PDHonline Course E402 (4 PDH)

Electromagnetic Pulse

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Electromagnetic Pulse
and its impact on the Electric Power Industry

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The photograph on the cover is of the July 1962 detonation of the Starfish Prime.

Introduction

An electromagnetic pulse (EMP) is a burst of electromagnetic radiation that results from the detonation of a nuclear weapon and/or a suddenly fluctuating magnetic field. The resulting rapidly changing electric fields and magnetic fields may couple with electric systems to produce damaging current and voltage surges.

In military terminology, a nuclear bomb detonated hundreds of kilometers above the Earth's surface is known as a high-altitude electromagnetic pulse (HEMP) device. Nuclear electromagnetic pulse has three distinct time components that result from different physical phenomena. Effects of a HEMP device depend on a very large number of factors, including the altitude of the detonation, energy yield, gamma ray output, interactions with the Earth's magnetic field, and electromagnetic shielding of targets. The high-altitude nuclear weapon-generated electromagnetic pulse (EMP) is one of a small number of threats that has the potential to hold society seriously at risk.

Briefly, a single nuclear weapon exploded at high altitude above the United States will interact with the Earth's atmosphere, ionosphere, and magnetic field to produce an electromagnetic pulse (EMP) radiating down to the Earth and additionally create electrical currents in the Earth. EMP effects are both direct and indirect. The former are due to electromagnetic "shocking" of electronics and stressing of electrical systems, and the latter arise from the damage that - upset, damaged, and destroyed - electronics controls then inflict on the systems in which they are embedded. The indirect effects can be even more severe than the direct effects.

The electromagnetic fields produced by weapons designed and deployed with the intent to produce EMP have a high likelihood of damaging electrical power systems, electronics, and information systems. Their effects on dependent systems and infrastructures could be sufficient to qualify as catastrophic to the U.S.

Depending on the specific characteristics of the attacks, unprecedented cascading failures of major infrastructures could result. The primary avenues for catastrophic damage are through the electric power infrastructure and thence into telecommunications, energy, and other infrastructures. These, in turn, can seriously impact other important aspects of life, including the financial system; means of getting food, water, and medical care to the citizenry; trade; and production of goods and services. The recovery of any one of the key national infrastructures is dependent on the recovery of others. The longer the outage, the more problematic and uncertain the recovery will be.

Because of the ubiquitous dependence on the electrical power system, its vulnerability to an EMP attack, coupled with the EMP's particular damage mechanisms, creates the possibility of long-term, catastrophic consequences. The implicit invitation to take advantage of this vulnerability, when coupled with increasing proliferation of nuclear weapons and their delivery systems, is a serious concern. A single EMP attack may seriously degrade or shut down a large part of the electric power grid in the geographic area of EMP exposure effectively instantaneously. There is also a possibility of functional collapse of grids beyond the exposed area, as electrical effects propagate from one region to another.

The time required for full recovery of service would depend on both the disruption and damage to the electrical power infrastructure and to other national infrastructures. Larger affected areas and stronger EMP field strengths will prolong the time to recover.

Widespread functional collapse of the electric power system in the area affected by EMP is likely.

There is a point in time at which the shortage or exhaustion of sustaining backup systems, including emergency power supplies, batteries, standby fuel supplies, communications, and manpower resources that can be mobilized, coordinated, and dispatched, together lead to a continuing degradation of critical infrastructures for a prolonged period of time.

Electrical power is necessary to support other critical infrastructures, including supply and distribution of water, food, fuel, communications, transport, financial transactions, emergency services, government services, and all other infrastructures supporting the national economy and welfare. Should significant parts of the electrical power infrastructure be lost for any substantial period of time, and the consequences are likely to be catastrophic, and many people may ultimately die for lack of the basic elements necessary to sustain life in dense urban and suburban communities. Such impacts are likely in the event of an EMP attack unless practical steps are taken to provide protection for critical elements of the electric system and for rapid restoration of electric power, particularly to essential services. The recovery plans for the individual infrastructures currently in place essentially assume, at worst, limited upsets to the other infrastructures that are important to their operation. Such plans may be of little or no value in the wake of an EMP attack because of its long-duration effects on all infrastructures that rely on electricity or electronics.

This course looks at the history of EMP effects as well as other catastrophic events to the electric power grid. The course explains the technical aspects of EMP, described the electric power system structure, and provides an overview of the vulnerabilities and mitigation options that electric utilities may employ to protect their systems from the effects of EMP.

Chapter 1
History of Electromagnetic Pulse

To understand how an electromagnetic pulse may impact and disrupt the electric grid we can look at history to see the inadvertent impact of above ground nuclear tests during the last century and we can look at how other major electrical grid disruptions have affected the electric system. We will first look at nuclear tests from the 1940's through the 1960's.

EMP Results from Nuclear Tests

The fact that an electromagnetic pulse is produced by a nuclear explosion was known since the earliest days of nuclear weapons testing, but the magnitude of the EMP and the significance of its effects were not realized for some time.

During the first United States nuclear test in July 1945, electronic equipment was shielded due to Enrico Fermi's expectation of an electromagnetic pulse from the detonation. The official technical history for that first nuclear test states, "All signal lines were completely shielded, in many cases doubly shielded. In spite of this many records were lost because of spurious pickup at the time of the explosion that paralyzed the recording equipment." During British nuclear testing in 1952–1953 there were instrumentation failures that were attributed to "radio flash," which was then the British term for EMP.

The high altitude nuclear tests of 1962, as described below, increased awareness of EMP beyond the original small population of nuclear weapons scientists and engineers. The larger scientific community became aware of the significance of the EMP problem after a series of three articles were published about nuclear electromagnetic pulse in 1981 by William J. Broad in the weekly publication Science.

In July 1962, a 1.44 megaton United States nuclear test in space, 400 kilometers above the mid-Pacific Ocean, called the *Starfish Prime test*, demonstrated to nuclear scientists that the magnitude and effects of a high altitude nuclear explosion were much larger than had been previously calculated. Starfish Prime also made those effects known to the public by causing electrical damage in Hawaii, about 900 miles away from the detonation point, knocking out about 300 streetlights, setting off numerous burglar alarms and damaging a telephone company microwave link.

The EMP damage of the Starfish Prime test was quickly repaired because of the ruggedness of the electrical and electronic infrastructure of Hawaii in 1962. Realization of the potential impacts of EMP became more apparent to some scientists and engineers during the 1970s as more sensitive solid-state electronics began to come into widespread use.

Starfish Prime was the first successful test in the series of United States high-altitude nuclear tests in 1962 known as *Operation Fishbowl*. The subsequent Operation Fishbowl tests gathered more data on the high-altitude EMP phenomenon.

The *Bluegill Triple Prime* and *Kingfish* high-altitude nuclear tests of October and November 1962 in Operation Fishbowl finally provided electromagnetic pulse data that was clear enough to enable physicists to accurately identify the physical mechanisms that were producing the electromagnetic pulses.

The images in Figure 1 below were taken of the U.S. nuclear tests between 1958 and 1962. The images, from left to right, are the Orange, Teak, Kingfish, Checkmate and Starfish high altitude tests, which were conducted near Johnston Island in the Pacific Ocean. As you can see in the images, burst conditions for each were unique, and each produced strikingly different phenomena and different enhancements of the radiation belts.

Figure 1

The relatively small magnitude of the Starfish Prime EMP in Hawaii (about 5.6 kV/meter) and the relatively small amount of damage done (for example, only 3 percent of streetlights extinguished) led some scientists to believe, in the early days of EMP research, that the problem might not be as significant as was later realized. Newer calculations showed that if the Starfish Prime warhead had been detonated over the northern continental United States, the magnitude of the EMP would have been much larger (22 to 30 kV/meter) because of the greater strength of the Earth's magnetic field over the United States, as well as the different orientation of the Earth's magnetic field at high latitudes. These new calculations, combined with the accelerating reliance on EMP-sensitive microelectronics, heightened awareness that the EMP threat could be a very significant problem.

In 1962, the Soviet Union also performed a series of three EMP-producing nuclear tests in space over Kazakhstan, which were the last in the series called *The K Project*. Although these weapons were much smaller (300 kilotons) than the Starfish Prime test, since those tests were done over a populated large land mass (and also at a location where the Earth's magnetic field was greater), the damage caused by the resulting EMP was reportedly much greater than in the

Starfish Prime nuclear test. The geomagnetic storm-like E3 pulse even induced an electric current surge in a long underground power line that caused a fire in the power plant in the city of Karaganda. After the collapse of the Soviet Union, the level of this damage was communicated informally to scientists in the United States. Formal documentation of some of the EMP damage in Kazakhstan exists but is still sparse in the open scientific literature.

Catastrophic events that have impacted the Electric Grid

While no single event serves as a model for an EMP scenario with incidence of long lasting widespread power outage, communications failure, and other effects, the combined analysis of the following case studies provides useful insight in determining human reactions following an EMP attack.

In 1965, a blackout occurred over the northeastern United States and parts of Canada. New Hampshire; Vermont; Massachusetts; Connecticut; Rhode Island; New York, including metropolitan New York City; and a small part of Pennsylvania were in the dark after operators at Consolidated Edison were forced to shut down its generators to avoid damage. Street traffic was chaotic, and some people were trapped in elevators, but there were few instances of antisocial behavior while the lights were out. It was a "long night in the dark," but the recovery proceeded without incident, and citizens experienced relative civility.

In contrast, TIME Magazine described New York's next blackout, in 1977, as a "Night of Terror." Widespread chaos reigned in the city until power was restored — entire blocks were looted and set ablaze, people flipped over cars and vans on the streets; the city was in pandemonium. That night thousands of arrests were made, and certainly not all looters, thieves, and arsonists were apprehended or arrested. While this is a dramatic example of antisocial behavior following a blackout, sociologists point to extraordinary demographic and historical issues that contributed to the looting. For instance, extreme poverty and socioeconomic inequality plagued New York neighborhoods, and many of the looters originated from the poorer sections of the city, engaging in "vigilante redistribution" by looting consumer goods and luxuries. Racial tensions were high, and a serial killer known as Son of Sam had recently terrorized New Yorkers.

In 1989, more than six million customers lost power when a geomagnetic storm caused a massive power failure in Quebec. The electricity failures caused by this geomagnetic storm reached a much larger area than is typically affected by traditional blackouts resulting from technological failure. However, the outage lasted just over nine hours, most of which were during the day. The local and national papers were curiously silent about the blackout, and little to no unusual or adverse human behavior was attributed to the power loss. The event was most significantly a lesson for operators of the North American electric grids because it revealed vulnerabilities in the system.

In 1998, Auckland, New Zealand, experienced a significant blackout that lasted more than five weeks and affected more than one million people. Civility reigned for the duration of the outage, which was likely attributed to a number of factors, including:

- There was no significant threat to public health, because water and sewage infrastructures were functioning,
- In anticipation of potential incidents, police increased their presence in urban areas,
- The recovery process was underway nearly immediately, communicating to the public that the situation would eventually be under control, and
- Nearly all blackout recovery resources of New Zealand were rushed to the capital for recovery efforts.

Recovery efforts from elsewhere in New Zealand were significant symbolically as well as practically, as demonstrated by the fact that electricity was available elsewhere. Businesses attempted to carry on as normally as possible, with some examples of opportunism, such as businesses relocating to more desirable spaces that had been vacated. Social consequences included criticism and blame of the authorities, both municipal and national, because the technological failures were attributed in large part to privatization of the power sector. However, this response never materialized into violence, crime, or social disorder.

Most recently, New York City and the eight states in the northeast experienced another significant blackout in August 2003. While the blackout inconvenienced many on a hot summer day, general civility remained intact. News coverage indicated that those affected by the blackout dealt with the obstacles quietly and even developed a sort of camaraderie while struggling through nights without running water and electricity. In contrast to the 1977 blackout, police made less than 1,000 arrests the night of the 2003 blackout, of which “only 250 to 300 were directly attributable to the blackout,” indicating a slight decline from the average number of arrests on a given summer day. While this blackout was widespread, it was not long lasting, and it did not interrupt the communications infrastructure significantly.

Chapter 2
Characteristics of EMP

High-altitude EMP results from the detonation of a nuclear warhead at altitudes of about 40 to 400 kilometers above the Earth's surface. The immediate effects of EMP are disruption of, and damage to, electronic systems and electrical infrastructure. EMP is not reported in the scientific literature to have direct effects on people in the parameter range of present interest.

As previously mentioned, EMP and its effects were observed during the U.S. and Soviet atmospheric test programs in 1962. Figure 2 depicts the Starfish nuclear detonation—not designed or intended as a generator of EMP—at an altitude of about 400 kilometers above Johnston Island in the Pacific Ocean. In this Figure, the widespread red air glow amid dark clouds, caused mostly by x-ray-excited atomic oxygen (i.e., oxygen by photoelectrons liberated by Starfish X-rays.) Some electronic and electrical systems in the Hawaiian Islands, 900 miles distant, were affected, causing the failure of street-lighting systems, tripping of circuit breakers, triggering of burglar alarms, and damage to a telecommunications relay facility. In their testing that year, the Soviets executed a series of nuclear detonations in which they exploded 300 kiloton weapons at approximately 300, 150, and 60 kilometers above their test site in South Central Asia. They report that on each shot they observed damage to overhead and underground buried cables at distances of 600 kilometers. They also observed surge arrestor burnout, spark-gap breakdown, blown fuses, and power supply breakdowns.

Figure 2

What is significant about an EMP attack is that one or a few high-altitude nuclear detonations can produce EMP effects that can potentially disrupt or damage electronic equipment.

Basic Overview of EMP

Gamma rays from a high-altitude nuclear detonation interact with the atmosphere to produce a radio-frequency wave of unique, spatially varying intensity that covers everything within line-of-sight of the explosion's center point. It is useful to focus on three major EMP components.

The case of a nuclear electromagnetic pulse differs from other kinds of electromagnetic pulse in being a complex electromagnetic multi-pulse. The complex multi-pulse is usually described in terms of three components, and these three components have been defined as such by the International Electrotechnical Commission (IEC). The three components of nuclear EMP, as defined by the IEC, are called E1, E2 and E3. See Figure 3 below.

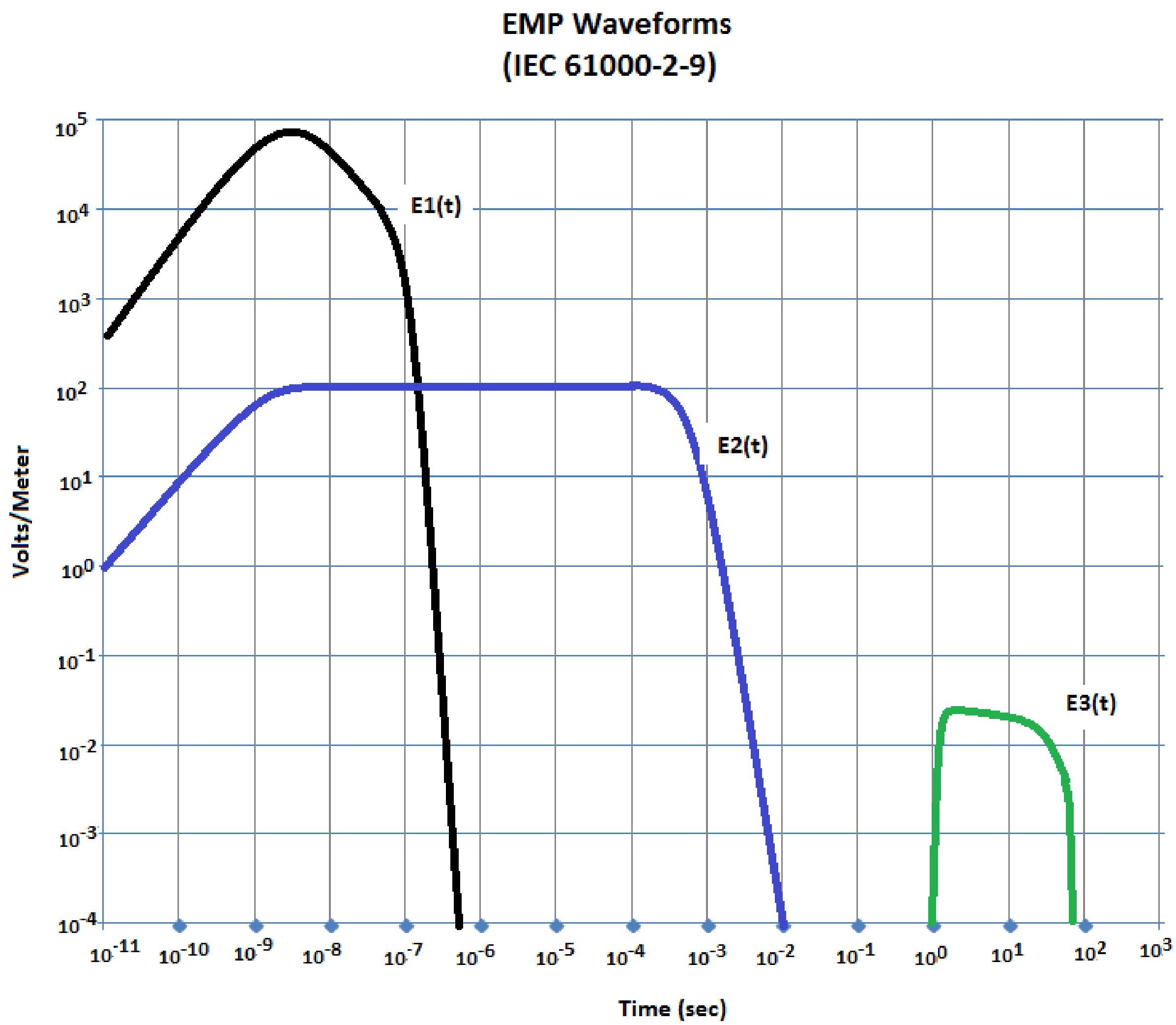


Figure 3

The E1 Pulse is the early time portion of the EMP and it arrives at the Earth's surface quickly and lasts about 1 microsecond. It is a fast spike and its energy is concentrated in the frequency band between one to several hundred megahertz

The E2 pulse is the intermediate portion of the EMP and occurs between 1 microsecond and 0.1 seconds. It frequency band is between 1 Hz and 100 kHz.

The E3 Pulse is the late time portion of the EMP and occurs between 0.1 seconds and several minutes. This pulse is characterized as a low amplitude, very low frequency signal.

Each pulse, E1, E2, and E3 are discussed in more detail below.

E1 Pulse

The first component is a free-field energy pulse with a rise-time measured in the range of a fraction of a billionth to a few billionths of a second. It is the "electromagnetic shock" that disrupts or damages electronics-based control systems, sensors, communication systems, protective systems, computers, and similar devices. Its damage or functional disruption occurs essentially simultaneously over a very large area, as illustrated in Figure 4.

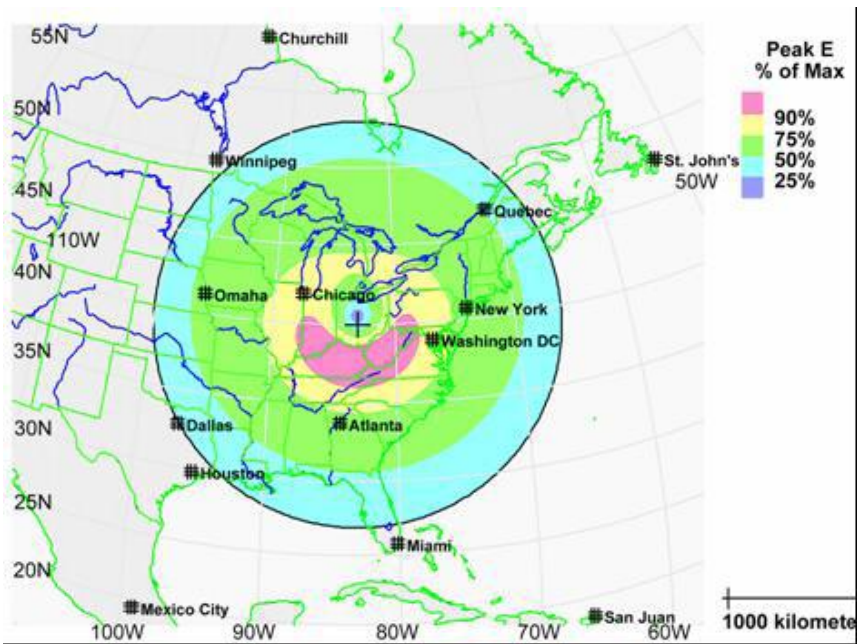


Figure 4

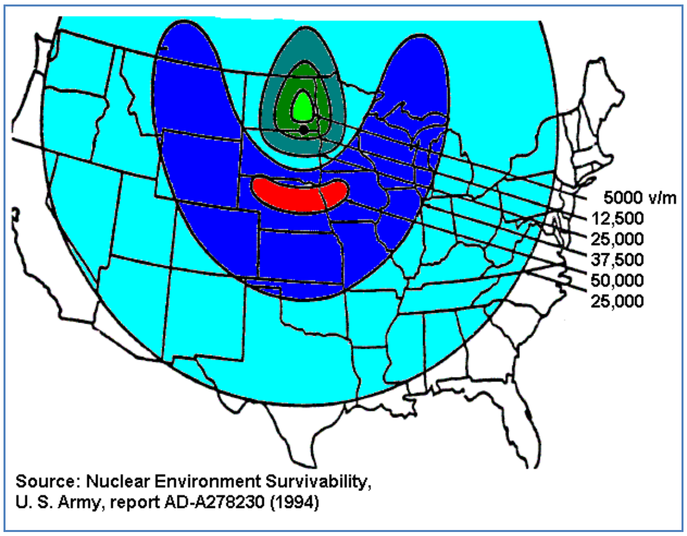
The E1 pulse is the very fast component of nuclear EMP. The E1 component is a very brief but intense electromagnetic field that can quickly induce very high voltages in electrical conductors. The E1 component causes most of its damage by causing electrical breakdown voltages to be exceeded. E1 is the component that can destroy computers and communications equipment and it changes too fast for ordinary lightning protectors to provide effective protection against it.

The E1 component is produced when gamma radiation from the nuclear detonation knocks electrons out of the atoms in the upper atmosphere. The electrons begin to travel in a generally downward direction at relativistic speeds (more than 90 percent of the speed of light). In the absence of a magnetic field, this would produce a large pulse of electric current vertically in the upper atmosphere over the entire affected area. The Earth's magnetic field acts on these electrons to change the direction of electron flow to a right angle to the geomagnetic field. This interaction of the Earth's magnetic field and the downward electron flow produces a very large, but very brief, electromagnetic pulse over the affected area.

The typical gamma rays given off by the weapon have an energy of about 2 MEV (million electron volts). When these gamma rays collide with atoms in the mid-stratosphere, the gamma rays knock out electrons. This is known as the *Compton Effect*, and the resulting electrons produce an electric current that is known as the Compton current. The gamma rays transfer about half of their energy to the electrons, so these initial electrons have an energy of about 1 MEV. This causes the electrons to begin to travel in a generally downward direction at about 94 percent of the speed of light. Relativistic effects cause the mass of these high energy electrons to increase to about three times their normal rest mass. If there were no geomagnetic field and no additional atoms in the lower atmosphere for additional collisions, the electrons would continue to travel downward with an average current density in the stratosphere of about 48 amps per square meter.

Compton scattering is a scattering of a photon by a free charged particle, usually an electron. It results in a decrease in energy (increase in wavelength) of the photon (which may be an X-ray or gamma ray photon), called the ***Compton effect***.

Part of the energy of the photon is transferred to the scattering electron.



Because of the downward tilt of the Earth's magnetic field at high latitudes, the area of peak field strength is a U-shaped region to the equatorial side of the nuclear detonation. As shown in Figure 5 for nuclear detonations over the continental United States, this U-shaped region is south of the detonation point. Near the equator, where the Earth's magnetic field is more nearly horizontal, the E1 field strength is more nearly symmetrical around the burst location.

Figure 5

The mechanism for a 400 km high altitude burst EMP begin when gamma rays hit the atmosphere between 20–40 km altitude, ejecting electrons which are then deflected sideways by the Earth's magnetic field. This makes the electrons radiate EMP over a massive area. Because of the curvature and downward tilt of Earth's magnetic field over the U.S., the maximum EMP occurs south of the detonation and the minimum occurs to the north.

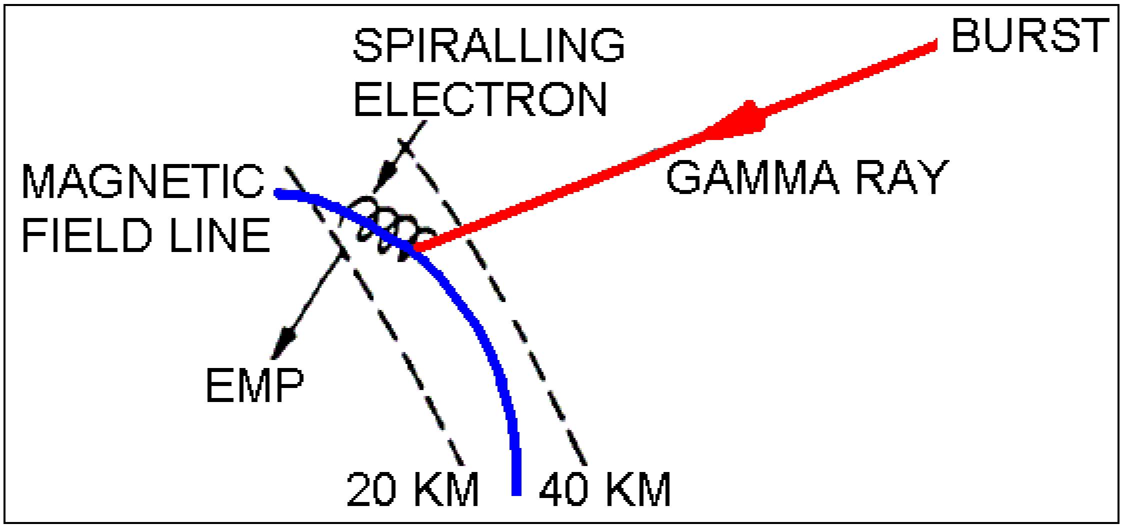


Figure 6

As we can see in Figure 6, the Earth's magnetic field quickly deflects the electrons at right angles to the geomagnetic field, and the extent of the deflection depends upon the strength of the magnetic field. At geomagnetic field strengths typical of the central United States, central Europe or Australia, these initial electrons spiral around the magnetic field lines in a circle with a typical radius of about 85 meters. These initial electrons are stopped by collisions with other air molecules at an average distance of about 170 meters. This means that most of the electrons are stopped by collisions with air molecules before they can complete one full circle of its spiral around the Earth's magnetic field lines.

This interaction of the very rapidly moving negatively charged electrons with the magnetic field radiates a pulse of electromagnetic energy. The pulse typically rises to its peak value in about 5 nanoseconds. The magnitude of this pulse typically decays to half of its peak value within 200 nanoseconds. (By the IEC definition, this E1 pulse is ended at one microsecond (1,000 nanoseconds) after it begins.) This process occurs simultaneously with about 1,025 other electrons.

There are a number of secondary collisions which cause the subsequent electrons to lose energy before they reach ground level. The electrons generated by these subsequent collisions have such reduced energy that they do not contribute significantly to the E1 pulse.

Gamma-rays have the smallest wavelengths and the most energy of any other wave in the electromagnetic spectrum. These waves are generated by radioactive atoms and in nuclear explosions.

These 2 MEV gamma rays will normally produce an E1 pulse near ground level at moderately high latitudes that peaks at about 50,000 volts per meter. This is a peak power density of 6.6 megawatts per square meter.

The process of the gamma rays knocking electrons out of the atoms in the mid-stratosphere causes this region of the atmosphere to become an electrical conductor due to ionization, a process which blocks the production of further electromagnetic signals and causes the field strength to saturate at about 50,000 volts per meter. The strength of the E1 pulse depends upon the number and intensity of the gamma rays produced by the weapon and upon the rapidity of the gamma ray burst from the weapon. The strength of the E1 pulse is also somewhat dependent upon the altitude of the detonation.

There are reports of "super-EMP" nuclear weapons that are able to overcome the 50,000 volt per meter limit by the very nearly instantaneous release of a burst of gamma radiation of much higher energy levels than are known to be produced by second generation nuclear weapons. However, the construction details of these weapons are classified.

E2 Pulse

The middle-time component covers roughly the same geographic area as the first component and is similar to lightning in its time-dependence, but is far more geographically widespread in its character and somewhat lower in amplitude. In general, it would not be an issue for critical infrastructure systems since they have existing protective measures for defense against occasional lightning strikes. The most significant risk is synergistic, because the E2 component follows a small fraction of a second after the first component’s impact, which has the ability to impair or destroy many protective and control features. The energy associated with the second component thus may be allowed to pass into and damage systems.

The E2 component is generated by scattered gamma rays and inelastic gammas produced by weapon neutrons. This E2 component is an "intermediate time" pulse that, by the IEC definition, lasts from about 1 microsecond to 1 second after the beginning of the electromagnetic pulse. The E2 component of the pulse has many similarities to the electromagnetic pulses produced by lightning, although the electromagnetic pulse induced by a nearby lightning strike may be considerably larger than the E2 component of a nuclear EMP. Because of the similarities to lightning-caused pulses and the widespread use of lightning protection technology, the E2 pulse is generally considered to be the easiest to protect against. The main potential problem with the E2 component is the fact that it immediately follows the E1 component, which may have damaged the devices that would normally protect against E2.

Therefore E2 pulses alone are not an issue for critical infrastructure systems since there are existing protective measures for defense against occasional lightning strikes. The most significant risk is synergistic, because the E2 component follows a small fraction of a second after the first component's impact, which has the ability to impair or destroy many protective and control features. The energy associated with the second component thus may be allowed to pass into and damage systems.

E3 Pulse

The final major component of EMP is a subsequent, slower-rising, longer-duration pulse that creates disruptive currents in long electricity transmission lines, resulting in damage to electrical supply and distribution systems connected to such lines. The sequence of E1, E2, and then E3 components of EMP is important because each can cause damage, and the later damage can be increased as a result of the earlier damage. About 70% of the total electrical power load of the United States may be exposed to an EMP event.

The E3 component is very different from the other two major components of nuclear EMP. The E3 component of the pulse is a very slow pulse, lasting tens to hundreds of seconds, that is caused by the nuclear detonation heaving the Earth's magnetic field out of the way, followed by the restoration of the magnetic field to its natural place. The E3 component has similarities to a geomagnetic storm caused by a very severe solar flare. Like a geomagnetic storm, E3 can produce geo-magnetically induced currents in long electrical conductors, which can then damage components such as power line transformers. Solar flares, such as shown in the photograph in Figure 7 create geomagnetically induced currents in power lines.

Figure 7

Because of the similarity between solar-induced geomagnetic storms and nuclear E3, it has become common to refer to solar-induced geomagnetic storms as "solar EMP." At ground level, however, "solar EMP" is not known to produce an E1 or E2 component.

Generation of nuclear EMP

Several major factors control the effectiveness of a nuclear EMP weapon. These are:

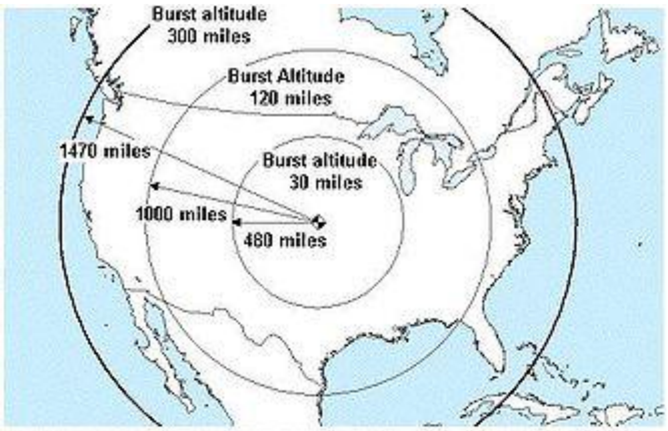
- The altitude of the weapon when detonated,
- The yield and construction details of the weapon,
- The distance from the weapon when detonated,
- Geographical depth or intervening geographical features, and
- The local strength of the Earth's magnetic field.

Beyond a certain altitude a nuclear weapon will not produce any EMP, as the gamma rays will have had sufficient distance to disperse.

Burst Altitude

A high-altitude nuclear detonation produces an immediate flux of gamma rays from the nuclear reactions within the device. These photons in turn produce high energy free electrons by Compton scattering at altitudes between 20 and 40 km. These electrons are then trapped in the Earth's magnetic field, giving rise to an oscillating electric current. This current is asymmetric in general and gives rise to a rapidly rising radiated electromagnetic field called an electromagnetic pulse (EMP). Because the electrons are trapped essentially simultaneously, a very large electromagnetic source radiates coherently.

The pulse can easily span continent-sized areas, and this radiation can affect systems on land, sea, and air. A large device detonated at 400–500 km over Kansas would affect all of the continental U.S. The signal from such an event extends to the visual horizon as seen from the burst point. See Figure 8 below.



EMP AREA BY BURSTS AT 30, 120 and 300 MILES
Gary Smith, "Electromagnetic Pulse Threats", testimony to House National Security Committee on July 16, 1997

Figure 8

Thus, for equipment to be affected, the weapon needs to be above the visual horizon. Because of the nature of the pulse as a large, high powered, noisy spike, it is doubtful that there would be much protection if the explosion were seen in the sky just below the tops of hills or mountains.

The area covered by an EMP is dependent on the altitude of the detonation and the yield of the weapon. Assuming a yield of sufficient strength the ground coverage can be estimated from the following formula,

$$\mathbf{R_t = R_e * \cos^{-1}\frac{R_e}{R_e + HOB} * 0.62}$$

Where,

Rt = Radius of the area affected, miles.

Re = Average radius of the Earth, kilometers (assumed to be 6,370 km)

HOB = Height of blast, km
$\cos^{-1}$ = Arc Cosine, radians.

(please note, this equation is in radians.)

For example, what is the expected coverage of a high yield EMP weapon detonated at 40 kilometers?

$$R_t = 6{,}370 * \cos^{-1} \frac{6{,}370}{6{,}370+40} * 0.62$$

R_t = 442 miles.

Weapon yield

Typical nuclear weapon yields used during Cold War planning for EMP attacks were in the range of 1 to 10 megatons. This is roughly 50 to 500 times the sizes of the weapons the United States used in Japan at Hiroshima and Nagasaki. Weapons with yields of 10 kilotons or less can also produce a very large EMP.

See Figure 9 for the relationship between prompt gamma output and electric fields as a function of burst altitude.

The weapon yield is the prompt gamma ray output measured in kilotons. This varies from 0.115–0.5% of the total weapon yield, depending on weapon design. The 1.4 Mt total yield of the 1962 Starfish Prime test had a gamma output of 0.1%, hence 1.4 kt of prompt gamma rays.

(The blue 'pre-ionization' curve applies to certain types of thermonuclear weapon, where gamma and x-rays from the primary fission stage ionize the atmosphere and make it electrically conductive before the main pulse from the thermonuclear stage. The pre-ionization in some situations can literally short out part of the final EMP, by allowing a conduction current to immediately oppose the Compton current of electrons.)

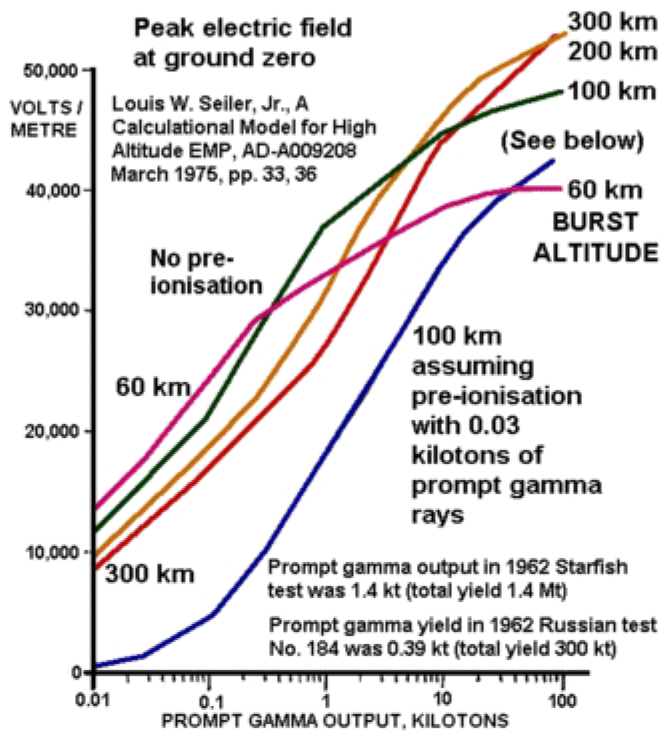


Figure 9

The EMP at a fixed distance from a nuclear weapon does not depend directly on the yield but at most only increases as the square root of the yield. This means that although a 10 kiloton weapon has only 0.7% of the total energy release of the 1.44-megaton Starfish Prime test, the EMP will be at least 8% as powerful. Since the E1 component of nuclear EMP depends on the prompt gamma ray output, which was only 0.1% of yield in Starfish Prime but can be 0.5% of yield in pure fission weapons of low yield, a 10 kiloton bomb can easily be 40% as powerful as the 1.44 megaton Starfish Prime at producing EMP.

The total prompt gamma ray energy in a fission explosion is 3.5% of the yield, but in a 10 kiloton detonation the high explosive around the bomb core absorbs about 85% of the prompt gamma rays, so the output is only about 0.5% of the yield in kilotons. In the thermonuclear Starfish Prime the fission yield was less than 100% to begin with, and then the thicker outer casing absorbed about 95% of the prompt gamma rays from the pusher around the fusion stage. Thermonuclear weapons are also less efficient at producing EMP because the first stage can pre-ionize the air which becomes conductive and hence rapidly shorts out the electron Compton currents generated by the final, larger yield thermonuclear stage. Hence, small pure fission weapons with thin cases are far more efficient at causing EMP than most megaton bombs. This analysis, however, only applies to the fast E1 and E2 components of nuclear EMP. The geomagnetic storm-like E3 component of nuclear EMP is more closely proportional to the total energy yield of the weapon.

Weapon distance

A unique and important aspect of nuclear EMP is that all of the components of the electromagnetic pulse are generated outside of the weapon. The important E1 component is generated by interaction with the electrons in the upper atmosphere that are hit by gamma radiation from the weapon — and the subsequent effects upon those electrons by the Earth's magnetic field.

For high-altitude nuclear explosions, this means that much of the EMP is actually generated at a large distance from the detonation (where the gamma radiation from the explosion hits the upper atmosphere). This causes the electric field from the EMP to be remarkably uniform over the large area affected.

The peak electric field (and its amplitude) at the Earth's surface from a high-altitude burst will depend upon the explosion yield, the height of the burst, the location of the observer, and the orientation with respect to the geomagnetic field. As a general rule, however, the field strength may be expected to be tens of kilovolts per meter over most of the area receiving the EMP radiation. And over most of the area affected by the EMP the electric field strength on the ground would exceed 0.5 E_{max}. For yields of less than a few hundred kilotons, this would not necessarily be true because the field strength at the Earth's tangent could be substantially less than 0.5 E_{max}. (E_{max} refers to the maximum electric field strength in the affected area.) In other words, the electric field strength in the entire area that is affected by the EMP will be fairly uniform for weapons with a large gamma ray output; but for much smaller weapons, the electric field may fall off at a comparatively faster rate at large distances from the detonation point. It is the peak electric field of the EMP that determines the peak voltage induced in equipment and other electrical conductors on the ground, and most of the damage is determined by induced voltages.

For nuclear detonations within the atmosphere, the situation is more complex. Within the range of gamma ray deposition, simple laws no longer hold as the air is ionized and there are other EMP effects, such as a radial electric field due to the separation of Compton electrons from air molecules, together with other complex phenomena. For a surface burst, absorption of gamma rays by air would limit the range of gamma ray deposition to approximately 10 miles, while for a burst in the lower-density air at high altitudes, the range of deposition would be far greater.

Non-nuclear electromagnetic pulse

Non-nuclear electromagnetic pulse (NNEMP) is an electromagnetic pulse generated without use of nuclear weapons. There are a number of devices that can achieve this objective, ranging from a large low-inductance capacitor bank discharged into a single-loop antenna or a microwave generator to an explosively pumped flux compression generator. To achieve the frequency characteristics of the pulse needed for optimal coupling into the target, wave-shaping circuits and/or microwave generators are added between the pulse source and the antenna.

NNEMP generators can be carried as a payload of bombs and cruise missiles, allowing construction of electromagnetic bombs with diminished mechanical, thermal and ionizing radiation effects and without the political consequences of deploying nuclear weapons.

The range of NNEMP weapons (non-nuclear electromagnetic bombs) is severely limited compared to nuclear EMP. This is because nearly all NNEMP devices used as weapons require chemical explosives as their initial energy source, but nuclear explosives have an energy yield on the order of one million times that of chemical explosives of similar weight. In addition to the large difference in the energy density of the initial energy source, the electromagnetic pulse from NNEMP weapons must come from within the weapon itself, while nuclear weapons generate EMP as a secondary effect, often at great distances from the detonation. These facts severely limit the range of NNEMP weapons as compared to their nuclear counterparts, but allow for more surgical target discrimination.

Chapter 3
Electric Power Infrastructure

The electrical power system is the largest single capital-intensive infrastructure in North America. It is an enormously complex system of systems containing fuel production, gathering and delivery systems, electrical generators, electrical transmission systems, control systems of all types, and distribution systems right down to the electrical outlet and interconnection at the point of use. It is this vast array of systems and components all acting in concert, integrated into a cohesive whole to deliver electrical power at the point of use, with supply-on-demand at a uniform frequency that provides the reliable, steady, and adequate electric supply on which everyone has come to expect and depend.

Today, the existing electrical system at peak demand periods increasingly operates at or near reliability limits of its physical capacity. Modern electronics, communications, protection, control and computers have allowed the physical system to be utilized fully with ever smaller margins for error. Therefore, a relatively modest upset to the system can cause functional collapse. As the system grows in complexity and interdependence, restoration from collapse or loss of significant portions of the system becomes exceedingly difficult. Over the last decade or two, relatively few new large-capacity electric transmission capabilities have been constructed and most of the additions to generation capacity that have been made have been located considerable distances from load for environmental, political, and economic reasons, adding stress and further limiting the system's ability to withstand disruption. Significant elements of the system, including many generating plants, are aging and becoming less reliable or are under pressure to be retired for environmental considerations, further exacerbating the situation.

The electrical power system routinely experiences disruptions. In most cases, the cause is the failure of one or a small number of components. The overall system has a degree of durability against such failures, although in some cases failures lead to a cascading loss of power up to a regional level that extends over relatively short to moderate periods of time. The current strategy for recovering from such failures is based on the assumption of sporadic failures of small numbers of components, and for larger failures, drawing on resources from outside the affected area. This strategy is not suitable to respond effectively to an EMP attack that would potentially result in damage to vast numbers of components nearly simultaneously over an unprecedented geographic scale.

The magnitude of an EMP event varies with the type, design and yield of the weapon, as well as its placement. Even a relatively modest-to-small yield weapon of particular characteristics can produce a potentially devastating E1 field strength over very large geographical regions. This followed by E2 impacts, and in some cases serious E3 impacts operating on electrical components left relatively unprotected by E1, can be extremely damaging.

Major Components in the Electric Power Infrastructure

There are three major elements of the electrical power infrastructure: (1) generation, (2) transmission (relatively high voltage for long distances), and (3) distribution, whose elements are interdependent, yet distinct (see Figure 10).

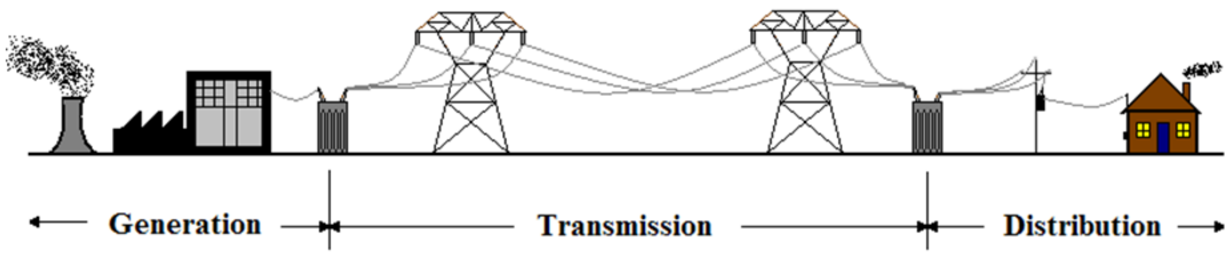


Figure 10

Generation

Power plants convert energy that is in some other form into electricity. The initial form of the energy can be mechanical (hydro, wind, or wave), chemical (hydrogen, coal, petroleum, refuse, natural gas, petroleum coke, or other solid combustible fuel), thermal (geothermal or solar), or nuclear. Power plants can range from single solar cells to huge central station complexes. In most circumstances the first stage of generation converts the original form of energy into rotational mechanical energy, as occurs in a turbine. The turbine then drives a generator.

Modern power plants all utilize complex protection and control systems to maximize efficiency and provide safety. They all have common electrical characteristics in order for them to be useable by all the various purposes to which electricity is put. Electronics have largely replaced all the electromechanical devices in older plants and are used exclusively in plants of the past one or two decades. Even generator exciters now have microprocessors and analog-to-digital converters. These electronics and, thus, the power plant itself are highly vulnerable to EMP assault. Identifying and locating damaged generation plant equipment with electronic sensors and communication interdicted and/or unreliable due to EMP and repairing the system would be a complex and time-consuming process, even when personnel and parts are readily available.

The fossil fuel supply system (coal, oil, wood, and natural gas) is largely dependent on electronics for its production and delivery of adequate fuel to the generators to produce nearly 75 percent of the electricity generated in the United States. There should not be a direct and immediate impact on the fuel supply for a nuclear power plant. The interdependency between the fuel necessary to generate electricity and the electricity and electronics to deliver the fuel is critical to the recovery. For example, natural gas normally is delivered just in time while oil and coal have some at-site storage. Nuclear generation supplies a major portion of the remainder of the U.S.'s electricity. It is unlikely for the timing of an EMP attack to be such that it would directly and immediately impact the fuel supply for a nuclear power plant. Of the balance, hydroelectric plants have their own fuel supplies as do geothermal, solar, and wind systems. However, wind and solar may or may not be generating in any event, given their inherent uncertainty. Hydro and geothermal are significant capabilities, but they are highly localized.

Transmission

Electrical power from the various power plants travels over a system of lines and substations to the regions and locales where it will be consumed. The transmission system moves large amounts of power generally over substantial distances and/or to directly serve very large electrical loads. This definition separates it from the distribution system, which is described below. Transmission includes lines (wires strung from insulator strings on towers or underground in special insulated containers) and substations (points where several lines intersect and protection and control functions are implemented). Within substations there are transformers (which transform power from one voltage to another); breakers (similar to on-and-off switches able to handle the large amounts of energy passing through); and protective devices, meters, and data transmitting and control systems. Protective devices protect the electrical components from unusual electrical disturbances that occur from time to time for many different reasons as well as for general safety reasons.

The delivery of electrical power across or through some medium, such as a wire, encounters resistance, which itself takes power to overcome. Electrical power is measured by the product of voltage and current. The electrical resistive losses (restricting the flow) are proportional to the square of the current. Thus it is most efficient to transmit power at the minimum current that is practical (this results in the highest voltage for the same amount of power). Otherwise, more power is consumed just to push the electricity through or over a path with higher resistance.

The drawing in Figure 11 shows the high-voltage transmission network in the United States.

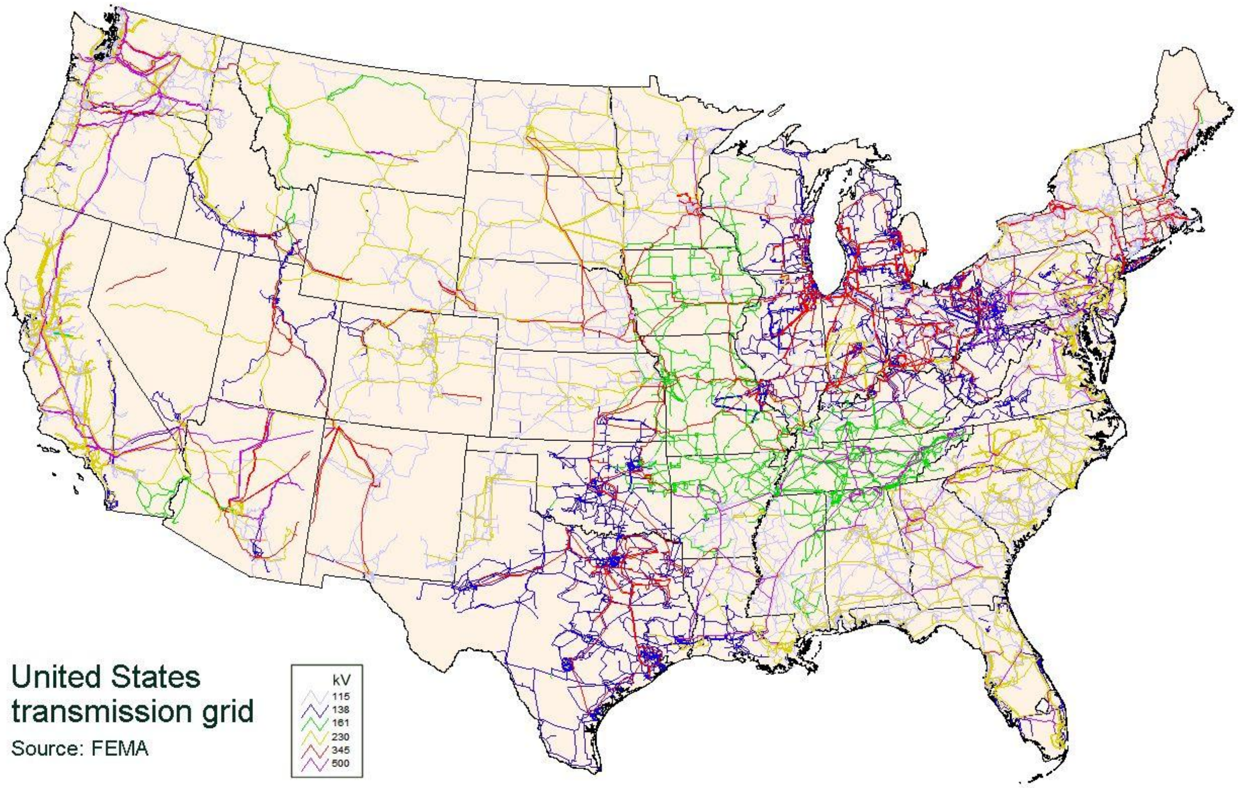


Figure 11

Standard values for modern alternating current (AC) transmission line voltage range from 115 kV to 765 kV, although some 1,100 kV transmission has been developed and tested. The current carried by these lines is typically up to a few thousand amps. Direct current (DC) is also used in some instances for moving large amounts of power great distances and for controlling the flow itself. The normal point of use of electricity is AC and thus the shift from AC to DC and back from DC to AC makes DC uneconomical other than in special circumstances. The use of DC is increasing, however, as power costs continue to grow and the technology to shift from AC to DC and back becomes less expensive. Transformers within the substations are used to move the voltage from one line or power plant up to or down to another voltage while maintaining essentially the same level of power.

Distribution

Loads or end users of electricity (residences, commercial establishments, and even most industry) require electrical power to be available in the voltages needed in adequate supply when they need it. This often means in relatively small quantities at low voltage and current. The size of the wires and switches in a typical house are able to be quite small and of much lower cost because the power available to that house is restricted to be relatively low. The electrical and electronic appliances similarly need only a small amount of power to be available. Therefore, the high-voltage power of the transmission system described previously is reduced (stepped down) through transformers and distributed to the end users in levels they need and can use. Reactive load balancing equipment is also part of the distribution system. This equipment is needed for system stability. The electrical power system's stability is finely tuned and fragile. Large-scale failures most often occur because the system is destabilized by local anomalies.

The distinction between transmission and distribution is sometimes a fuzzy one because it depends on the size and need of the load and the specific system involved. The distinction is relevant for regulatory and business purposes. It does vary somewhat from region to region.

Traditionally distribution distances are under 20 miles and voltages are less than 35kV (more commonly 15kV). However voltages up to 115 kV are used in some locations. Distribution has substations just like transmission, only smaller. These are not manned. Of importance is that the local switching, controls, and critical equipment have become largely electronic with concomitant vulnerability to EMP.

Alternating current, as opposed to direct current, is the medium for use of electricity as a general matter. Electricity production, transmission, distribution, and use require a precise frequency. Thus it is necessary across the vast electrical power system to precisely and reliably synchronize the frequency and phase of power coming from different generating sources and reaching and being utilized by different loads. Testimony to the accuracy of this control has been the wide use and dependence on electric clocks and the functioning of many electronic devices. The difficulty of maintaining the frequency synchronization during off-normal conditions is usually a factor in large-scale power outages.

For example, when the frequency moves very far from a constant required level, protective schemes at the generators within the transmission system and at the loads alarm and often automatically trip. Occasionally these trip out of proper sequence causing the system to compound rather than mitigate the problem, and the system collapses.

Control and Protection Systems

Overlaid on these three primary elements — generation, transmission and distribution — is a control system that directs the power where it is needed, maintains the frequency, and protects the system. Control is also necessary for commercial aspects. The controls must protect the system from transients such as lightning, correct synchronization errors by activating reactive sources or loads, isolate malfunctioning elements of the grid, and prevent self-damage from improper compensation or human error. The control systems also enable the deregulated energy marketplace by tracking the origin, route, and destination of the energy commodity. Central to the monitoring and coordination of the power grid is a broad class of devices called supervisory control and data acquisition (SCADA) systems. These conform to an agreed set of standards that make it possible to network many such systems over a generic communications system, regardless of modality. SCADA devices are in broad use in a variety of applications other than power.

The revolution in communication, information, system and component protection, and control technologies has reached essentially every segment of the economy, and its heavy impact on the electric power industry is no exception. The growing dependence of infrastructures on ubiquitous electronic control and protection systems confers great benefits in terms of economic and operational efficiency, rapid diagnosis of problems, and real-time remote control. At the same time and less often remarked, it also represents a potential new vector of vulnerability that could be exploited by determined adversaries. The infrastructure's vulnerability to EMP and other broad-impact events raises the threat to an entirely new and vastly expanded plane of serious to catastrophic impacts.

Electronics have enabled electric power systems — generation, transmission, and distribution — to achieve greater levels of efficiency and safety with much lower adverse environmental impacts. Far less generation, transmission, and distribution are now necessary to provide the same amount of benefit to the end user, thus significantly enhancing productivity and overall quality of life. In doing so, however, the electrical system operates closer to theoretical capacity and thus at narrower margins of safety and reliability. Electronics have improved system economics and lowered the overall cost of power to the end user while reducing pressure on basic resources and limiting potential adverse impacts on the environment. This enhanced capability, both on the provider and consumer side, is in part responsible (along with the regulatory environment) for the low rate of investment in the high-value components of the electric system infrastructure. For example, slowly increasing electrical transmission demand has largely been met within the limits of current production capacity for these components.

Electrical System Operation

The integrated electrical power system of the United States and integrated systems in Canada and Mexico is broken into only three truly separate systems at the present time — the Eastern Interconnection, the Western Interconnection, and Texas. The dividing line geographically between the Eastern and Western systems is roughly a line between Montana and North Dakota continuing southward. The largest of these, the Eastern Interconnection, serves roughly 70 percent of the electrical load and population of the United States. The three regions are separated electrically in AC in order to provide barriers for transfer of major frequency deviations associated with system separations. This mode of operation between regions is referred to as maintaining frequency independence. Importantly, this also acts as a barrier to EMP-caused system disruption or any other major system disruption and consequent collapse crossing between these three regions.

In Figure 12 is a map of the three interconnects and shows the divisions geographically and the barriers for transfer of major frequency deviations associated with system separations.

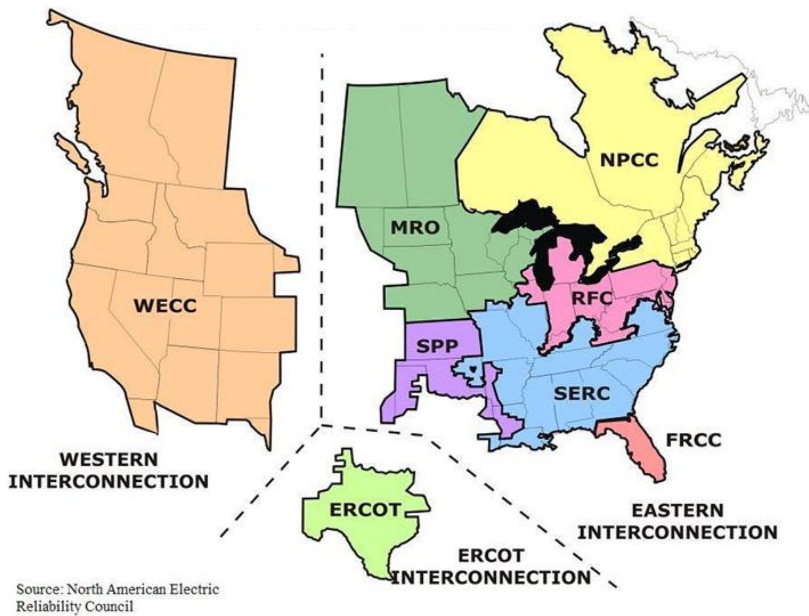


Figure 12

There are some non-synchronous connections, such as DC back-to-back converter installations that facilitate limited power transfers yet maintain a barrier. The sub-regions Shown in Figure 12 are NERC divisions which are for organizational, record keeping, and management only. They do not have frequency independence from one another at this time.

Thus at present, whole regions can be caused to collapse by sufficiently large electrical disturbances, like EMP, which severely exacerbates the problem of service to critical loads and importantly impedes restoration where delay increases the adverse impacts virtually exponentially.

Although greater conservation and efficiency at the end user has reduced the need for new generation largely through the use of improved electronics and controls, the growing economy and use of ever greater labor- and material-saving devices continues to drive the need for new generation. Furthermore, older generation is being replaced for economic, environmental, and locational reasons. Increasing capital costs emanating from world market competition and natural disasters, plus the increasing cost of capital, have slowed the addition of new generation capacity. The inability in many cases to get generation to market with reasonable assurance due to limited transmission has similarly limited new generation additions. Finally, regulatory returns and pressure from competing uses of capital within utility systems or their parents, including municipal and public systems, have further restricted new generation of consequence. As a result, generation capacity margins have decreased.

Changes in the regulatory environment with greater deregulation of the generating sector have further encouraged recent increases in new generation capacity along with retirement of older units. Most of the new power plants over the past decade or two have been natural gas-fired units that are agile in their ability to adapt to market demands and opportunities, are relatively clean environmentally for fossil plants, faster to build and have lower capital cost than many alternative generator options. They have been located farther from load in most instances than the older plants or previously planned additions, and they are operated and integrated very differently than in the past as economic decisions are often driven by very diverse and nonintegrated responsibility. This can stretch the ability of the transmission system to get the new generation to load. The type and location of new generation stresses the system and increases its vulnerability to various threats including EMP.

The capacity margin (standby capacity for emergencies or other unplanned needs) for the transmission system grid (system of higher voltage lines and substations) has decreased from about 20 percent twenty years ago to about 10 percent now as an overall system matter although there are considerable regional or local variations. This reduced margin is due to little new construction, improved efficiency of the existing system, and the location of new generation away from load. It is further exacerbated by the addition of significant generation from renewable resources such as wind energy, which operates when the wind blows, not when the electrical system might otherwise require power. This results in shifting the generation between the wind and other controllable generation on an unpredictable basis regardless of the transmission system reliability needs, all of which results in greater and less predictable stresses on the overall system.

Operation of the transmission system at today’s reduced margin while maintaining excellent reliability has been enabled by improved technology and operating practices for protection, command, and control of the transmission grid. While power production and consumption have grown, almost all of the growth has been absorbed on existing power lines although new substations have been added. There has been very little construction of transmission capacity, particularly of new longer distance transmission lines, or renewal and replacement of existing infrastructure for many reasons, including deregulation (discussed in the next section of this chapter). The transmission system thus is operating with little ability to absorb adverse electrical impacts.

Overall, as a result of reduced generation capacity margins, the generation component of the system is far less able to compensate for the difficulties that may be encountered within the transmission system and vice versa. Together, the consequence is a power system far more vulnerable to disruption than in the past, and this vulnerability is increasing.

While greater protection and control schemes have still provided a very reliable system in spite of this, the system is being stressed beyond reasonable limits. The electrical power system has become virtually fully dependent upon electronic systems working nearly flawlessly. The overall system reliability is testimony to the skill and effectiveness of the control systems. However, the lack of margin (combination of generation and transmission margins) results in making catastrophic cascading outages far more likely, and should the electronics be disrupted, the system is highly likely to fail on a broad scale.

Thus, the small margin and reliance on electronics give rise to EMP vulnerability. High-value assets (assets that are critical to the production and delivery of large volumes of electrical power and those critical for service to key loads) in the system are vulnerable to EMP through the loss of protection equipment due to E1 and even if E3 levels were not large enough to cause damage. The largest and most critical of these are transformers. Transformers are the critical link (1) between generation and transmission, (2) within the transmission network, (3) between the transmission and distribution systems, and (4) from the distribution to the load.

The transformers that handle electrical power within the transmission system and its interfaces with the generation and distribution systems are large, expensive, and to a considerable extent, custom built. The transmission system is far less standardized than the power plants are, which themselves are somewhat unique from one to another.

Delivery time for these items under benign circumstances is typically one to two years. There are about 2,000 such transformers rated at or above 345 kV in the United States with about one percent per year being replaced due to failure or by the addition of new ones. Worldwide production capacity is less than 100 units per year and serves a world market, one that is growing at a rapid rate in such countries as China and India. Delivery of a new large transformer ordered today is nearly three years, including both manufacturing and transportation. An event damaging several of these transformers at once means it may extend the delivery times to well beyond current time frames as production is taxed. The resulting impact on timing for restoration can be devastating. Lack of high voltage equipment manufacturing capacity represents a glaring weakness in the recovery to the extent these transformers are vulnerable. Distribution capability is roughly in the same condition although current delivery times are much less.

Chapter 4
Electric System Vulnerabilities

Depending on the explosive yield of the nuclear weapon used, EMP-induced currents may be several times larger than the GIC produced by the average geomagnetic storm, and may even be comparable to those expected to arise in the largest geomagnetic storm ever observed. It may also occur over an area not normally affected by historic geomagnetic storms.

The North American economy and the functioning of the society as a whole are critically dependent on the availability of electricity, as needed, where and when needed. The electric power system in the U.S. and interconnected areas of Canada and Mexico is outstanding in terms of its ability to meet load demands with high quality and reliable electricity at reasonable cost. However, over the last decade or two, there has been relatively little large-capacity electric transmission constructed and the generation additions that have been made, while barely adequate, have been increasingly located considerable distances from load for environmental, political, and economic reasons. As a result, the existing electrical system not infrequently operates at or very near local limits on its physical capacity to move power from generation to load. Therefore, the slightest impact or upset to the system can cause functional collapse affecting significant numbers of people, businesses, and manufacturing. It is not surprising that a single EMP attack may well encompass and degrade at least 70% of the electrical service in the U.S., all in one instant.

The impact of such EMP is different and far more catastrophic than that effected by historic blackouts, in three primary respects:

1. The EMP impact is virtually instantaneous and occurs simultaneously over a much larger geographic area. Generally, there are neither precursors nor warning, and no opportunity for human-initiated protective action. The early-time EMP component is the "electromagnetic shock" that disrupts or damages electronics-based control systems and sensors, communication systems, protective systems, and control computers, all of which are used to control and bring electricity from generation sites to customer loads in the quantity and quality needed. The E1 pulse also causes some insulator flashovers in the lower-voltage electricity distribution systems (those found in suburban neighborhoods, in rural areas and inside cities), resulting in immediate broad-scale loss-of-load. Functional collapse of the power system is almost definite over the entire affected region, and may cascade into adjacent geographic areas.

2. The middle-time EMP component is similar to lightning in its time-dependence but is far more widespread in its character although of lower amplitude—essentially a great many lightning-type events over a large geographic area which might obviate protection. The

late-time EMP component couples very efficiently to long electrical transmission lines and forces large direct electrical currents to flow in them, although they are designed to carry only alternating currents. The energy levels thereby concentrated at the ends of these long lines can become large enough to damage major electrical power system components. The most significant risk is synergistic, because the middle and late-time pulses follow after the early-time pulse, which can impair or destroy protective and control features of the power grid. Then the energies associated with the middle and late-time EMP thus may pass into major system components and damage them. It may also pass electrical surges or fault currents into the loads connected to the system, creating damage in assets that are not normally considered part of the electric infrastructure. Net result is recovery times of months to years, instead of days to weeks.

3. Proper functioning of the electrical power system requires communication systems, financial systems, transportation systems, and—for much of the generation—continuous or nearly continuous supply of various fuels. However, the fuel-supply, communications, transportation, and financial infrastructures would be simultaneously disabled or degraded in an EMP attack and are dependent upon electricity for proper functioning. For electrical system recovery and restoration of service, the availability of these other infrastructures is essential. The longer the outage, the more problematic, and uncertainty-fraught the recovery will be.

The recent cascading outage of August 14, 2003, is an example of a single failure compounded by system weaknesses and human mistakes. It also provides an example of the effectiveness of protective equipment. However, with EMP there are multiple events coupled with the disabling of protective devices simultaneously over an extremely broad region—damage to the system is likely and recovery slow.

In order to assess the nature of EMP effects on the electrical system potential effects of an electromagnetic pulse on each of the three main constituents of the power system — generation, transmission, and distribution were separately analyzed. We will look at each component briefly in this Chapter.

Generation

A power plant is designed to protect itself in the event of instantaneous loss of load, electrical faults or trips on the interconnected transmission system or internally, frequency excursions beyond rather tight limits, and often for the loss of an external power source for proper shutdown. None of these conditions should damage a power plant if the protective systems function properly, as frequently has been demonstrated. Very little damage to generation has occurred in previous blackouts, including the August 14, 2003, blackout. However, some malfunctioning in the multiple controls throughout a power plant does occur, albeit rarely. Therefore, on a broad enough scale, as in an EMP attack affecting many power plants at once, damage to a small number of these power plants would be expected statistically. Since E2 and E3 are not assessed as direct threats to the generation system, the critical vulnerability question is E1-induced plant control system failure.

The E1 pulse can upset the protection and control system, including damaging control and protective system components, and cause the plant to trip or trigger emergency controlled shut down. Current, temperature, pressure, frequency, and other physical parameters are monitored by the control systems. These provide independent measurements of same system, and all can cause the plant to trip off line and go to controlled shut down.

Given the redundancy of protective system design, either several protective devices or devices in the critical path would have to fail in order for the plant not to initiate protective shutdown. If the control system itself or secondary controls and receivers critical to orderly shut-down are themselves damaged, as is reasonably possible with E1, then the plant is seriously at risk. Power plants, particularly newer ones, are highly sophisticated, very high-speed machines, and improper shut down can damage or destroy any of the many critical components and can even cause a catastrophic failure. Nuclear plants are an exception due to the nature of their protection schemes.

Given the range of potential E1 levels, analysis and test results provide a basis to expect sufficient upset to cause a plant's system to shut down improperly in many cases. Proper shutdown depends on synchronized operation of multiple controllers and switches. For example: coal intake and exhaust turbines must operate together or else explosion or implosion of the furnace may occur. Cooling systems must respond properly to temperature changes during shut down or thermal gradients can cause boiler deformation or rupture.

Orderly spin-down of the turbine is required to avoid shaft sagging and blades impacting the casings. Bearings can easily fail and freeze or damage the shaft if the shut down does not engage emergency lubrication. There are similar issues inside very complex machines operating at high temperatures at fast speeds with tight tolerances. Thus, power plant survivability depends on a great many protective systems creating multiple pathways to plant damage and failure.

Restoration of some damage can be very long term, certainly months and in some instances years. The loss of generation of any size itself would contribute to system wide collapse and certainly would limit restoration. More and more these systems are using computer-controlled microelectronics, and thus are more susceptible to EMP disruption.

At the device level, power plant protective systems are less exposed than the corresponding systems in the transmission grid. They act on local information, so failure of telecommunications systems is not as much of an issue for plant protection where operators are available in most instances 24/7 and can independently assess the situation and act. The control equipment, protective systems, sensors, and current transformers typically will be inside the plant although this does not necessarily mean they will not be exposed. In general there are limited outside cable runs, so the building itself will provide some EMP protection. However the lengths of these interior cables can be on the order of several hundred feet. Cable trays may or may not provide additional protection, depending on their material and installation method.

Transmission

Most generation is located outside major population areas and thus sometimes at great distances from the load being served. In general, electricity often travels great distances on an efficient high-voltage transmission system. The transmission system is made up of different owners, voltage levels, and controls. Yet power must be routed to where it is needed, so there are substations where the power lines join and are switched, and where power is moved from one voltage level to another level, interconnected with other transmission system components, and sent on to distribution systems. Finally as it gets closer to load, power is stepped down (reduced in voltage) and then down again and often down yet again to and within the distribution system and then normally down again to the delivery point for the load. Each of those step-down points requires a transformer to effect the change and breakers to isolate the transformer when necessary.

In the event of the loss of a generation facility, a fully functional transmission system can move the remaining generation from whatever plants can operate to areas otherwise affected by loss of a particular generating station. This occurs in normal practice as generation plants are brought in and out of service for one reason or another. The same thing happens when part of the transmission system is down for whatever reason. Other transmission in the network picks up the loss and generation is shifted so that the loads can continue to be served. All this is accomplished regularly as part of system operation. The ability to adjust quickly given access to a multitude of resources, generation, and transmission makes the system reliable. Incapacitation of sufficient elements of the transmission system would mean the inability to deliver power whether the generation is available or not. The same inability would be true for incapacitation of sufficient generation. In the case of EMP, both would be likely to be impacted simultaneously. This is what results in a blackout where the load does not get served. The transmission system is highly vulnerable to EMP.

Substation control systems at the hubs in the transmission system are inherently more exposed to the E1 pulse than their power plant counterparts, which are often not in buildings at all. The sensors, communications, and power connections are outdoors and cables (i.e., antennas in the sense of an EMP receptor) which may be hundreds of feet long may be buried, run along the ground, or elevated. The control devices themselves, including the protective relays, may even be in remote structures that provide little electromagnetic attenuation. Most substations do not have operators present but are remotely controlled from power dispatch centers, in some instances hundreds of miles away.

Operation of transmission substations depends on various communications modalities, including telephone, microwave, power line communications, cell phones, satellite phones, the Internet, and others. Typically, these modes are used for dedicated purposes; they do not necessarily provide a multiple redundant system. From the point of view of managing routine system perturbations and preventing their propagation, the plain old telephone remains the most important mode. If the voice communications were completely interrupted, it would be difficult, but still reasonably possible, to successfully continue operations — provided there were no significant system disruptions. However in the case of an EMP event with multiple simultaneous disruptions, continued operation is not possible. Restoration without some form of communication is also not possible. Communication is clearly critical in the path to restoration.

Just as in the case involving power plants, the first critical issue is the proper functioning of the protective elements, specifically relays, followed by the local control systems. These elements protect the high-voltage breakers and transformers that are high-value assets. High-value assets are those that are critical to system functioning and take a very long time to replace or repair.

Other protected devices, such as capacitors and reactive power generators, are also high value and nearly as critical as the transformers. E1 is likely to disrupt and perhaps damage protective relays, not uniformly but in statistically very significant numbers. Left unprotected, as would likely result from E1 damage or degradation to the protective relays, the high-value assets would likely suffer damage by the transient currents produced during the system collapse, as well as potentially from E2 and E3 depending upon relative magnitudes.

The high-value transmission equipment is subject to potentially large stress from the E3 pulse. The E3 pulse is not a freely propagating wave like E1 and E2, but the result of distortions in the Earth's magnetic field caused by the upper atmosphere nuclear explosion. The distortion couples very efficiently to long transmission lines and induces quasi-direct current electrical currents to flow. The currents in these long lines can aggregate to become very large (minute-long ground-induced currents (GIC) of hundreds to thousands of amps) sufficient to damage major electrical power system components. With respect to transformers - probably the hardest to replace quickly - this quasi-direct current, carried by all three phases on the primary windings of the transformer, drives the transformer to saturation, creating harmonics and reactive power. The harmonics cause transformer case heating and over-currents in capacitors potentially resulting in fires. The reactive power flow would add to the stresses on the grid if it were not already in a state of collapse. Historically, we know that geomagnetic storms, which can induce GIC flows similar to but less intense than those likely to be produced by E3, have caused transformer and capacitor damage even on properly protected equipment. Damage would be highly likely on equipment unprotected or partially protected due to E1.

The likelihood and scope of the E3 problem are exacerbated by the small transmission margins currently available. The closer a transformer is operating to its performance limit, the smaller the GIC needed to cause failure. Moreover, newer transmission substations are increasingly using three single-phase transformers to handle higher power transfer, since the equivalently rated three-phase transformers are too large to ship. The three phase systems are more resistant to GIC, since their design presumes a balanced three phase operation. Thus the separate single-phase transformers are more susceptible to damage from GIC.

Distribution

Most of the long power outages that consumers have experienced were due to physical damage to the distribution system — local damage. This damage is usually caused by natural events such as weather. Windblown trees fall on neighborhood power lines or ice buildup drops lines that in some instances make contact with live lines causing arcs that in turn can even result in distribution transformers exploding.

EMP damage to the distribution system would be less dramatic than that inflicted upon the transmission system but still would result in loss of load. The principal effect of EMP would be E1-induced arcing across the insulators that separate the power lines from the supporting wood or metal poles. The arcing can damage the insulator itself and in some cases result in pole-mounted transformer explosions. Damage to large numbers of insulators and pole-mounted transformers could also result in a shortage of replacement parts, as these items are fairly reliable under normal conditions, and spares are not kept to cover widespread losses. Ultimately workarounds and replacements can be found in most circumstances although widespread damage and impact to related infrastructures will cause delay.

The important effect of the loss of load in the EMP scenario is that it happens simultaneously. Thus it represents a substantial upset to the entire grid, causing the frequency to rise and protective relays to open on generation and can by itself result in a cascading failure and blackout of an entire region. Similarly, any consumer or industrial electrical device that is shut down or damaged by EMP contributes to the load loss and further drives the system to collapse. It becomes a case of what comes first to cause what failure since the EMP E1 impulse is virtually simultaneously disrupting all facets of the electrical system and load.

Control and Protection Systems

The continuing evolution of electronic devices into systems that once were exclusively electromechanical, enabling computer control instead of direct human intervention and use of broad networks like the Internet, results in ever greater reliance on microelectronics and thus the present and sharply growing vulnerability of the power system to EMP attack. Just as the computer networks have opened the possibility to cyber assault on the power system or to electrical power system collapse associated with software failure (as during the August 14, 2003, blackout), they have provided an opportunistic pathway for EMP attack that is likely to be far more widespread, devastating, and difficult to assess and restore. Switches, relays, and even generator exciters now have microprocessors and analog-to-digital converters. These and other low-power electronics cannot be expected to withstand EMP-generated stresses unless they are well protected. Protection must encompass both device design and system integration. Even a well-designed system installed without regard for EMP intrusion via connecting lines can be rendered inoperative by EMP stress.

The key vulnerable electronic systems are SCADA along with digital control systems (DCS) and programmable logic controllers (PLC). SCADAs are used for data acquisition and control over large and geographically distributed infrastructure systems while DCSs and PLCs are used in localized applications. These systems all share similar electronic components, generally representative of components that form the internal physical architectures of portable computers. The different acronyms by which we presently identify SCADA, DCS, and PLC should not obscure the fact that the electronics have evolved to the point where the differing taxonomies are more representative of the functional differences of the electronics equipment rather than differences in the electronics hardware itself.

Electronic control equipment and innovative use of electronic controllers in equipment that is not usually considered control equipment are rapidly replacing the purely electromechanical systems and devices that were their predecessors. The use of such control equipment is growing worldwide, and existing users are upgrading equipment as new functionalities develop. The U.S. power industry alone is investing about $1.4 billion annually in new SCADA equipment. This is perhaps 50 times the reinvestment rate in transformers for transmission. The present rate represents upgrade and replacement of the protection and control systems to ever more sophisticated microelectronics at roughly 25 to 30 percent annually, with each new component more susceptible to EMP than its predecessor. The shift to greater electronic controls, computers, and the Internet also results in fewer operators and different operator training. Thus the ability to operate the system in the absence of such electronics and computer-driven actions is fast disappearing. This is almost certain to have a highly detrimental effect on restoring service in the event of an EMP attack.

Synergistic Effects of E1, E2, and E3 Pulses

The effects of EMP on the electrical power system are fundamentally partitioned into its early, middle, and late time effects (caused by the E1, E2, and E3 components, respectively). The net impact on the electric power grid includes the synergistic interaction of all three, occurring nearly simultaneously over a large geographic area. An electrical system so disrupted will collapse with near certainty. Thus one or more of the three integrated, frequency-independent electric grids will be without electrical service. This loss is very large geographically and restoration is very likely to be beyond short-term emergency backup generators and batteries.

Any reasonable EMP event would be much larger than the Texas grid so basically the concern is the Eastern and Western grids with Texas either included or not depending upon the location of the weapon. The basic threat to the U.S. that moves an EMP event from a local or short-term adverse impact to a more prolonged and injurious event is the time it takes to restore electrical and other infrastructure service.

The early time EMP, or E1, is a freely propagating field with a rise time in the range of less than one to a few nanoseconds. E1 damages or disrupts electronics such as the SCADA, DCS, and PLC as well as communications and to some extent transportation. This disrupts control systems, sensors, communication systems, protective systems, generator systems, fuel systems, environmental mitigation systems and their related computers, as well as the ability to repair.

SCADA components, in particular, are frequently situated in remote environments and operate without proximate human intervention. While their critical electronic elements are usually contained within some sort of metallic box, the enclosures' service as a protective *Faraday cage* is inadequate. Such metallic containers are designed only to provide protection from the weather and physical security. They are not designed to protect the electronics from high-energy electromagnetic pulses, which may infiltrate either from the free field or from the many antennae (cable connections) that compromise electromagnetic integrity.

A **Faraday cage** is an enclosure formed by conducting material or by a mesh of such material. Such an enclosure blocks external static and non-static electric fields. Faraday cages are named after the English scientist Michael Faraday, who invented them in 1836.

A Faraday cage's operation depends on the fact that an external static electrical field will cause the electric charges within the cage's conducting material to redistribute so as to cancel the field's effects in the cage's interior. This phenomenon is used, for example, to protect electronic equipment from lightning strikes and electrostatic discharges.

The E1 pulse also causes flashovers in the lower voltage distribution system, resulting in immediate broad geographic scale loss of electrical load and requiring line or insulator replacement for restoration.

The intermediate time EMP, or E2, is similar in frequency regime to lightning, but vastly more widespread, like thousands to millions of simultaneous lightning strikes, even if each strike is at lower amplitude than most naturally occurring lightning. The electrical power system has existing protective measures for lightning, which are probably adequate. However, the impact of this many simultaneous lightning-like strike disruptions over an extremely large geographic area may exceed those protections. The most significant risk, however, is synergistic because the E2 pulse follows on the heels of the E1. Thus where E1-induced damage has circumvented lightning protection, the E2 impact could pass directly into major system components and damage them.

The late time EMP, or E3, follows E1 and E2 and may last for a minute or more. The E3 pulse is similar in a great many respects to geomagnetic effects induced by solar storms. Solar storms and their impacts on electrical systems with long lines have been thoroughly evaluated and are known to cause serious damage to major electrical system components at much lower levels than the reasonably possible E3 impact. This damage has been incurred in spite of functioning, in-place protective systems. Given the preceding E1 and E2 pulse damage to the protective systems and other system components, damage from E3 to unprotected major system components is virtually assured.

EMP is detrimental to the continued functioning of the electrical power system and the reliable behavior of electronics. Each of the three EMP modes of system impact is sufficient by itself to cause disruption and probable functional collapse of large portions of the interconnected electrical power system at EMP threat levels. In every EMP attack, all three assaults (E1, E2, and E3) are delivered in sequence and nearly simultaneously. It is widely believed that functional collapse of the electrical power system interconnect within the primary area of assault is virtually certain. Furthermore, widespread functional collapse may result even from a small weapon with a significant E1 component.

The level of damage depends primarily on the functioning of the protective equipment, but it also depends on various aspects of the collapse. In an EMP event, the collapse is virtually instantaneous. The size of the transients on the system may be greater than existing protective systems are capable of handling, even those not damaged by the EMP itself.

Damage to the large transformers and other high-value equipment is directly related to protective relay failure, although it is possible for E1-induced arcs inside transformers to damage transformers irrespective of relay failure. A properly functioning relay has a reasonable chance of protecting the device; an improperly functioning one will probably result in some level of damage in an ensuing system collapse. The level of damage depends on the failure mode.

Chapter 5
Mitigation Strategies

The electrical system must be protected against the consequences of an EMP event to the extent reasonably possible. The level of vulnerability and extreme consequence combine to invite an EMP attack. Thus reduction of vulnerability to attack and the resulting consequences reduces the probability of attack. The two key elements of the mitigation strategy for the electrical system are protection and restoration.

Timely restoration depends on protection, first of high-value assets, protection necessary for the ability to restore service quickly to strategically important loads, and finally protection as required to restore electrical service to all loads. The approach is to utilize a comprehensive, strategic approach to achieve an acceptable risk-weighted protection in terms of performance, schedule, timing, and cost. The effort will include evolution to greater and greater levels of protection in an orderly and cost-effective manner consistent with the anticipated threat level.

Protection Strategies

It is not practical to try to protect the entire electrical power system or even all high value components from damage by an EMP event. There are too many components of too many different types, manufactures, ages, and designs. The cost and time would be prohibitive.

Widespread collapse of the electrical power system in the area affected by EMP is virtually inevitable after a broad geographic EMP attack, with even a modest number of unprotected components. Since this is a given, the focus of protection is to retain and restore service to critical loads while permitting relatively rapid restoration.

The approach to protection has the following fundamental aspects. These will collectively reduce the recovery and restoration times and minimize the net impact from assault. All of this is feasible in terms of cost and timing if done as part of a comprehensive and reasonable response to the threats, whether the assault is physical, electromagnetic (such as EMP), or cyber.

1. Protect high-value assets through hardening. Hardening, providing for special grounding, and other schemes are required to assure the functional operation of protection equipment for large high-value assets such as transformers, breakers, and generators and to so protect against sequential, subsequent impacts from E2 and E3 creating damage. Protection through hardening critical elements of the natural gas transportation and gas supply systems to key power plants that will be necessary for electrical system recovery is imperative.

2. Assure there are adequate communication assets dedicated or available to the electrical system operators so that damage during system collapse can be minimized; components requiring human intervention to bring them on-line are identified and located; critical manpower can be contacted and dispatched; fuel, spare parts and other commodities critical to the electrical system restoration can be allocated; and provide the ability to match generation to load and bring the system back on line.

3. Protect the use of emergency power supplies and fuel delivery, and importantly, provide for their sustained use as part of the protection of critical loads.

4. Perhaps separate the present interconnected systems, particularly the Eastern Interconnection, into several non-synchronous connected sub-grids or electrical islands. It is very important to protect the ability of the system to retain as much in operation as possible through reconfiguration particularly of the Eastern Interconnect into a number of non-synchronous connected regions, so disruptions will not cascade beyond those EMP-disrupted areas. Basically, this means eliminating total Eastern Interconnect service loss, while at the same time maintaining the present interconnection status with its inherent reliability and commercial elements. This is the most practical and easiest way to allow the system to break into islands of service and greatly enhance restoration timing. This will not protect most within the EMP-impact area, but it should increase the amount of viable fringe areas remaining in operation.

5. Install substantially more black start generation units coupled with specific transmission that can be readily isolated to balancing loads. Requiring all power plants above a certain significant size to have black start or fuel-switching capability (with site-stored fuel) would provide major benefits against all disruptions including non-adversarial ones. Black start generator, operation, and interconnection mechanisms must be EMP hardened or be manual without microelectronic dependence. This also will require the ability to isolate these facilities from the main electrical power system during emergency generation operation and that isolation switching is EMP hardened. In addition, sufficient fuel must be provided, as necessary, to substantially expand the critical period for recovery.

6. Improve, extend, and exercise recovery capabilities. Develop procedures for addressing the impact of such attacks to identify weaknesses, provide training for personnel and develop EMP response training procedures and coordinate all activities and appropriate agencies and industry. While developing response plans, training and coordination are the primary purpose.

Restoration Strategies

The key to minimizing catastrophic impacts from loss of electrical power is rapid restoration. The protective strategy described is aimed primarily at preserving the system in a recoverable state after the attack, maintaining service to critical loads, and enhancing recovery.

The first step in recovery is identifying the extent and nature of the damage to the system and then implementing a comprehensive plan with trained personnel and a reservoir of spare parts to repair the damage. A priority schedule for repair of generation, transmission, and even distribution is necessary since resources of all types will be precious and in short supply should the EMP impact be broad enough and interdependent infrastructures be adversely impacted (e.g., communication, transportation, financial and life-supporting functions).

Restoration is complicated in the best of circumstances, as experienced in past blackouts. In the instance of EMP attack, the complications are magnified by the unprecedented scope of the damage both in nature and geographical extent, by the lack of information post attack, and by the concurrent and interrelated impact on other infrastructures impeding restoration.

Restoration plans for priority loads are a key focus. Widely scattered or single or small group loads are in most cases impractical to isolate and restore individually given the nature of the electrical system. Restoration of special islands can be made practical by the non-synchronous connected sub-regions if they are identified as necessary very far in advance of any assault. Otherwise, the system's resources and available personnel will need to act expeditiously to get as many islands of balanced load and generation back into operation. This will begin by system operators identifying those easiest to repair and restore them first. As these stabilize, the system recovery will flow outward as, increment by increment, the system is repaired and brought back in service. It is much more feasible and practical to restore by adding incrementally to an operating island rather than black starting the recovery for an island.

<u>Generation</u>

The restoration of the system from collapse is very complex in operation, almost an art rather than a science, and it requires highly trained and experienced operators with considerable information and controls at hand. Basically, in isolated cases or when beginning restoration, a load and generation source has to be identified and interconnected without interference from other loads or generation. These are then matched and gradually restored together. Thereafter, each increment of generation and load is added in turn to a larger operating system of generation and load. As each component of load and generation are included, the frequency will be impacted. If it varies outside very tight limits, it will all trip off and have to be put back together again. In most system disruptions leading to blackouts, there are large amounts of system still intact on the periphery of the disruption, which are able to greatly assist in the restoration, more easily allowing and absorbing each addition of generation and load until all is restored.

Every generator requires a load to match its electrical output as every load requires electricity. In the case of the generator, it needs load so it does not overspin and fail, yet not so much load it cannot function. In a large integrated system, where increments of load and generation are not sufficient to cause the frequency to drop or rise above acceptable margins, it is relatively straightforward and commonplace, just as turning on a light switch causes a generator someplace to pick up the load. In the case where the system is being restored and there are few loads and generators connected, this matching requires careful management and communication between load and generation.

Generation start-up for most plants requires power from another source to drive pumps, fans, safety systems, fuel delivery, and so on. Some, like hydroelectric and smaller diesels can start directly or from battery sources assuming they can control their access to matching load. In the case of EMP, large geographic areas of the electrical system will be down, and there may be no existing system operating on the periphery for the generation and loads to be incrementally added with ease. Furthermore, recovery of lost generation would be impacted by the loss of other infrastructure in varying degrees according to the type of plant. In that instance, it is necessary to have a “black start”: a start without external power source. Coal plants, nuclear plants, large gas- and oil-fired plants, geothermal plants, and some others all require power from another source to restart. In general, nuclear plants are not allowed to restart until and unless there are independent sources of power from the interconnected transmission grid to provide for independent shutdown power. This is a regulatory requirement for protection rather than a physical impediment.

Black-start generation is that kind of generator that is independent of outside power sources to get started, hence the term black start. Most black start units today are hydroelectric plants, small gas peaking units, small oil-fired peaking units and diesel units. In some cases the black start unit may be collocated with a larger power plant in order to get the larger one started for system restoration. Fuel supply would then be the only issue from the generation perspective; for example, a gas plant might not have the fuel due to EMP damage someplace in the delivery system. Assuming the black start units were not damaged by EMP or have been repaired and assuming they are large enough to be significant, workers can begin the system restoration as building blocks from the generation side of the equation. E1 may have also damaged their startup electronics, which will need to be repaired first. It is often the case that generation capable of black start is not manned, so if they fail to start remotely, a person will need to be dispatched to find the problem, locate the needed parts, and get it operating. There are not many black start-capable units in locations that are suitable to independent restoration at this time. Recovery in most regions therefore needs to wait for other areas to restore power and then be reconnected increment by increment.

Even if partially disabled control systems successfully protect the critical generating equipment, all affected plants would face a long process of testing and repairing control, protective, and sensor systems. Protective and safety systems have to be carefully checked out before start up or greater loss might occur. Repair of furnaces, boilers, turbines, blades, bearings, and other heavy high-value and long lead-time equipment would be limited by production and transportation availability once at-site spares are exhausted.

While some spare components are at each site and sometimes in spare parts pools domestically, these would not cover very large high-value items in most cases, so external sources would be needed. Often supply from an external source can take many weeks or several months in the best of times, if only one plant is seeking repair, and sometimes a year or more. With multiple plants affected at the same time, let alone considering infrastructure impediments, restoration time would certainly become protracted.

Balancing an isolated portion of generation and load first, and then integrating each new increment is a reasonably difficult and time-consuming process in the best of circumstances. In an EMP attack with multiple damaged components, related infrastructure failures, and difficulty in communications, restoring the system could take a very long time unless preparatory action is taken.

Generating plants have several advantages over the widely spread transmission network as it relates to protection and restoration from an EMP event. The plant is one complete unit with a single DCS control network. It is manned in most cases so operators and maintenance personnel are immediately available and on site. The operating environment electronically requires a level of protection that may provide at least a minimal protection against EMP. Nevertheless, it is important to harden critical controls sufficiently to enable manual operation at a minimum. Providing for at-site spares to include the probably needed replacements for control of operation and safety would be straightforward and not expensive to accomplish, thus assisting rapid restoration of capability.

As controls and other critical components of the electrical transmission and generation system suffer damage, so do similar components on the production, processing, and delivery systems providing fuel to the electric generators. Restoration of the electrical power system is not feasible on a wide scale without a parallel restoration of these fuel processing and delivery systems.

Hydropower, wind, geothermal, and solar power each has a naturally reoccurring fuel supply that is unaffected by EMP. However, the controls of these plants themselves are subject to damage by EMP at present. In addition, only hydropower and geothermal have controllable fuel (i.e. they can operate when needed versus wind and solar that operate when nature provides the fuel just-in-time). As a practical matter, only hydropower is of sufficient size and controllability in some regions to be a highly effective resource for restoration, such as the Pacific Northwest, the Ohio/Tennessee valley, and northern California.

Beyond the renewable resources, coal and wood waste plants typically have significant stockpiles of fuel so the delay in rail and other delivery systems for a couple of weeks and in some instances up to a month is not an issue for fuel. Beyond that, rail and truck fuel will be needed and delivery times are often relatively slow, so the delivery process must start well before the fuel at the generator runs out.

Operating nuclear plants do not have a fuel problem per se, but they are prohibited by regulation from operating in an environment where multiple reliable power supply sources are not available for safe shutdown, which would not be available in this circumstance. However, it is physically feasible and safe for nuclear plants to operate in such a circumstance since they all have emergency generation at site. It would simply have to be fueled sufficiently to be in operation when the nuclear plant is operating without external electrical supply sources. Nuclear power backup would need to be significantly expanded. Natural gas-fired power plants are very important in restoration because of their inherent flexibility and often their relatively small size, yet they have no on-site fuel storage and are totally dependent upon the natural gas supply and gas transportation system which are just in time for this purpose. Therefore, the natural gas fuel delivery system must be brought back on-line before these power plants can feasibly operate. It is operated largely with gas turbines of its own along the major pipelines. The key will be to have the protection, safety, and controls be hardened against EMP.

Transmission

The transmission system is the lynch pin between generation and load. It is also a network interconnecting numerous individual loads and generating sources. To restore the overall power system to get generation to load, as noted earlier, an increment of generation needs to be matched to an increment of load and then add the next matching increments and so on. As the number of increments becomes greater, there is some flex in the system to absorb variations. As a result, the restoration is easier and goes much faster. In the initial increments however, the transmission system link between generation and load has to be isolated so other loads, which may well remain connected, do not impact the effort. This is tricky and requires careful coordination to adjust the breakers in the substations so the link is routed correctly and safely.

The power transmission grid is designed to break into islands of hopefully matched generation and load when the system receives a sufficient electrical disruption. This is both to protect service in the nonimpacted regions and to allow for the stable systems to be used to restart the island that lost functionality. With EMP, broad geographic reach and simultaneous multiple levels of disruption result in a situation in which the islanding schemes themselves will probably fail to work in the EMP-affected area. Since the geographic area is so large, perhaps encompassing an entire Interconnect or possibly more, restoring the system from the still functioning perimeter may well not be possible at all or would take a great deal of time; maybe weeks to months, at least in the best circumstance.

Recovery from transmission system damage and power plant damage will be impeded primarily by the manufacture and delivery of long lead-time components. Delivery time for a single, large transformer today is typically one to two years and some very large special transformers, critical to the system, are even longer. There are roughly 2,000 transformers in use in the transmission system today at 345 kV and above with many more at lesser voltages that are only slightly less critical. The current U.S. replacement rate for the 345 kV and higher voltage units is 10 per year; worldwide production capacity of these units is less than 100 per year. Spare transformers are available in some areas and systems, but because of the unique requirements of each transformer, there are no standard spares. The spares also are owned by individual utilities and not generally available to others due to the risk over the long lead time if they are being used. Transformers that will cover several options are very expensive and are both large and difficult to move.

Recovery will be limited by the rate of testing and repair of SCADA, DCS, and PLC and protective relay systems. With a large, contiguous area affected, the availability of outside assistance, skilled manpower, and spares may well be negligible in light of the scope of the problem. Determining the source of a bad electrical signal or tiny component that is not working can take a long time. On the low side, on-site relay technicians typically take three weeks for initial shakedown of a new substation. Simply replacing whole units is much faster, but here too, inserting new electronic devices and ensuring the whole system works properly is still time consuming.

It must be noted that the substations are typically not manned so skilled technicians must be located, dispatched, and reach the site where they are needed. Many of these locations are not close to the technicians. It is not possible to readily estimate the time it will take in the event of an EMP attack since the aftermath of an EMP attack would not be routine and a certain level of risk would likely be accepted to accelerate return to service. It is estimated that an entire substation control system recovery time will be at least several days, if not weeks.

Unlike generation, recovery of the transmission system will require off-site communications because coordination between remote locations is necessary. Communications assets used for this purpose now include dedicated microwave systems and, increasingly, cell phones and satellite systems. If faced with a prolonged outage of the telecommunications infrastructures, repairs to dedicated communication systems or establishment of new ad-hoc communications will be necessary. This might take one or more weeks and would set a lower limit on recovery time, but it would be unlikely to affect the duration of a months-long outage.

Restoration to electrical service of a widely damaged power system is complex. Beginning with a total blackout, it requires adequate communication to match and coordinate a generating plant to a load with an interconnected transmission that normally can be isolated via switching at several substations, so it is not affected by other loads or generation.

The simultaneous loss of communication and power system controls and the resulting lack of knowledge about the location of the damage all greatly complicate restoration. There are also a diminishing number of operators who can execute the processes necessary for restoration without the aid of computers and system controls.

Without communication, both voice and data links, it is nearly impossible to ascertain the nature and location of damage to be repaired, to dispatch manpower and parts, and to match generation to load. Transportation limitations further impede movement of material and people. Disruption of the financial system will make acquisition of services and parts difficult. In summary, actions are needed to assure that difficult and complex recovery operations can take place and be effective in an extraordinarily problematic post attack environment.

Conclusion

History has shown that the electric power industry is susceptible to EMP. The increased reliance on electronics to control the electric power grid, along with thinner operating margins, put the electric power grid at greater risk than ever before.

The continuing need to improve and expand the electric power system as a normal course of business provides an opportunity to judiciously improve both security and reliability in an economically acceptable manner — provided that technically well-informed decisions are made with accepted priorities.

By protecting key system components, structuring the network to maximize fringe service, through the non-synchronous interconnections, expanding the black start and system emergency power support, creating comprehensive recovery plans for the most critical power needs, and providing adequate training of personnel, the risk of catastrophic impact from EMP can be significantly reduced. The mitigation plan must be developed by the electric power industry, instilled into systems operations, and practiced to maintain a ready capability to respond. It must also be fully coordinated with the interdependent infrastructures, owners, and producers.

Most of the precautions identified to protect and restore the system from EMP will also apply to cyber and physical attacks. However, the solutions must not seriously penalize the existing and excellent system but should enhance its performance wherever possible.

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