm.[11] One published estimate of the probability of a Carrington class event is 10% per decade.[12]

A high-altitude EMP event over or near U.S. territory would constitute an attack on the United States. EMP is known to be part of the military strategy of other nuclear powers and nuclear aspirants. For example, official North Korean outlets have explicitly defined the ability to execute an EMP strike against the United States as a “strategic goal” of the regime’s nuclear program.[13]

Increasing EMP Vulnerabilities

After the end of the Cold War, national security policymakers shifted their focus from nuclear weapon threats, including EMP, to “peace dividends.” Simultaneously, vulnerabilities to EMP have increased dramatically throughout civilian critical infrastructures. These inadvertent vulnerabilities have been largely the byproduct of other trends, including reliance on high-speed, compact digital circuity; use of cheap, ubiquitous telecommunications (including the Internet); and long-distance transmission of electricity.

To this day, standard engineering practice for nearly all civilian infrastructures, including engineering of electric grid components, fails to consider EMP protection in equipment design and operation. The result, as the reader will see through numerous examples in this report, is pervasive vulnerability to EMP.

Use of digital controls and E1-exposed (but easily accessed and maintained) sensors, communications cabling, and power cords is preferred practice—accounting for much of the EMP problem. Long-distance electricity transmission results in power that is cheaper and cleaner but unreliable during solar storms.

The expense of EMP protection could have been greatly reduced had standards for such protection been incorporated into designs of electric grid equipment soon after the 1962 Starfish Prime test. EMP protection costs—including the cost of retrofits—will continue to escalate if equipment is not designed and manufactured for EMP resilience.

2. EMP Protection Techniques

E1 Protection

The E1 pulse induces electric fields in the 50 kV/meter regime.[†] Electrical conductors, such as cables, collect the electromagnetic energy and direct it into vulnerable components. A long cable is not requisite to produce a high-induced voltage from E1. For example, a 50 kV/meter pulse of optimum polarization exposing a 1-meter cable can induce a 50 kV potential between the ends.

While the total energy carried by the E1 pulse is low, the pulse is extremely brief and causes large power spikes, impinging on electronics that rely on sensitive, integrated circuits. The E1 pulse can destabilize semiconductor junctions, causing them to self-destruct under powered-on conditions. Moreover, the E1 pulse can cause power supplies to malfunction, feeding harmful voltages to equipment.

Devices can be shielded from E1 fields by enclosure in a three-dimensional conductive shield known as a Faraday cage. For good EMP protection, any apertures must be small relative to the wavelength of electromagnetic radiation impinging on the cage.

While Faraday cages are effective shields, the infeasibility of enclosing large systems should be readily apparent—most generation plants and substations are too big for this solution. Enclosing individual devices is more feasible but can also be problematic. Conductive cables penetrating the Faraday cage will act as funnels for the electromagnetic energy, collecting and directing it into equipment within. This issue can be mitigated by using non-conductive fiber optic cables, using shielded cables, or incorporating protective devices at points of entry into the cage (e.g., ferrite cores).

It is important to note that the E1 pulse travels at a speed that makes operational procedures ineffective for protection following a HEMP event. When a nuclear weapon detonates, the E1-induced current pulse reaches its highest amplitude in less than 10-50 nanoseconds, a small fraction of the time duration of a single cycle in a 60 Hz system. No procedural protection can be implemented in such a timeframe.

E3 and GMD protection

The E3 pulse and GMD induce lower amplitude fields than the E1 pulse but at a longer wavelength. Threat E3 waveforms extrapolated from the Soviet nuclear EMP test measurements peak at 85 V/km.[14] Threat levels for GMD can be up to 30 volts/kilometer. These pulses can act over larger areas and longer times, depositing more energy on the illuminated system. To pick up appreciable effects from long wavelength

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[†] Nuclear weapons designed specifically for EMP generation may produce higher E1 levels.

E3 and GMD, conductors typically must be miles long, such as conductors found in long-distance transmission lines.

Electric transmission lines form a conductive loop consisting of the overhead conductors, transformer windings, and conductive ground path. An electric current is induced as the E3 or GMD shifts the Earth's magnetic field through this loop. Geomagnetically induced currents (GICs) can be approximated as quasi-direct current (DC).

Geomagnetically induced current with its DC characteristics causes malfunction of grid components designed to operate in an AC environment. Issues include component overheating, induced harmonics, and malfunction of sensors designed to monitor AC signals.

Capacitors are an effective means of protecting transmission systems against E3 and GMD. Capacitors may be placed in series with transmission lines, blocking the DC current while allowing AC to pass. Alternatively, DC current passing through the neutrals of generator and substation transformers may be blocked with capacitors. Because the E3 pulse reaches its peak value seconds later than the E1 pulse, E3 protective devices could be effectively triggered by E1 using automated procedures. For GMD, there is sufficient time to switch in capacitors when the early stages of solar storms are detected by monitoring DC currents.

3. Methodology

We apply a bottom-up methodology to estimate the cost of protecting generation and transmission facilities and their control systems. Broadly, the approach is to multiply the unit costs of EMP protection by the number of facilities or components and sum the results. Where unit costs for protection are not available, replacement costs are used instead.

Section 5 of this report summarizes the expected vulnerabilities of each facility or component based on literature reviews and interviews with experts. Section 6 proposes protection mechanisms for the vulnerabilities summarized in the preceding section and estimates cost of implementation. Section 7 examines testing for EMP protection. Section 8 counts and characterizes the facilities or components. Section 9 calculates our initial estimates of HEMP and GMD protection and examines cost factors and policy implications. Section 10 discusses the societal benefits for protecting against HEMP and GMD. Section 11 presents key conclusions from the report. Section 12 briefly summarizes opportunities for future work.

The EMP protection costs estimated in this report are intended to be the first in an iterative process. The Foundation for Resilient Societies invites comments and suggestions to improve vulnerability assessments, EMP protection strategies, counts of facilities and their components, and per-unit protection costs. Ultimately, no major electric grid has been comprehensively protected against EMP; therefore, any cost estimates for protection are necessarily approximate.

Grid Assets Covered

To assure electric grid restoration, multiple classes of assets would require prioritized EMP protections, including electric generation plants, transmission systems, control rooms, and the communication systems that coordinate these systems. We assume protection of electric grid assets operating at a voltage of 100kV or above, which is defined under federal regulatory standards as the "bulk power system." To gain size efficiencies for protecting generation stations, we assume protection only for dispatchable generators with at least 100MW capacity. Likewise, we assume protection for control rooms dispatching at least 100MW of total capacity. Hydro plants with at least 10MW capacity are also protected in our methodology, since they are cheaper to protect than other generation resources and are important for black start.

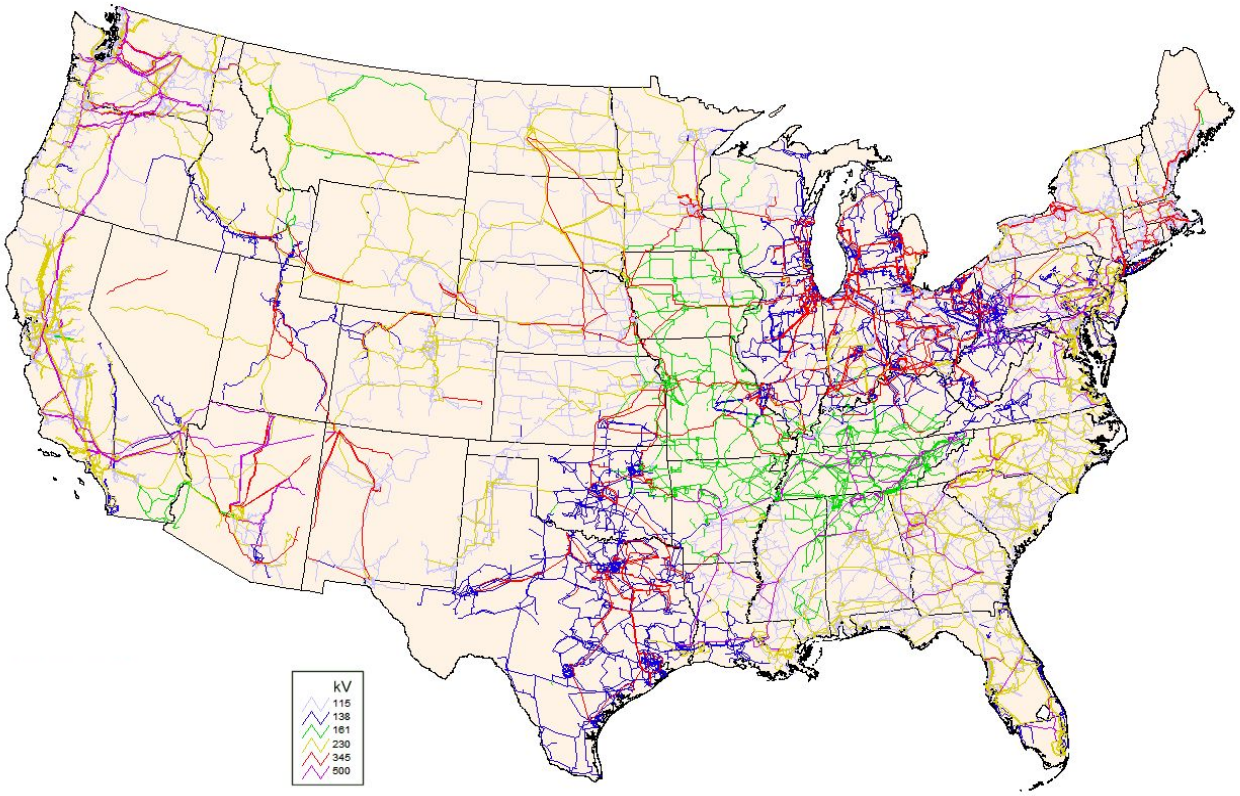

Figure 4: United States Bulk Power System. America's electric grid uses transmission lines in the bulk power system to transport energy from generation plants often located long distances from local consumers. Varying voltage levels are employed. Graphic credit: Federal Emergency Management Agency

This study does not address EMP protection for wind, solar thermal, solar photovoltaic generation technologies because they are non-dispatchable during grid restoration if weather conditions are not supportive. However, renewable energy will positively contribute to the energy balance of the grid and could delay depletion of fuel reserves after an EMP event. Protecting renewable technologies from EMP deserves future technical and economic study.

We do not examine the cost of protecting local distribution systems at voltages less than 100 kV, nor do we examine the vulnerability of customer loads to EMP. Partial failures in local distribution systems and on customer premises are less likely to cause wide-area, long-term electric grid collapse. Moreover, failure in local distribution systems should not prevent restoration of the bulk power system. Nonetheless, long-lasting outages of these systems could degrade societal functioning and cause loss of life.

Costing Approaches

This study applies two approaches in estimating the per-unit costs of EMP protection. The direct approach estimates unit costs directly, describing the strategy to be applied and estimating the material and installation costs of each protective device. When this approach cannot be used, we estimate protection costs indirectly from the replacement costs of protected assets.

Using the direct approach, we estimate unit costs for the transmission system and for control rooms. Material and installation costs may be tied to a cost driver that accounts for scaling (e.g., the cost of a higher voltage protective device or a larger Faraday cage). Where applicable, estimation of unit costs draws on U.S. Department of Defense (DoD) experience with EMP hardening. However, while the DoD has protected certain electronic systems against HEMP, its protection techniques and costs are not always applicable to the electric power systems and components.

We use the replacement cost approach for generation facilities. This cost estimation technique, while crudely approximate, is necessary due to the current lack of both engineering studies and experience in protecting generation plants against EMP. This method could result in an overestimation of costs when control systems can be easily enclosed in small EMP-shielded barriers. It could also result in an underestimation of costs when integrating EMP protection into non-electrical components of an overall system is difficult.

4. Electric Grid Vulnerability to EMP

A necessary first step in assessing the cost of comprehensive EMP protection for the U.S. electric grid is a determination of which grid components are susceptible to damage or upset by EMP environments and, therefore, require protection. Alternatively, certain grid components may be inherently resilient to EMP and, therefore, protection costs are likely negligible. For example, transmission system pylons are unlikely to be directly damaged by EMP. In contrast, equipment using unshielded integrated circuitry is likely to be highly vulnerable to EMP.

Because of a lack of controlled experiments on components within an operational electric grid, the degree of component vulnerability in many cases requires more study, including hardware testing. Testing will also be needed to confirm EMP protections. Since conducting controlled experiments on operating power systems is risky and often infeasible, other methods can be used to assess component vulnerability. This report draws on several methods; each is imperfect but has merit:

- Historical cases
- Physical experiments of components in isolation
- Mathematical models, analysis, and simulations
- Expert judgement

The historical cases:

- 1962 American and Soviet high-altitude nuclear weapons tests provide limited experience on the reaction of operational, interconnected electrical grids to the actual threat environment. Of importance for HEMP is the exposure of an operating electrical system to E1, E2, and E3 threats in succession.

- A moderate solar storm In March 1989 caused a cascading blackout for the province of Quebec, Canada.
- Smaller solar storms in 2003 caused tripping of the Phase II High-voltage Direct Current (HVDC) transmission line from Quebec to Ayer, Massachusetts.

The U.S. electric grid has evolved substantially since these prior EMP events. Digitization has increased vulnerability to HEMP E1.[6] More long-distance transmission lines have increased vulnerability to both the HEMP E3 pulse and GMD.

Physical EMP experiments are typically conducted on components in isolation or on small test systems. The threat environment is an artificially induced electromagnetic field or pulse current injection. These experiments allow replicability and a degree of control, but rely on accurate assumptions of the threat environment. EMP experiments cannot be safely conducted on an operational, interconnected grid and, in the case of HEMP, cannot replicate the rapid E1, E2, E3 sequence. Additionally, physical tests on expensive grid components have been limited; testing at high threat levels is likely to be destructive and increases the cost of testing. This complication is especially true for generators and high-voltage transformers that cost millions of dollars per unit.

Mathematical models and simulations should be based on empirical failure data from historical cases and physical tests conducted on a smaller scale. Some models may attempt to account for the interdependencies of an operational grid. Models, however, are only as good as the assumptions upon which they are built. Validating these assumptions is particularly difficult for the complex system-of-systems that is the electric grid. Without empirical test data on system failures, analytical uncertainties inherent in EMP effects models can be orders of magnitude.[15]

Expert judgement is the synthesis of a career of experience and analysis in grid operation and electromagnetic protection and its extrapolation to new situations. While able to produce flexible insights, the conclusions from expert judgement are not transparently derived.

The vulnerability assessments presented here are our best synthesis of the existing literature and interviews with subject matter experts. Significant uncertainties in component vulnerability to HEMP and GMD remain in many instances due to the lack of test data. Cost estimates for EMP protection should be updated when more test data is available.

Overview of Grid Components

The U. S. electric grid is a meshed network of generating stations with step up transformers, high-voltage transmission lines, substations with step-down transformers, and distribution lines used to supply power to consumers. Control rooms and communications systems coordinate the flow of electricity. All these electric grid components may be vulnerable to EMP.

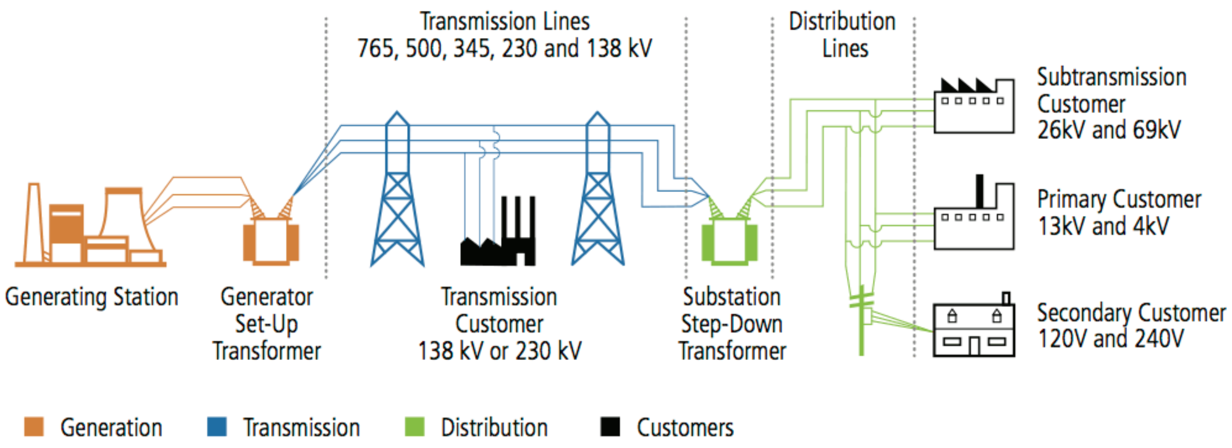

Figure 5: Electric Grid Generation, Transmission, Distribution, and Customers. Electricity is produced at generating stations, stepped up to high voltage for transmission, and then stepped down for distribution to homes and businesses. Generation and transmission assets supporting the high-voltage portions of the electric grid have the highest priority for EMP protections, because failures here can cause cascading collapse and prevent system restoration. Graphic credit: U.S. Department of Energy.

Generating Stations

Generating systems are essential to the electric grid and, therefore, their protection against EMP is of prime importance. Vulnerability to HEMP and GMD is expected to vary widely by generation technology. In this report we briefly address engineering challenges in protecting major categories of generation from EMP. More accurate cost estimates will require comprehensive engineering studies for each generation technology.

Technologies

In the United States, thermal generating stations supply baseload power. Technologies for thermal generating stations include natural gas, coal, oil-fired, and nuclear. These large facilities convert chemical or nuclear energy stored in fuel into heat that is deposited into a working fluid. This fluid is then used to drive a turbine-generator to convert heat into electricity. Roughly 80% of U.S. power generation comes from thermal power plants.

The share of renewable generation is growing due to concerns about climate change. Renewable technologies include hydroelectric, biomass, geothermal, wind, solar thermal, and solar photovoltaic. Hydroelectric generation relies on the gravitational potential of energy stored in water to drive a turbine-generator and is most common in the western watershed of the Rocky Mountains, California, and the Pacific Northwest. Biomass is important in locales with forest harvesting, such as in Maine and the southeast Atlantic Seaboard. Geothermal is used in the western portion of the United States. Wind and solar generation are currently small contributors to the U.S. generation mix but are growing in importance.

Natural Gas-Fired

Natural gas-fired plants tend to be recently constructed and almost always employ digital control systems vulnerable to the E1 pulse. Additionally, natural gas-fired plants do not have fuel stored on-site, but depend on pipelines with digital controls and, increasingly, electric-drive compressors. While the issue of EMP protection for fuel supplies is beyond the scope of this report, it should be a priority for future study.

Figure 6: Natural Gas-Fired Generation Plant. Photo shows a natural gas-fired generation plant with modular design. Use of open cable troughs (center) leaves control systems potentially vulnerable to the E1 pulse. Photo credit: Wikimedia Commons/Pro-Per Energy Services

Coal-Fired

Coal-fired plants are commonly large, enclosed structures with complex fuel systems for coal transport and pulverization. Many coal-fired plants originally built with analog controls resilient to the E1 pulse, have been retrofitted with vulnerable, digital controls. EPA-mandated emissions controls add another level of complexity and E1 vulnerability. However, coal-fired plants typically have 30-90 days of fuel stored on-site, a distinct advantage after disruptive EMP events.

Figure 7: Coal-Fired Generation Plant Complex. The John P. Madgett Station (left) and Alma Station (center, now decommissioned) in Wisconsin are coal-fired generation plants. The EMP vulnerability of coal-fired plants with complex fuel handling systems from the coal pile (center) to the furnaces near the smokestacks needs engineering study. Photo credit: Wikipedia/USGS.

Oil-Fired

Oil-fired plants have a range of sizes and combustion technologies, including steam turbine, combustion turbine, and internal combustion. These plants were typically built when oil was more cost-effective than natural gas and now near the end of their operational lives. Original designs included analog control systems less vulnerable to the E1 pulse, but updates can use digital controls. Larger oil-fired plants often have adjacent tank farms that store several weeks of fuel—an advantage after EMP events that may disrupt supply chains.

Figure 8: Oil-Fired Generation Plant. Wyman Station in Yarmouth, Maine is an 810 megawatt oil-fired generation plant. This plant was originally built in 1957-58 and has been updated several times with Unit 4, its largest unit, beginning operation in 1978. Pollution controls were installed in the early 2000s. EMP protection for pollution controls needs engineering study. Photo credit: Wikimedia Commons/NewTestLeper79

Nuclear

Nuclear power plants typically are enclosed in reinforced concrete structures that provide some degree of E1 shielding. Nonetheless, conductor penetrations into plants pose problems, because they introduce E1 transients to internal spaces and equipment. Also, the large power capacities of the plants and common use of single-phase GSU transformers make them vulnerable to the E3 pulse and GMD. Nuclear power plants have several years of fuel stored in the reactor core, a key resilience characteristic after EMP events. However, under Nuclear Regulatory Commission regulations, nuclear plants must be shut down when the bulk power system becomes unstable.

Figure 9: Nuclear Power Plant. Seabrook Station, New Hampshire is in a region susceptible to GIC during solar storms. The plant's 1,244 megawatt output requires use of single-phase GSUs. During a November 10, 1998 solar storm, vibrations induced by GIC caused a four-inch bolt to shake loose in the Phase "A" transformer. Subsequent melting caused loss of the transformer and several weeks of downtime. Photo credit: Creative Commons/Jim Richmond

Hydroelectric

Hydroelectric plants have simple electrical designs compared to other technologies. When most large hydroelectric plants were built in the first half of the 20th century, analog control systems were the norm. Analog controls are less vulnerable to the E1 pulse, especially when mechanical relays are used exclusively. While many hydroelectric plants have upgraded to digital control systems, some retain their original analog controls as a backup. Because the energy source for hydroelectric plants is water stored in a reservoir, their fuel supplies are resilient to disruption from EMP events.

Figure 10: Generator Hall at Grand Coulee Hydroelectric Dam. This photo of the Grand Coulee generator hall shows the original analog control panels to the left of the row of generators. Analog controls can still be used to run this plant. Instructions are communicated to manual operators by means of telephones on the control panels. This extremely simple system may continue to function following a HEMP attack. Photo credit: Creative Commons/Linda Moving Ahead.

Biomass

Biomass plants share basic engineering principles with other large thermal generators using combustion and, therefore, should have similar EMP vulnerabilities. Because most biomass plants are of recent construction, they have digital controls vulnerable to the E1 pulse.

Figure 11: Biomass Generation Plant. The 20 MW Savannah River Site Biomass Cogeneration Facility in South Carolina replaced a coal-fired plant. This plant burns forest residue. Note the complex fuel handling system in the foreground, which may be vulnerable to the E1 pulse. Photo credit: U.S. Department of Energy.

Geothermal

Geothermal plants commonly use wells to extract steam from underground heat sources to power turbine generators. Effective use of geothermal energy requires a system of pipes, sensors, and valve actuators. The digital control systems used at geothermal plants of recent vintage will be vulnerable to the E1 pulse.

Figure 12: Control Equipment at Geothermal Plant. This photo shows pipes and control equipment at the Steamboat Springs geothermal generation plant south of Reno, Nevada. Note the exposed sensor and actuator wiring that may conduct the E1 pulse into the green control cabinet. Buried wiring ducts exiting the control cabinet (bottom left) may also expose plant-level communications to the E1 pulse. Photo credit: Creative Commons/Rjglewis

EMP Vulnerabilities at Generating Stations

Overall, there is a lack of experimental data on EMP vulnerability of generating stations.[22] In general, we would expect large generating units to be vulnerable given reliance on digital control electronics. Sensing devices, actuators, and motors are commonly connected to central control rooms by long lengths of unshielded cable. Reliance on microprocessor-based components increases E1 vulnerabilities.[6]

Figure 13: Dual-Fuel Generation Plant. The Ravenswood dual-fueled generation plant (natural gas and oil) supplies power to New York City. Massive structures such as this will be very challenging to protect against EMP. Photo credit: Creative Commons/Rhododendrites

Some generating station technologies may be less vulnerable to EMP. Idaho National Labs claims that nuclear power plants may have resilience to EMP, though it does not expound on this claim.[22] Hydroelectric generators, less reliant on complex controls and employing older vintage equipment, are expected to have lower E1 vulnerability than fossil fuel generators. Fossil fuel generation, while potentially costlier to protect than hydroelectric or nuclear generation, is an important component of an EMP protection strategy due to its ubiquity and dispatchability.

Generator Step-Up Transformers

Generator step-up (GSU) transformers are large power transformers designed to increase voltage from the level produced by a power plant's generator to transmission levels. For large baseload generators, GSUs are typically single-phase, full transformers operated at a high load factor. The primary E3 and GMD threat to power plants is expected to be the GSU transformers and associated high-voltage equipment in the adjacent switchyard.[18]

Figure 14: Generator Step-Up Transformers at Arizona-Nevada Switchyard for Hoover Dam. Single-phase generator step-up transformers raise voltage for long-distance transmission. During HEMP and GMD events, the transmission lines from Los Angeles to the switchyard can conduct geomagnetically induced currents into the windings of the transformers, causing overheating and harmonics. Without use of neutral ground blocking devices, harmonics can also be conducted into the dam's massive generators, causing vibrations and heating. Photo credit. Wikimedia Commons/Deborah Dobson-Brown.

E1 Vulnerability

As with other large power transformers, some GSU vulnerability to E1 is expected, but is presently uncertain due to lack of test data. A large concern is failure of low-voltage components used for active cooling of the transformer; another concern is winding insulation failure during the E1 pulse.

E3 and GMD Vulnerability

GSUs are expected to be at risk of oversaturation from E3 and GMD, given the prevalence of high load factors and single-phase configurations at generating plants. These transformers are designed with low winding resistance and are located within extra high-voltage (EHV) grid with long, low resistance conductors, causing them to carry the highest GIC. [18]

In the event of catastrophic failure, fire at GSU transformers could ignite the oil coolant, in this case leading to widespread damage to the generation plant beyond the GSU.[3] Alternatively, if the transformer continues to operate during oversaturation, resulting harmonics could also damage the connected generator.

During the 1989 solar storms, thermal damage occurred to multiple, single-phase GSU transformers at the Salem nuclear plant. The U.S. Nuclear Regulatory Commission (NRC) reported that the damage sustained by the transformer occurred after just a few minutes of GIC exposure.[11 18]

Generators

Generators are large electro-mechanical rotating machines that convert mechanical energy into electrical energy. In thermal plants, a heated working fluid is expanded through a turbine causing the turbine to rotate. This rotation is transferred to the generator along a shaft. The generator, itself, is comprised of conductive coils within a magnetic field. Rotation of the coils within the magnetic field induces an electric current in the windings via Faraday's law. Low-voltage buses connected to generator windings conduct current to GSU transformers, where voltage is increased to transmission levels.

E1 Vulnerability

While windings of the generators may conduct the E1 pulse, generator stators, rotors, and frames are built to be robust and may not sustain damage. However, damage or upset to a generator's control electronics from E1 is likely. Future engineering study of generator vulnerability to E1 is needed.

E3 and GMD Vulnerability

Generators are protected from direct exposure to GIC by use of delta-wye transformer connection employed in GSUs. Harmonics caused by GIC in transformers, however, can create overheating and vibrations in generators. Mechanical vibrations could reduce generator life, but are unlikely to cause immediate failure.[3 11 21]

Figure 15: Generator Driven by Steam Turbine. Steam turbine (foreground) drives the electric generator (background). Generators can be vulnerable to overheating and vibration from harmonics caused by the E3 pulse and GMD. Photo credit: Wikipedia/ Siemens Pressebild

Control Systems

Generating stations use Supervisory Control and Data Acquisition (SCADA) and programmable logic controllers (PLCs) extensively to enable plant automation, centralized monitoring, and control. Plant SCADA systems are wired by either fiber or copper cabling.

E1 Vulnerability

For cabling in generating stations, induced voltages may be as high as 70kV in a small proportion of cables.[4]

Power plants use PLCs extensively. These are particularly susceptible to upset and damage from E1 and can fail at relatively low levels of E1-inducted current. Generating station PLCs appear to be more vulnerable than relays used in transmission substations, as PLCs are not designed with the same degree of electromagnetic protections due to the lower voltage environment.

Figure 16: Control System Cabling for Combined Cycle Power Plant. Combined cycle power plants often have open-air designs with exposed control system cables running in open troughs between plant components and buildings. Note the exposed cable troughs at the center of this photo taken at a gas-fired generation plant. Photo credit: Foundation for Resilient Societies

E3 and GMD Vulnerability

Since the conductors associated with generating station controls and embedded systems are short relative to the E3/GMD wavelength, these systems are not expected to be directly vulnerable to E3 or GMD. Uninterruptible power supplies for generating station controls are known to be susceptible to upset and damage from E3/GMD harmonics.

Transmission Lines

Transmission towers and conductors are expected to be resilient to EMP. However, during 1962 Soviet EMP tests over Kazakhstan, transmission line insulators experienced flashover from the E1 pulse, causing the lines to fall to the ground. It is not known if modern insulators have this same vulnerability. Engineering study of insulator EMP vulnerability is needed.

Figure 17: Transmission Tower, Insulators, and Lines. A common method of constructing high-voltage transmission lines is to use steel towers that support aluminum conductors. Ceramic insulators isolate the conductors from the towers. During the E1 pulse, an electrical arc may be established over the ceramic insulators to electrical ground, persisting after the pulse ends and causing catastrophic insulator failure. Vulnerability of modern insulators needs engineering study. Photo credit: Pixabay.

Substations

Substations, where power flow is controlled and often reduced in voltage, are the intermediate nodes of the transmission network. Design and configuration of substations vary widely. Equipment at substations commonly includes step-down transformers to reduce voltage, circuit breakers to interrupt and reroute power, instrumentation devices to sense power flow, relays to control circuit breakers and protect transformers from overload, and SCADA devices to permit remote operation. Substation communication, data processing, and control devices are often enclosed within small, on-site buildings— "control houses" or "control huts." Some substations have voltage support devices such as capacitors, reactors, and SVCs.

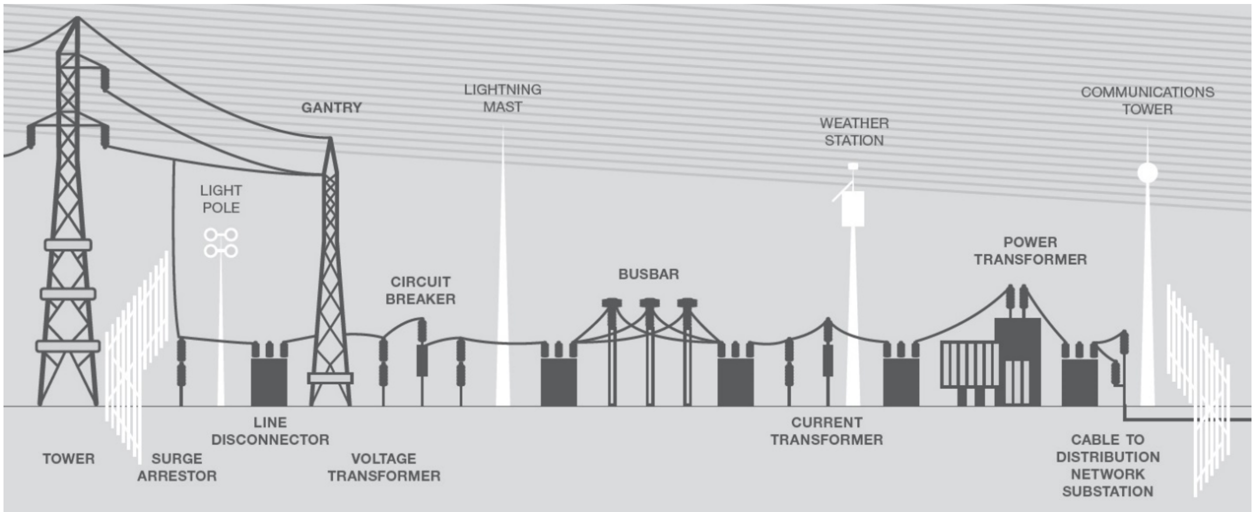

Figure 18: Power Flow through Notional Substation. When high-voltage power enters a substation, it is controlled by line disconnectors and circuit breakers, routed by busbars, sensed by current transformers, and stepped down by power transformers before exiting to distribution networks. Graphic credit: ElectraNet

Figure 19: Bulk Power System Substation. Substations for the bulk power system transform high voltage electricity into lower voltages for homes and businesses. Circuit breakers at the left section of substation control power flow into high voltage transformers at the right. Communications for the substation are carried by microwave radio dishes on the tower at the rear. Open-air designs such as this expose substation components to the E1 pulse from HEMP. Photo credit: Creative Commons/vaxomatic

Substations can be small, with only a single set of circuit breakers and transformers. However, long-distance electricity transmission for the bulk power system often requires large substations with dozens of components arrayed over an acre or more of land. Substations are commonly an open-air design, although entire substations in urban areas may be enclosed in buildings.

Power Transformers

Step-down power transformers located at transmission substations decrease voltage from transmission levels to distribution levels.

Figure 20: Substation Power Transformer. Three-phase substation power transformer steps down electricity voltage for local distribution system. Note the connected circuit breaker with swinging control housing doors near transformer. The control circuits for both transformers and circuit breakers are likely to be vulnerable to the E1 pulse from HEMP. Photo credit: First Energy.

Although highly efficient, transformers generate significant amounts of heat from losses inside the transformers. The E3 pulse and GIC from GMD change flux distribution within transformers, increasing losses. Even relatively brief periods of overheating can damage a transformer's internal windings and insulation.[11]

Replacing large power transformers is a lengthy and logistically challenging task. Typical replacement lead times range from one to three years under normal conditions in part because these transformers are usually custom designed. Most large power transformers now used in the United States are produced abroad. Domestic supply has been increasing in recent years but faces supply chain bottlenecks. For example, high-grade electrical steel, one of the primary material components of a transformer, has only a single domestic producer. Transportation of a transmission-scale transformer to the substation is, itself, a challenge; it can weigh up to 400 tons and requires specialized rail cars or vehicles to move.[9] [16]

HEMP and GMD-induced currents can cause transformers to overheat, leading to degradation and potentially to immediate failure, especially should the electric grid and transformer remain online long enough for damage to occur. Assessing the risk of immediate damage to transformers during a HEMP or GMD event will require additional engineering study.

During HEMP and GMD events, transformers produce harmonics and increase reactive power consumption, which can cause grid collapse from relay tripping and low voltage. A HEMP or GMD event can damage transformers indirectly through overload conditions experienced during an uncontrolled grid collapse.

E1 Vulnerability

Published data on the vulnerability of large power transformers in E1 environments is sparse. However, some researchers assert that transmission transformers can withstand the E1 pulse without damage, since the transformer is a passive device without microelectronics and designed to operate at high-voltages[17] The Congressional EMP Commission, however, warned that E1-induced arcing might damage insulation for internal transformer windings.

Of greater concern for E1 vulnerability are the low-voltage sensor and control lines connected to transformers.[4] A loss of proper relaying could leave transformers vulnerable to damage subsequent to the E1 pulse, such as the following E3 pulse. The electronics for relay systems are typically located within the substation control house and can, therefore, be protected separately from the transformer, itself.

Figure 21: Cooling Components for Power Transformer. Power transformers commonly have oil pumps, radiators, and cooling fans. The exposed electrical wiring for these fans will conduct the E1 pulse into control circuitry for the transformer. Photo Credit: T&D World

Cooling equipment for power transformers is controlled by microprocessors vulnerable to E1 damage. Without active cooling, the transformer would be unable to operate at design capacity. With properly functioning sensors and relays, damage to cooling controls may not cause transformer damage but could impede grid recovery by constraining transmission capacity.

Transformer monitoring systems are becoming increasingly common. These systems monitor temperature, pressure, and gas bubble generation in the cooling oil. For some transformers, GIC can also be monitored. The digital circuitry for monitoring systems can be vulnerable to the E1 pulse from HEMP. At generation plants, alarm signals from transformer sensors may be used to shut down generators during HEMP and GMD events.

Figure 22: Transformer Monitoring System. Transformer monitoring systems collect and analyze data, presenting alarms when abnormal conditions are detected. While data from these monitoring systems would be extremely useful during a HEMP or GMD event, the copper wiring used for sensor cables can conduct the E1 pulse into monitoring system cabinets. Photo credit: GE Digital Energy

E3 Vulnerability

Published literature and test data is lacking on high-voltage (HV) and EHV transformer vulnerability to the E3 pulse from HEMP. Significant experience does exist for transformer operation in the similar GMD environment, though some differences between the threats are pertinent. From GMD experience, it is known that GIC, common to both the GMD and E3 pulses, can cause transformer overheating and vibration. E3 also causes transformers to produce harmonics and increase reactive power consumption. Harmonics further contribute to heating and can adversely affect other components of the grid, possibly leading to cascading collapse. Increasing reactive power consumption leads to voltage drops and decreases availability of active power, which can also collapse the grid.

The E3 pulse induces currents up to hundreds or thousands of amps in long power lines for between ten seconds and four minutes.[17] This low-frequency GIC appears as a quasi-DC bias compared to the typical 60 Hz power flow. The transmission lines conduct this GIC to transformers. If the quasi-DC bias combined with the existing power flow is sufficiently high, the transformer will experience half-cycle saturation, leading to bulk and localized overheating, production of harmonics, and an increase in reactive power consumption.[18]

The effects of overheating from the E3 pulse are cumulative and will degrade transformer life, but there is dispute on whether large numbers of transformers will immediately fail. According to an Electric Power Research Institute (EPRI) report that relied on mathematical simulations and non-destructive testing of only two transformers, the brevity of the E3 pulse may limit internal heating.[17] Other analysis suggests saturation quickly follows GIC injection and debilitating damage from internal heating can occur on E3 time scales.[3] [11] [19]

Production of harmonics from the E3 pulse could lead to transformer relay misoperation and protective tripping of transformers and generators.[3] Given the wide-area effects of E3 and GMD, the near simultaneous tripping of many transformers could precipitate a system collapse that would expose transformers remaining online to damaging overvoltages. Harmonics also contribute to transformer overheating[9] and can damage other grid components, such as devices to support reactive power.

Heightened reactive power consumption by transformers reduces real power, potentially leading to an unstable grid and a damaging, cascading collapse. For a given level of GIC, single-phase transformers and high-voltage transformers experience a greater increase in reactive power consumption than similar transformers of three-phase configuration or lower voltage.[3]

Because transformer damage occurs via oversaturation, vulnerability is dependent on the transmission system loading at the time of the event. Transformers operating closer to design capacity are at greater risk. Transformers on higher voltage lines with lower resistance and in single-phase configurations are also more susceptible to damage.[8] These effects combine to make GSU transformers for large, baseload power plants particularly susceptible. GSU transformers typically operate continually near design capacity, connect to high-voltage lines, and are often single-phase due to the difficulty of manufacturing and moving three-phase transformers of this size.

Step-down transformers typically found in substation nodes are less likely to be operating near design capacity at any given time. These transformers must be sized to accommodate peak electrical demand, but typically are loaded at less than 50% of capacity. The automatic disconnection of some transformers from the grid following the E1 and E2 pulses, however, would result in more power being rerouted through remaining transformers, increasing their vulnerability. While GSU transformers are generally more vulnerable, the autotransformer design used for many substation step-down transformers has tertiary windings vulnerable to localized overheating.[17]

GMD Vulnerability

GMD affects transformers similarly to the E3 pulse. As with E3 pulse, the potential for bulk and localized heating arises from transformer oversaturation. GMD events have lower intensity but longer duration than E3. As a result, GMD allows more time for heat to build up in transformer components.

The solar storm of March 1989 clearly illustrated the vulnerabilities of transformers to GMD. Across the Hydro-Quebec grid, harmonics from oversaturated transformers caused multiple SVCs to trip. This loss of reactive power supply, combined with the increased reactive power draw from saturated transformers, led to a cascading collapse. Overvoltage conditions created by the uncontrolled collapse damaged two GSU transformers at the La Grande 4 hydro plant.[20]

Figure 23: Failure of Salem Nuclear Plant GSU Transformer. Pictured below is one of the three single-phase transformers at the Salem Unit 1 nuclear plant. This transformer failed shortly after the March 13, 1989 solar storm. Geomagnetically-induced currents in transmission lines conducted into the transformer windings, causing saturation and overheating. Forensic examination showed charred insulation and melted windings. Photo credit: PSE&G.

No transformers failed during the March 1989 storm as a direct result of overheating. Routine inspection after the storm, however, revealed the GSU transformers of Salem Nuclear Power Plant Unit 1 had sustained severe damage. Overheating burned insulation and melted copper conductors. Damaged transformers had to be removed from service.[20]

While damage to the Salem Unit 1 transformer was most obvious, the storm may have contributed to widespread life-shortening of other high-voltage transformers, including at Salem Unit 2 and at Maine Yankee. In the two years following the March 1989 storm, 18% of U.S. nuclear power plants experienced GSU failures, much higher than would be anticipated absent a common cause.[7] Following the storm, Allegheny Power System also reported damage to 36% of its EHV transformer fleet from overheating.[11]

Circuit Breakers

Circuit breakers are designed to interrupt current on live transmission lines. The ability to break circuits is necessary to control grid flows, isolate damaged equipment for maintenance, and protect equipment in the event of a fault. Given their importance for grid operation, EHV substations are typically arranged in a breaker-and-a-half configuration in which all circuit breakers share an online spare.

Interruption of the circuit at high voltage leads to arcing between the electrical contacts. Circuit breakers use various insulators to extinguish the arc, including oil, air, and inert gas. The optimal time to interrupt the arc is at instants of zero-current that occur twice on an AC cycle.

Figure 24: Substation Circuit Breaker. This gas-insulated circuit breaker interrupts all three phases of high voltage electricity. Note the exposed control cables underneath the breakers that would conduct the E1 pulse into the gray-colored circuitry cabinet. Photo credit: The Toledo Blade.

An E1 pulse may damage the low-voltage circuits used to signal and operate the circuit breaker. Testing and rigorous analysis of this vulnerability are missing from the EMP literature.

Both the E3 pulse and GIC from GMD impose a DC bias on high-voltage lines. This DC bias could eliminate the zero-current event on which AC circuit breakers depend to extinguish arcing. Attempting to operate the breaker in the absence of a zero-current crossing could result in catastrophic failure of the breaker. Rapid voltage fluctuations during a GMD event could also lead to damaging current restrikes.

E1 Vulnerability

Theoretical analysis of circuit breakers exposed to E1 also appears to be a gap in the EMP vulnerability research and literature. Our interviews with industry experts revealed disagreement on the anticipated effects of an E1 pulse on circuit breakers.

As with other high-voltage equipment, some experts believe the high-voltage components of circuit breakers will withstand an induced E1 pulse, since these components are exposed to even higher voltages during normal operation. Circuit breakers, however, also rely on small motors, pressurized components, recharging springs, release solenoids, and other control circuitry to break the high-voltage contacts. Since these components operate at low voltage, experts suggested E1 could damage these components, most especially their electrical controls. In instances where E1 damages the recharging system but energy is still stored mechanically within the breaker, breakers may be able to operate once or twice after the E1 event. Some circuit breakers have control logic at the breaker to coordinate the break with the zero-current crossing. Control microprocessors could be vulnerable to the E1 pulse. Disruption of control logic could lead to the breaker attempting to break when zero-crossing may not exist during the subsequent E3 pulse, which could cause catastrophic breaker failure.

Other experts, however, believe low-voltage portions of some circuit breakers may not be vulnerable to the E1 pulse. The cheapest and most common circuit breakers are dead-tank breakers, in which components inside the metal tank may be sufficiently protected from an E1 pulse.

In summary, while the controls of some circuit breakers may be resilient to the E1 pulse, this is not universally true for all circuit breakers. Figure 25, for example, shows an open cabinet for a high-voltage circuit breaker. This metal cabinet with swinging doors and multiple cable penetrations would not provide an effective E1 shield to any enclosed digital components.

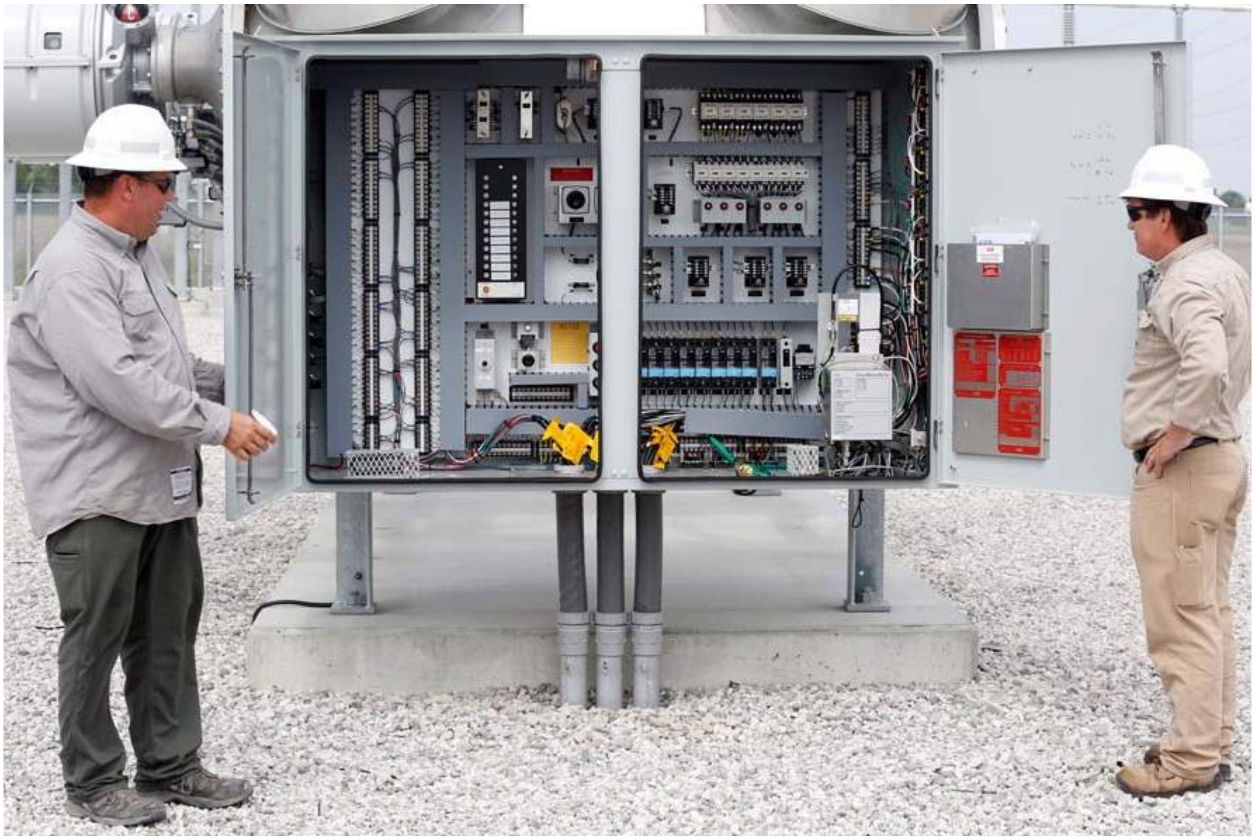

Figure 25: Substation Circuit Breaker Cabinet. Cables exit the underside of the circuit breaker control cabinet, passing underground to relays located in a substation control house. Even buried cables would conduct the E1 pulse into the cabinet and into the relays. Photo credit: The Toledo Blade.

E3 and GMD Vulnerabilities

While data on high-voltage circuit breakers in HEMP environments is not publicly available, circuit breakers have been exposed to GIC during solar storms. We are not aware of any circuit breaker failures during GMD events, though the North American Electric Reliability Corporation (NERC) reports that circuit breakers have been "impacted" by previous storms. Interviewed experts agreed circuit breakers could fail during E3 or extreme GMD events.[9] Without controlled testing of circuit breakers to failure, however, it is difficult to assess the degree of circuit breaker vulnerability.

AC circuit breakers depend upon instances of zero-current (as happens twice a cycle in AC circuits) to disconnect high-voltage contacts. If the GIC greatly exceeds the current on the line, the DC bias could remove any occurrence of a zero-crossing. Attempting to break a live circuit without a zero-current crossing could result in a sustained arc lasting for several seconds or minutes until the circuit breaker is damaged. In such a situation, circuit breaker control of bulk power flows within the transmission system would be lost.[3] [9] [19] [21]

Circuit breakers on lines with low loadings would be most susceptible to zero crossing failure as even a weak GIC can eliminate the occurrence of zero-current when line current is small. The relationship between vulnerability and loading for circuit breakers is thus opposite of that for power transformers.

Power transformers are more likely to experience saturation and overheating while at high loadings, whereas circuit breakers are more likely to lose zero-current crossings while at low load.

Additionally, attempting to operate circuit breakers during highly variable GIC could lead to catastrophic damage due to presence of high current or voltage transients. Strong voltage transients could cause arc restrikes and chopping current, resulting in damage to breakers and connected devices.[11]

Instrument Transformers

Instrument transformers convert grid current (current transformers) or voltage (potential transformers) to a proportional low-power signal used for relaying or metering. Essentially, instrument transformers are the sensors that read grid conditions. Instrument transformers can be installed in the bushings of transformers or as part of circuit breaker assemblies, though they can also be deployed as stand-alone assemblies. Many instrument transformers have an online backup.

Some interviewed experts expect the low-voltage sides of instrument transformers to be vulnerable to the E1 pulse. The high-voltage sides are expected to withstand the E1 pulse. Instrument transformers may be driven into saturation via their connection to the high-voltage line and GIC. Additionally, harmonics from the power transformer will be conveyed through the instrument transformers to the relays.[17] Should saturation occur, instrument transformers are not expected to fail immediately and have additional resiliency through redundant deployment, though the distorted signal resulting from saturation could lead to relay misoperation.

Figure 26: Instrument Transformers in Substation. Instrument transformers sense voltage and current by means of the transmission line conductor passing through an annular core wrapped with copper windings. All three phases of current pass through this inline set of instrument transformers to the right of the power transformers. Photo Credit: Pixabay.

E1 Vulnerability

No results of instrument transformers against E1 pulses are available in open literature. In a published report, SARA Corporation asserted that insulation in transformer primaries should withstand the conducted E1 pulse, since these windings connect directly to the high-voltage grid. Conductors connecting the low-voltage sides of these transformers to the substation control house will be sufficiently long to conduct the maximum E1 pulse, possibly necessitating protection of the secondary windings. If required, protection of secondaries with metal oxide varistors (MOV) or filters is likely to be feasible, but no tests have been conducted.[17] If instrument transformers have digital circuitry for analog to digital signal conversion or amplification of signals, this circuitry is likely to be vulnerable to the E1 pulse.

E3 and GMD Vulnerabilities

We do not expect that instrument transformers will be vulnerable to permanent damage from E3 and GMD, although saturation from GIC may cause erroneous readings. Further engineering study of instrument transformers under GIC conditions is needed.

Voltage Regulation Devices

Capacitor banks, reactors, and SVCs are used to stabilize voltage by managing reactive power on the electric grid. Reactors consume excess reactive power and are typically disconnected from the grid, except for situations such as black starts when generation and load mismatch may cause an excess of reactive power. SVCs combine capacitors and reactors along with fast automated switching to provide finer reactive power control in both directions. Loss of reactive power devices can lead to voltage swings and cascading collapse in power systems.

Capacitors

Capacitors provide additional reactive power to the grid and are typically located at the grid edge to counteract degradation in power delivery efficiency caused by the high inductance of transmission lines and rotating machinery loads. Capacitors in series with transmission lines can protect against the GIC caused by the E3 pulse and GMD.

Figure 27: Substation Capacitor Bank Capacitor banks are installed in substations to provide reactive power support. Substation capacitors operate at the voltage level of the connected transmission line and, therefore, are expected to be resistant to the high voltage of the E1 pulse. Photo Credit: [Wikimedia/Phillipe Mertens]

E1 Vulnerability

Since substation capacitors are designed to operate at transmission level voltages, we expect capacitors may accommodate the E1 pulse without damage; but testing will be required. The E1 pulse could cause breakdown across capacitor plates resulting in damage. E1 could also affect the relay systems controlling capacitor operation.

E3 Vulnerability

Substation capacitors can be tripped offline by a reversal in GIC flow during GMD events. This could cause loss of capacitors at a lower level than would necessitate relay operation to protect against overcurrent.

GMD Vulnerability

In addition to the issues of overcurrent exposure for E3, the fluctuations in the DC power flow experienced during a GMD event introduce issues for capacitors not experienced during E3. A large GIC can induce reactive power compensation from capacitors, but then swing to a negligible GIC causing overvoltage and leaving the capacitor bank unavailable for several minutes.

Shunt Reactors

Shunt reactors reduce reactive power in the electric grid and are typically located in substations or near generating stations.

Figure 28: Substation Shunt Reactor Air core shunt reactors at a substation in Montana near the Noxon Rapids hydroelectric generation dam are designed to absorb reactive power. The spinning generators at hydroelectric plants produce large amounts of reactive power; shunt reactors balance this power during grid restoration. While shunt reactors operating at high voltage may be resilient to the E1 pulse, the vulnerability of their control systems needs engineering study. Photo Credit: Creative Commons/VARsity

E1/E3/GMD Vulnerabilities

Shunt reactors are typically disconnected by a mechanical switch from the grid and are brought online following outages to compensate for low load conditions. Even if connected to the grid, the basic structure of the reactor is expected to be resilient to EMP. However, if the switching systems for the reactors have digital components, these components could be vulnerable to the E1 pulse.

Static VAR Compensators

SVCs are faster and more flexible reactive power control systems than mechanically switched capacitors and reactors. As reactive power needs change due to leading or lagging power factor, SVCs switch capacitors and reactors in and out of the active circuit. The sensing of power factor and control of capacitor and reactor switching depends on digital circuitry. As a result, SVC control systems may be vulnerable to E1 damage.

SVCs and their capacitors might be damaged by E3 or GMD if the event causes sufficient overvoltage. Proper relaying and redundant protections mitigate this risk, but the tripping of the SVCs or capacitors would still contribute to system collapse. Harmonics generated in transformers from E3 and GMD can also cause SVC relay misoperation, tripping SVCs offline when they are most needed by the electric grid.

Figure 29: Static VAR Compensator Capacitor banks are on the left of the facility reactors in center. The building on the right contains controls for switching capacitors and reactors to provide lagging or leading power factor. The digital controls for SVCs are likely to be vulnerable to the E1 pulse. Photo Credit: T&D World.

E1 Vulnerability

SVCs rely on digital controls and actively cooled thyristor valves housed separately from the main substation control house. These digital control systems may be vulnerable to E1 depending on the efficacy of protections designed for other electromagnetic threats against the E1 pulse. We are, however, unaware of any testing specific to SVC controls in E1 environments. SVCs have long cables connecting the controls to components in the substation yard.

E3 and GMD Vulnerabilities

SVCs can be damaged from overcurrent occurring from the quasi-DC bias induced by E3 and GMD. Proper relays can trip the SVC to protect it, but this may remove needed voltage support from the rest of the system. The fast-acting reactive power management of SVCs are of increased importance during an E3 or GMD event due to the increase in reactive power consumption in saturated power transformers.

The loss of SVCs due to protective relaying was a primary contributor to the Hydro-Quebec blackout. In this event, relays misoperated in response to harmonics introduced to the signal from transformer saturation caused by the ongoing solar storm. NERC determined that, in this case, SVCs could have remained operational without damage and proper relaying may have averted the blackout.[9] [21] Nonetheless, E3 and GMD events can produce sufficient overcurrent to trip SVCs and, in such instances, improved relaying would not necessarily protect the system from collapse.[3]

Control Houses

Substation control and communications equipment are typically located within control houses or huts, commonly constructed from metal or concrete. Because most control houses are not designed as for E1 protection (shielding plus penetration treatments), EMP field and current attenuation they provide can be minimal. Thus, equipment in the interior of the control house will likely be vulnerable to the E1 pulse.

Figure 30: Exterior of Substation Control House. Sheet metal is often used to construct substation control houses. Note the HVAC unit hung on the exterior wall of the control house; these units can have digital circuitry vulnerable to the E1 pulse. Photo credit: Creative Commons/Paul Chernikhowsky.

E1 Vulnerability

Relays and other control electronics within control houses can be susceptible to E1-pulse. Because equipment in control houses produces heat, air conditioning or other active cooling is almost always necessary. Without temperature control, relays and other equipment in the control house will experience failure or shortened operational life. The digital controls for this cooling equipment can be vulnerable to the E1 pulse.

E3 and GMD Vulnerabilities

Because the HVAC equipment for control houses does not connect to long conductors (such as transmission lines), it is not directly vulnerable to E3 and GMD. However, during tests at the Idaho National Laboratory, air conditioning connected to power lines with E3-induced harmonics suffered misoperation. Unlike relays and other equipment within substation control houses, HVAC does not have the benefit of conditioned power from uninterruptible power supplies.

SCADA

SCADA systems allow control and monitoring of large systems via digital connections. A typical SCADA system is essentially a network of digital processors, sensors, and controls connected to a central unit. The hardware components that comprise a SCADA system use many of the same digital technologies as computers with Ethernet connections. SCADA systems monitor and coordinate substations from a central control center. Damage to SCADA could result in a loss of operational awareness or loss of central control of substations.

Figure 31: Rack Populated with Relays and SCADA in Substation Control House. SCADA, relays, and other digital equipment are typically contained in substation control houses. The E1 pulse, conducted into equipment interfaces, can cause upset and permanent damage. Photo credit: The Toronto Blade

E1 Vulnerability

Since SCADA units are commonly comprised of microprocessors connected to conductive cabling, they are susceptible to E1 damage. The Congressional EMP Commission conducted testing and analysis on SCADA systems and concluded SCADA represents "the key vulnerable electronic system" to EMP. Free field tests resulted in incorrect readings of process status as well as some instances of damage to SCADA sensing equipment. Ethernet connection ports were particularly vulnerable. Idaho National Laboratory also notes, "unshielded embedded systems [such as SCADA] will likely be damaged by an EMP." [22]

Attenuation from the control house or control cabinet (in the case of remote terminal units (RTU) located in the switch yard) may provide some protection to SCADA devices, but cabling running through the switchyard connecting SCADA units would direct E1 pulses into terminals. The Congressional EMP Commission also conducted current injection testing to simulate this effect. The Commission found that while SCADA systems are well protected against fast transients up to the level specified by existing electromagnetic interference standards, SCADA failed when subjected to the stronger transients expected from an E1 event.

Metatech Corporation tested electronic systems against simulated E1 environments, but only a single brand of SCADA communication unit. The Schweitzer Engineering Laboratories (SEL) unit tested withstood the E1 fast transient, but other brands and designs of SCADA remained untested.[4]

E3 and GMD Vulnerabilities

SCADA units are not directly connected to the transmission lines that couple to the E3 or GMD. The cables connecting SCADA units, while long from an E1 coupling perspective, are not sufficient in length to couple E3 or GMD currents.

Relays

Protective relays at substations assess grid stability and isolate equipment from line surges, faults, and other conditions that could cause damage. Potential transformers and current transformers are the sensors for these relays. Lines connecting protective relays to substation sensors typically run a hundred feet or more through the yard and into the control house.

Upon detection of conditions that could damage equipment, such as excessive voltages or currents, protective relays open circuit breakers to remove exposed equipment from service. Relays are commonly programmed to reclose the breaker when transients clear on their own.

The flexibility of digital relays allows them to combine protection against multiple threats in a single unit and incorporate greater intelligence into relay decision-making compared to their analog counterparts. This flexibility, however, depends on solid-state circuitry that is typically more susceptible to electromagnetic threats.

Electromechanical relays are more robust than solid state digital relays. They serve the same protective function as digital relays but utilize analog operations. Electromechanical relays have been widely replaced with newer digital relays in high-voltage substations but are still present in a minority of substations.

Figure 32: Vintage Electromechanical Relay. Electromechanical relays such as the General Electric model pictured here were once widely installed in substations, but now represent a minority of relays in use. Testing shows these devices are resilient to the E1 pulse. Photo credit: Pinterest/MCBIA Sales.

Digital Relays

Digital relays contain microprocessors sensitive to the high amplitude pulse of E1 and connect to long cable leads from the switchyard that can conduct the pulse. Relays, however, are designed to operate in environments with electromagnetic transients. Some testing suggests that robust relay designs already have sufficient protection to avoid E1 damage. Other tests suggest for some digital relays E1 resiliency could benefit from improved shielding and signal filtering. Even if relays do not sustain damage from the E1 pulse, the pulse could contribute to relay misoperation, which, in turn, could result in catastrophic damage to high-voltage grid components.

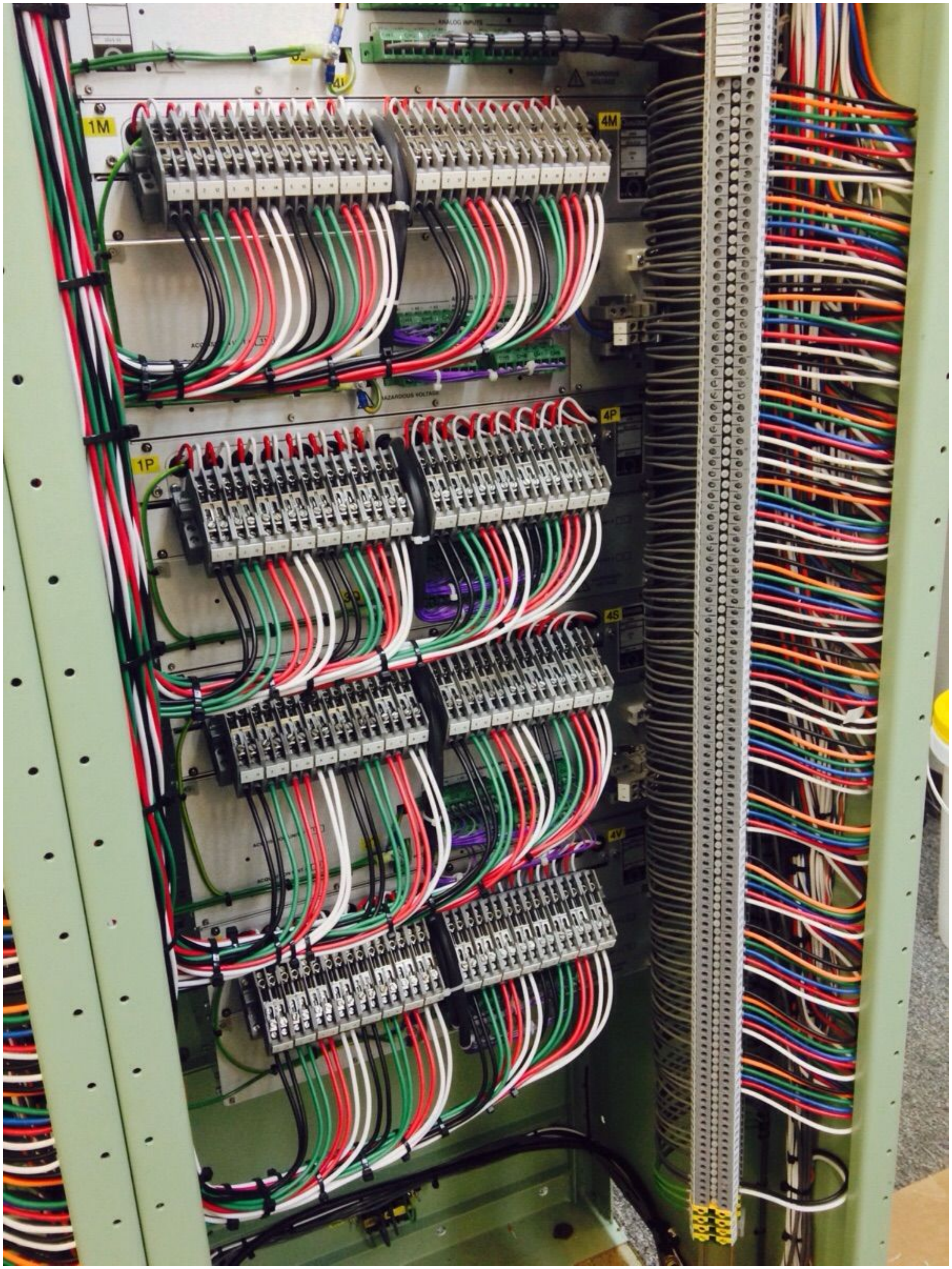

Figure 33: Cabling for Substation Relays. Plastic-sheathed, copper-conductor cabling can conduct the E1 pulse into racked equipment, causing upset and damage. [Photo Credit: Pinterest/imgur](#).

E1 Vulnerability

Multiple researchers have conducted tests on digital relays to assess their vulnerability to electromagnetic fields and the conducted E1 pulse. The Congressional EMP Commission conducted tests on digital relays and reported these devices were the “most robust of any electronic device tested” but were liable to upset. Metatech conducted its own tests on SEL brand digital relays. Metatech’s pulse current injection tests resulted in no damage to tested relays through the strongest pulse tested with a peak voltage of 8kV but upsets repeatedly occurred.[4]

Engineers from SEL also conducted HEMP tests on SEL relays. The SEL units withstood all tests, leading the study’s authors to conclude SEL and other digital relays that comply with IEC 60255-26 or IEC 60255-27 or have a 5kV impulse voltage withstand are HEMP resilient.[23] At least one researcher highly criticized the SEL methodology used in this study.[24]

SARA conducted electromagnetic field and pulse tests on three brands of digital relays. SARA reported all but one digital relay was eventually damaged via pulse current injection when used without a protective MOV. Failures began with injected currents as low as 200A. Implementation of MOV protection greatly improved performance with only one unit failing and only at 2500A—the highest current injection tested.[17]

Despite the resilience of some relay designs to the E1 pulse, concurrent failure of even a small proportion of substation relays during an EMP event could cause loss of control of the bulk power system and potential system-wide collapse, including damage to high-voltage grid components.

E3 and GMD Vulnerability

Because relays do not connect directly to long transmission lines, they are expected to be resilient to damage from E3/GMD.[17] Harmonics resulting from transformer saturation will be transferred to the relay through current transformers and could result in misoperation. Newer digital relays with improved logic can detect the presence of harmonics and continue proper operation in the E3 environment.[3]

Electromechanical Relays

Given their hard-wire design, electromechanical relays are robust against damage from HEMP and GMD. The absence of signal filtering, however, leaves electromechanical relays more susceptible to misoperation than their digital counterparts.

E1 Vulnerability

Several tests of electromechanical relays demonstrated resiliency to E1 damage. The Congressional EMP Commission tested electromechanical relays and found them immune to damage up to the highest test levels. Metatech conducted pulse testing on two electromechanical relays up to 8kV level (injector limit) without failures.[4] SARA also tested electromechanical relays up to 8kV without signs of damage.[17]

E3 and GMD Vulnerabilities

Electromechanical relays are expected to be immune from E3/GMD damage but may be susceptible to misoperation.[3] Electromechanical relays are designed to operate on the fundamental frequency and have limited ability to discriminate among higher-order harmonics.[25] Digital relays, however, can be programmed to be resistant to tripping during E3 or GMD events. As a result, electromechanical relays have a greater probability of misoperation during E3 and GMD than well-designed digital relays.[9]

Uninterruptible Power Supplies and Battery Chargers

Substations are powered using auxiliary power from the grid stepped down and processed through an uninterruptible power supply and battery system. In the event of a loss of grid power, the battery system remains available to power the substation, typically for a duration of eight hours.

Figure 34: Uninterruptible Power Supply and Battery System. UPS and backup battery systems supply power to low-voltage substation devices, including circuit breakers, relays, and other control devices. Power leads into the UPS will conduct the E1 pulse and harmonics resulting from E3/GMD; malfunction or equipment damage could result. Photo Credit: BTECH

E1 Vulnerability

SARA conducted pulsed current injection tests on a typical substation battery charger and found damage occurred at the highest stress associated with a conducted E1 pulse and temporary upsets associated with weaker pulses.[17] Potential for damage exists, given the length of unshielded cable connected to the battery charger and UPS and reliance on low-voltage electronics.

E3 and GMD Vulnerabilities

Battery chargers and UPS will see harmonic distortion from grid power during EMP events. While SARA did not test battery chargers and UPS in E3 environments, SARA predicts the design margin of typical devices installed in substations is sufficient to withstand an E3 pulse.[17] An NRC assessment of UPS in nuclear generating stations similarly found UPS to be “nearly immune” to GMD-induced harmonic distortion.[18] Nonetheless, some evidence suggests vulnerabilities may exist for UPS in other applications. Testing at Idaho National Laboratory indicates UPS is vulnerable to harmonics caused by GIC within transformers. For example, Central Maine Power reported customer complaints due to UPS malfunctions during moderate solar storms.

Station Auxiliary Power Sources

Station auxiliary power sources feed uninterruptible power supplies that, in turn, power substation relays, SCADA units, and other low-voltage devices. The two principal sources of station auxiliary power are dedicated station power transformers and tertiary windings in step-down transformers. Some studies have found tertiary windings to be vulnerable to overheating from the E3 pulse and GMD. The vulnerability of station auxiliary power sources is an area appropriate for future study.

Backup Generators

Roughly 5% of substations have dedicated backup generators in addition to the battery and UPS system. These generators maintain station power in the event of an outage lasting longer than the battery charge. Substations without dedicated backup generators can also be restored by mobile generators.

Figure 35: Backup Diesel Generator. Backup diesel generators can provide emergency substation power for circuit breakers, relays, and other control equipment. However, without specific design for EMP protection, generators can be vulnerable to the E1 pulse. Note the ventilation grates on the front and side of this metal enclosure that prevent the enclosure from providing Faraday cage shielding. Photo Credit: Wikimedia Commons/Dwight Burdette.

E1 Vulnerability

Because of the common use of digital controls, backup generators can be vulnerable to the E1 component of HEMP. Diesel generators were damaged during the Soviet HEMP tests. Soviet scientists evaluating test results judged the damage resulted from the E1 portion of the pulse.[5] Subsequent Russian experiments confirmed vulnerability of mobile diesel generators to HEMP.[22] This would be expected from the exposed cabling on generators conducting the pulse towards onboard, low-voltage electronics.

Generators connected to the substation UPS are expected to be more vulnerable than disconnected generators, because the power cables to the UPS will conduct the E1 pulse into the generators.

E3 and GMD Vulnerabilities

Backup generators are not directly connected to long lines that would conduct the slower E3 or GMD pulses and are, therefore, not vulnerable.

Distribution Systems

The electric distribution system is a radial network of distribution lines and transformers used to transmit electric power from the transmission system to the end consumer.

The scope of our study is protecting the bulk power system, which does not include distribution assets. This scope was selected because it is considered the highest priority from a cost-benefit perspective and the diversity of the distribution and load assets that would need to be considered to assess vulnerability.

However, the E1 vulnerability of distribution systems and load has important implications for protection of the bulk power system. Because most generation plants cannot operate without external load, some load from the distribution system will be needed to blackstart the grid. The loss of load can facilitate system collapse and complicate efforts at system restoration.

Distribution systems are expected to experience E1 vulnerabilities analogous to those found in transmission systems. Insulators and transformers, designed to work at lower voltages, are expected to be more vulnerable to E1 than transformers supporting high-voltage transmission systems. The Congressional EMP commission estimated near instantaneous loss of more than 10% of load following an EMP. Metatech and the Congressional EMP Commission both list failures of insulators on distribution lines due to E1 induced flashovers as a key vulnerability warranting further study.[4]

The Congressional EMP Commission also assessed expected damage to the distribution system as "less dramatic" than that to the transmission system following an EMP, likely due to lower levels of digitization in the distribution system. Additionally, distribution systems and their loads are expected to be less vulnerable to E3 due to shorter transmission line lengths.

Communications and Control

In the United States, a network of regional control centers manages the generation and transmission of electricity. Utilities use control centers and communications to monitor and forecast grid conditions and send operating instructions to other utilities or directly to grid assets.

Control Centers

Control centers rely on computer equipment and are similar in construction to large data centers. Their components—workstation computers, servers, routers, and other IT equipment with unshielded microprocessors—are expected to be highly vulnerable to the E1 component of EMP. Ethernet ports, in particular, are vulnerable to low levels of E1.[4] Equipment within control centers is typically powered by uninterruptible power supplies, which may vulnerable to transformer harmonics caused by the E3 pulse and GMD.

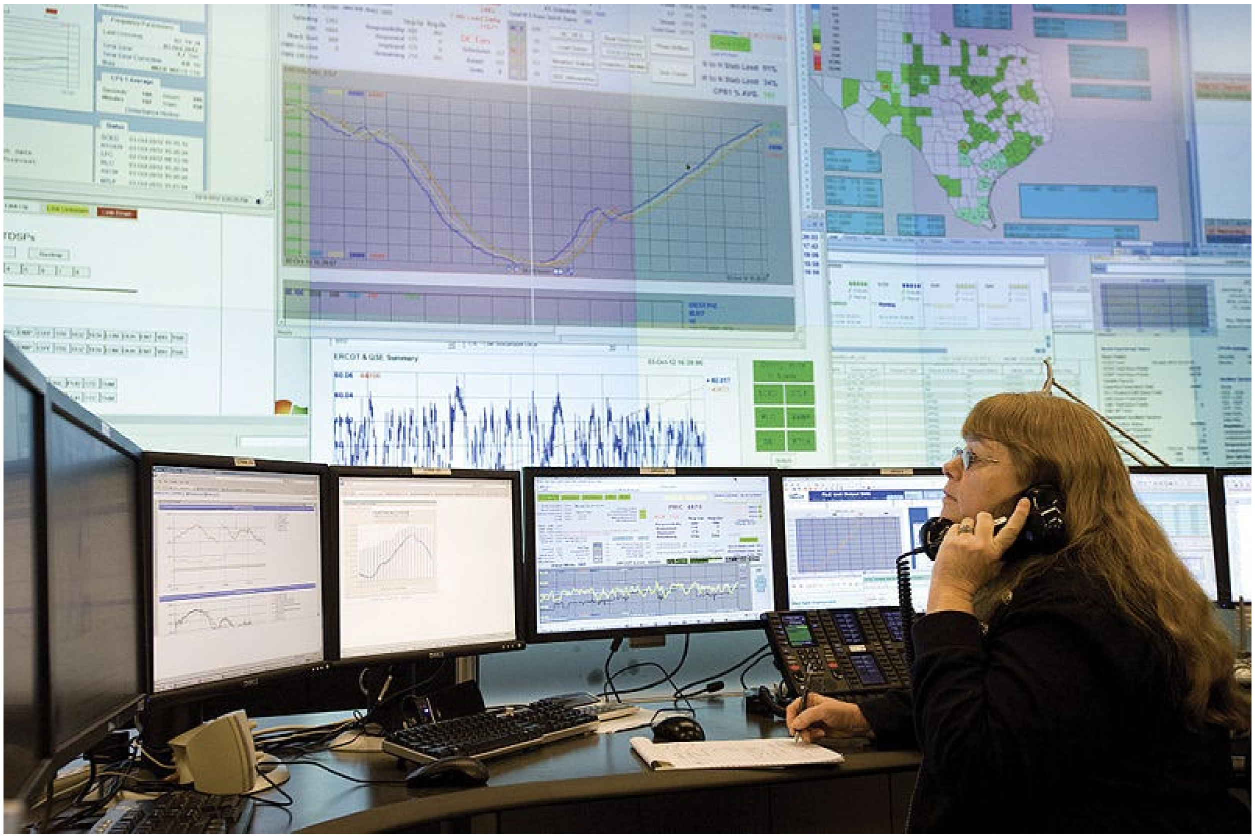

Figure 36: Reliability Coordinator Control Room. This reliability coordinator control room contains numerous monitors and large screen displays. The digital circuitry necessary to operate this equipment can be vulnerable to the E1 pulse. E3/GMD can cause harmonic effects misoperation of UPS if the control facility is unprotected. Photo Credit: Wikimedia Commons/Dpysh w.

Communications

Electric grid operators make extensive use of diverse communications technologies, including dedicated fiber optics, microwave, wireless cellular, and copper-conductor landlines. While much of electric grid communications is owned and operated by electric utilities, use of leased lines and the public internet has increased in recent years.

Nearly all electric grid substations are unmanned and remotely controlled, necessitating long-haul communications between control centers and the substations. While most electric generation plants are manned, their dispatch is done remotely, necessitating communication between control centers and the plants. Automatic generation control (AGC), the technology used to fine-balance generation and load, also requires communications between control centers and generation plants. This electric grid communication is performed using equipment not designed for EMP resilience and, therefore, possibly susceptible to temporary upset or permanent damage from the E1 pulse and GMD. Utilities use leased lines and the public Internet for many grid control activities. The cost of protecting electric grid communications against EMP is covered in our companion report, “Protecting U.S. Electric Grid Communications from Electromagnetic Pulse.”[26]

5. EMP Protection Strategies and Unit Costs

We developed EMP protection strategies based on the vulnerabilities addressed above and present them in two categories: hardening strategies and sparing strategies. We then used these strategies to develop per-unit estimates for EMP protection.

Hardening strategies directly protect equipment by blocking the EMP or designing equipment to withstand the EMP environment while operating. Within the DoD, the primary EMP hardening strategy is to block EMP by enclosing the equipment or facility within an electromagnetic barrier.[27] Given the scale of electric power transmission and generation infrastructure, applying this strategy directly to most grid assets would be cost prohibitive. Therefore, in most cases where hardening is applied, protection must occur at the subsystem or box level. Since DoD experience is not always directly applicable to grid protection and since little experience exists for EMP hardening of high-voltage grid components, our hardening cost estimations are necessarily approximate.

Sparing strategies increase grid resilience by facilitating timely restoration of systems damaged by EMP. These strategies can be cost-effective for grid components expected to have a low failure rate during an EMP event and for grid components with a high degree of redundancy, because not every component will incur a protection cost.

We estimated the cost of implementing spares by referencing RSMeans™ electric equipment cost data.[28] We supplemented RSMeans™ by using other industry cost estimates, where appropriate. In estimating the cost of implementing a sparing strategy, a source of uncertainty is the appropriate number of spares to stock. Since few grid components have been widely tested to failure against EMP environments, expected failure rates are largely unknown. Increased equipment testing will improve estimation of the requisite spares to ensure grid resilience from an EMP event and could lead to lower protection costs.

Transmission System Substations

We implement the following protection strategies for substations in our cost model:

- To protect against E3 and GMD, install neutral ground blockers on large power transformers at substations operating at 345kV or above
- To protect against E3 and GMD, maintain offline, on-site, spare circuit breakers at substations operating at 100kV or above
- To protect against E1, install electromagnetically shielded control houses with protected points of entry at substations operating at 100kV or above
- To aid in grid restoration after EMP events, install stationary backup generators at critical substations operating at 230kV or above

Our cost model does not include protections for these substation elements:

- Voltage support devices such as capacitors, reactors, and static VAR compensators and their digital controls
- Digital monitoring devices exposed to the E1 pulse in the open air of the substation, including digital instrument transformers and power transformer health monitors
- Cooling systems for power transformers
- Physical security systems such as closed-circuit television (CCTV)
- SCADA terminals outside the substation control house
- Any other digital devices in the open air of the substation that lack inherent E1 resilience or sufficient spares stocked on site

Comprehensive EMP protection for substations will require an inventory of digital devices exposed to the E1 pulse and evaluation of their vulnerability. Our cost estimate does include $1 million per substation for engineering study of the substation's EMP vulnerabilities.

Costs for EMP hardening of communications used in transmission systems are covered in our companion report, "Protecting U.S. Electric Grid Communications from Electromagnetic Pulse."[26]

Neutral Ground Blocking Devices

Neutral ground blocking devices are capacitor-based devices able to block GIC from E3/GMD, directly protecting power transformers. In addition to protecting the transformer, installation of a neutral ground blocking devices, by interrupting GIC, prevents the formation of harmonics due to transformer half-cycle saturation.

An alternative protection strategy could be to design and install new transformers with greater tolerance for overheating.[11] [29] However, greater thermal tolerance would not prevent the formation of harmful harmonics. A protection strategy incorporating neutral ground blockers would protect other equipment vulnerable to harmonics and reduce instances of relay misoperation from E3 and GMD. Installation of neutral ground blockers at some but not all substations, however, may increase GIC in transformers without blocking devices; network-specific modeling will be required to quantify this risk.

Figure 37: Neutral Ground Blocking Device. Utility workers examine a neutral ground blocking device installed to left of step-down transformer in an operational transmission system. This device blocks harmful GIC and prevents transformer oversaturation, overheating, and harmonic production. Installation of these devices at key grid nodes could protect against both E3 and GMD. Photo credit: Emprimus

Direct protection for large transformers is important due to the difficulty and cost of replacing them. Large power transformers have long replacement lead times—two years under normal circumstances—and most are uniquely designed, complicating implementation of a sparing strategy. Furthermore, the size and weight of large power transformers make transportation and installation difficult, often necessitating shipment by specialized rail cars and tractor trailers.

DOE has, however, awarded several contracts to develop lighter, modular transformer designs that could be used to more effectively implement a sparing strategy.[16] These transformers could be an important supplement to neutral ground blockers or reduce the need for neutral ground blockers for less critical transformers.

At the time of this report, only a single neutral ground blocking device had been installed within the U.S. electric grid.[30] Equipment costs were approximately $500,000. A recent DOE pilot study of the device found installation costs to be an additional $470,000.[31] Representatives from the company that designed the device stated this cost reflects the additional time to install a first-of-a-kind device and estimated that Nth-of-a-kind installations could cost as little as $25,000.

Our cost model applies a neutral ground blocking device to each transformer operating at the transmission level at or above voltage of 345 kV. We used the quoted equipment cost of $500,000 and $100,000 for installation as a conservative estimate of an Nth-of-a-kind installation.

Circuit Breaker Spares

Circuit breakers are well-suited to a sparing strategy for two reasons. First, circuit breakers may experience a low failure rate during a HEMP or extreme GMD event if they are not operated. Second, unlike transformers, circuit breakers are more standardized and can be used across substations if the breaker is of a sufficient voltage rating.

Additionally, circuit breakers in the bulk power system already have substantial redundancy. Most extra high-voltage substations, which comprise the backbone of the bulk power system, are configured in a ‘breaker and a half’ configuration. While this redundancy reduces the need for additional offline spares, the lack of data on expected circuit breaker failure rates during HEMP and GMD events complicates development of an adequate sparing strategy. More engineering study is needed.

Our cost model provides for an offline, spare circuit breaker rated for the substation’s highest voltage for each substation operating at the transmission level. We used cost data adapted from RSMeans to estimate the breaker cost for several voltage classes. [32] Since the breaker is offline, no installation cost is added.

Table 1: Circuit Breaker Cost Estimates

Min Voltage (kV)	Max Voltage (kV)	Cost
500	1,000	$ 1,175,000
345	499	$ 780,000
235	344	$ 500,000
100	234	$ 310,000

Table 1 shows how the cost of spare circuit breakers would vary by maximum operating voltage. Circuit breaker costs increase with higher voltage class.

Shielded Control Houses

Substation control houses contain relays and SCADA components as well as the uninterruptible power supply from which they draw power. Given the small footprint of these buildings and the number of potentially vulnerable devices they contain, creating a hardened enclosure is expected to be the most cost-effective protection strategy.

At its substations, American Electric Power (AEP) has begun installing modular control houses with electromagnetic shielding. AEP has found these modular control houses, including electromagnetic shielding, are less expensive than their previous, unshielded control houses due to the economies of scale from mass production of the structures. AEP reports these structures cost $500,000 to procure.

Figure 38: Shielded Control Enclosure. This modular shielded enclosure can be used at grid substations to protect relays, SCADA, and communications equipment. Photo credit: ARMAG Corporation

Our cost model assumes a modular, hardened control house at each substation operating at the transmission level, 100 kV or above. Based on information from AEP and discussions with other vendors, we estimate the cost of an installed, EMP-hardened, substation control house at $1 million, twice the procurement cost.

Backup Generators

During a blackout, substations do not receive grid power to run the relays, SCADA, breakers, and switches necessary to operate and repower the substation. Substations, instead, rely on backup power sources to provide auxiliary power to the station until the grid is restored. Typically, backup power is provided by batteries with approximately eight hours of life, though this can be lengthened by reducing power consumption. In approximately 5% of transmission substations, batteries are supplemented by on-site backup generators.

Figure 39: Backup Generator in Shielded Enclosure. This modular shielded enclosure is used to EMP protect a backup diesel generator manufactured by Caterpillar. A protection strategy for shielded enclosures may be more cost effective than protecting individual components of the generator, such as engine controls. Photo credit: ARMAG Corporation

In the event of an EMP, GMD, or any blackout resulting from widespread damage to the bulk power system, restoration times may exceed the eight-hour life of substation batteries. To ensure control of these stations remains viable beyond this timeframe, additional backup generation capacity coupled with on-site fuel storage could be added to key substations. Such online generation capacity would, itself, require EMP protection, which could be achieved by housing the generator in an electromagnetically shielded container.

An alternative strategy would be to use fleets of offline mobile generators. Since mobile generators are normally offline, less EMP protection is required. A single unit might serve multiple substations sequentially. This strategy of using an offline mobile generator fleet compared to hardened, onsite generators could be more cost effective. However, ubiquitous EMP effects across wide regions and resulting logistics problems could render off-site equipment strategies ineffective.

Our cost model assumes installation of EMP-hardened backup generators at substations at or above 230kV. We assume the cost of a hardened generator and its fuel storage to be $100,000.

Engineering Studies

Site-specific engineering studies are needed to implement the prescribed substation protections and evaluate other EMP vulnerabilities. We estimate a rough order of magnitude cost of these studies at $1 million per substation, where protections are installed.

Substation Protection Methodology

Table 2: Example of Substation Protection Methodology

Substation Name	Item	Protection Basis	Unit Cost ($M)	Estimated Quantity	Cost ($M)
Substation 1	Backup Generator (230+ kV)	New Equipment	$0.10M	1	$0.10M
	Circuit Breaker (345-499 kV)	Spare	$0.78M	1	$0.78M
	Control House	New Equipment	$1.00M	1	$1.00M
	Neutral Ground Blocker (345+ kV)	New Equipment	$0.60M	2	$1.20M
	Engineering Study	Overhead	$1.00M	1	$1.00M
Total					**$4.08M**

Table 2 summarizes our protection cost estimation methodology for an example substation operating between 345-499 kV. Elements of substation protection are a spare circuit breaker, EMP-protected control house, backup generator for substations operating at 230 kV and above, and neutral ground blockers for substations operating at 345 kV and above. Different voltage circuit breakers are implemented depending on the substation's operating voltage (see Table 1).

Control Centers

Our proposed protection strategy for operations and control centers is to retrofit existing facilities with an electromagnetic shield with protected points of entry at all electrical and aperture penetrations (doors, pipes, vents, etc.). Our model applies EMP protection to all generating station operators responsible for generation that receives EMP protection, all transmission operators, and all reliability coordinators.

Significant experience exists in hardening operations centers against EMP. DoD EMP protection techniques and cost figures can be applied to electric grid control rooms and communications systems, because they are analogous to DoD operations centers and their communications. Additionally, two utilities recently completed new control centers with integrated EMP protection. CenterPoint Energy, a Houston-based transmission owner/operator, constructed a new control center at a total cost of $170 million of which $8M was directly attributed to EMP protection, less than 5% of total cost.[33] Dominion Energy's new EMP-hardened control center was built for $80 million.[34] [35]

Michael Caruso, an EMP protection consultant, provided congressional testimony on the cost of constructing operations and control facilities with EMP hardening based on his experience in the industry and with ETS-Lindgren, a company that implements EMP hardening for both the DoD and commercial customers. To retrofit a two-story, control center with 44,000 square feet of EMP hardened space, Caruso estimated $26 million total project cost or $590/ft^2.[36] Our model assumes Caruso's estimate of $590/ft^2 for control room retrofit EMP protection.

We classify control centers into three categories based on space requirements. Small control rooms require 2,400 ft^2 of protected space, medium centers 6,000 ft^2, and large centers 20,000 ft^2. Control centers are classified based on the entity's NERC designation and the size of assets for which the entity is responsible. Size is assigned based on the following rules:

Large:

- Transmission operators with peak load of 10 GW or more
- Generation dispatch centers with capacity of 10 GW or more
- All entities that are both reliability coordinators and transmission operators

Medium:

- Transmission operators with peak load less than 10 GW but at least 5 GW
- Generation dispatch centers with capacity less than 10 GW but at least 5 GW
- Reliability coordinators that are not transmission operators

Small:

- Transmission operators with less than 5 GW of peak load
- Generation dispatch centers with less than 5 GW of capacity

Very small generation dispatch centers responsible for less than 100MW of dispatchable capacity are not included in the cost estimate.

Table 3: Examples of Control Room Protection Methodology

Utility Name	Role	Peak Load/ Capacity (MW)	Estimated Protected Area (ft^2)	Cost ($\$/ft^2$)	Cost ($M)
Control Room 1	Transmission	7,500	6,000	$ 590.00	$3.54M
Control Room 2	General Dispatch	1,200	2,400	$ 590.00	$1.42M
Control Room 3	Reliability Coordinator & Transmission	-	20,000	$ 590.00	$11.80M

Table 3 summarizes our control room protection strategy and cost estimation methodology for three types of control rooms.

These examples of control rooms have the following characteristics:

- Control Room 1 is a transmission operator with 7,500 MW of peak load. It is classified as a medium control room requiring 6,000 ft^2 of protected space, costing $590/ ft^2
- Control Room 2 is a generation dispatcher responsible for dispatching 1,200 MW of capacity and is classified as a small control room
- Control Room 3 is designated as both a reliability coordinator and transmission operator. It is classified as a large control room based solely on this designation

Generation Plants

To date, no large electrical generation plant has been hardened against EMP. Our review of power plant vulnerabilities finds electrical control systems to be E1 vulnerable, GSU transformers to be vulnerable to E3 and GMD, and generators to be vulnerable to E3/GMD indirectly via saturation-induced harmonics. GSU transformer and generator vulnerability to E1 has yet to be determined via test.

Our current cost model uses a rough estimate of the cost to retrofit existing power plants for EMP protection, based on the current cost of the asset's electrical and control systems and the cost of a neutral ground blocker. While crudely approximate, this method is necessitated by the diversity of power plant designs and lack of experience in protecting generation plants against EMP.

We adapt data on the costs of power plant electrical, instrumentation, and control from EIA's Capital Cost Estimates for Utility Scale Electricity Generating Plants, supplemented by a 2009 EPA-sponsored study on the performance and capital cost of subcritical coal power plants.[37] [38] [39] Estimates for power plant electrical, instrumentation, and control costs scale with the capacity of the plant and are subdivided by the type of plant. These costs include, "electrical transformers, switchgear, distributed control systems and other electrical commodities." As a conservative, order of magnitude estimate, we assume the cost of retroactively adding E1 protection to the plant's vulnerable electronics to be equal to the unhardened electrical, instrumentation, and control cost.

We make a small correction for the inclusion of the GSU transformer in EIA's electrical, instrumentation, and control cost estimate. We consider the cost protecting the GSU separately and explicitly as the equipment and installation cost of a neutral ground blocker. To separately account for this protection strategy, we estimate the cost of GSU transformers for a power plant to be $10,000/MVA. We then convert a plant's rated nameplate capacity in MW to MVA via its power factor (assuming a power factor of 0.85 if power factor data is unavailable). The cost of GSU transformers is subtracted from the electrical, instrumentation, and control costs. We added equipment and installation costs for a single neutral ground blocker for each generator (costs of $500,000 and $100,000 respectively).

Table 4: Power Plant Electrical, Instrumentation & Control Costs

Fuel	Type	Capital Cost ($/kW)	Electrical, Instrumentation & Controls Cost ($/kW)	Electrical, Instrumentation & Controls Cost (%)
Coal	Subcritical	$3,555	$213	6.0%
Coal	Supercritical	$3,246	$203	6.3%
Coal	UltraSupercritical	$3,636	$218	6.0%
Coal	IGCC	$4,400	$412	9.4%
Hydro	Conventional	$2,936	$141	4.8%
Hydro	Pumped Storage	$5,288	$256	4.8%
Gas	Steam Turbine	$978	$141	14.4%
Gas	Combustion Turbine	$917	$121	13.2%
Gas	Combined Cycle	$978	$141	14.4%
Gas	Internal Combustion	$1,342	$127	9.5%
Geothermal	Binary	$4,362	$367	8.4%
Geothermal	Dual Flash	$6,243	$359	5.8%
Nuclear	All	$5,945	$314	5.3%
Wind	Onshore	$1,877	$154	8.2%
Wind	Offshore	$6,230	$386	6.2%
Solar	Small (20 MW)	$2,671	$450	16.8%
Solar	Large (150 MW)	$2,534	$359	14.2%
Biomass	All	$4,985	$458	9.2%
Oil	All	$917	$121	13.2%

Table 4 shows how capital cost and electrical system cost vary by generating station technology. Because we assume EMP protection costs to be approximately equal to the electrical, instrumentation, and control system cost, plant technology is a significant cost driver. Hydroelectric plants, with their simple control systems, have lower EMP protection costs (as a percentage of plant capital cost) than modern, gas-fired plants with complex, digital control systems.

Table 5: Example of Generation Protection Methodology

Generator Name	Technology	Capacity (MW)	Capacity (MVA)	Power Factor	Cost Driver	Unit Cost	Quantity	Cost ($M)
Generator 1	Nuclear - Dual Unit	1000	1176	0.85	Electrical, Instrumentation & Controls Cost ($/MW)	$314,000	1000	$314.00M
					Generator Step-up Transformer ($/MVA)	$10,000	1176	($11.76M)
					Neutral Ground Blocker ($/ea.)	$600,000	1	$0.60M
Total								**$302.84M**

Table 5 summarizes our generating station protection strategy and cost estimation methodology. Generator 1 is a 1,000 MW nuclear generator located at a two-unit facility. The cost of electrical, instrumentation, and controls is estimated to be $314,000/MW or $314 million for the entire generating station. The cost of the GSU transformer is estimated to be $10,000/MVA. With an assumed power factor of 0.85, this totals $11.76 million, which is subtracted from the cost of electrical, instrumentation, and controls. The cost of a neutral ground blocker ($600,000 installed) is added to separately account for GSU protection. The total EMP protection cost for the example generating station is estimated to be $303 million.

6. EMP Protection Testing

Rigorous testing of EMP protection for the bulk power system will be challenging as it is impossible to test HEMP protection on a system-wide basis. (Russia is the only nation that has conducted a HEMP test over a large regional electric grid; this atmospheric test was conducted over Kazakhstan in 1962.) Instead, individual components and isolated systems must be tested to validate survivability. Rigorous HEMP testing will be costly, although economies might be gained through certification programs for commonly used electric grid devices and designs.

Once prototype EMP-protection of a grid component or system is completed, testing will be necessary for both EMP hardness and protection failure rates. There is a stochastic aspect to EMP failures; sufficient tests will be required to establish failure probabilities. Even a small percentage of projected failures among critical components in a large system such as the U.S. electric grid could cause system-wide cascading collapse.

Testing some components under loaded conditions—for example, large power transformers—will be complicated by hesitancy to risk interrupted load for commercial grid customers. Fortunately, Idaho National Laboratory has a moderate-scale electric grid within its boundaries that can be used for loaded condition testing.

Individual electric grid components can be EMP tested using current injection. This technique works well when the primary risk is EMP pulses conducted into equipment from attached cabling and cords. For transformers subjected to the E3 pulse and GMD, DC currents can be injected to simulate GIC in transmission lines.

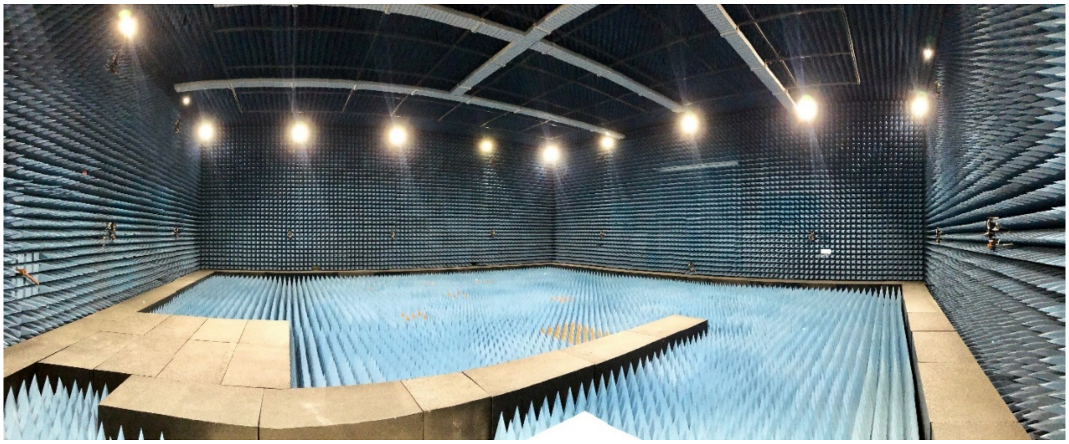

Figure 40: EMP Test Chamber. Anechoic EMP test chambers can be used to test equipment up to the size of an automobile or small truck. Photo credit: Global Resilience Institute at Northeastern University.

Small and moderately sized components can also be tested within an EMP chamber. Because such testing is already required for compliance with electromagnetic interference (EMI) standards, an established vendor base exists for such testing. The walls of EMP test chambers are typically lined with material to absorb electromagnetic radiation to make them anechoic (non-reflecting).

For devices protected by an enclosure, EMP can be generated outside (or inside) the enclosure and then the signal strength monitored inside (or outside) the enclosure. This technique is well-developed for testing enclosures used for DoD systems; the same techniques could be used for electric grid control centers and control houses at grid substations.

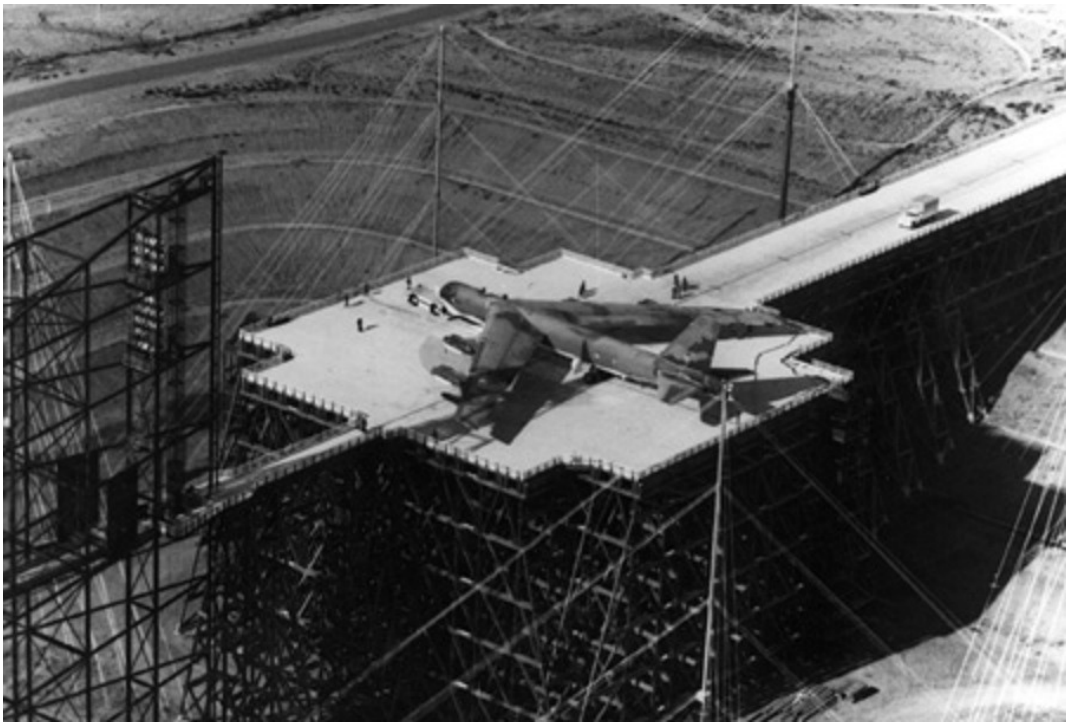

Figure 41: EMP Trestle. A Boeing B-52 strategic bomber being prepared for EMP testing at Atlas Trestle in 1982. Photo credit: U.S. Air Force

A testing approach for moderately sized systems is to use a "trestle"—a wooden support structure surrounded by EMP generators using capacitors, rapid-firing switches, and antennas. The U.S. Air Force used such a device from 1980 to 1991 under the Air Force Weapons Lab Transmission-Line Aircraft Simulator (ATLAS) program. Large military aircraft were placed within the trestle, then destructively tested. While the ATLAS program was shut down, knowledge gained was used to build the Z Pulsed Power Facility (Z Machine), the world's largest high-frequency electromagnetic wave generator located at Sandia National Laboratories. Small systems such as portable substations might be tested within EMP trestles.

7. Characterization of Bulk Power System Assets

In assessing the cost of protecting the U.S. electric grid against EMP and GMD threats, the Foundation for Resilient Societies constructed a database of bulk power system assets from publicly and commercially available sources. Resilient Societies' database of U.S. bulk power systems contains counts, key attributes, and locations of grid-connected electric generators, high-voltage lines and substations, and utility and reliability coordinator control centers. The database is implemented in Sequential Query Language (SQL). Data was compiled from the following sources:

Generation:

- EIA 860 – Data on generation units and power plants [40]

Transmission:

- HIFLD – Data on transmission lines and substations [41]
- S&P Platts – Data on substations
- FERC Form 1 – Data on substations [42]

Control Centers:

- NERC Registry Matrix – Data on transmission operators and reliability coordinators [43]
- EIA 860 – Data on generation operators including independent power producers [40]
- EIA 861 – Data on electric utility companies [44]

Jurisdictions:

- U.S. Census – State, county, statistical area, and congressional district boundaries
- NERC – ISO, NERC region, and Balancing Authority boundaries

When assets were reported by multiple sources, data was synthesized to create the most complete characterization of the assets and to avoid duplicate asset counts.

In total, our database characterizes over 32,000 substations above 100kV; 5,400 utilities and other entities with responsibility for the electric grid; and over 18,000 power plants comprising 1,156 GW of electrical generation capacity.

8. Estimated Cost of EMP Protection

We aggregated EMP protection cost estimates by applying each per-unit protection strategy identified in Section 6 to the applicable number of assets identified in the bulk power system database described in Section 8 and then summing the costs. We present here a breakdown of the national and state-level cost estimates.

Using our first-order cost model, we estimate the "overnight cost"[‡] of EMP protecting critical elements of U.S. bulk electric system to be on the order of $255 billion. This cost estimate includes protection for transmission system assets connected at 100kV and above; for dispatchable generators with at least 100MW of capacity; and for control rooms for transmission operators, generation dispatch, and reliability coordinators. Addition of EMP protection for voltage regulation devices such as SVCs could substantially increase protection costs, as could addition of vulnerable digital devices in the open air of substations. Alternatively, technological innovations and scale economies achieved over thousands of grid facilities could reduce EMP protection costs. Additional engineering and economic study would be required to refine these cost estimates for EMP protection.

It is important to note, cost estimates presented here consider only the cost of bulk power system protection and not the cost to protect the downstream assets that receive power (i.e., distribution and load).

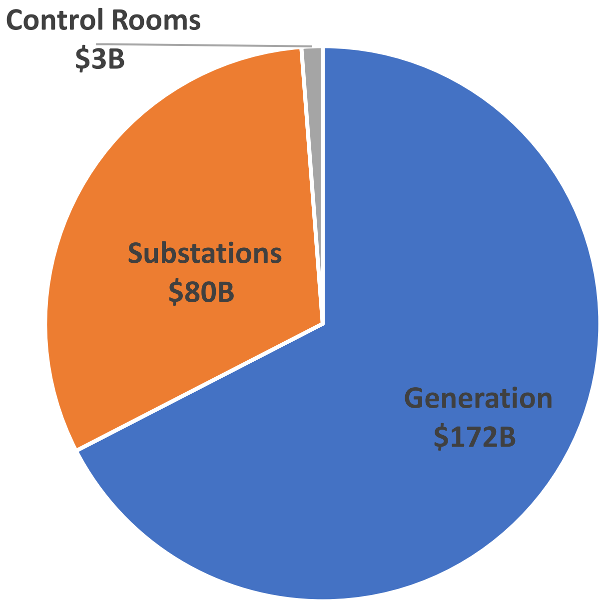

Figure 42: Estimated U.S EMP Protection Costs by Grid Facility Type

We estimate over two-thirds of this EMP protection cost is attributable to generating station protection, nearly one-third to substations, and only 1% to control room protection (Figure 42).

[‡] In the electric utility industry, "overnight cost" is the theoretical cost of building a facility or making an improvement in just one night. Obviously, this schedule would not be practical for EMP protection. Instead, we propose implementation of EMP protection over a full decade.

Our cost estimate for hardening control rooms is based on square footage provided in Michael Caruso's congressional testimony based on his experience with ETS Lindgren.[36] While we believe this is the best available data on the subject, we find our estimates for control room protection are lower than expected from costs realized by the two hardened control centers built at CenterPoint and Dominion Power. While control room costs may increase in subsequent iterations of EMP protection cost models, even an order of magnitude increase in control room cost would increase our overall protection estimate by only 10%.

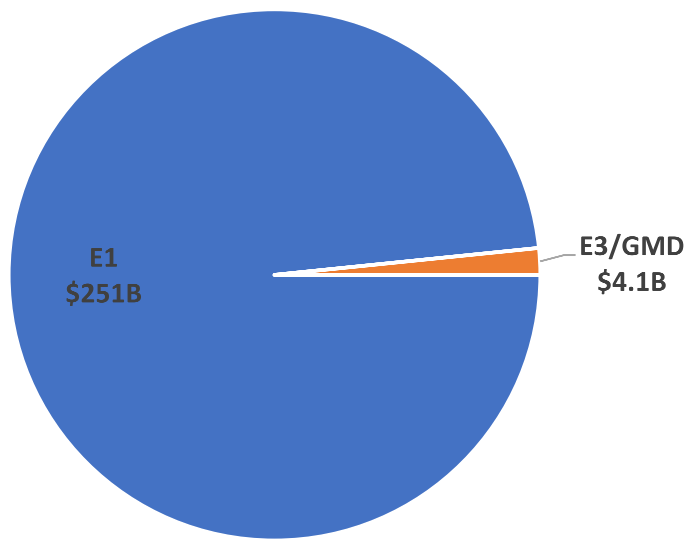

Figure 43: Estimated U.S. EMP Protection Costs by Grid Threat

We find the cost of protection against the E1 pulse is significantly greater than the cost of protecting against E3 and GMD. We allocate the cost of neutral ground blocking devices at substations and generating station to the E3/GMD threat with all other protections allocated to E1. Under this classification, E3/GMD constitutes less than 2% of total protection costs (Figure 43).

E3 and GMD protection should be prioritized because they threaten large power transformers—expensive assets with long lead times—and, GMD is a natural phenomenon that cannot be deterred. Lloyd's of London (Lloyd's) estimates the economic cost of a Carrington-class solar storm on the North American electric grid at between $0.6 and $2.6 trillion based on the value of lost load (VOLL).[8] By this conservative assessment, the value at risk could be over 500 times the cost of E3/GMD hardening.

Breakdown of EMP Protection Costs

Because our first-order methodology estimates the cost of protecting most large assets within the U.S. bulk power system, our estimate of $255 billion could be higher than for a prioritized program of EMP protection. A credible deterrent against nuclear HEMP could be established by protecting grid assets sufficient to ensure basic societal functioning.

Table 6: Breakdown of EMP Protection Costs by Substation Operating Voltage

Substation Operating Voltage	Number of Substations	Number of Protected Substations	Protection Cost	Percent Protected	Percent of Protection Costs
500 kV+	930	930	$4,162M	100%	5%
345-499 kV	1,785	1,785	$7,283M	100%	9%
230-344 kV	4,657	4,657	$11,224M	100%	14%
116-229 kV	13,253	13,253	$30,614M	100%	38%
100-115 kV	11,590	11,590	$26,773M	100%	33%
Total	**32,215**	**32,215**	**$80,056M**	**100%**	**100%**

Table 6 breaks down substation assets within the United States by maximum substation operating voltage. This analysis shows as the operating voltage of substations declines, their count and proportional costs of EMP protection rise. Protecting only the most critical substations—those operating at 230 kV and above—might save 71% of estimated costs to protect substations. If we were to take a more cautious approach and install Neutral Ground Blockers for any substation operating above 100kV, we would see the protection cost due to blockers increase by 44% to $115,456M. This may not be cost-effective but should be considered if blocker technology advancements reduce the protection cost.

Table 7: Breakdown of EMP Protection Costs by Generation Plant Capacity

Genration Plant Capacity	Total Capacity (MW)	Number of Units	Protected Capacity (MW)	Number of Protected Units	Percent Protected	Protection Cost	Percent of Protection Costs
1,000+ MW	90,543	75	90,543	75	100%	$25,459M	15%
500-999 MW	262,933	377	262,933	377	100%	$51,988M	30%
250-499 MW	177,532	531	168,829	501	95%	$27,687M	16%
100-249 MW	366,683	2,249	320,411	1,941	87%	$44,222M	26%
0-99 MW	259,014	14,843	172,603	3,931	67%	$22,834M	13%
Total	**1,156,705**	**18,075**	**1,015,319**	**6,825**	**88%**	**$172,190M**	100%

Table 7 breaks down generation plants by capacity. In this table, plants under 100MW, renewables, and hydro plants under 10MW are not considered, as it might not be cost effective to protect them. This analysis shows that a strategy of protecting only the largest generation plants could save substantial funds. Protecting the most critical generation plants—those with capacity of 500 MW or more—could save 55% of estimated costs to protect generators.

Table 8: Breakdown of EMP Protection Costs by Generator Technology

Generator Technology	Total Capacity (MW)	Number of Units	Protected Capacity (MW)	Percent Protected	Protection Cost	Percent of Protection Costs
Gas	504,036	5,716	480,745	95%	$60,041M	35%
Coal	304,846	968	301,146	99%	$60,198M	35%
Nuclear	103,865	99	103,865	100%	$31,511M	18%
Hydro	100,812	4,176	94,576	94%	$14,862M	9%
Wind	73,511	1,098	-	0%	$0M	0%
Oil	39,941	3,510	29,462	74%	$3,282M	2%
Solar	13,543	1,649	-	0%	$0M	0%
Biomass	12,317	662	3,756	30%	$1,678M	1%
Geothermal	3,834	197	1,769	46%	$618M	0%
Total	**1,156,705**	**18,075**	**1,015,319**	**88%**	**$172,190M**	**100%**

Table 8 breaks down generation plants and protection costs by technology. This analysis indicates a strategy of excluding certain technologies from protection is unlikely to produce substantial savings. Gas-fired, coal-fired, nuclear, and hydro plants account for the majority of generation capacity. Under our protection scheme, these plants also account for 97% of estimated protection costs.

Allocation Methodologies for Costs

We allocated EMP protections by political jurisdictions (states), by annual electricity billings within states, by annual electricity sales (consumption) with states, average annual electricity expenditure, and per capita (by population). In general, we find that allocating costs by state results in residents of states that export power shouldering a disproportionate share of EMP protections costs—because generating stations account for the two-thirds of estimated EMP protection costs.

Table 9: Estimated EMP Protection Costs by State and Facility Type

State	Generation	Substations	Control Rooms	Total
Alabama	$5,678M	$4,798M	$47M	$10,523M
Alaska	$204M	$120M	$36M	$361M
Arizona	$4,969M	$887M	$58M	$5,914M
Arkansas	$2,837M	$1,927M	$33M	$4,798M
California	$8,476M	$4,178M	$278M	$12,932M
Colorado	$2,161M	$1,351M	$67M	$3,580M
Connecticut	$1,450M	$616M	$48M	$2,114M
Delaware	$440M	$303M	$10M	$753M
District of Columbi	$0M	$31M	$5M	$35M
Florida	$9,807M	$4,002M	$146M	$13,955M
Georgia	$6,300M	$4,019M	$77M	$10,396M
Hawaii	$392M	$113M	$22M	$527M
Idaho	$482M	$888M	$19M	$1,389M
Illinois	$9,085M	$2,645M	$107M	$11,837M
Indiana	$4,880M	$1,706M	$63M	$6,649M
Iowa	$1,905M	$1,017M	$55M	$2,977M
Kansas	$1,859M	$1,002M	$46M	$2,907M
Kentucky	$4,116M	$997M	$34M	$5,146M
Louisiana	$4,288M	$1,931M	$51M	$6,269M
Maine	$508M	$484M	$19M	$1,011M
Maryland	$2,263M	$697M	$34M	$2,993M
Massachusetts	$2,106M	$1,119M	$102M	$3,327M
Michigan	$5,500M	$1,828M	$80M	$7,408M
Minnesota	$2,158M	$1,881M	$65M	$4,103M
Mississippi	$2,722M	$2,330M	$22M	$5,074M
Missouri	$3,925M	$1,655M	$77M	$5,658M

Table 9: Estimated EMP Protection Costs by State and Facility Type – Continued

State	Generation	Substations	Control Rooms	Total
Montana	$829M	$467M	$22M	$1,317M
Nebraska	$1,509M	$846M	$72M	$2,427M
Nevada	$1,464M	$718M	$36M	$2,218M
New Hampshire	$784M	$279M	$19M	$1,082M
New Jersey	$3,284M	$951M	$45M	$4,280M
New Mexico	$1,178M	$1,317M	$19M	$2,514M
New York	$6,105M	$2,402M	$121M	$8,629M
North Carolina	$5,683M	$2,367M	$116M	$8,166M
North Dakota	$1,009M	$471M	$22M	$1,501M
Ohio	$5,182M	$2,434M	$124M	$7,741M
Oklahoma	$3,262M	$1,436M	$66M	$4,764M
Oregon	$1,718M	$1,608M	$79M	$3,405M
Pennsylvania	$8,272M	$1,865M	$101M	$10,239M
Rhode Island	$248M	$185M	$10M	$443M
South Carolina	$4,959M	$1,482M	$24M	$6,465M
South Dakota	$448M	$412M	$27M	$887M
Tennessee	$4,229M	$1,970M	$43M	$6,242M
Texas	$16,418M	$7,868M	$360M	$24,647M
Utah	$1,394M	$592M	$24M	$2,010M
Vermont	$16M	$230M	$21M	$268M
Virginia	$4,549M	$1,925M	$52M	$6,526M
Washington	$4,010M	$2,524M	$70M	$6,604M
West Virginia	$2,790M	$1,380M	$10M	$4,180M
Wisconsin	$2,870M	$1,310M	$42M	$4,222M
Wyoming	$1,471M	$483M	$7M	$1,961M
Total	**$172,190M**	**$80,049M**	**$3,134M**	**$255,373M**

Table 9 shows the absolute cost of EMP protecting assets in each state. As expected, larger states have more electric grid assets and, therefore, greater estimated costs for EMP protection.

Table 10: Impact of EMP Protection on Electricity Rates

State	Annual Electricity Billings	Annualized EMP Protection Cost	Percent Increase in Electricity Cost
Alabama	$8,436M	$1,052M	12.5%
Alaska	$1,097M	$36M	3.3%
Arizona	$8,082M	$591M	7.3%
Arkansas	$3,753M	$480M	12.8%
California	$37,193M	$1,293M	3.5%
Colorado	$5,386M	$358M	6.6%
Connecticut	$3,609M	$211M	5.9%
Delaware	$1,168M	$75M	6.4%
District of Columbia	$990M	$4M	0.4%
Florida	$23,348M	$1,396M	6.0%
Georgia	$13,239M	$1,040M	7.9%
Hawaii	$2,254M	$53M	2.3%
Idaho	$1,864M	$139M	7.4%
Illinois	$10,754M	$1,184M	11.0%
Indiana	$9,557M	$665M	7.0%
Iowa	$4,142M	$298M	7.2%
Kansas	$4,282M	$291M	6.8%
Kentucky	$6,275M	$515M	8.2%
Louisiana	$6,811M	$627M	9.2%
Maine	$1,216M	$101M	8.3%
Maryland	$6,341M	$299M	4.7%
Massachusetts	$6,623M	$333M	5.0%
Michigan	$11,441M	$741M	6.5%
Minnesota	$6,623M	$410M	6.2%
Mississippi	$4,238M	$507M	12.0%
Missouri	$7,660M	$566M	7.4%

Table 10: Impact of EMP Protection on Electricity Rates – Continued

State	Annual Electricity Billings	Annualized EMP Protection Cost	Percent Increase in Electricity Cost
Montana	$1,230M	$132M	10.7%
Nebraska	$2,732M	$243M	8.9%
Nevada	$3,023M	$222M	7.3%
New Hampshire	$1,472M	$108M	7.4%
New Jersey	$8,677M	$428M	4.9%
New Mexico	$2,100M	$251M	12.0%
New York	$16,399M	$863M	5.3%
North Carolina	$12,301M	$817M	6.6%
North Dakota	$1,655M	$150M	9.1%
Ohio	$11,237M	$774M	6.9%
Oklahoma	$4,746M	$476M	10.0%
Oregon	$4,142M	$341M	8.2%
Pennsylvania	$12,416M	$1,024M	8.2%
Rhode Island	$998M	$44M	4.4%
South Carolina	$7,676M	$646M	8.4%
South Dakota	$1,192M	$89M	7.4%
Tennessee	$9,299M	$624M	6.7%
Texas	$33,584M	$2,465M	7.3%
Utah	$2,631M	$201M	7.6%
Vermont	$797M	$27M	3.4%
Virginia	$10,137M	$653M	6.4%
Washington	$6,793M	$660M	9.7%
West Virginia	$2,879M	$418M	14.5%
Wisconsin	$7,375M	$422M	5.7%
Wyoming	$1,355M	$196M	14.5%
Total	**$363,228M**	**$25,537M**	**7.5%**

Table 10 shows the annual cost of EMP protection if evenly divided across a 10-year program in comparison to the total annual cost of serving electricity in each state.[§] We estimate EMP protection of the entire bulk power system would increase the cost of serving electricity on average by 7.5% nationally if implemented over a 10-year period. If costs were allocated on a state-by-state basis, some states would experience a higher relative cost due to the make-up of their portfolio of power system infrastructure. States that are significant importers of electricity, such as California and Vermont, would see the lowest relative increase in costs at approximately 3%, since they rely on generation assets outside their borders. Conversely, Wyoming and West Virginia, the states with the greatest relative increase in costs at roughly 14%, are significant electricity exporters. As expected, Texas, with a self-sufficient grid largely isolated from the rest of the nation, experiences a relative increase in cost in line with the national average at roughly 7%.

[§] This analysis represents a first-order estimation. For simplicity, it is conducted in nominal dollars.

Table 11: Impact of EMP Protection on Volumetric Rates

State	Annual Electricity Sales (TWh)	Annualized EMP Protection Cost ($M)	Volumetric Increase in Electricity Cost ($/MWh)
Alabama	88.2	$1,052M	$11.93
Alaska	6.1	$36M	$5.89
Arizona	78.2	$591M	$7.56
Arkansas	46.2	$480M	$10.39
California	256.8	$1,293M	$5.04
Colorado	54.8	$358M	$6.53
Connecticut	28.9	$211M	$7.31
Delaware	11.3	$75M	$6.68
District of Columbia	11.4	$4M	$0.31
Florida	235.7	$1,396M	$5.92
Georgia	138.1	$1,040M	$7.53
Hawaii	9.4	$53M	$5.58
Idaho	23.1	$139M	$6.02
Illinois	141.1	$1,184M	$8.39
Indiana	103.7	$665M	$6.41
Iowa	48.4	$298M	$6.15
Kansas	40.8	$291M	$7.12
Kentucky	74.6	$515M	$6.90
Louisiana	91.5	$627M	$6.86
Maine	11.4	$101M	$8.83
Maryland	61.4	$299M	$4.88
Massachusetts	53.5	$333M	$6.22
Michigan	104.5	$741M	$7.09
Minnesota	66.5	$410M	$6.17
Mississippi	49.1	$507M	$10.34
Missouri	78.6	$566M	$7.20

Table 11: Impact of EMP Protection on Volumetric Rates – Continued

State	Annual Electricity Sales (TWh)	Annualized EMP Protection Cost ($M)	Volumetric Increase in Electricity Cost ($/MWh)
Montana	14.1	$132M	$9.34
Nebraska	30.2	$243M	$8.04
Nevada	36.1	$222M	$6.14
New Hampshire	10.9	$108M	$9.92
New Jersey	75.4	$428M	$5.68
New Mexico	23.0	$251M	$10.91
New York	147.8	$863M	$5.84
North Carolina	134.4	$817M	$6.08
North Dakota	18.5	$150M	$8.11
Ohio	150.6	$774M	$5.14
Oklahoma	61.5	$476M	$7.75
Oregon	47.3	$341M	$7.19
Pennsylvania	145.3	$1,024M	$7.05
Rhode Island	7.5	$44M	$5.88
South Carolina	79.6	$646M	$8.12
South Dakota	12.1	$89M	$7.32
Tennessee	100.8	$624M	$6.20
Texas	398.7	$2,465M	$6.18
Utah	30.2	$201M	$6.66
Vermont	5.5	$27M	$4.86
Virginia	112.3	$653M	$5.81
Washington	88.9	$660M	$7.43
West Virginia	32.1	$418M	$13.03
Wisconsin	69.7	$422M	$6.05
Wyoming	16.6	$196M	$11.85
Total	**3,762**	**$25,537M**	**$7.17**

Table 11 shows the impact on electricity costs on a per megawatt-hour basis if this annualized cost were allocated volumetrically to the rate base on a state-by-state basis. Under this allocation methodology, the per-megawatt hour price of electricity would increase on average by approximately $7.17 (0.72 cents per kilowatt-hour). This would correspond to a $73 increase in an annual electricity expenditure for the average residential ratepayer for the life of the program (see Table 12).

While volumetric allocation provides a useful sense of scale of the cost of an EMP protection program, allocating costs in proportion to electricity consumption would have a distortive effect on electricity consumption as not all loads would demand EMP-resilient service. Recovering costs through volumetric rates could become particularly distortive if sufficient EMP protected capacity were guaranteed only to serve critical public services. To mitigate this effect, EMP protection costs could be added as a fixed cost to ratepayer bills. Alternatively, EMP protection may best be viewed as a defense expenditure with costs socialized throughout the tax base.

Table 12: Impact of EMP Protection on Residential Ratepayers

State	Average Annual Electricity Expenditure ($)	Annualized Protection Cost Per Average Ratepayer ($)	Percent Increase for Average Ratepayer
Alabama	$1,393	$174	12.5%
Alaska	$1,270	$42	3.3%
Arizona	$1,277	$93	7.3%
Arkansas	$1,056	$135	12.8%
California	$951	$33	3.5%
Colorado	$819	$54	6.6%
Connecticut	$1,064	$62	5.9%
Delaware	$1,179	$76	6.4%
District of Columbia	$839	$3	0.4%
Florida	$1,335	$80	6.0%
Georgia	$1,309	$103	7.9%
Hawaii	$1,447	$34	2.3%
Idaho	$925	$69	7.4%
Illinois	$670	$74	11.0%
Indiana	$1,079	$75	7.0%
Iowa	$887	$64	7.2%
Kansas	$1,132	$77	6.8%
Kentucky	$1,133	$93	8.2%
Louisiana	$1,108	$102	9.2%
Maine	$697	$58	8.3%
Maryland	$1,234	$58	4.7%
Massachusetts	$890	$45	5.0%
Michigan	$878	$57	6.5%
Minnesota	$912	$57	6.2%
Mississippi	$1,248	$149	12.0%
Missouri	$1,217	$90	7.4%

Table 12: Impact of EMP Protection on Residential Ratepayers – Continued

State	Average Annual Electricity Expenditure ($)	Annualized Protection Cost Per Average Ratepayer ($)	Percent Increase for Average Ratepayer
Montana	$852	$91	10.7%
Nebraska	$1,056	$94	8.9%
Nevada	$928	$68	7.3%
New Hampshire	$978	$72	7.4%
New Jersey	$954	$47	4.9%
New Mexico	$691	$83	12.0%
New York	$792	$42	5.3%
North Carolina	$1,209	$80	6.6%
North Dakota	$1,122	$102	9.1%
Ohio	$798	$55	6.9%
Oklahoma	$1,013	$102	10.0%
Oregon	$952	$78	8.2%
Pennsylvania	$863	$71	8.2%
Rhode Island	$932	$41	4.4%
South Carolina	$1,336	$113	8.4%
South Dakota	$1,158	$86	7.4%
Tennessee	$1,371	$92	6.7%
Texas	$1,169	$86	7.3%
Utah	$784	$60	7.6%
Vermont	$953	$32	3.4%
Virginia	$1,213	$78	6.4%
Washington	$876	$85	9.7%
West Virginia	$1,187	$172	14.5%
Wisconsin	$867	$50	5.7%
Wyoming	$835	$121	14.5%
National Average	**$1,039**	**$73**	**7.0%**

Table 12 shows the impact on EMP protection on residential ratepayers if costs were to be allocated based on ratepayers’ annual expenditures for electricity. Ratepayers in states such as West Virginia would be forced to pay much more in rate increases than ratepayers in states such as Maryland and Virginia. This is because West Virginia exports large amounts of power to Maryland and Virginia. Essentially, under this allocation scheme, ratepayers in West Virginia would pay to protect power for those in other states.

Table 13: EMP Protection Cost Per Capita

State	Population (M)	Annualized EMP Protection Cost	Annual Cost Per Capita ($)
Alabama	4.9M	$1,052M	$216.37
Alaska	0.7M	$36M	$48.64
Arizona	6.9M	$591M	$85.32
Arkansas	3.0M	$480M	$160.55
California	39.3M	$1,293M	$32.95
Colorado	5.5M	$358M	$64.61
Connecticut	3.6M	$211M	$59.12
Delaware	1.0M	$75M	$79.04
District of Columbia	0.7M	$4M	$5.21
Florida	20.6M	$1,396M	$67.70
Georgia	10.3M	$1,040M	$100.83
Hawaii	1.4M	$53M	$36.87
Idaho	1.7M	$139M	$82.50
Illinois	12.8M	$1,184M	$92.47
Indiana	6.6M	$665M	$100.24
Iowa	3.1M	$298M	$94.98
Kansas	2.9M	$291M	$100.01
Kentucky	4.4M	$515M	$115.99
Louisiana	4.7M	$627M	$133.91
Maine	1.3M	$101M	$75.96
Maryland	6.0M	$299M	$49.75
Massachusetts	6.8M	$333M	$48.84
Michigan	9.9M	$741M	$74.62
Minnesota	5.5M	$410M	$74.34
Mississippi	3.0M	$507M	$169.76
Missouri	6.1M	$566M	$92.85

Table 13: EMP Protection Cost Per Capita – Continued

State	Population (M)	Annualized EMP Protection Cost	Annual Cost Per Capita ($)
Montana	1.0M	$132M	$126.35
Nebraska	1.9M	$243M	$127.25
Nevada	2.9M	$222M	$75.43
New Hampshire	1.3M	$108M	$81.07
New Jersey	8.9M	$428M	$47.85
New Mexico	2.1M	$251M	$120.82
New York	19.7M	$863M	$43.70
North Carolina	10.1M	$817M	$80.48
North Dakota	0.8M	$150M	$198.10
Ohio	11.6M	$774M	$66.65
Oklahoma	3.9M	$476M	$121.43
Oregon	4.1M	$341M	$83.19
Pennsylvania	12.8M	$1,024M	$80.09
Rhode Island	1.1M	$44M	$41.90
South Carolina	5.0M	$646M	$130.31
South Dakota	0.9M	$89M	$102.54
Tennessee	6.7M	$624M	$93.85
Texas	27.9M	$2,465M	$88.46
Utah	3.1M	$201M	$65.87
Vermont	0.6M	$27M	$42.90
Virginia	8.4M	$653M	$77.58
Washington	7.3M	$660M	$90.62
West Virginia	1.8M	$418M	$228.26
Wisconsin	5.8M	$422M	$73.06
Wyoming	0.6M	$196M	$334.90
Total	**323.1M**	**$25,537M**	**$79.03**

Table 13 shows the cost to protect assets on state-by-state basis, over a 10-year program, with costs allocated per capita. If funded nationally, the program described above would cost approximately $79 per resident per year for the life of the program. Per capita costs would vary dramatically by state, because citizens in low-population states that export large amounts of power would pay a disproportionate share of costs for EMP protection.

9. Benefits of EMP Protection

The benefits of EMP protection are substantial, because an EMP attack or severe solar storm could cause a nation-wide, long-term collapse of the electric grid. Economic activity could also collapse, and millions of deaths could result. For example, Lloyd's estimates a Carrington-class solar storm over North America could cause between $0.6 and $2.6 trillion in economic losses, where the area of impact is limited mostly to the Atlantic coast area. Because the Lloyd's estimate is based on a metric commonly used to estimate losses from power disruptions of a few hours, a long-term outage could result in far greater losses.

If an EMP protection program is implemented, society would pay the costs of protection with 100 percent certainty, while the risk-adjusted benefits of EMP protection depend on the probability of an adverse outcome occurring. Because an EMP attack depends on human volition, its probability cannot be definitively estimated, but the deterrent effect of EMP protection should weigh heavily on the willingness of an adversary to risk an attack. Extreme geomagnetic disturbance, on the other hand, is a naturally occurring phenomenon. According to published research, the probability of a severe solar storm is approximately 10 percent per decade or over 50 percent during a full human lifetime.

The National Institute of Building Sciences has found that for every dollar invested in mitigation, six dollars are saved in restoration.[45] We have seen from the COVID-19 pandemic that the U.S. economy can be drastically affected by unmitigated vulnerabilities. An EMP event could have economic impact several times greater than the COVID-19 pandemic.

Protecting the U.S. electric grid is essential to preserve operation of lifeline sectors, which include water, wastewater services, food, healthcare, transportation, fuel, and emergency services. Paramount of these are water and wastewater services, both dependent on electric power. Lack of water and sanitation could directly lead to illness and epidemics. Electricity is also critical in manufacturing medical supplies, operating oil refineries and chemical plants, and preserving supply chains for other vital goods. All critical infrastructures are interdependent with the electric grid. Protecting the U.S. electric grid from EMP protects the nation.

10. Conclusions

EMP protection for the U.S. bulk power system against HEMP from nuclear attack and GMD from solar storms would be a significant but affordable cost for American society. Using a transparent methodology, we assess the cost to be approximately $255 billion in total or $25.5 billion annually over ten years.

After a 10-year period to implement initial protection, maintenance costs would be incurred, as well as cost to protect equipment newly installed. As a first-order estimate, we propose that ongoing protection costs would be roughly equivalent to annual costs during the initial 10-year period.

These costs, while significant, would be a small percentage of the annual U.S. billings for electricity service, about 7% for the EIA billing data available for 2016. EMP protection would also be a small percentage of average per capita income within the United States; our estimated $79 per capita cost would be only 0.16% of mean per-capita income of $50,413 for 2018.

For comparison, our estimated annual cost of $25.5 billion would be about 5% of the annual U.S. defense budget and approximately 20% of capital expenditures for shareholder-owned electric utilities in 2018. The cost of EMP protection of the bulk power system, if implemented by regulation, would be within the same order of magnitude of other costly federal regulations. For example, the EPA estimates the Mercury and Air Toxics Rule, the costliest of EPA rules, to have an annual cost of $9.6 billion.[46]

This EMP protection program would protect much of the bulk power system. We would expect a program prioritized to protect only the most critical transmission assets and a sufficient amount of generation capacity to meet critical loads to cost less. Notably, our cost estimates for EMP protection do not include electricity distribution systems. Future study is needed for distribution protection, because distribution elements are important to support critical public services and load for blackstart.

A comprehensive program to protect only against GMD or the E3 component of HEMP would cost substantially less—approximately 1.6% of the cost of more comprehensive EMP protection.

We expect the E3 pulse from a HEMP attack to cause greater damage than a severe solar storm, exacerbated by the damage from the E1 pulse to computer and telecommunications systems. If long-term disruption of electricity supply via an EMP attack or solar storm were to cause a one-year loss of 50% of GDP, this avoided cost would be on the order of $10 trillion. Using the EPA standard of $7.4 million per avoided death, if an EMP attack or severe solar storm were to cause a long-term blackout and the deaths of 10 million Americans, this avoided cost would be on the order of $74 trillion.

In summary, while the costs of EMP protection would certainly be substantial, they should be manageable in terms of overall expenditures for American society and far less than losses from an attack or severe solar storm. Protection of the bulk power system from HEMP, while not being comprehensive for all of the electric grid, would likely change the calculus of potential attackers and thereby increase nuclear deterrence. Protection against GMD would be a small portion of overall EMP protection costs—and would have high payoff in reducing risks from unavoidable solar storms. Because EMP is an existential threat to the United States—and therefore nearly unlimited in its potential for societal damage—a multi-year program of EMP protection should be both justified and affordable, especially if protections were prioritized and implemented over realistic timeframes. Improved understanding of the scope and costs of needed EMP protections is essential.

11. Further Work

This report presents a framework for estimating the cost of EMP protection and an initial estimate of the cost to protect the bulk power system. With further research, improvements to the underlying methodology could and should be made. Within the transmission sector, these should include addition of protection strategies for voltage regulation devices and exposed digital devices in substations. The vulnerability of high-voltage transformers and circuit breakers has yet to be determined by test. Improvements to our cost estimation methodology for generating stations would have important impacts on the overall estimated cost of protection, given the lack of experience hardening such facilities and the high cost of protection. Better understanding of generation vulnerabilities will require engineering study and testing using EMP simulations; this work has been undertaken by the Defense Threat Reduction Agency. Refinements to the counts of equipment and facilities to be protected would significantly improve cost estimates, including prioritization strategies to maximize deterrence while minimizing costs.

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