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Blackstarting the North American power grid after a nuclear electromagnetic pulse (EMP) event or major solar storm

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or Major Solar Storm

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Abstract

The electric power grid is our most critical infrastructure. This key resource provides the energy required for all other infrastructures to function. In modern times, electricity has become necessary to sustain life. The power grid in the U.S. is a target for terrorists and is vulnerable to naturally-occurring events. Numerous assessments have been performed on the vulnerability of our national power grid to both manmade and natural events.[1]

Two significant wide-area threats against our power grid are solar storms and electromagnetic pulse (EMP) attacks. Solar storms are naturally-occurring events that have the potential to create large-scale blackouts that could potentially affect more than 50% of the U.S. population.[2] EMP attacks occur when nuclear weapons are detonated at high altitudes; although there is no threat of direct blast or radiation dangers to humans, EMP events can wreck power grids.

Although numerous studies have been conducted on the effects of EMP events and solar storms on the U.S. power grid, little has been done to plan for restarting or "blackstarting" the power grid after such an event. If electricity from unaffected areas is not available, the blackstart process becomes much more challenging. The procedures required to blackstart the power grid following a wide area outage are very different from the procedures used to restart the power grid following the major but limited blackouts that have occurred to date such as the 2003 Northeast blackout. This document develops a starting point for blackstarting the U.S. power grid based on likely effects on critical infrastructures caused by solar storms and EMP events. Previous regional blackstarts were assessed to glean empirical information on aspects that could be extrapolated to a national blackstart contingency.

[1] U.S. House of Representatives Committee on Government Reform. "Telecommunications and SCADA: Secure Links or Open Portals to The Security of Our Nation's Critical Infrastructure." *Hearing Before the Subcommittee on Technology, Information, Policy, Intergovernmental Relations and the Census.* March 30, 2004. http://www.gpo.gov/fdsys/pkg/CHRG-108hhrg95799/pdf/CHRG-108hhrg95799.pdf, p. 2.

[2] CENTRA Technology Group. *Geomagnetic Storms.* Washington, D.C.: Office of Risk Management and Analysis, U.S. Department of Homeland Security, 2011, p. 9.

1.0 Introduction

Two wide area electromagnetic threats are capable of causing the collapse of a large portion of the North American electric power grid. The electromagnetic pulse (EMP) from high altitude nuclear explosions and its natural analogue, major solar storms will be addressed in terms of their potential large scale effects on the power grid and the process that will be involved in restarting the grid from the large scale blackouts that could occur. Such blackouts are more difficult to recover from because, unlike local blackouts that have occurred in the past, EMP and major solar storm events have the potential to shut down more than half of the U.S. power grid.[3] The North American power grid has never experienced a shutdown of this scale. Since the last major solar storm and EMP test, the size and amount of power delivered by the North American power grid has grown more than a factor of ten and we have become much more dependent on electricity for critical human life sustainment functions. A major blackout is complicated by the fact that large electric power sources are required to restart the grid and may not be available over considerable distances.

There have been numerous studies in the past on the effects of such wide-area catastrophic events on the North American electric power grid. However, very little has been done to examine the challenges of restarting the grid and the blackstart tasks and sequences that would be required.[4] It is the purpose of this paper to provide initial guidance on how a national blackstart process would work.

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[3] Ibid., p. 8.
[4] James Marusek, *Solar Storm Threat Analysis,* Bloomfield, IN: Impact, 2007.

2.0 Wide-Area Electromagnetic Phenomenology and Effects

2.1 Electric Power Grid Nomenclature

For the purposes of this paper, the terms "power lines" and "power grids" refer to the electric *transmission* system. The transmission system moves electric power from its source of generation to distribution facilities. These power lines generally run at 230kV up to 765kV and can be as long as 1000 km or more. Power lines begin at step-up transformers at generation stations and "step up" the voltage to move energy through the power grid more efficiently. Transmitting power at high voltages is done to lower the electric current and therefore power loss.[5]

In order for electricity to be used in homes and businesses, the transmission voltage must be stepped down. This is usually done at substations. From substations, the electricity moves to the distribution system at voltages between 2,400 V and 69,000 V. These lower voltage power lines are then routed to homes and businesses.[6]

The power grid is dependent on itself- electricity is required to generate electricity. It is extremely difficult to start power generation systems without electricity and products and services from other infrastructures that depend on electricity.

2.2 EMP and Solar Storm Environments – Comparisons and Contrasts

The two wide-area electromagnetic threats to the power grid are both caused by the interaction of charged particles with the Earth's magnetic field. These events behave somewhat differently in their interactions with the power grid in many respects. However, there are also many effects on the power grid that are shared by both EMP events and solar storms. The effects from both EMP and solar storm events can best be described as localized damage over a continental area.

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[5] Naval Facilities Engineering Command, *Electric Power Distribution Systems Operations*, Alexandria, VA: Naval Facilities Engineering Command, 1990, p. 17.

[6] Ibid., p. 18.

We have considerable experience on solar storm effects due to their continuing natural occurrence. The same is not true for EMP Limited atmospheric data from the 1950s and the early 1960s reveal that EMP has two major components - an early time component, E1, and a late time component, E3. EMP's E1 fields have fast rise times, and very short durations. The broadband nature of these fields means they couple to electronic boxes, short cables, and antennas as well as long-lines. E3 and solar storms, because of their extremely low frequency nature, couple significantly only to long lines.

E1 field environments are different from any naturally-occurring electromagnetic environment. Fields from nearby lightning strikes are the closest natural analog but lack the fast rise times associated with E1; therefore, we cannot easily compare EMP system effects with any natural analogs.[7] Today we must rely on simulations and models to attempt to predict how a EMP event will affect the power grid.[8]

The large number of variables involved in predicting EMP effects on the grid is problematic; thus, models give us only rough estimates of the potential problems created by an E1 event. Further testing of equipment thresholds will be important to better predict the types of effects that can occur. Threshold data on individual components of the grid can then be combined in network models to determine large-scale effects on the grid. From previous experiments completed in the 1960's and testing completed at various national laboratories, we can determine that damage will be stochastic over large regions from the E1 pulse.

2.3 EMP and Solar Storm System Consequences

The advent of the national grid and the fact that, today, almost all infrastructures currently rely on the electric power infrastructure to function, makes continental-scale solar storms survival-threatening events analogous to nuclear EMP. These wide-area electromagnetic

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[7] James Gilbert, Edward Savage, and William Radasky, *The Early-Time (E1) High-Altitude Electromagnetic Pulse (HEMP) and Its Impact on the U.S. Power Grid*, Goleta, CA: Metatech Corporation, 2010, p. 14.

[8] Pfeffer, op.cit., p. 9.

effects engender a scale of catastrophe that has never occurred in North America. In the U.S., power outages typically last 2-3 days or less.

The consequences of being unprepared for EMP or geomagnetic disturbances are dire at best. The main area of concern will be collapse of the power grid. However, direct and cascading failures of other infrastructures also have life-threatening consequences. Within days of such an event, it is likely that lack of life-sustaining infrastructure would lead to the breakdown of governance, resulting in general chaos, especially in urban areas. Modern society depends on the electric grid to sustain life. Direct and cascading electromagnetic effects on communication systems will greatly impede the ability of police and first responders to respond in emergency situations. The most direct cascading problem vis-à-vis grid restoral is that most grid operators would not have communications to coordinate the restart of the grid or to assess damage to the grid.[9]

Given these EMP and solar-induced critical infrastructure failures, the U.S. would essentially lose 150 years of technology advancement in a few days. The resulting devastation and death rates have not been experienced since the bubonic plague in Europe. Typical of other critical infrastructure sites, the vast majority of medical facilities have a limited amount of fuel on site for their backup generators. In most locations, backup generation is used as a temporary power source during weather events and other short-term events lasting from hours to a few days. Without electricity, once on-site fuel is depleted, there is little ability to refill supplies because the United States relies almost entirely on electricity to pump various types of fuel including gasoline, diesel and natural gas. The rapid breakdown in the transportation industry would inhibit our ability to provide critical supplies to most of the nation. Because of the loss of the refrigeration systems required to preserve a large portion of our food supply (from the farm to the table), food shortages would become a major issue within days.

[9] *NSTAC Report*, op. cit., p. 5.

Perhaps the largest life-threatening impact from the debilitation of electric power grid would be the loss of drinking water supply systems critical to sustaining life. Most municipalities supply drinking water by using electric pumps to move the water from its source to the area that it will be used. When the electricity goes out, in most areas the water supply is limited to the amount of water held in water towers, which would be depleted within one or two days in most areas .[10] The sanitation system we have come to rely is just as dependent on electricity to pump sewage to water treatment facilities. Sanitation pumps generally do not have a backup power supply. Therefore if a power failures were to last more than a few days, raw sewage would back up onto the streets and into homes.

Due to advances in modern medicine (such as treatment for diabetes and beta blockers for those with heart conditions), many Americans with health problems can now live normal lives. In the event of a power outage of more than a few days, those with health conditions requiring medications to support life would be among the first to expire. This would occur due to a lack of ability to cool insulin and lack of ability to transport pharmaceuticals. Local pharmacies often receive daily shipments of medication to keep inventory costs down and reduce spoilage; without daily shipments and refrigeration, pharmacies would quickly be rendered useless.

Nuclear facilities are a special concern. These facilities can only keep active and spent fuel rods cool as long as they have backup power. Japan's Fukushima Daiichi nuclear reactors experienced this problem following the 2011 tsunami with disastrous consequences. The tsunami destroyed the backup generators and caused a long-term power outage. Due to the power outage, electric pumps were not able to circulate water to cool the reactor cores or spent rod pools and the fuel rods overheated and interacted with water to produce hydrogen gas which exploded, destroying the reactor buildings and spreading highly radioactive fission products into the surrounding region. Inside reactors, heated fuel assemblies also breached the containment

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[10] Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack. "Report of the Commission to Assess the Threat to the United States from Electromagnetic Pulse (EMP) Attack: Critical National Infrastructures." Washington, D.C., 2008, p.8

vessels, resulting in a core meltdown. In the United States, most nuclear facilities only have a few days' of generator fuel stored on site for backup electric power.[11] Once this is depleted, pumps used to cool spent fuel rods and reactors cannot be operated. Thus, EMP or solar storms could result in Fukushima-type disasters in a large number (perhaps hundreds) of locations across the blackout region.[12] .

The key to sustaining a viable society after a severe solar storm or an EMP attack is ensuring infrastructure resiliency. This means protecting vulnerable assets in a cost-effective manner, having spare replacement components when feasible, and having a plan of action to restore and restart the grid from scratch [i.e., "blackstart" the grid]. It is extremely important that this plan be modeled and field-tested. The purpose of this research is to identify the challenges associated with restoring the power grid following an EMP or solar storm event and identify the sequence of actions required to restore and blackstart the U.S. power grid after a nationwide blackout.[13]

Both EMP and solar storms couple to long-line networks and will damage heavy-duty power systems on the grid such as transformers, motors and generators. However EMP, because of the broad-band nature of E1 will also couple to and damage microelectronics. Damaging these pieces of equipment can have also affect the operation of heavy-duty power systems such as transformers and generation facilities. In both instances, the "cascading" of these events through the entire electrical grid and other infrastructures makes them catastrophic events that can profoundly affect society.

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[11] Josie Garthwaite, *How Is Japan's Nuclear Disaster Different?*, March 16, 2011, http://news.nationalgeographic.com/news/energy/2011/03/1103165-japan-nuclear-chernobyl-three-mile-island// (accessed 13, 2012).

[12] Matthew Stein, *400 Chernobyls: Solar Flares, EMP, and Nuclear Armageddon,* 2012, http://www.whentechfails.com/node/1545.

[13] North American Electric Reliability Corporation. *High Impact Low Frequency Event Risk to the North American Bulk Power System: A Jointly Commissioned Summary Report of the North American Electric Reliability Corporation and the U.S. Department of Energy's November 2009 Workshop.* North American Electric Reliability Corporation, 2010, p. 3.

2.4 EMP Effects

2.4.1 EMP Test History. In 1962 the U. S. Military detonated a hydrogen bomb 250 miles above the Pacific Ocean, roughly 900 miles from Hawaii.[14] This experiment, known as the Starfish Prime event, was based on the work of James Van Allen, who developed the theory concerning the belts of energetic particles surrounding the earth, now known as the Van Allen Belts. Immediately after Van Allen published his theory, the military asked him to assist with high altitude nuclear weapon effects testing.[15]

The Starfish Prime test was designed to determine if it would be possible to disrupt the Van Allen belts and, if so, the effects on satellites and radio transmission. When the detonation took place, the effects were immediate. Power outages were reported in Hawaii, as well as unusual behavior from electrical devices. Garage doors raised and lowered without any assistance. Burglar and fire alarms went off without being tripped, and a telephone system microwave link was damaged. Several strings of street lights were tripped due to blown fuses. Analysis concluded that this was most likely caused by the Starfish Prime nuclear test. The streetlight incidents had several characteristics consistent with damage from the early time (E1) wave of EMP, and they possessed several characteristics that made them more vulnerable to EMP (E1) effects.[16] Post-test calculations of the EMP-induced line voltage indicated it peaked at the upper electrical code limits. The lines were positioned to maximize horizontal E1 coupling. The damage to the electrical and electronic systems was unexpected, as was the magnitude of the electromagnetic pulse.[17] The military had deployed instruments to measure the size of the

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[14] Robert Krulwich, *A Very Scary Light Show: Exploding H-Bombs In Space*, July 1, 2010, http://www.npr.org/templates/story/story.php?storyId=128170775 (accessed November 8, 2011).

[15] Ibid.

[16] Vittitoe, Charles. Did High Altitude EMP Cause the Hawaiian Streetlight Incident? Albuquerque, NM: Sandia National Laboratories, 1989

[17] Jerry Emanuelson, *Test 184*, 2004, http://www.futurescience.com/emp/test184, p. 3

electromagnetic pulse; however the pulse overwhelmed the instrumentation. Other aspects of the test are still classified.[18]

Figure 1: Artist's Concept of a High Altitude Nuclear Detonation[19]

The Soviet Union closely monitored the Starfish Prime event, which prompted them to conduct additional EMP testing. Soviet tests were conducted over Kazakhstan during the early 1960's. Soviet Test 184 involved a nuclear detonation roughly 180 miles above the ground. The EMP from the detonation instantly damaged Kazakhstan's power and telephone infrastructure. The ceramic insulators on overhead lines were severely damaged, causing power lines to fall from the poles to the ground. A power plant caught fire and a 600 mile underground power line was destroyed in this test. Multiple diesel generators failed shortly after the blast, which was attributed to their windings failing from the late time EMP (E3) component that occurred 20 seconds after the blast. Telephone lines in Kazakhstan had currents induced in them of 1500 to 3400 amperes, and radar systems were knocked out 600 miles from the detonation point.[20]

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[18] Ibid., p. 3.
[19] http://www.atomicarchive.com/Effects/effects21.shtml.
[20] Ibid., p. 4.

An interesting aspect of the Russian event was that the prompt EMP (E1) component did not blow fuses in systems; rather, the E3 event blew every fuse in the telephone system. The Russian test introduced geomagnetic field perturbations of 1300nT/min whereas the Starfish Prime test caused perturbations of 4800nT/min. It is believed that the lack of more serious effects in the U.S. test was because the detonation took place over the ocean far from the Hawaiian Islands, whose small geographic size and associated power and communication line lengths limited the currents and voltages that could be induced by EMP. If the North American continent were to be exposed to a Starfish Prime size detonation, it is estimated that roughly 40% of the population would instantly lose power.[21]

It is worth noting that, at the time of their high altitude EMP tests, Russian communications and power systems relied primarily on vacuum tubes. Vacuum tubes are much more resistant to electromagnetic overstress than the solid state electronics in use today. Most of the results of the tests conducted by the Soviet Union are still classified and have not been released. Also note that the Russian bomb was inefficient at producing an EMP. Had it been as efficient as the Starfish Prime test, the damage would have been more extensive. The U.S. and Soviet nuclear test devices were both thermonuclear (fusion) weapons whose designs were not optimized for producing fast rising E1 components. Much smaller nuclear fusion weapons are capable of producing more severe E1 components using special designs.[22] The U.S. and Soviet high altitude tests of the 1960's confirmed that the EMP effect is real and can be exploited to debilitate electrical and electronic systems across wide areas.

2.4.2 EMP Generation Physics. EMP is produced by nuclear weapon detonations above 30km. E1 is produced when gamma rays from the nuclear weapon stream down into the atmosphere and liberate free electrons in the region between 20 and 40 km by a process known as the Compton Effect. These "Compton electrons" are synchronously deflected by the earth's

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[21] Ibid., p. 5.
[22] Ibid., p. 4.

magnetic field to generate a very high amplitude electromagnetic field. The high altitude EMP field has a characteristically brief duration compared to that of solar storm fields. This initial Compton effect EMP waveform rises in a few nanoseconds and decays in 100's of nanoseconds.

The late-time EMP field, referred to as magnetohydrodynamic EMP or E3, is produced by fireball and X-ray plasma effects, peaks in ten to twenty seconds, and lasts several minutes.[23] The fast, broadband E1 signal produces system effects that are more widespread and damaging than the electromagnetic effects produced by E3 or space weather events. EMP events also produce an intermediate time waveform (referred to as E2) due to neutron interaction with the upper atmosphere. This field waveform is similar in amplitude and content to fields radiated by lightning.

Because of its very high amplitude and broadband characteristics, E1 is the effect of most concern relative to EMP events. The pulsed electric field that develops travels at the speed of light to the earth's surface. The E1 pulse can cause damage in electrical devices over continental-sized areas by inducing voltages on cables and antennas that penetrate connected electrical and electronic systems.[24] The pulses severely affect the power grid because they use grid supervisory control and data acquisition (SCADA) systems and the interconnectedness of the power grid.[25] The most significant damage during an E1 pulse is the damage to solid state electronics. The damage that a particular system sustains depends on the most intricate details of current paths and interior electrical connections. Thus it is very difficult to predict the current flow and system effects before an event occurs. The North American power grid has become dependent on digital microelectronics over the last 20 years. Because these systems operate at low voltages, minor increases in voltages can destroy them.

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[23] J.R. Pierce, *Evaluation of Methodologies for Estimating Vulnerability to Electromagnetic Pulse Effects*, Washington, D.C.: National Research Council, 1984, p. 11.

[24] Ibid., p.75.

[25] Nuclear and National EMP Scenario, "Consequences of Living Unprepared," Situation Manual, 2010, p. 13.

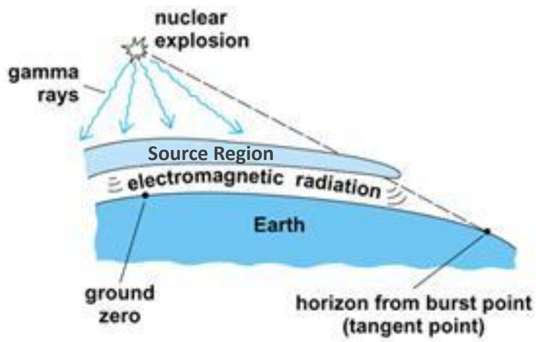

Figure 2: Schematic Representation of EMP in High Altitude Burst[26]

In summary, there are three phases of an EMP event. The E1 occurs first, and is caused by gamma rays, followed by the slower, lower amplitude neutron induced signal known as E2. Expanding debris and a rising atmospheric plasma layer causes the final EMP signal referred to as E3, or magneto hydrodynamic (MHD) EMP. The E1 component couples onto virtually all electronic equipment. Because of its lower amplitude and similarity to lightning, E2 effects are limited relative to E1 and E3.

2.4.3 EMP Effects on the Electric Power Grid. The threat to the U. S. from an EMP (or severe solar storm) event arguably poses the most catastrophic failure scenario for critical infrastructure, due to the possible immediate collapse of the national electric power grid with damage to components requiring long periods to repair or replace. This presents an unusually challenging problem because many of these grid components, such as large transformers, cannot be easily replaced: the lead-time to manufacture and replace these components can be months and sometimes years[27]. Many of these components are no longer manufactured in the United States, further complicating the replacement process[28]. Because we depend on electricity for life-supporting functions, many lives would be at risk in such scenarios. Because of their continental scale coverage, in the absence of planning and grid protection, these events have the potential to cause societal breakdown.

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[26] http://accessscience.com/content/Electromagnetic-pulse-(EMP)/222550.

[27] The President's National Security Telecommunications Advisory Committee. "Report to the President on Telecommunications and Electric Power Interdependencies: People and Processes: Current State of Telecommunications and Electric Power Interdependencies." 2006, p. 10-14.

[28] Ibid., p. 13.

The high altitude nuclear burst E3 waveform is similar in effect to the electromagnetic environments produced by solar storms. The E3 effect causes problems in long conductors and transformers, including half cycle saturation and transformer burnout. This occurs because the relatively long duration of the E3 waveform can last for several minutes. The E3 waveform and system effects are very similar to those of solar storms. It is the E1 environment that distinguishes EMP effects and protection requirements from those of solar storms.

Generally, devices connected to wires of less than 1 km in length only need to be concerned with E1 events. EMP events differ from solar storms in that the E1 (gamma) signal has much higher frequency content and couples not only to long lines, but electronic control systems. The faster than lightning rise time of an E1 event overcomes the ability of many of the power grid's protection devices. Available E1 energy density averages around 0.1 and 0.9 joules/m^2.[29] A piece of equipment connected to a line several meters long can collect several joules of E1 energy. A few microjoules of energy entering the input/output ports of equipment electronics is sufficient to cause component upset or permanent thermal breakdown failure.[30]

The amplitude of long-line voltages induced by the E1 early time event peak can reach above a megavolt.[31] The large current levels induced by E1 onto communications and power lines could destroy generators and transformers.[32] The scope of damage in terms of the diversity of systems affected by EMP is significantly more severe than for solar storms, based on E1's broad-band characteristics and the amplitude and duration of the current induced on the grid. The rapid rise time of E1 completely bypasses safety relays and lightning protection, and drives large currents and voltages into generation stations and step up transformers that may cause permanent damage due to winding breakdown and semiconductor failure.[33]

[29] Ibid., p.78.
[30] Ibid.
[31] Edward Vance, "Coupling to Cables," In *DNA Handbook*, Menlo Park, CA: Stanford Research Institute, 1974, p. 43-44.
[32] Pfeffer, op. cit.
[33] Ibid.

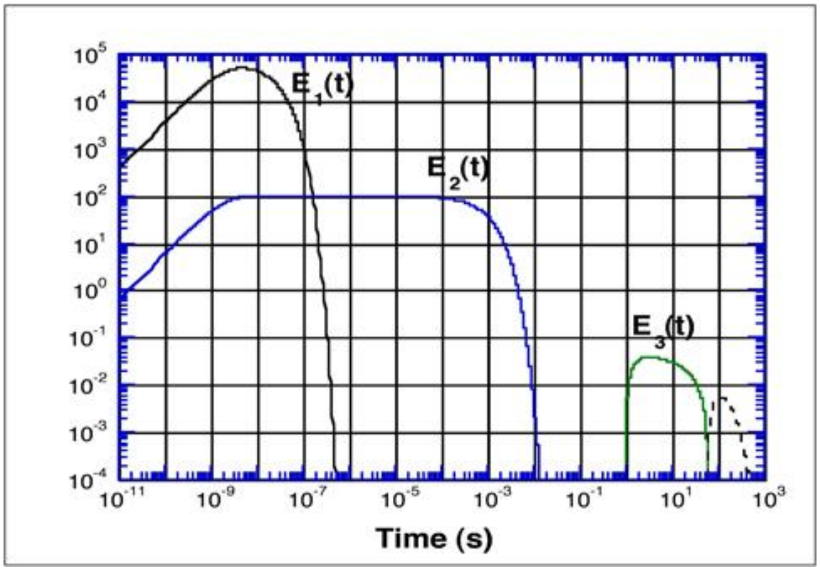

Figure 3: EMP Waveform [34]

Because of their size and complexity, determining the vulnerability of the electric grid and electromagnetic coupling processes to an EMP or solar storm event is very difficult. The size, type, and location of the weapon being detonated will have a significant impact on power grid behavior. Other variables include soil conditions and the geography of the area.[35] The geometry of powerlines relative to the direction of the electromagnetic fields is an important factor.[36] System vulnerability is also contingent on the soundness of the engineering of exposed grid components. Systems that are engineered to better resist other types of electromagnetic interference are thought to be more resilient to EMP events.[37] Timing is also important: E1 will have much a more devastating effect if it is timed to coincide with the peak of the grid's 60 Hz sine wave.[38]

The primary power grid systems affected by the early time E1 event in an EMP detonation are high voltage substations and communications, power controls and

[34] EMPRIMUS & ABB. "Solid Ground Electric Grid Resiliency Sensory & Control System," "New Technology to Protect the U.S. Powergrid from Solar Storms and EMP threats," 2011.
[35] Gilbert, op. cit., p. 63.
[36] Ibid.
[37] Pierce, op.cit., p.13.
[38] G. Baker, verbal communication.

communications, power line insulators, transformers, and generation facilities.[39] The E1 voltages reach the control rooms of electronic control systems through field cables connecting the control rooms to grid equipment. The voltage could wreak havoc on control rooms, due to the amount of voltage induced into microelectronics and the amount of wire used in a typical control room.[40] Connecting cables are generally long enough to allow coupled current to reach its maximum possible value. If the peak field were 30kV/m, a piece of wire around 6 inches long could have 5000 volts induced on it, which is sufficient to damage some types of electronic equipment.[41]

Power generation facilities contain electronic control equipment similar to modern industrial processing plants. Generation facilities now contain programmable logic controllers to control fuel supplies along with the SCADA systems used to control generation and transmission processes (see Appendix 1). Tests have shown that SCADA components can fail when extraneous voltages as low as 3.3kV are introduced.[42] It is likely that in the event of an EMP, some components of the SCADA system would be inoperable. Idaho National Laboratories has conducted testing by injecting currents into SCADA systems commonly used within the power industry. They concluded that the possibility of 100 to 700 amperes being induced onto the Ethernet wires would have a dramatic effect. Further testing would need to be conducted in order to accurately predict real world system behavior, because of the variety of communication standards and different SCADA manufacturers.[43] EMP-induced currents on control systems could lead to improper control signals being transmitted, thereby resulting in inappropriate automated response and human actions taken. The control system malfunctions alone in grid control and generation facilities could cause the grid to collapse. In addition, early and/or late time EMP currents are capable of causing permanent damage to large transformers. The most

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[39] Gilbert, op. cit., p.116.

[40] Ibid., p.56.

[41] Ibid.

[42] Ibid., p. 145.

[43] Ken Barnes, Briam Johnson, and Reva Nickelson, *Review of Supervisory Control and Data Acquisition (SCADA) Systems,* Idaho Falls: ID: Idaho National Engineering and Environmental Laboratory, 2004.

significant damage during an E1 pulse is the damage to solid state electronics. SCADA system components are connected over both commercial and private lines, spanning long distances. Because there are many different types of SCADA systems used on the power grid, it is not known how effects would vary from one manufacturer's equipment to another. However, a small number of Programmable Logic Controllers (PLC's) were tested; most failed when subjected to 7kVvoltage transients.[44]

SCADA vulnerability is compounded because the substations that utilize these components are not usually manned; if problems occur, there is no one available to take immediate action to correct the system. Loss of these of components could cause the grid to destroy itself. PC's and other components used in power generation can be destroyed by as little as 600V. This usually occurs at computer communication ports and other circuit boards used in SCADA systems.[45] These currents will be induced into the components by field lines strung across substations and generation facilities.

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[44] Gilbert, Savage, and Radasky, op. cit., p. 144.
[45] Ibid., p. 145.

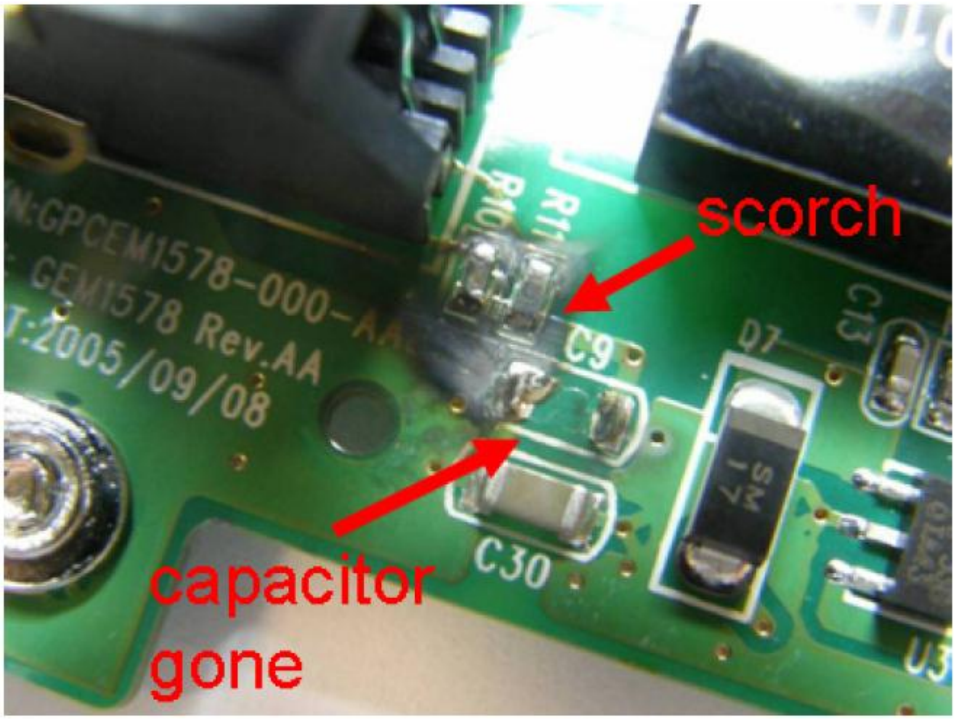

Figure 4: SCADA Circuit Board Capacitor Damage from Pulse Testing[46]

Long transmission lines themselves do not transmit the E1 component over wide areas, as occurs during the E3 pulse. The E1 pulse duration is several hundred nanoseconds which translates to a spatial coverage of several hundred feet. Thus, the induced current pulse builds up only over this distance before the waveform stimulus ends. The peak current tends to be more dependent on the field waveform's duration than its rise time.

The prompt E1 signal is large enough to permanently damage transformer windings.[47] E1-induced overvoltages in long lines are capable of causing flashover conditions in which the insulator fails due to thermal damage from electrical arcs causing pinhole punctures in insulator materials. Prior analysis by Metatech indicates that E1-induced over voltages of 200 kV to 400 kV can occur on the grid over geographically wide areas.[48] Electrical arc energies are greatly enhanced if the flashover occurs at the peak of the grid's 60Hz voltage transmission sine wave.

[46] Ibid., p. 168.

[47] Manweiler, *Effects of Nuclear Electromagnetic Pulse (EMP) on Synchronous of the Electric Power System*, Oak Ridge, TN: Oak Ridge National Laboratory, 1975.

[48] Gilbert, Savage, and Radasky, op. cit., p. 147.

In this event, the full grid power at the location of the arc will follow the EMP arc path, causing major system damage. Although the exact location at which an insulator will fail is unknown, we do know that repeated pulses from lightening lower the threshold at which flashover will occur.[49] Thus, older transformers have higher failure probabilities.

Pole-mounted insulators are also susceptible to flashover and damage. There are many manufacturers of insulators and several different types of insulators used on the North American power grid. The effects of an insulator failure on a high voltage transmission line can cascade throughout the grid causing large-scale outages.

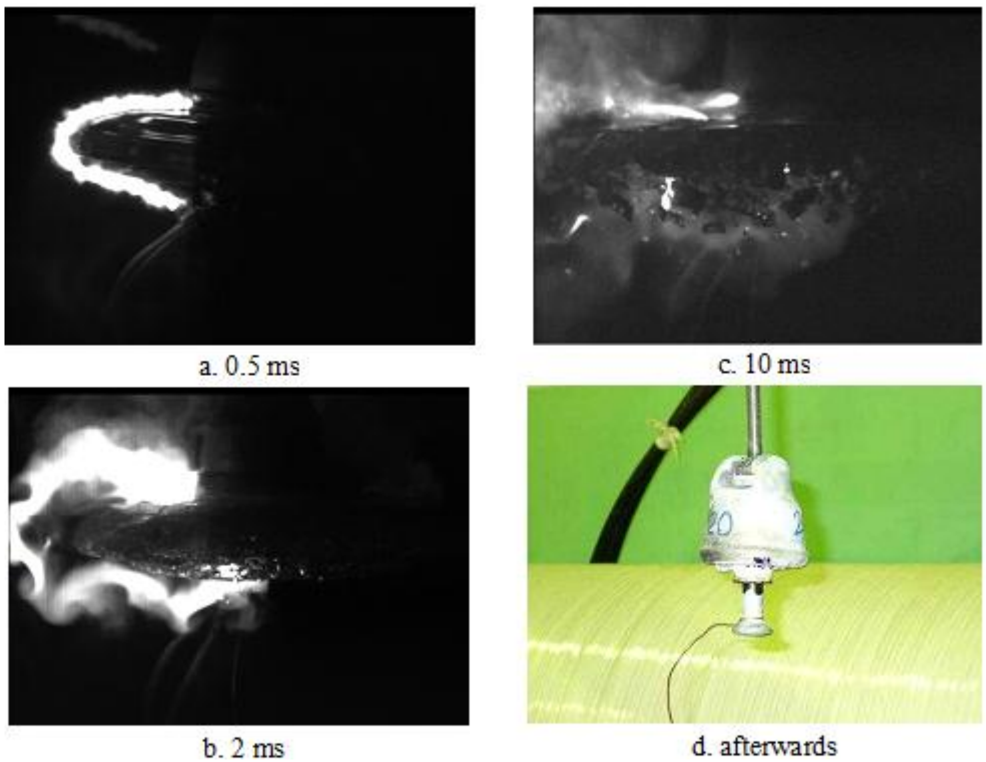

Figure 5: Snapshots from an Insulator Test Showing Damage due to Flashover[50]

[49] Ibid., p. 153.
[50] Ibid.

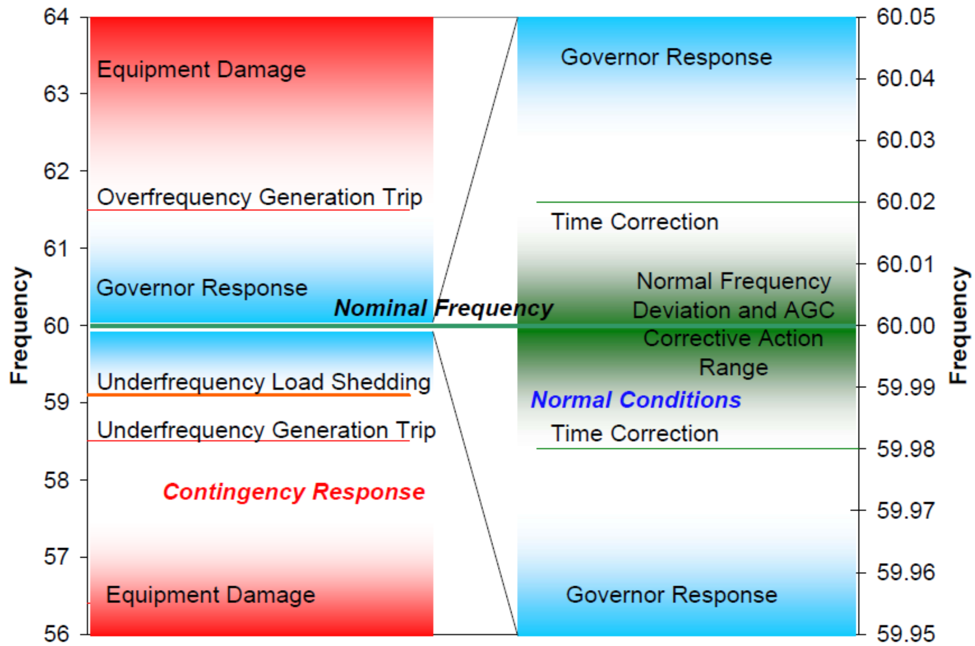

Figure 6: Structure of the Frequency Control, Protection and Equipment Damage Limits (Frequency in Hz)[51]

Damage to system controllers could cause generators to substantially deviate from 60Hz, possibly resulting in physical damage.[52] Mechanical vibration from off-frequency torques on rotating equipment would severely damage turbines, ensuring that they would not be operational without major time-consuming refurbishment.[53] Figure 6 above shows the effects of deviation from the 60 Hz utility frequency synchronization. For reasons previously discussed, an EMP event that occurred at the peak of the waveform would be detrimental to generators. EMP voltages introduced into this system could render these facilities unusable for an extended period of time. Unfortunately, due to the cost of power generation facilities and step up transformers, there has not been significant testing done on this type of equipment to determine their susceptibility to damage.[54]

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[51] J. Dagle, J. Dyer, R. Guttromson, B. J. Kirby, R. Shoureshi and C. Martinez, *Frequency Control Concerns In The North American Electric Power System*, Oak Ridge, TN: Oak Ridge National Laboratory, 2002, p. 13.

[52] Ibid., p. 15.

[53] Ibid.

[54] William Radasky and Edward Savage, *High-Frequency Protection Concepts for the Electric Power Grid*, Goleta, CA: Metatech Corporation, 2010, p. 36.

The effect that the E1 pulse has on transformers is not fully understood. Preliminary studies indicate that, if the peak fast pulse induced line voltages are between 264 and 304 kV, damage can be severe. Pulses of lower amplitude seem to have little effect on transformers.[55] The presence of lightning protection on transformers increases the amplitude of induced voltage that they can withstand. Additionally, standard procedure in mounting lightning protection on transformers involves long lead wires between the arrestor and the transformer. The inductance associated with long lead wires reduces the arrestors' ability to protect transformers from the E1 transmission line waveform.

The point at which the E1 occurs can have much more devastating effects if it is timed to coincide with power grid 60 Hz waveform peak. In order to connect various power systems, their frequencies must be synchronized. The North America grid is tightly synchronized at 60Hz,[56] and this frequency is maintained using GPS signals. The frequencies are adjusted on the half hour and hour to compensate for varying loads. This information is well-understood and readily available. If an E1 were timed to occur during the peak amplitude of the grid waveform, the damage to grid components would significantly increase. Grid "power follow" through E1-caused arc paths could cause severe damage to generators, step up transformers and substation transformers.[57]

The damage to the power grid could be accelerated even further by simply watching a weather forecast and timing the detonation with unusually cold weather conditions across the U.S. The heavy demand of electricity would increase damage to the grid because of the stress on the capacity of the system. The system would also be much more difficult to restart. Breakers and equipment at substations are notoriously difficult to restart in cold weather. Generation

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[55] Gilbert, Kappenman, Radasky, and Savage, op. cit.
[56] Ibid.
[57] G. H. Baker, private communication

plants cool rapidly during cold weather, complicating the restart of the facility as the proper shutdown sequences cannot be followed.[58]

2.5 Solar Storm Effects

2.5.1 Solar Storm Phenomenology. Solar storms occur naturally when plasma eruptions on the surface of the sun eject high energy charged particles toward the earth. This flux of charged particles is referred to as the "solar wind." Prior to the advent of electric technologies, critical infrastructure was prey to normal weather events such as droughts, floods, blizzards, and hurricanes. With the advent of long line communication and power systems, the developed world discovered around the 19th century that they were also vulnerable to "space weather."[59] Technologically-developed nations first learned that space-weather disturbances were the culprit when they experienced periodic problems with telegraph systems. Violent eruptions of the sun's corona, or "coronal Mass ejections (CME's)," are the root cause of major solar storm effects.[60] The shock waves that result from CME's create solar energetic particles (SEP's),[61] which consist of high energy particles that include electrons and solar wind ions.[62] If projected earthward, the charged particles are trapped by the earth's magnetic field. The presence of the trapped ionized particles distorts the earth's magnetic field. These changes in the earth's magnetic field over time at the ground induces significant voltages and in long conducting lines.[63] The magnitude of the induced voltages and currents is governed by Faraday's law.

In order for a geomagnetic storm to be dangerous to the electrical infrastructure, several factors must converge to maximize the intensity of the storm. The CME must be launched from

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[58] Gilbert, Kappenman, Radasky, and Savage, op. cit., p. 101.
[59] National Research Council. *Severe Space Weather Events-Understanding Societal and Economic Impacts of Severe Space Weather Events: A workshop.* Washington, D.C.: The National Academics Press, 2008, p. 6.
[60] CENTRA, op. cit., p. 8.
[61] Ibid., p. 8.
[62] Ibid.
[63] Riswadkar and Dobbins, op. cit., p. 57.

the center of the sun in a path that will cause it to intercept the earth.[64] The CME must also be fast-moving, at speeds greater than 100 kilometers per second.[65] In order to produce a dangerous solar storm, the CME must be massive enough to transport a large amount of kinetic energy.[66] The magnetic field vector produced by the solar wind must be strong and oriented in the opposite direction of the earth's magnetic field. Disturbances that have these characteristics can be extremely destructive to the electric power grid.[67] The CME particles excite the ionosphere by ionizing air molecules to cause an aurora. Electrical currents generated from these events perturb the earth's magnetic field. The slowly varying magnetic field at the earth's surface induces quasi-DC voltages and currents on long conductors such as power lines, communication lines, and pipelines.[68]

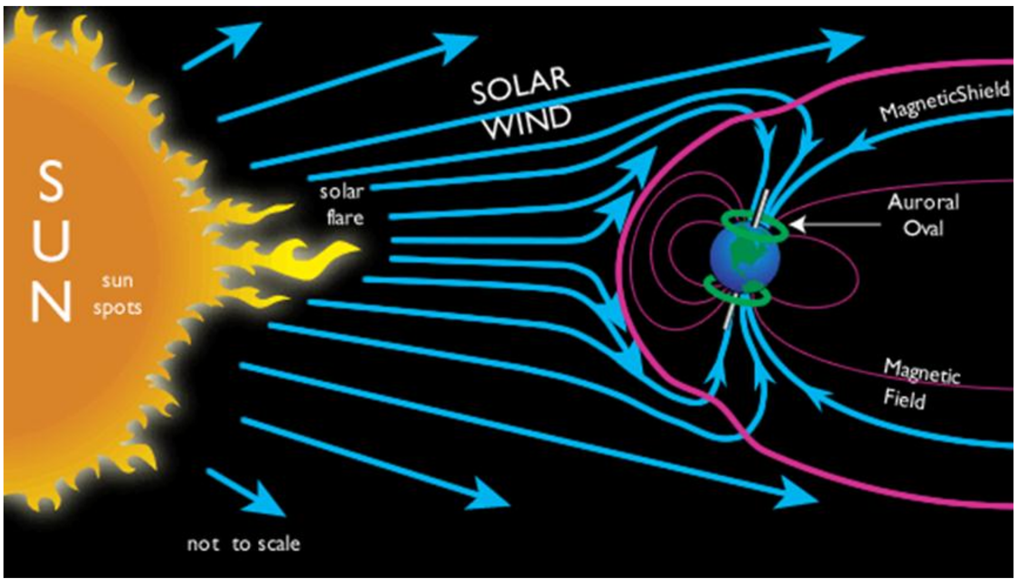

Figure 7: Solar Storm[69]

[64] Ibid.
[65] Ibid., p. 6.
[66] Ibid.
[67] Center for Computational Heliophysics in Hawaii at the Institute for Astronomy, 2011, http://c2h2.ifa.hawaii.edu/Pages/Education/space_weather_geomagnetic.php (accessed December 17, 2011).
[68] CENTRA, op.cit., p. 8.
[69] http://scienceprep.org/sun.htm.

The strength of geomagnetic storms is expressed in a negative value DST (Disturbance Storm Time) index[70]. DST is a measure of the strength of the magnetic field produced by the solar wind. It is expressed in nanoteslas, which is the general unit of measurement for magnetic fields. DST values are based on the average value of the horizontal component of the Earth's magnetic field measured hourly at four near-equatorial geomagnetic observatories.[71] Severe geomagnetic storms are those classified as having a DST absolute value of greater than 500 nanoteslas (nT).[72] By comparison, the Earth's magnetic field strength ranges between 25,000 and 65,000 nT, depending on location.

It usually takes geomagnetic storms 2 to 3 days to reach the earth after initiating on the surface of the sun. Typically, there are three phases of interaction once a geomagnetic storm reaches earth. The first phase can last from a few minutes to an hour or more. During this phase, the solar storm perturbation of the magnetic field typically reaches a maximum of tens of nT. The second phase produces the main effects. During this "main phase" of a solar storm, perturbations of hundreds of nT can be produced, lasting between 30 minutes and several hours.[73] The third phase is the recovery phase and may last up to several weeks. During this period, the Earth's magnetic field returns to normal levels.[74] Damage to long line power and communication systems can occur in all three phases; however, the second phase is by far the most destructive as half cycle saturation is the most severe.

2.5.2 Solar Storm Effects on the Electric Power Grid. Solar storms induce currents on the electric grid similar in nature to those induced by the late time component of nuclear EMP (E3). The system effects described here for solar storms also apply to EMP's E3 component.

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[70] Ibid., p. 6.
[71] Southwest Research Institute, Dst Index, http://pluto.space.swri.edu/image/glossary/dst.html.
[72] Ibid.
[73] Ibid.
[74] Ibid., p. 11.

Solar storm intensity and duration varies significantly and cyclically. The "Carrington Event" was the most significant solar storm documented and occurred in 1859.[75] This geomagnetic storm caused telegraphs to fail across North America and Europe. In some cases, operators received electrical shocks and telegraph paper spontaneously caught fire due to storm-induced electrical arcs.[76]

Due to Faraday's law, the voltage induced in long lines is proportional to the rate of change of the magnetic field in time. As a result, higher values of nanoteslas per minute also correlate with higher induced current levels. Very large currents may be induced in grounding conductors. These currents are referred to as ground-induced currents or GIC's. Large solar storm GIC's can destabilize the power grid and even damage critical components.

Based on prior solar storm experience, GIC effects are most pronounced in transformers.[77] Severe geomagnetic storms at higher negative DST levels cause higher GIC surges with correspondingly faster effects on the grid. A 1989 solar storm caused the Hydro Quebec grid to fail in about 1 minute. Because the Earth's magnetic field lines are more concentrated at higher geographic latitudes, areas of the globe closer to the poles are more susceptible to geomagnetic storm activity. However, major geomagnetic storms can disrupt electric grids at mid-latitudes as well. For example, damage from solar storms has occurred in U.S. Mid-Atlantic States, Japan and South Africa in the past. In addition to the strength of normal geomagnetic fields, the geology and presence of igneous rock have a strong influence on GIC current levels and the resulting effects on the power grid.

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[75] A. V. Riswadkar and Buddy Dobbins, *Solar Storms: Protecting Your Operations*, Zurich Services Corporation, 2010.

[76] Scott DiSavino, *Power Companies Prepare as Solar Storms Set to Hit Earth,* August 6, 2011, http://www.reuters.com/article/2011/08/06/us-utilities-noaa-solarstorms-idUSTRE7746UA20110806.

[77] Center for Computational Heliophysics in Hawaii, op. cit.

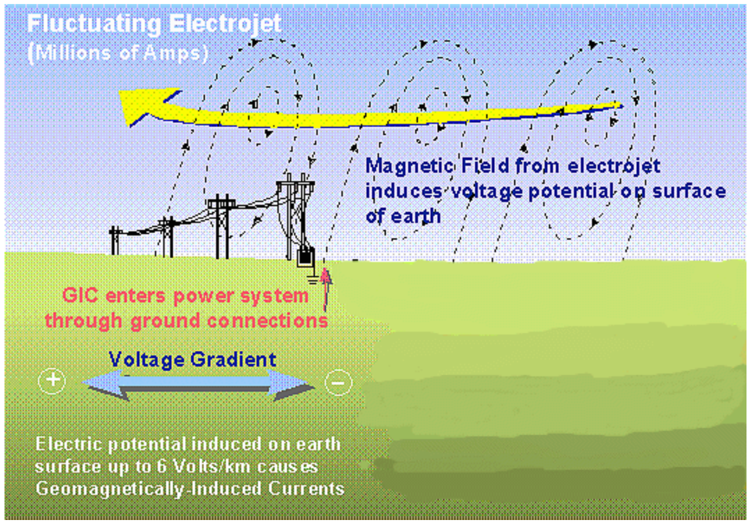

Figure 8: GIC Currents Induced into Infrastructure[78]

Predicting how a geomagnetic storm will affect the power grid on a large scale is an extremely difficult problem. As previously explained, there are many parameters involved in predicting the geomagnetic storm environment alone. The configuration of the power grid plays a key role in how the events play out.[79] During a solar storm, currents flow onto the power grid at numerous points. Solar storm-induced changes in the Earth's magnetic field induce currents on long transmission lines and in the Earth itself. Line and ground currents flow on and off of the grid at each earth-ground connection point and GIC's in the hundreds of amperes have been measured in transformer neutral ground connections. The largest current measured in a single transformer neutral occurred in Finland and exceeded 200 A.[80] The largest future geomagnetic storms may induce neutral currents on the order of 500 A.

The orientation of power transmission lines also affects how much current is induced in them. Lines running east-west are far more susceptible then lines running north to south. This occurs because of the polar orientation of the earth's magnetic field. The longer the line, the more voltage will be induced along its length. Long transmission line systems are susceptible to

[78] William Radasky, "High-Power Electromagnetic (HPEM) Threats and the Electric Power System." *Elite Electronic Engineering.* October 20, 2010. http://www.elitetest.com/latest-news/high-power-electromagnetic-hpem-threats-and-the-electric-power-system.html.

[79] Ibid.

[80] Ibid.

outages from solar storm-induced electric fields as low as 1 Volt/km.[81] The amplitude of the corresponding current is influenced by the method of station grounding and geology-determined earth resistance. Generally, the more voltage the line is designed to carry, the lower its line and ground resistance. Thus, 745 kV (the highest transmission voltage currently in use) transmission lines and transformers are the most susceptible to solar storm effects.

Long, high voltage lines typically require voltage regulating devices such as capacitor banks and volt-ampere-reactive (VAR) power compensators. These devices are also highly susceptible to geomagnetic currents. In the event of severe solar storms, these devices are likely to be prematurely tripped off-line by protective relays. Grid protective relays are designed to trip when the power waveform deviates from its normal 60 Hz coherent sine wave. Solar storm-induced GIC's introduce unusual harmonics in transformers by causing half cycle saturation of transformer cores, which force the transformers to operate in the nonlinear part of their hysteresis curve for half of every cycle, thus generating harmonics.

In addition to generating grid-destabilizing harmonics, transformers themselves can be directly damaged by solar storm GIC's. After half cycle saturation occurs, the transformer core becomes loaded beyond its capacity. The transformer magnetic field, normally confined to the core, now leaks into surrounding spaces and creates stray eddy currents that heat transformer windings, case and cooling oil. The windings in the transformers can become hot enough to melt, and tank wall hot spots often occur. The highest recorded transformer temperature was 347°F.[82]

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[81] Ibid.
[82] Ibid.

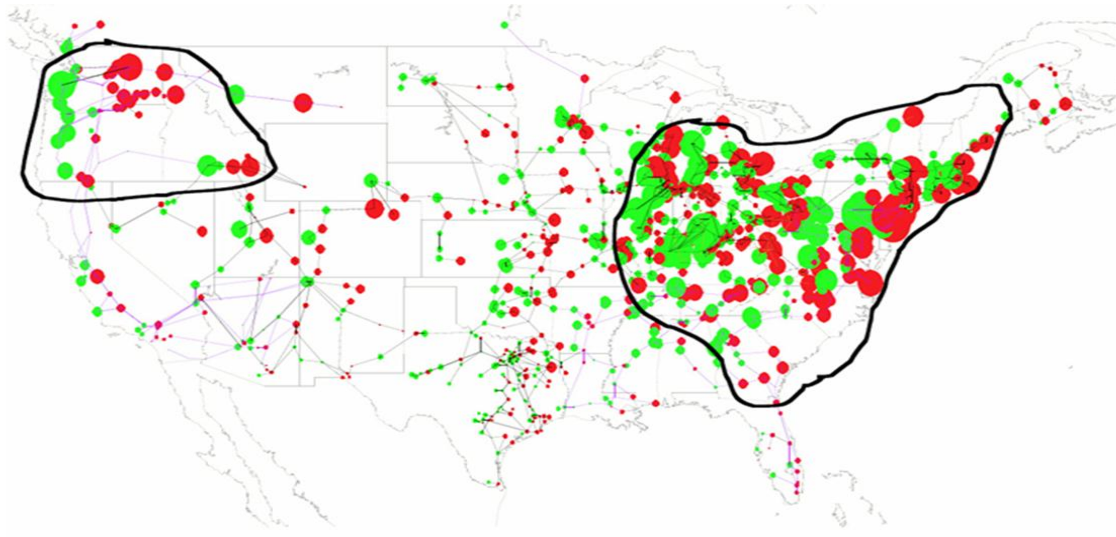

Figure 9: 100-Year Geomagnetic Storm – 50 Degree Geomagnetic Disturbance Scenario[83]

Because of the nonlinear nature of the saturated transformer behavior and cumulative degradation in older transformers, transformer damage is difficult to predict. Past exposure to geomagnetic currents and other damaging events that were not strong enough to cause visible damage can weaken transformers, making them more susceptible to overstress from geomagnetic events. Three phase transformers are less susceptible than three single phase transformers because three phase transformer designs cancel some of the harmonic-producing stray magnetic fields between the phases. Transformer location is also an important parameter since geomagnetic storms are typically strongest in North America between 55°N to 70°N.[84]

[83] John Kappenman, *Geomagnetic Storms and Their Impacts on the U.S. Powergrid*, Goleta, CA: Metatech Corporation, 2010.

[84] Ibid.

3.0 Lessons from Past Geomagnetic Events

To anticipate the process and effort involved in blackstarting the North American power grid, it is instructive to examine the events that occurred following the major solar storm of 1989, in which significant portions of the Hydro-Quebec grid failed. On March 10, 1989, a solar flare erupted on the Sun's surface. Fifty-four hours later, on March 13, 1989 the effects were felt on earth. The power grid in the Canadian province of Quebec suffered the most significant effects. The geomagnetic storm caused a total loss of 21,550 MW of power and nearly caused the entire Hydro-Quebec power grid to collapse.[85] In order to understand how power was restored during the Hydro-Quebec incident, we must first understand how the Hydro-Quebec grid failed.

3.1 Collapse of the Grid

Hydro-Quebec's geography, its 1,000 km transmission lines, and high latitude made it more susceptible to geomagnetic events than other grid systems. The failure of the system began at 1:00 a.m. on March 13, 1989. Due to transformer harmonics caused by quasi-DC solar storm currents, the grid became unstable at this time, threatening to trip breakers and relays. Operators had sufficient time to perform the switching necessary to reduce the voltage on the system but failed to do so. This would have lowered the load on the system by minimizing the wild voltage swings caused by geomagnetic-induced transformer harmonics. At 2:45 a.m., a particularly intense geomagnetic disturbance took place that tripped or shut down seven static compensators.

Static compensators are reactive devices used to balance power oscillations and are relatively new products replacing synchronous condensers in the power grid.[86] These compensators have no moving parts, unlike synchronous condensers. Static compensators are much more efficient than synchronous condensers, however, because they are set to operate within much closer tolerance, they are much more vulnerable to malfunction in the presence of

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[85] CENTRA Technology Group, *Better Policies for Better Lives*, Washington, D.C.: Office of Risk Management and Analysis, U.S. Department of Homeland Security, 2011. p. 3-4.

[86] Vedam, R. Sastry, and Mulukutla Sarma. *Power Quality: VAR Compensation in Power Systems.* Boca Raton, FL: CRC Press, 2008, p. 27-28.

GIC induced currents. Unfortunately, static compensators can act as an energy sink during geomagnetic storms. During the wild oscillations caused by a geomagnetic event, static compensators overload and completely shut down. This leaves the voltage on transmission lines unregulated.[87] The figure below shows a simple static compensator schematic of the kind used in the Hydro Quebec system. The design includes three capacitors controlled by a thyristor. During the Hydro-Quebec incident the static compensators engaged instantly as designed, but they proved ineffective because of overwhelming reactive power produced by the geomagnetic storm-induced quasi-DC current.

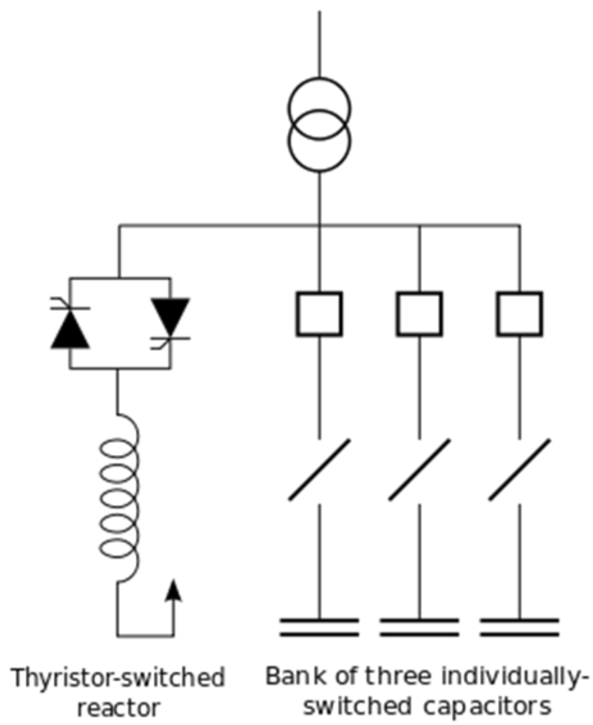

Figure 10: Static Compensator[88]

The 2:45 am geomagnetic disturbance occurred too rapidly for human intervention. Two of the affected static compensators were at Hydro-Quebec's Chibougamau substation. It has been assumed that these static compensators were the first to fail. Within seconds, four static compensators at the Albanel and Nemiscau substations failed. Those failures caused the La

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[87] Ibid.
[88] http://en.wikipedia.org/wiki/Static_VAR_compensator.

Verendrye substation's static compensator to fail. The failure of the static compensators caused one of the 735 kV lines at the La Grande transmission network to trip. The La Grande facility is a large hydroelectric generating plant on the Hydro-Quebec system. Shortly thereafter, three additional lines tripped from the La Grande network, causing the La Grande facility to become completely disconnected from the Hydro-Quebec network.

In response to the lost transmission lines, two generating units at the La Grande complex automatically tripped off with a corresponding loss of 9,400 MW of generation. The network connecting the Church Hill Falls and Manicougan then tripped, causing a remote load shedding signal to be sent to Montreal, which caused the entire system to collapse, shedding all loads. A total of three hydro-electric generation facilities were shut down, including the La Grande Generation Complex, the Church Hill Generation Complex, and the Manicougan Generation Complex. [89] The figure below shows the status of the grid following the GMD, including areas continuing to provide electricity post-event and the areas that lost generation capabilities. The area in the yellow circle in the lower left corner is the Gatineau Generation complex that was still operable but was completely isolated and unable to transmit electricity.

[89] North American Electric Reliability Corporation, *NERC Position Statement on Solar Magnetic Disturbance Forecasting*, Washington, D.C.: North American Electric Reliability Corporation 1990.

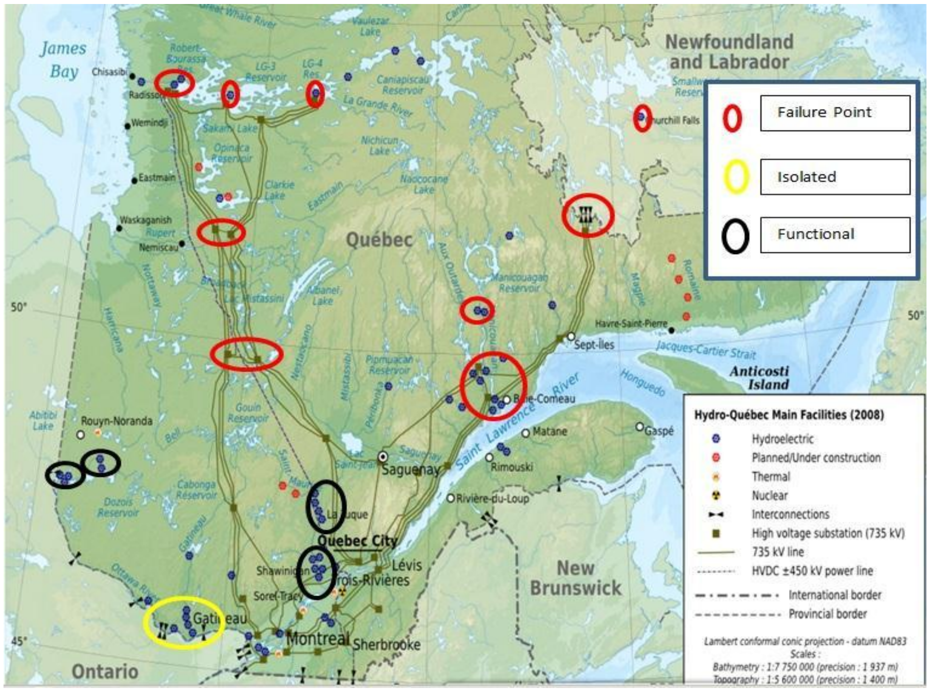

Figure 11: Map Post-GIC Event Conditions[90]

Once the system had completely collapsed, 430 MW of electricity was still available to supply the area. The Abitibi generating system circled in black on the far left of Figure 11 continued to produce 250 MW of power. The Gran Mere and Shawinigan generating stations were able to produce 160 MW of power. These areas are circled in black on the lower center of Figure 11. The Hull 2 generating station located just above the Shawinigan station was able to produce 13 MW of electricity. In addition, neighboring systems that were isolated from the failed portion of the network continued to generate 573 MW of electricity and remained in service.

Strategic equipment on the Hydro-Quebec network was damaged due to the failure of the static compensators. Once these compensators failed, voltage was not regulated on the Hydro-Quebec grid, resulting in overvoltage damage to two step up transformers when the network separated. A shunt reactor at Nemiscau was damaged so severely that the manufacturer had to be brought in to conduct the repairs. Static compensators at the Albanel and Nemiscau substations suffered minor damage. The thyristors were damaged at Nemiscau and the capacitor bank units

[90] http://upload.wikimedia.org/wikipedia/commons/4/4f/Quebec_Map_with_Hydro-Qu%C3%A9bec_infrastructures-en.png.

failed at Albanel. Overvoltage damaged the SVC-C transformer at the Chibougamau substation, which occurred in addition to the SVC compensators failing at Chibougamau.[91] Figure 12 below shows the locations of the failure points on the Hydro-Quebec system, and Figure 13 shows the area that was affected during the Hydro-Quebec blackout.

Figure 12: Hydro-Quebec Failure Points (red arrows) [92]

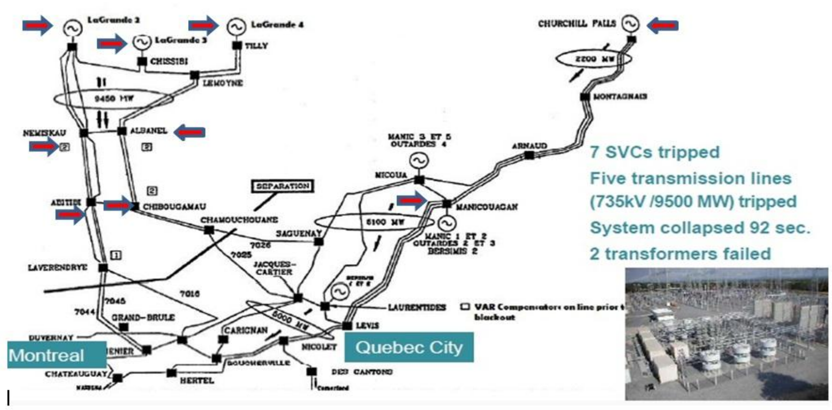

Figure 13: Area Affected by 1989 Hydro-Quebec Collapse[93]

3.2 Restoration of the Grid

Restoration of the Hydro-Quebec grid depended heavily on the assistance of nearby generation facilities that were not affected. Power assistance was received from New York as well as the Alcan and McLaren systems based elsewhere in Quebec. These transmission systems

[91] NERC, "High-Impact, Low-Frequency," op. cit.

[92] William Bartley, "The Risk of Solar Storms." Hartford, CT: The Hartford Steam Boiler and Insurance Company, October 13, 2011.

[93] http://standeyo.com/NEWS/08_Sci_Tech/080121.blackout.2003.html.

supplied Hydro-Quebec with the electricity needed to restart their generation, transmission, and distribution systems. Industrial customers in the region voluntarily reduced power demands to allow the system to be restarted. The restoration plan was significantly altered because of the equipment damage that occurred, and delays were encountered due to the unavailability of a replacement shunt capacitor at Nemiscau that was needed to restart the La Grande network. Operators restarted the system even though two step up generators at La Grande 4 were damaged from overvoltage. Albanel and Nemiscau had damaged SVC's, and the substation at Chibougamau also had a damaged SVC.[94]

The following task sequence was required to restore the collapsed portion of the Hydro-Quebec grid:[95]

1. New England power sources and what little power was left in Quebec were switched to provide Quebec with emergency power.
2. System engineers assessed the damage to the failed static compensators in the La Grande network.
3. Protection settings were increased to enable the use of equipment's overload capacity. This was done to avoid the need to replace relays prior to restarting the system. Utilizing overload capabilities is a short-term solution that reduces the lifespan of transformers and static compensators.
4. The grid was reconnected in small steps, by connecting autonomous "island" networks one after another, thus expanding the basic grid in increments.

There is not much available information explaining the details of the Hydro Quebec system blackstart. There are many disincentives for power companies to publish such information. Information indicating that the power grid is not resilient to these types of events is likely to lead to additional regulation. The power industry has been staunchly opposed to any sort

[94] NERC, op. cit.
[95] Ibid.p.52.

of regulation. In addition, information released by power companies is scrutinized, especially if grid reliability is questioned.[96] This can lead to fines if there are any indication procedures and regulations were not followed.

Power companies are expected to keep the power grid reliable. However, neither the Federal Energy Regulatory Council (FERC)'s 2000 Standard Market Design Proposal, nor the latest Wholesale Market Platform (WMP) establishes a clear cost-recovery model for transmission grid operators.[97] Operators are not paid based on the reliable product they provide through the transmission network, but rather on how cheaply they can price energy and their current stock price. Instead of developing solutions to grid problems, regulatory agencies fine operators when problems occur and offer them no opportunity to receive additional revenues to improve reliability.[98] Additional regulations translate into lower profit margins and lower stock prices.[99]

Hydro-Quebec has admitted that startup procedures were modified in order to restart the grid rapidly, which can be deduced from the relatively brief amount of time that it took to restart the grid. Due to the above mentioned reasons it would be unwise for a power company to publish the details of putting damaged components into service. This could result in sanctions from regulatory agencies as well as create liabilities in the event of the loss of power or component damage, possibly leading to lawsuits.

It is not likely that replacements for the large HV transformers were available within the Hydro-Quebec system and, given the short duration of the outage, it would have been almost impossible to make field repairs. The system was restarted in nine hours, which is significantly less time than it would have taken to repair a transformer of that size. Even if backup transformers were available (older, functional transformers that have been replaced are often left

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[96] Tyson Slocum, *The Failure of Electricity Deregulation: History, Status and Needed Reforms.* Public Citizen's Energy Program, 2007, p. 4.

[97] Ibid..p. 6.

[98] Ibid.,p. 5.

[99] Ibid., p. 6.

on- site), it is unlikely they could have been put into service. The most probable scenario is that the damaged transformers were used until a later date during a planned outage to enable field repairs.

Studies indicate that solar storms' stress on transformers and other major grid components reduces their life span. Estimates show that transformers fail 60% more often in New England than in other areas of the United States.[100] This indicates that GIC currents could have a cumulative deleterious effect on the power grid. It must be noted that the restart of Hydro-Quebec was not a true blackstart, since significant power was available from adjacent areas. Also, basic communication and control systems had power, which may not be the case in a large scale EMP or solar storm blackstart. As noted by Kappenman, all generation plants were hydroelectric facilities, which are relatively easy to bring back online.[101] Finally, communications did not fail throughout the entire process, which made it possible to coordinate recovery.

Despite the relatively limited effects of this blackout, it still took nine hours to restart the system. Had a critical transmission line pathway been damaged beyond use, this event would have had a vastly different outcome. In addition, the Hydro-Quebec incident occurred in March, neither in the deep winter or in the heat of summer, meaning the system was not under peak demand conditions. Furthermore, the incident occurred at around 3:00 a.m., when demand for electricity is much lower than during the day and evening hours. The consequences could have been far worse if the event had occurred in the winter months during the day when demand for electricity was high. Based on the restart experience following the 1989 Hydro-Quebec blackout, this event is better characterized as a near-miss GMD incident.

To mitigate future GMD effects, Hydro-Quebec has installed protection in the form of series capacitors at a cost of $1.2 billion. The series capacitors used by Hydro-Quebec have very high impedance for GIC current. Short lines and most tie lines did not receive series capacitors,

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[100] A. V. Riswadkar and Buddy Dobbins, op. cit.p. 101.
[101] Kappenman, op. cit.

leaving those lines presently unshielded[102] AC voltage asymmetry is now monitored in four key locations, including La Grande 2. The protection settings at Albanel and Nemiscau have been changed as indicated below.

Type Of Protection	Setting Before 3/13/1989	Current Settings
H.V. XFO. O/C Protection 1 p.u. = 236 A (rms)[1]	1.27 p.u.	1.5 p.u.
Capacitor bank overload protection 1 p.u. = 2,200 A (rms)	1.35 p.u.	1.8 p.u.
Capacitor and 3rd harmonic filter overload protection 1 p.u. = 2,200 A (rms)	1.08 p.u.	1.8 p.u.
Third harmonic filter resistor overload protection	1.03 p.u.[1] Trip	1.25 p.u.[2] Alarm Only
Capacitor unbalance protection for main and 3rd harmonic filter capacitor branch	Alarm: Loss of 3 units in main capacitor bank Loss of one unit in 3rd harmonic filter branch Trip: Loss of 4 in main branch. Loss of 2C in the 3rd harmonic filter branch	Temporary adjustment for loss of 8[3] filter-branch capacitors Loss of 9[4] filter-branch capacitor

Table 1: Settings Altered to Mitigate Future Geomagnetic Events[103]

[1]RMS is defined as root meaning square
[2] This protection initiated tripping of the SVC at Albanel substation.
[3] Connected to the oscillograph for further analysis during GIC conditions.
[4]To take into consideration natural unbalance during normal conditions; compensating circuits will be installed in the near future.
[5]To comply with 1.1 p.u. overvoltage limit remaining units

[102] P. Czech, S. Chano, H. Hunyh, and A. Dute. "The Hydro-Quebec System Blackout of 13 March 1989; System Response to Geomagnetic Disturbance." *Proceedings of Geomagnetically Induced Currents Conference.* Millbrae, CA, 1989. 19.1-19.21.

[103] NERC, op. cit.

In addition to the changes in Figure 14, upon detection of 3% voltage asymmetry, an alarm is sent to central operators in Montreal to allow them time to take action. In the event of forecasted geomagnetic events, HVDC loading can be adjusted to between 40% and 90% of normal full-load rating.[104] This indicates that Hydro-Quebec and regulators felt the incident was more of a reminder of what could occur due to more severe geomagnetic storms rather than the temporary effects of the 1989 event.[105] Nonetheless, the steps that have been taken to prevent another failure of the Hydro-Quebec system are an improvement to reliability but short of what is needed for long term protection.

The 1989 geomagnetic event produced a maximum 480nT/min., while the 1859 Carrington event is estimated to be as high as 5000 nT/min.[106] The last storm to hit North America that registered near the level of the Carrington event was in 1972.[107] The power grid at that time was less than half its current size. Moreover the present grid uses longer transmission lines that act as longer antennas, introducing larger GIC voltages and currents into the grid.[108] The new protection could save the Hydro-Quebec grid from a future geomagnetic storm that is close in size and intensity of the 1989 event.

If a storm that had the magnitude of the Carrington event were to occur, the Hydro-Quebec grid would most likely suffer severe damage more far-reaching than in 1989. The adjusted protection settings would be insufficient to protect the grid from Carrington levels. Hydro-Quebec has installed some neutral blocking capacitors, but the extent of these retrofits does not appear to have been published.

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[104] NERC, op. cit.

[105] Riswadkar and Dobbins, op. cit., p. 3-6.

[106] Loannis Daglis, *Effects of Space Weather on Technology Infrastructure*, Boston: Kluwer Academic Publishers, p. 273.

[107] Kappenmen, op. cit., p. 32.

[108] Ibid., p. 43

4.0 Large Scale Blackstart Contingencies

EMP and major solar storms pose blackout threats and cascading effects on critical infrastructures that are unprecedented. No civilization with a reliable and developed electric grid has experienced a total grid failure with such a large number of key components damaged. The fundamental difference between a "normal" blackstart and a blackstart following an EMP or major solar storm is the size of the affected area. Due to the large size of the affected area, other infrastructures that would normally be available during a blackstart may not be available. During a major EMP event, more than 50% of the total power customers in the U.S. could lose power.

During previous blackout events, such as ice storms and hurricanes, neighboring utilities have retained grid functionality post-event. During an EMP event, it is likely that neighboring power grids will also be mostly (if not completely) nonfunctional, precluding assistance from the "edges" of the affected area. The lack of electricity available to blackstart the power grid is a major challenge that must be overcome to minimize the collateral damage from a geomagnetic storm or EMP event.

The power grid must be restarted in a timely fashion to avoid the cascading effects of a long-term outage. During the blackstart following a wide-area EMP or solar storm event, normal blackstart plans will not be adequate, as was discovered by field personnel following the Hydro-Quebec geomagnetic storm. Presently, no plans exist which details how to restart the grid following a wide-area EMP or solar storm catastrophe. The closest applicable guidance relative to the North American grid is a NERC manual that mentions possible effects from geomagnetic storms - however the manual does not address the areas of a wide area outage.[109]

[109] North American Electric Reliability Corporation. *Electric System Restoration ReferenceDocument.* Princeton, NJ: North American Electric Reliabilty Corporation, 1993

4.1 Large Scale Blackstart Challenges

The solar storm that affected Hydro-Quebec was a localized near miss. From a historical perspective it was a relatively weak solar storm, registering 480 nT/min. By comparison, the Carrington event that occurred in 1859 registered 4800nT/min. In addition to the Hydro-Quebec event, many lessons can be learned from the restoration effort that took place after Hurricane Katrina in 2005.

The blackstart sequence outlined in the following sections uses the NERC blackstart guide, with modifications made to accommodate the vast area coverage of an EMP or solar storm event. Lessons are drawn from the United Kingdom's blackstart plan and Southern Company's restoration efforts following Hurricane Katrina.

Due to the uniqueness of the different power grids in the U.S., no two systems may be restarted in the same sequence. Some systems will be more prepared to conduct a blackstart due to the type of generation and blackstart resources they have acquired before the event. Other utilities may be simply at the mercy of neighboring systems ability to blackstart and then provide them the power they need to bring their equipment back online. The stochastic nature of EMP and solar events will prevent accurate assessments of what post-event conditions will exist until utilities assess their individual system's ability to withstand EMP and solar storm stresses. The more rapidly a blackstart occurs, the fewer resources will be required to complete the process. Timeliness will determine success or failure of the operation.

In order to put the resource needs into perspective, the total logistical acquisitions for Southern Company after Hurricane Katina included finding 4,800 beds for personnel (hotels, mobile trailers, dorms, military installations, tents, and cots). Other acquisitions included 60 tractor trailer loads of material and 65 buses put into service. During the peak restoration period, 32,500 meals were served each day, and 93,000 pounds of laundry were processed. These resources were required to support 11,000 electrical workers.[110] On a national level, this is simply not possible. We do not have the personnel or resources to sustain a recovery of that magnitude.[111]

Events such as Hurricane Katrina have exhausted our emergency management systems. First responders were brought in from several states during that event. Hurricane Katrina was a regional event. Had it been a national event, and first responders from other locations would have been busy dealing with problems in their own back yards, the response would not have progressed. During an EMP event, even if other first responders were available, communication and a lack of transportation would present additional formidable challenges.

During Hurricane Katrina, it quickly became apparent that supplies and personnel were inadequate for the level of demand. This rapidly became a cascading problem that was eventually solved by pooling additional available resources; however, this did not happen in a timely fashion. One can only imagine what would have happened if the additional resources were not available, as would be the case during a large scale power outage.

4.2 Introduction to a Large Scale Blackstart

Post EMP/solar storm event utilities must face the realities of the seriousness of the situation that they face. Most likely, communications systems will not be functioning. This includes cell phones, land lines and other forms of commercial communications. Utilities that own their own communication networks may have some localized communication with crews or other operators. Assessment of the system must start immediately. Initially, there will probably be a great deal of chaos and confusion, exacerbated by communication problems. At first, operators will not know the geographic extent of the blackout or what initially caused the event, especially in the case of an EMP event.

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[110] Billy Ball, "Rebuilding Electrical Infrastructure Along the Gulf Coast: A Case Study." *The Bridge* (National Academy of Engineering) 36, no. 1 (Spring 2006): p. 23.

[111] Federal Financial Institutions Examination Council. *Lessons Learned From Hurricane Katrina: Preparing Your Institution for a Catastrophic Event.* Washington, D.C.: Federal Financial Instiutions Examination Council, 2009, p. 8.

The blackstart tasks will truly be a race against the clock. With each passing hour, the grid will degrade further and the effects of the loss of other infrastructures, affected by power outages, will continue to grow. Decisions made early in the event will affect the success or failure of the restart. If communications are available, they should be used to contact NERC and coordinate with neighboring utilities. Due to grid collapse and component damage, it is likely that SCADA systems will be unable to provide operators an accurate view of the current state of the grid. These systems may be completely nonfunctional or send out inaccurate reports. Operators will need to send out personnel to perform visual assessments of the current state of the grid, and they will need to protect and stabilize any parts of the grid that are still operational.

During the early phase, local and regional authorities should be immediately notified about the current situation, as well as any others who will need status information. If it is known that the problem is widespread, federal authorities should be informed as soon as possible. Local government officials should be used as for intermediary communication with federal authorities. One of the lessons learned from Hurricane Katrina is that the seriousness of the situation should not be underestimated when communicating with local authorities and emergency personnel.

In retrospect, most of the grid restoration effort during Hurricane Katrina was successful. However, Southern Power underestimated the materials and manpower that would be needed to complete the restoration process and federal assistance did not arrive quickly enough to avert the cascading effects that occurred.[112] Unlike Hurricane Katrina, federal assistance may not be available during an EMP event – it will depend on how widespread the effects are. It will be imperative that everyone assisting in the restoration effort understands the need for self-sufficiency in blackstarting the power grid. The lack of communication with the general public also contributed to the chaos following Katrina. Emergency personnel, together with utility operators, should explain the situation to the general public calmly (that is, in a way that does not create panic).

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[112] Ibid., p. 25.

Employers should use any means necessary to summon their employees to work. Southern Company had a contingency plan after Hurricane Katrina for employees to report for duty. If the problem is known to be severe, such as an EMP event or major solar storm, authorities should be notified so they can take appropriate action. They should also be notified of the equipment and supplies that will be required to restart the power grid.

If nuclear power plants operate within the transmission system, the determination of whether these plants have electricity and are still operational must be a top priority. They must continue to receive electric power whether or not they are operational, because they require electricity to circulate cooling water within the reactor vessel and spent rod cooling pools in order to prevent release of radioactive material.

4.3 Large Scale Blackstart Contingency

Each electric utility operator will have to evaluate current conditions against their blackstart plan. Utility operators must take into consideration their list of restoration priorities when developing this plan. Their priority list may change due to the location and severity of damage to their systems, the information about each specific situation, and whether there are alternate priorities to restore other critical infrastructures. For example, if service could be quickly restored to the public water system, this may be a higher priority than restarting a 911 center, provided the emergency center has adequate fuel for backup generation. The blackstart plan must be generated rapidly in real time, and should be flexible enough for changes to be made as field conditions change. The plan must be thorough and well-practiced, because it will act as a guide for utilities through the entire blackstart process. The more effective the plan, the more likely that restoration efforts will be efficient and successful. Because resources will be limited, this plan should be exercised by the utilities by conducting mock drills and simulations as part of their regular, continuing training.

Reliability coordinators should establish priorities as stated in the NERC Electric Restoration Reference Document.[113] The level of equipment damage will determine what aspects of the grid can be rapidly restored. Nuclear power facilities will be a main priority as well, because they serve as a strong base power source for restarting other portions of the grid. NERC will need to constantly evaluate progress and determine the next steps in the plans for local operators. It will also need to remain flexible as the system rapidly changes.

Personnel may need to be directed by NERC. This authority is granted to NERC as listed in the Power Restoration Document section VII after initial generating stations are restarted. As part of pre-event planning, NERC should appoint an agency to be in charge of supplies and determine where strategic fuel can be acquired.

In the event a blackstart is required, all necessary resources must be secured. Local, state, and federal government agencies should be informed about the equipment and personnel required to perform the blackstart. Reliability coordinators need to be notified concerning the requirements for their particular sector of the grid to become operational. They have the authority to lobby for more resources through NERC and the Department of Energy. These agencies can be used to secure precious fuel needed for the restoration effort as well as arranging transportation for fuel and other materials. Fuel needs cannot be over-emphasized. While restoring power after Hurricane Katrina, Southern Company used on average 80,000 gallons of fuel per day, with peak usage of 110,000 gallons per day.[114]

In previous blackouts, one significant cause of delay has been a lack of communication between government officials and utility operators. The utilities will need to quickly and effectively convey the message that assistance will be needed. Resources will be more readily available at the beginning of the EMP or solar storm event rather than later, when resources become scarce due to the cascading effects of electric power outages on dependent

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[113] North American Electric Reliability Corporation. *Electric System Restoration Reference*, op. cit., p. 26.

[114] Ibid., p. 24.

infrastructures. Blackstart personnel will need food, water, and shelter. Resource needs will be extensive and transportation availability limited. For example, it is likely that air transportation will not be available due to outages within the air traffic control system.

Infrastructure industries in the area should be immediately contacted to seek resources. Cable television and internet cannot operate without electricity, so these companies may have personnel and equipment they are willing to provide for restoration efforts. Although most electric utility companies have ongoing relationships with utility contractors, it is likely that these resources would not be available: because many of these contractors travel long distances to reach work sites, this may simply not be feasible under wide-area emergency conditions. However, local utility contractors will be more accessible; even if they have contracts out of town, they will likely be unable to honor those contracts. Contractors in different industries will likely have equipment that is valuable in restoration efforts, including truck-mounted fuel transfer tanks. Outside vendors such as catering companies and contractors may be more likely to lend a helping hand in the initial stages of a major power outage, rather than after a week or more has passed without replenished supplies. At this point, it is possible that many organizations would start to hoard resources such as occurred during Hurricane Katrina.

It is quite plausible that security will be needed to safeguard resources obtained by utility companies. There is good reason to believe that law enforcement and other first responders will respond quickly, since they need electricity to continue their missions and provide essential services to the civilian population. Law enforcement personnel may be able to assist in this operation; however, their resources will almost certainly be stretched immediately after the event. National Guardsman, where available, could assist in this operation. Shortly after Hurricane Katrina, Southern Company brought in a security force to safeguard life and property.[115] In the event of a wide-area power grid collapse, the threats to utility resources would be even greater.

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[115] Ball, p. 22.

Several issues need to be addressed before grid operators blackstart their portion of the grid. The primary consideration is checking the status of generation stations and step -up transformers located at generation stations. Generator power is worthless if it cannot be moved beyond the generating station. The second consideration is ensuring that necessary fuel supplies are available at nuclear power plant sites. If the nuclear power plant has a blackstart capability, this is less of a concern. However care must be taken that all components of the nuclear plant blackstart system are functional. The time required to restart a nuclear power plant with functioning blackstart capabilities is a minimum of 48 hours.[116]

Because resources will be limited, available plants should be thoroughly inspected to ensure that, if restarted, they will function properly. If it is determined that a non-nuclear generation facility cannot be put into service with the resources provided, then that station must be abandoned until more time and resources are available. Prioritizing the blackstarting of generation stations utilizing natural gas should be done with extreme caution. It is advisable to verify that sufficient quantities of natural gas will be available to permit the continued operation of these systems. If natural gas pumping stations do not have power, then natural gas supplies will run out within a few hours.

The best plants for blackstarting the grid are hydroelectric generation plants because they do not depend on fuel reserves. Also, coal-fired generation plants usually have a 90-day supply of coal on hand.[117] These plants should be sufficient to blackstart the grid, provided that damage to grid components is not extensive and their SCADA systems do not impede this operation. Once coal supplies run out, transportation networks must be available to replenish facilities' fuel supplies.

On a national grid level, the New England grid is the most logical place to initiate a blackstart. The New England grid is divided into much smaller islands than the rest of the U.S.

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[116] Ibid., p.13
[117] CENTRA, op. cit., p. 29.

grid. These islands usually contain more than one interconnection node, reducing the incidence of single point failure locations. Because New England experiences a cold winter climate, it is prudent to restart this region first during winter to avert cascading effects on the population and critical systems due to cold temperatures. The New England power grid serves a large, concentrated population, so restoration of service in the region would provide the greatest good to the largest percentage of the population. From experience, grid breakers and relays in the New England grid behave oddly in cold weather; they are more difficult to restart once tripped. Substations often have DC battery packs that can run equipment for a limited amount of time, but cold weather can reduce the period that batteries will last without recharging.[118] However, the most significant benefit to restarting the New England grid first is preventing cooling problems at nuclear power plants. There are a large number of nuclear power plants within the New England network (the nation's most densely populated region), presenting an urgent threat to human life.

Blackstart will need to begin at different times for different facilities. NERC should coordinate major blackstart sequences and plans. In some locations where the blackstart is relatively straightforward, it may be feasible to blackstart immediately following the event. However, load shedding may be needed to prevent immediate shut down of some network sectors. Most coal-fired plant operators should be blackstarted almost immediately following a blackout. Because these plants are critical baseline components of the grid, they should be restarted within two hours of initial shut down. Units that are "hot" should be prioritized, because they can be returned to service immediately, with secondary consideration for units that can be restarted within several hours. Caution should be taken to ensure that sludge is not allowed to build up in the emission-controlling scrubbers because this could delay the blackstart process.

Generation station operators must be prepared to blackstart several times. It is possible that generators could immediately trip offline on the first restart attempt due to unidentified damages. When small network islands are reconnected and load is placed on the system, some

[118] NERC, op. cit., p. 9.

generation stations will likely trip offline and need to be restarted. Generator voltage regulators should be used in order to limit voltage oscillations.

During the primary blackstart, the grid should be divided in small islands, ideally transferring power to local nuclear reactors and restarting other critical infrastructures. The individual islands need not be frequency-synchronized with each other. This will be aggravated by the lack of generators on the system. As more power generation comes online, islands will tend to become more harmonically stable. To increase stabilization, substantial load should be placed on these islands.

Once the individual islands are stabilized, the systems needs to be prepared to be connected to the transmission system. The most effective method for doing this after an EMP or solar storm event is to utilize "controlled operation." This will effectively limit the system to operating only those breakers needed to power the required transmission lines. This method is preferable following an EMP or solar storm event, because there are still likely to be damaged components that were not identified during the initial system assessment. This method also reduces the amount of switching required. If the blackstart occurs during cold weather, manual operation will most likely be required because interlocks will prevent the operation of automatic controls, even if SCADA systems are functional. The time frame for completing this switching process automatically in cold weather can be as short as 30 minutes.[119]

Grid islands can be coordinated using handheld radios, reducing the need for land lines. The islands will not need to be synchronized with each other at this point, reducing the likelihood that generation stations will be tripped off line. Loads should not be added in blocks that exceed 5% of synchronized generating capacity. The frequency must be maintained between 59.75Hz and 61.00Hz. If necessary, manual load shedding should be utilized to keep the frequency above 59.50Hz.[120]

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[119] Ibid., p. 24.
[120] Ibid., p. 23.

The location of damaged components will become more apparent as power is restored. These components need to be evaluated to determine the most effective way to proceed with grid restoration. If the components can be replaced or repaired in a timely manner, then those operations should be completed. If not, the component should be evaluated to determine if it can be used in its damaged state without affecting other grid components or reducing stability. If this is not possible, then it may need to be bypassed. Both portable and make-shift towers can be used to divert transmission lines around damaged components. Direct-bury transmission line can be used, but only in extreme emergencies. The most useful line type for these applications is the self-contained, fluid-filled pipe, which is designed to go under water and is efficient at dissipating heat.

The process of synchronizing and reconnecting the islands will determine the stability of the grid and the extent of its damage. It is likely that component damage not identified during the initial assessment will now become apparent. This is the riskiest step and will likely trip some generators. After any remaining components are replaced, repaired, or bypassed, the grid should be relatively stable.

To prepare the grid for total restoration, voltages should be maintained between 90% and 110% of normal levels. Field personnel should be used to visually verify breaker positions. Once a line is energized, some local load should be introduced to reduce voltages. Shunt capacitors should be used to manage reactive power. Automatic relays need to be disabled to prevent automatic closure of lines placed into service.

5.0 Major Challenges Associated with a Wide-Area Blackstart

EHV (Extreme High Voltage) transformers will likely be primary failure points during an EMP or solar storm event. These are large transformers most often found in the power transmission network and are used to step voltage up at generation facilities and to step voltage down at substations. Transformers are generally considered to be EHV if their voltage rating is 115 kV or above. The largest EHV transformers used in North America have voltage ratings of 765 kV. These transformers can be extremely large and difficult to transport. Figures 15 and16 below shows an EHV transformer in transit. Because of their size, it is extremely difficult to transport these units - they can be three stories tall and weigh as much as 300 tons.[123]

Based on prior experience from solar storms, EHV transformers will likely sustain damage during wide area electromagnetic events. This occurred in the Hydro-Quebec blackout and will likely occur in future events unless protecting them becomes a priority. Because of the lack of test data, it is difficult to predict which EHV transformers will be affected. What is known is they will be difficult to replace.

The first obstacle to replacing the transformers is the scarcity of spare transformers. The manufacture of EHV transformers has become a global business, with firms located in the U.S., Mexico, Korea, Europe, Japan and China. The U.S. production of these transformers has slowed dramatically due to cheaper labor in China as well as the largest demand stemming from the developing economies of China and India.[124] The lead time to obtain these transformers would likely be between 6 and 15 months.[125] There are a few surplus transformers available; however, their typical age is 40 years and their voltages ranges from 115 kV to 230 kV, far below the 500 kV and 765 kV range needed for the bulk power transmission system. Due to the age of these transformers, there is no guarantee that this equipment will work once it is put into service. Some

[123] Gar Smith, *Flare-up: How the Sun Could Put an End to Nuclear Power.* Spring 2012. http://www.earthisland.org/journal/index.php/eij/article/flare-up_how_the_sun_could_put_an_end_to_nuclear_power (accessed March 2, 2012).

[124] CENTRA, op. cit., p. 29.

[125] Ibid.

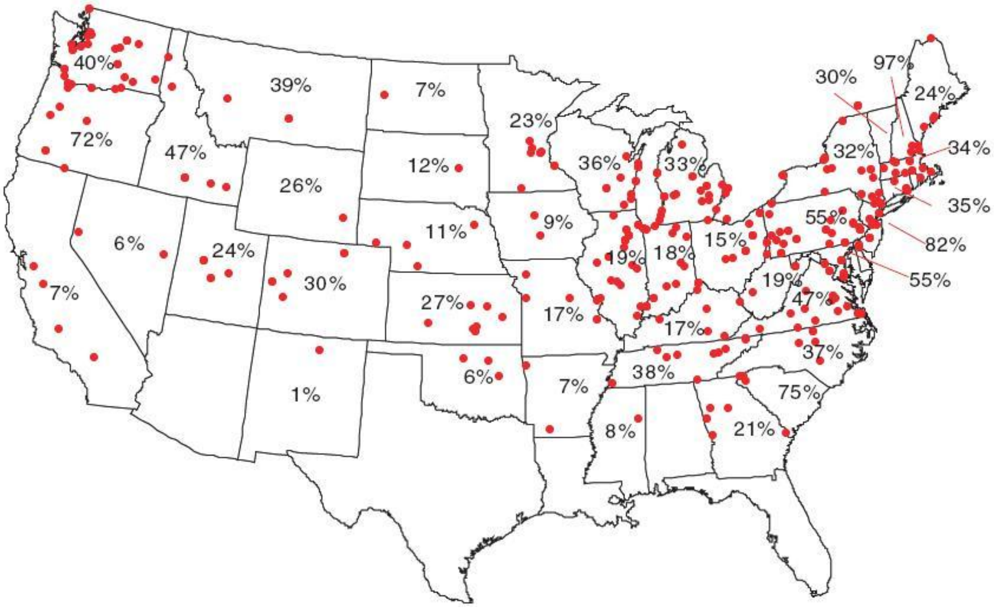

Figure 14: Map Showing At-Risk Transformer Capacity (estimated at 365kV and larger) by State for a 4800 nT/min Geomagnetic Field Disturbance at 50° Geomagnetic Latitude. Regions with high percentages of at-risk capacity could experience long duration outages that could extend multiple years.[126]

surplus transformers have been refurbished by the manufacturer, but many have been left onsite to avoid shipping costs.[127]

At EHV levels, the standard approach is to use three single phase transformers and purchase an extra single phase transformer to be used as a spare that can be switched in if one of the phases fails. However, in cases where three-phase transformers are used or severe damage occurs in more than one phase of a single-phase triplet, replacement in a timely fashion is nearly impossible.

The transportation of EHV transformers presents extremely challenging logistical problems. The size and weight of these transformers prevents them from being airlifted; thus, they must be moved across the ocean by ship and across land by rail and truck. Once the transformer is manufactured abroad, it takes several weeks by sea to reach the U.S. mainland.

[126] John Kappenman, "The Vulnerability of the U.S. Electric Power Grid to Severe Space Weather Events, and Future Outlook." *Severe Space Weather Events - Understanding Societal and Economic Impacts*, May 23, 2008.

[127] Ibid.

Because of the size of the EHV transformers, their transport across the U.S. requires permission from municipalities. This is because transport speeds are very slow and their size often exceeds highway and bridge weight and height restrictions. Routes must be carefully planned before the move and road and bridge load-bearing capabilities must be certified by civil engineers. In most cases, traffic lights and overhead lines crossing highways must be moved prior to transport. It is not uncommon for trips to be planned and work with municipalities to begin six months before a move.[128] Shipment across land by rail is also difficult because special rail cars must be used to meet height and weight limitations. These rail cars often have additional axles and allow the transformer to sit lower than on a typical rail car. Locating this equipment and mobilizing the limited number of these rail cars will be extremely difficult during a large scale power outage with limited transportation options.[129] The absence of electricity and electric-powered infrastructure greatly complicates the transport process. [130]

[128] Kappenman, op.cit., p. 128.
[129] Ibid., p. 129.
[130] Ibid.

Figure 15: Nuclear Plant Step-up Transformer Being Transported through Ohio[131]

Once the transformer arrives on location, oil radiators and bushings must be installed, and the transformer must be filled with oil. If the transformer is installed during cold weather, which is likely due to GIC being more severe in higher latitudes, the oil must be heated before it is pumped into the transformer. A vacuum must then be placed on the oil system before the system is hermetically sealed. Often, circulating pumps must be installed. Bus systems must be modified because different heights and layouts of connections are required. The replacement transformers themselves would have to be modified to fit the installation. In the best conditions, with a fully staffed and trained crew, this process will take several days. In the aftermath of an EMP or solar storm event, this situation will likely replicate itself hundreds of times. In the absence of electricity to complete simple tasks such as using air tools to loosen rust bolts or a heat source to heat transformer oil, the time involved will increase significantly.

[131] http://www.cleveland.com/business/index.ssf/2011/10/firstenergy_moves_a_115-ton_el.html.

Figure 16: Transformer on Specialty Rail Car[132]

A large proportion of the EHV transmission step-up transformer spares strategically placed or protected would greatly speed up the recovery process. Unfortunately, the expense of these transformers, each costing several million dollars, has prevented the establishment of a significant spare inventory.

5.1 SCADA Systems

During a blackstart, the primary coordination functions will occur between power grid operators and communication system operators. SCADA systems are so important to the power grid that some operations can simply not be accomplished without these systems.[133] Most utility operators own their own communications for crew dispatch and generation; however, within the transmission network, SCADA systems are often mixed between utility-owned communication and commercially-leased lines. Utilities have a variety of options to choose from when purchasing SCADA systems. The trend is to run SCADA controls interfaces over the internet ("in the cloud"). In an EMP or solar storm event, these controls may not be functional in the

[132] http://tonbridgepower.com/Projects/Montana-Alberta-Tie-Ltd/Construction-Update/default.aspx.

[133] *NSTAC Report,* op. cit., p. 4.

restoration period. EMP and solar storm electromagnetic fields do not couple to fiber optic lines; thus, those parts of the system that utilize fiber optic lines will be more resilient.[134]

Most systems still have some level of manual control, which allows operators and personnel to take over the system if necessary. The speed at which the SCADA system automatically reacts is a particular concern.[135] SCADA systems that react quickly, beyond human monitoring capability, could cause the grid to self-destruct if controls are confused by EMP or solar storm-induced signals and cause improper generator or substation switching operations. This could occur much faster than operators could manually override the automatic controls. Unfortunately, the reaction of SCADA systems during a nuclear EMP or solar storm is not well understood and difficult to predict.

5.2 Communication

There are many interdependencies among the critical infrastructures in the U.S. Most of these infrastructures depend on reliable electric power to be functional in the event of a large scale power outage (beyond a day). Backup power longevity depends on whether control centers use battery or generators as a backup power supply. Communication systems are of paramount importance during blackstart operations. They would rapidly be rendered nonfunctional in the event of a wide area power outage, including internet and telecommunication systems.[136] The degree of damage done to the communication systems will depend on the location and severity of the event.

Nuclear EMP events would likely debilitate significant numbers of microelectronics used throughout the communications industry.[137] Solar storms will directly damage only systems

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[134] Ibid.

[135] Gilbert, Savage, and Radasky, op. cit., p. 155.

[136] Rich Miller, *FCC Ruling May Spur Generator Demand.* December 10, 2007. http://www.datacenterknowledge.com/archives/2007/12/10/fcc-ruling-may-spur-generator-demand/ (accessed March 3, 2012).

[137] *NSTAC Report,* op. cit., p. 11.

connected to long lines. In either case, electricity must be present for these systems to operate effectively.

Cellular phone service, upon which the utility industry has come to depend, would be difficult to restore because cell phone tower locations are dependent on electricity. These towers require both wired communications and electricity to produce a cell phone signal, and they may have neither following exposure to EMP or solar storms. Most cell phone towers have battery backup; however, it is usually designed to provide power for up to four hours.[138] The lack of communications will significantly hamper the coordination of grid blackstart activities in the event of a large scale power outage.

5.3 Fuel

In the event of large scale power outage, the lack of various types of fuels will be a significant problem, including the fuels our society has come to depend on to maintain the quality of life we currently enjoy. Diesel fuel is used in many backup generators. These generators are used by the government, utility industries, and private entities. To a lesser extent, gasoline is also used for backup generation.

In the absence of electricity, our ability to transport and refuel gasoline and diesel is severely limited. Most large storage tanks for liquid fuels have electric pumps. Once the onsite fuel storage units are depleted, replenishing fuel in generators or onsite fuel tanks used for equipment and transportation would be nearly impossible. Regional fuel storage centers will not be able to move fuel to tanker trucks for transport. Retail locations will not be able to move fuel from underground storage tanks to vehicles or other equipment.[139]

Petroleum pipelines require pumping stations to pressurize the contents in order to create flow. These pumps operate by either electricity or diesel; increasingly, electrical pumps are

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[138] UPS Backup Systems. *Cell Phone Towers All Have Battery Backup Systems.* n.d. http://www.ups-battery-backup.com/cell-phone-ups.php (accessed January 29, 2012).

[139] Gilbert, Kappenman, Radasky, and Savage, op. cit., p. 111.

replacing diesel pumps.[140] Unless all the petroleum pumping stations from source to destination are powered by diesel fuel, which is unlikely, fuel will not move once the electricity goes out. Natural gas pipelines use either natural gas or electricity to power pumping stations.[141] If all stations from source to destination are powered by natural gas, the system will still most likely function, provided SCADA systems do not interrupt operations; however, at some point, most systems utilize electrical pumps. As time goes by and fuel supplies dwindle, fuel transportation will become a target for hijackers and theft. This scenario has played during many other disruptions to fuel supplies, both in the U.S. and internationally.[142]

Nuclear power plants also depend on fuel for backup generators to cool reactors and spent fuel rods should the grid fail. These plants typically only have a one week's worth of fuel available on site. Once this fuel is depleted, if additional fuel cannot be delivered, the pumps that are used to pump water for cooling will fail. This situation would be similar to what occurred during the Fukushima Daiichi facility accident. The tsunami did not directly cause the meltdown; rather, it was the loss of electricity and damage to backup generators that prevented the cooling pumps from operating.[143] The pools of spent fuel rods are far more dangerous than the reactors themselves. Typically spent fuel rods remain in cooling pools from 3 to 5 years, after which time they can be moved to air-cooled storage.[144] The "boil down time" for these containment pools is between 4 and 22 days,[145] depending on the design of the system and when the last spent fuel rods were placed in the pool. The spent fuel rod pools typically have larger quantities of radioactive material than the active reactors. These pools have a zirconium cladding which, when

[140] Association of Oil Pipe Lines. *About Pipelines.* n.d. http://www.aopl.org/aboutPipelines/ (accessed March 3, 2012).

[141] Natural Gas Supply Association. *The Transportation of Natural Gas.* n.d. http://www.naturalgas.org/naturalgas/transport.asp (accessed March 2, 2012).

[142] CENTRA, op. cit., p. 33.

[143] Stein, op. cit., p. 11.

[144] Ibid., p. 10.

[145] Ibid., p. 9.

super-heated and exposed to air, burns like magnesium.[146] When burning cladding is exposed to water, the reaction produces explosive hydrogen gas.

In the event of a prolonged power outage, government agencies have promised around-the-clock deliveries of diesel fuel for nuclear power plants.[147] However, this fuel would most likely not be available in the event of a severe GMD event due to theft and the inability to pump fuel. Just half of the world's spent fuel rods melting down would be the equivalent of 400 Chernobyls[148]

In the U.S., the meltdown of just a single nuclear plant would be catastrophic, and the effects would be far worse if that plant were located near a densely populated area. This scenario often occurs in New England, where solar storms are also likely to have the most significant affects due to the latitude and geological structure. New York City is located just 24 miles from the Indian Point nuclear power plant.[149] Unfortunately, other New England cities such as Boston, MA, New Haven CT, Hartford, CT, and White Plains, NY, are also located in close proximity to nuclear power plants.[150]

One significant geomagnetic storm could replicate the Fukushima disaster ten times over in the most densely populated region of the U.S. Evacuating the population in this area would be impossible in the best of times. A massive power outage, combined with transportation problems, would make an evacuation inconceivable. The only viable way to prevent massive loss of life would be the rapid restoration of power to cooling pumps at the nuclear facilities.

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[146] Ibid.

[147] Ibid., p. 11.

[148] Ibid.

[149] AnimatedSoftware.com. *Nuclear Power Plants and Other Large Nuclear Facilities in the United States.* n.d. http://www.animatedsoftware.com/environm/no_nukes/nukelist1.htm#NewEnglandStates (accessed Febuary 2, 2012).

[150] Ibid.

Natural gas will only be available for a few hours following a large scale power outage[151]. Currently, natural gas is transported through pipelines that utilize electric pumps to apply pressure to the gas, causing it to flow through pipelines. Without electricity to power these pumps, only a few hours of gas will be available until the pressure of the gas lines drop below the threshold required to maintain flow. The primary concern is the inability to restart gas-fired power generation plants. These plants will not be able to be brought back online until electricity is restored to gas pumping stations. The secondary concern is that natural gas is used in many homes for hot water, heating and cooking. If an EMP event occurs during the winter months, the lack of home heating would accelerate social unrest and potentially contribute to loss of life.[152] This would occur as those vulnerable to the cold suffered from lack of heat. Over time, others would improvise potentially unsafe methods to heat their homes, causing fires and carbon monoxide poisoning. Civilian unrest and fire suppression would squander valuable resources that would be needed to fix the core problem of restoring electric service.

As previously mentioned, coal-fired generation plants usually keep a 90-day supply of coal on site.[153] Once this supply runs out, coal must be transported to the plant by rail or truck, both requiring diesel fuel to operate. Railroads rely on automatic switching gear and other electricity-based systems. Freight trains generally hold between 3,500 and 5,000 gallons of diesel fuel. Fully-loaded, these trains can burn up to 165 gallons per hour. If fuel for refueling rail transportation is unavailable, coal transportation would quickly fail. Transporting coal by truck is much less efficient, and also subjects the product and equipment used to transport it to social unrest and a possibly disrupted highway transportation system.

5.4 Water and Wastewater Systems

In most metropolitan areas, clean water and sewage systems rely on electricity to remain functional. Water is usually pumped with electricity and water treatment facilities must have

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[151] CENTRA, op. cit., p. 30.
[152] Ibid., p. 29.
[153] Ibid., p. 11.

electricity in order to treat potable water. Sewage systems are also dependent on electricity to operate pumps and waste treatment facilities. In the event of large-scale power outages, water reserves would quickly be diminished, perhaps within a few days. This would not only affect the general population, but also those attempting to restore the power grid. The human body can only survive without water for 3 days. The lack of sanitation would rapidly result in disease outbreaks. When water supplies run out, society would turn to non-potable sources, further accelerating the outbreak of disease. In addition, those with water supplies will become vulnerable to attack from those lacking potable water.[154]

5.5 Staffing Issues

In the event of a natural disaster, an individual's primary reaction is to protect their families and ensure that they are safe before tending to other duties. During Hurricane Katrina, first responders and other essential personnel quickly left their posts and evacuated. Many of those who did stay left their posts and discontinued their duties after the storm. Many felt they had few options after basic resources became very difficult to obtain.[155]

Utility companies once maintained and built their own transmission lines and substations, and also constructed or managed the construction of their generation stations; however, deregulation changed this. The utility industry has shed roughly 40% of its staff since 1990, and utility companies now rely heavily on contractors, primarily due to deregulation and the pressure to operate leaner organizations. The positions that have been eliminated have occurred in technical fields such as lineman, ground man, and substation personnel (first responders) as well as professional fields such as engineering.[156] During a recent severe snow storm, one utility in a

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[154] Ibid., p. 30.

[155] Ibid., p. 36.

[156] Badrul Chowdhury, "Power Education at the Crossroads." *IEEE Spectrum*, October 2000: p. 64.

major metropolitan area had 600 of its own workers call out sick. In order to restore power, the company had to recruit 1,200 employees from neighboring utilities and contractors.[157]

During a large scale EMP event, there will not be enough qualified personnel to handle the situation. First, a large number of linemen, engineers, and operators, would most likely not report for duty. Second, it is unlikely that personnel would be shared among utility companies, because the surrounding utility companies will probably be shorthanded as well. This scenario actually occurred during Hurricane Katrina. During the storm, Mississippi Power had estimated that, in a worst-case scenario, they would need 5,000 outside personnel to complete restoration. Once it was evident the storm would make a direct impact, they attempted to recruit lineman. Within 7 days, 10,800 outside workers were brought in from 23 states and Canada.[158]

Unfortunately the events that occurred in New Orleans are common. Utility companies maintain a skeleton staff and then subcontract work to outside vendors during major events.[159] It generally takes lineman four years to complete their training, including classroom sections and an apprentice program. During a large-scale event, there would not be enough qualified personnel to complete restoration in a timely fashion.

In addition to major fuel shortages and other transportation-related problems, companies will find it difficult to motivate employees who are experiencing difficult situations at home to leave their homes to travel hundreds of miles. Again, this situation became apparent during Hurricane Katrina: Mississippi Power immediately mobilized support teams from within the company to help employees' families arrange housing, repair homes, move furniture to storage and other essential tasks. Southern Company, the parent company to Mississippi Power, arranged these services to ensure workers stayed on the job.[160]

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[157] Ellen Bartlett, "Power to the People," January 2011, http://www.bethesdamagazine.com/Bethesda-Magazine/January-February-2011/Power-to-the-People/ (accessed January 20, 2012).

[158] Ball, p. 21.

[159] Ibid., p. 23.

[160] Ibid., p. 26.

5.6 Time

The most critical issue hindering a rapid blackstart following an EMP or solar storm event is response time. Response time will govern success and failure, and will determine the depth of the problems the U.S. faces during and after a blackout. The longer the response time, the more difficult it will be to restart the grid. Several factors must be considered when determining a timely response. Most importantly, the more time it takes to restart the grid during a blackout, the more likely it will be that other infrastructures become unusable. Next, failed infrastructures lead to the inability to replace depleted resources. As time passes, resources will need to be diverted from the blackstart operations as additional emergencies compete for those resources. Additionally, social unrest will escalate as more infrastructures dwindle and resources are depleted. Social unrest was not a factor in the 1989 Hydro-Quebec geomagnetic storm, because the affected region was relatively contained and the recovery time was only a few hours.

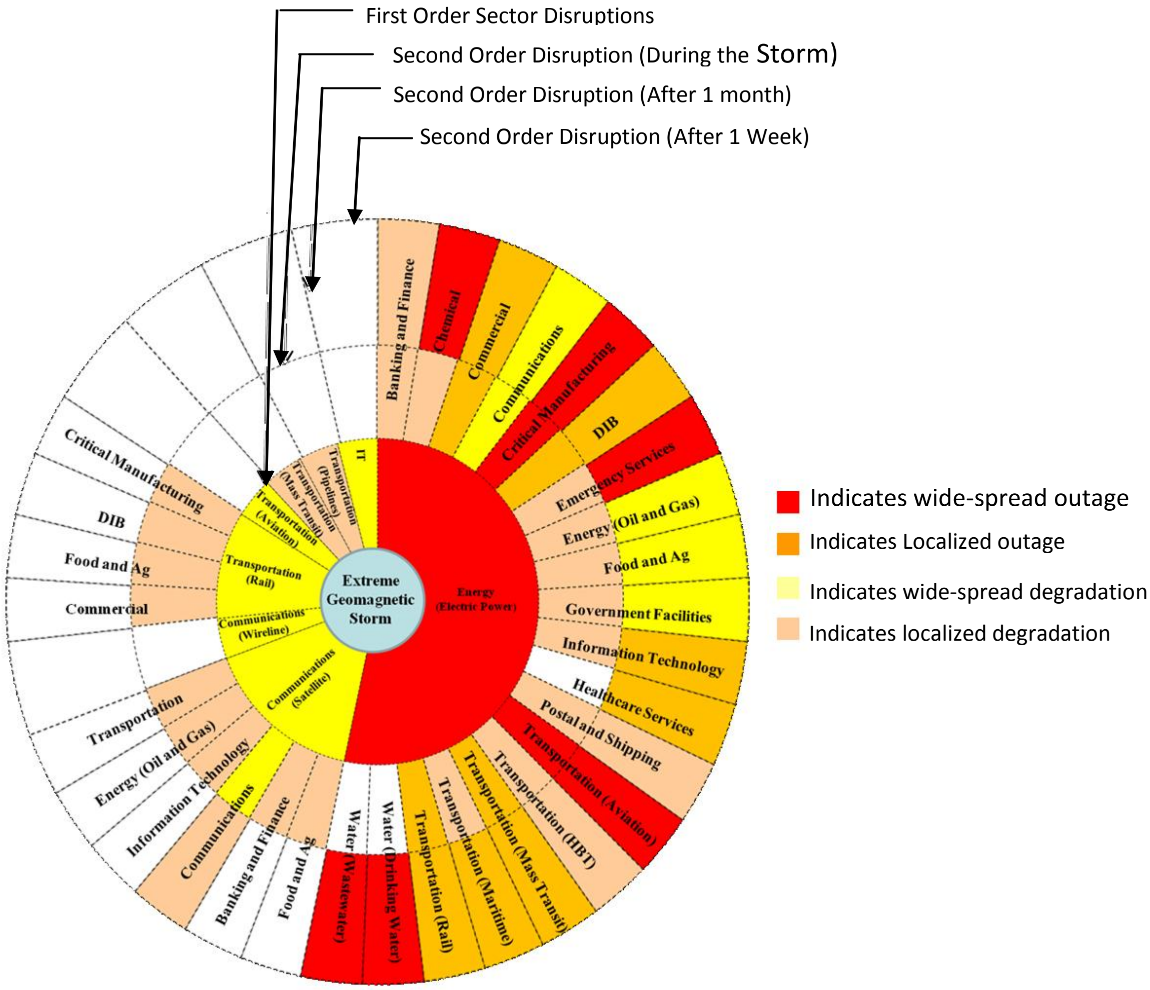

Figure 17: Critical Infrastructure Disruptions[161]

[161] CENTRA, op. cit., p. 3.

6.0 Conclusions and Recommendations

The threat of a wide-area electromagnetic catastrophe, whether manmade or naturally-occurring, is real. The likelihood that we will face the "big one" is unknown, but what is certain is that these events have occurred in the past. During previous major solar storms, the power grid was either nonexistent or relatively uncoupled and localized.[162] The very few EMP tests that have been conducted indicate that the electrical grid can be damaged, potentially on a large scale. Now, with the proliferation to nuclear weapons; there are nations that possess the capability to deliver such a nuclear weapon. Some of these nations have clearly indicated malicious intent toward the U.S., and, in one case, have conducted tests that appear to exercise a high-altitude detonation.[163] At this time, it seems that planning and preparation has been minimal at all levels: local, state, national, and international. Thanks to the efforts of the Congressional EMP commission and the National Academies of Science, there is a great deal of understanding of EMP and solar storms generation physics and system effects. What is not understood is how infrastructure operators and public leaders will react during such an event[164] The trend among most public officials has been to ignore EMP by dismissing its likelihood or downplaying its consequences. However, the consequences of such an event are so severe in terms of economic damage and breakdown of governance that it must be taken seriously. A simple analogy used by Congressman Roscoe Bartlett is that failure to protect the grid to wide-area electromagnetic effects is equivalent to a homeowner purchasing a home in the one hundred year flood plain and not purchasing flood insurance.[165] Before deregulation, utility companies were rewarded cost recoveries for developing reliable power grids and maintaining adequate staffing levels.

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[162] Ibid., p. 53.

[163] P. Hung Nguyen, *Iran's Nuclear Surprise: Super EMP Weapons?* Science and Technology Corporation, 2007.

[164] CENTRA, op. cit., p. 21.

[165] Congressman Roscoe Bartlett address, U.S. Capitol Visitor Center Auditorium, 6 October 2011

Currently, grid operators are only responsible to shareholders and not to the individual customers that purchase the power they transfer across the nation. This must change before the grid is truly resilient against wide-area electromagnetic threats. Warren Buffet, CEO, Berkshire Hathaway Incorporated claimed "most of deregulation was a mistake, in a deregulated market generators have a clear incentive to reduce power reserves. The last thing they want is excess capacity".[166]

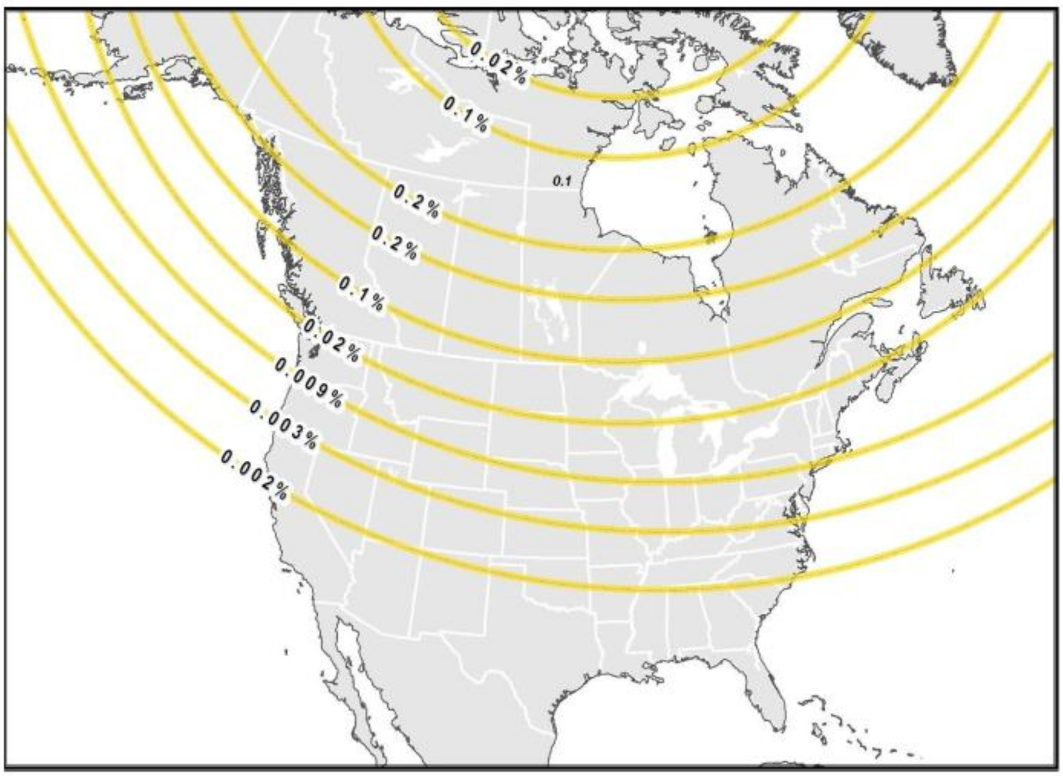

Figure 18: Probability of a Geomagnetic Solar Storm[167]

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[166] Lonkevich, Dan. Bloomberg. November 13, 2006. http://www.bloomberg.com/apps/news?pid=newsarchive&sid=arFRDHiq9Dgg&refer=energy (accessed March 15, 2012).

[167] Congressman Roscoe Bartlett, op. cit., p.19.

Based on this research, at this time the U.S. is not prepared to deal with the impact of an EMP event or solar storm. However, there are many options available to make the U.S. more resilient to such events.

6.1 Wide-Area Electromagnetic Effect Mitigation Methods

There are two basic strategies for mitigating the risks to the electrical power grid from an EMP event. The first method is through operational procedures, which involves taking assets offline when space weather is in the forecast. Operational procedures will most likely protect the power grid against mild solar storms, but they are limited in their ability to protect the power grid against severe solar storms. There is also the question of whether or not grid operators could (or even would) initiate load shedding, given the short or nonexistent warning intervals for wide-area electromagnetic threats.[168] In the past, operators have waited too long to initiate load shedding, thus missing opportunities to save the grid from major collapse. As an example, the massive August 2003 Northeast power outage would not have occurred if the First Electric Corporation had taken the advice of neighboring power companies to shed load. Due to the risk of penalties and lawsuits for initiating a deliberate power outage, load shedding is frowned upon by operators. There are also important questions of operational awareness: when grid operators make decisions based only upon the circumstances they know about, rather than the complete state of the grid, serious operator errors can occur.

The second method used to mitigate effects is limiting the consequences of wide-area electromagnetic threats through physical protection by installing passive devices or circuit modifications.[169] Hardening against EMP or solar storm events is the most effective of protection, but it is also the most expensive method. The Canadian government established such a measure for Hydro Quebec that had a total price of $1.2 billion[170]

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[168] CENTRA, op. cit., p. 20.
[169] Ibid.
[170] Ibid.

Figure 19: Metal Oxide Varistors (MOVs) mounted on transformers for lightning protection also moderate the effects of E1 [171]

Cost estimates to protect the roughly 2000 major generation and transmission network transformers in the U.S. grid are in the $1 billion range. Of these, the step up transformers at generation facilities are the highest priority. Generation capacity is virtually useless if electricity cannot be transmitted beyond the power plant. Generation units with blackstart capabilities are the most important units to protect, followed by units that supply power to nuclear generation facilities. These assets cannot be replaced in a timely fashion because of the lack of spares and lead- time required to purchase new units. Although the roughly $1 billion dollar price tag to protect the major EHV transformers on the grid seems excessive, remember that each of these transformers costs between one and ten million dollars to replace. Just considering transformer replacements costs, the potential losses from an EMP or solar storm event dwarfs the protection costs by at least a factor of ten. The total losses from a major long term outage are estimated in the trillions, not taking into account the effects of the breakdown of national governance.

The average life of these EHV transformers can be 35 years or more. Thus, protection will be largely devoted to retrofitting existing units that have a long operational life remaining. It

[171] EMPRIMUS & ABB op. cit.

will also be important for decision makers to realize that those facilities that are not hardened will experience additional stresses from DC current diverted from those facilities that have been hardened,[172] which will increase damage to non-hardened assets. Thus, it will be important to establish and enforce protection requirements that extend to all electric power providers.

6.2 Developing a U.S. Canadian Cooperative

To prevent complete chaos, planning for a wide-area blackstart event must begin before the event occurs. The effects of EMP and major solar storms will likely involve both the U.S. and Canada. The high consequences of such an event will require planning on an international level.[173] It is important to note the current NERC blackstart plan only briefly mentions the threat from geomagnetic induced currents and also assumes that power will be available from unaffected regions to restart the grid. This assumption negates the applicability of the plan for dealing with continental-scale events. A new plan will be needed for wide-area blackstart contingencies. The blackstart operational plan developed must be thoroughly tested, exercised, and kept up to date, taking into account grid expansion.

International organizations need to understand their responsibilities and authority before such an event occurs. First, an allocation process for replacing EHV transformers needs to be developed. In addition, the international community needs to decide how these transformers would be rationed during such an event and the logistics of transporting them. The potential for price-gouging and allocating transformers for political reasons will not be acceptable.

Social impact studies will be needed to determine which areas are at the greatest risk for such events. Each grid will need to be evaluated to determine that particular system's vulnerability to EMP and solar storm events. This should include SCADA systems that could be

[172] John Kappenman, *Low-Frequency Protection Concepts for the Electric Power Grid: Geomagnetically Induced Current (GIC) and E3 HEMP Mitigation*, Goleta, CA: Metatech Corporation, 2010, p. 33.

[173] Marusek, op. cit., p. 10.

debilitated by EMP. The cascading effects to infrastructures dependent on electric power must be assessed and understood.[174]

Each transmission and generation operator must develop a plan to explain how EMP events would most likely affect their operations. This is especially important in areas that have single point failures.[175] This plan must contain a database of facilities with blackstart capabilities, and this database must be updated constantly. Back-up transformers need to be accurately tracked, and the information about their location, design details, age, and current operating condition must be kept up-to-date as well.

Due to the international nature of the planning, that will be involved in the response to an EMP event, a federal agency should be responsible for coordinating the development and implementation of this plan. The Department of Energy probably best fits this role. The actual execution of the plan within the U.S. will involve resources and activities that are quite different from prior experiences. The U.S. Army might be best-qualified to complete such a large and complex task because of the vast resources that will be needed to complete the project.[176] The effort will require an enormous amount of manpower, transportation resources, and logistics while dealing with a lack of most infrastructures.[177] Post-Katrina, it became apparent very quickly that state and local agencies lacked the necessary resources to respond with an appropriate level of manpower.

Communication during the restoration process will be very important, thus, operators must have access to reliable communication immediately after an EMP event or major solar storm, these systems should be initiated early on.[178] Communications will also be important for determining post-event grid status and, once islands are restored, coordination and

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[174] CENTRA, op. cit., p. 21.

[175] National Grid Company PLC. *An Introduction to Black Start Market Development.* National Grid PLC, 2001, p. 10.

[176] Ball, op. cit., p. 10.

[177] Marusek, op. cit., p. 10.

[178] National Grid Company, op. cit., p. 10.

synchronization of grid operating frequencies. Coordination with the military should establish whether their resources can be used to ensure reliable communications during an EMP event.[179]

In addition to communication issues, the military will have an important role in ensuring that fuel and transportation routes are available. Due to the lack of electricity, fuel will be difficult to transfer and may need to be rationed. Part of the national effort to develop an EMP recovery plan should be the development of a system to ensure that fueling areas have enough backup generation power to operate electrical fuel pumps. It is probably not necessary that every gas station have backup capabilities; rather, areas in strategic locations should have back up capabilities.

Roads could become impassible or extremely congested during an EMP event. Traffic control will be important to move essential goods and manpower across our highways. Also, commercial aviation will most likely be significantly limited as air traffic control and navigation systems are likely to be negatively affected and inoperable. This is yet another area where military resources will be important. This may be necessary to send smaller parts and rapidly transport manpower.[180]

The British transmission system (controlled by National Grid) presents insights into the value of public-private partnerships in blackstarting the grid. Based on the British model, it is important to insure that all blackstart generation facilities are functional. The British plan designates dedicated blackstart capable facilities as strategic generation systems. The National Grid organization has determined which facilities need to have blackstart capabilities, and these areas then construct a blackstart sequence and are required to practice this sequence nationally every two years. Those generation facilities with blackstart capabilities practice their blackstart and ensure they can get electricity to the substation. When they do get power to the substation, it

[179] Ibid., p. 15.
[180] Ball, op. cit., p. 10-15.

can be assumed that the generation station truly has a blackstart capability and at that point has everything necessary to transmit power through the power grid [181]

Obviously, the recommendations above come at a cost. Utility companies do not have any way of recovering this cost in the current market-based model.[182] There must be a cost recovery structure for securing the grid against EMP events that must fairly charge those who benefit from a resilient electrical grid. In order to implement such as strategy, grid operators must be allowed to pass these costs on to their customers. Currently, there is no uniform policy to accomplish this task, so it is often left to state commissions to determine whether rates can be raised or utilities can write off expenses incurred due to unusual events.[183]

In the event a bulk transmission operator supplies only bulk power to separate distribution companies, the cost should be passed to the distribution company. The distribution companies should then obtain authorization to charge their customers for the cost that was charged by bulk system operators through increased rates. Because almost every structure in the U.S. is a power customer, this cost would not have a large effect in individual consumers. Dividing a billion dollars by every electric customer in the U.S. does not result in a very large amount per customer. The cost recovery is perhaps the most significant challenge facing the implementation of EMP and major solar storm protection.

The electric power grid is decidedly our most vital infrastructure. This research has illuminated the causes and potential damage from wide area electromagnetic threats posed by EMP and major solar storms and explained the elements of alternative solutions. These threats, in their worst case manifestations, have the potential to reverse the technological state-of-the nation by 150 years.

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[181] National Grid Company, op. cit., p. 10.

[182] Bradley Johnson, *After the Disaster: Utility Restoration Cost Recovery*, Washington, D.C.: Edison Electric Institute, 2005.

[183] Ibid., p. 14.

The cost to protect the grid is not large compared to the value of the infrastructure and services at risk. However it will take major efforts in planning, coordination, and implementation from both the private sector and public sector. Although this paper is not intended to be a step-by-step manual on how to blackstart the North American grid, it is a starting point for evaluating which systems would be affected and approaches for addressing the problem. Because of their high consequences and despite their uncertain likelihood, the threat from such events deserves the same level of concern devoted to higher likelihood, lower consequence events such as major hurricanes and earthquakes.

The preferred approach to addressing these threats is protection. New and existing products are available to protect the grid from wide-area electromagnetic threats. These products should be evaluated for effectiveness, certified by testing, and then implemented.

More research is needed to understand how the power grid will behave during an EMP event. Specifically, little is known about the cascading failure of the grid or the specifics of how modern SCADA systems will react to direct effects of EMP and solar storms.

The cascading effects caused by grid harmonics and failure of other infrastructures should also be studied further. However, there is enough information available to conclude that the effects can be catastrophic and protection is feasible. Thus far, policies have been developed that are intended to address the problem, but none of them have gained significant momentum in our political system.[184]

After Hurricane Katrina, plans that had been made in the days before the storm moved across the Atlantic were found to be severely inadequate. The predicted worst case scenario fell far short of the actual consequences[185] Six years later and the gulf coast area has yet to fully recover. Such lack of preparedness must not be allowed in the face of potential large scale collapse of the North American power grid.

[184] Franks, Trent. Guard The Grid. n.d. http://www.shieldact.com/about-the-shield-act/ (accessed March 15, 2012)

[185] Federal Financial Institutions Examination Council, op. cit., p. 21.

Appendix 1: SCADA (Supervisory Control and Data Acquisition) Systems

Introduction

Supervisory Control and Data Acquisition (SCADA) systems are systems that the general public rarely hears about. They are complex systems that control the vital resources we rely on to control and monitor many inter-related physical systems in the electronic age. SCADA systems span America and connect our vital infrastructure to those of our neighbors to the south in Mexico and to the north in Canada. The Committee on Government Reform of the United States Congress contends that, "The nation's health, wealth, and security rely on these systems but, until recently, computer security for these systems was not a major focus. As a result these systems on which we rely so heavily are undeniable vulnerable to cyber-attack or terrorism".[1] EMP also threatens the operation of these systems.

Prior to September 11, 2001, not much thought was given to the plausibility of our nation's infrastructure being used as a major target for economic and military strategic goals by enemies of the U.S. SCADA systems control the electric grid and enable power to continuously to flow on days when the power grid is taxed to maximum capacity. In many locations they also selectively cut electricity when lightning strikes occur to prevent entire cities from losing power.[2] The systems are now used to remotely control most components of the power grid. SCADA systems are used in many industries, but this report will focus on their use on the electric power grid. The grid was initially not designed to transmit power over long distances; however, this is the current business model used by utilities in the U.S. Deregulation was directed to open generation markets, not to expand transmission networks. As a result, we are transmitting more power over the same number of transmission networks and over longer distances. Utilities are building generation facilities in rural areas where land and labor are cheap and regulations are lax. From those areas, the power is brought to areas where it is consumed via overtaxed transmission

[1] U.S. House of Representatives Committee on Government Reform, op. cit., p. 2.
[2] NERC, "High-Impact, Low-Frequency," op. cit., p. 8.

lines. Instead of expanding our transmission capabilities, we have implemented more complex SCADA systems that are capable of micromanaging the power grid to achieve higher outputs, while inputs to the system have remained the same.[3] SCADA systems represent a double-edged sword – they improve the efficiency of the grid yet, at the same time, introduce additional vulnerabilities associated with the complexity of their design and operation.

The North American Electric Reliability Corporation (NERC) has estimated that, unless serious changes are made, the excess capacity in the electric grid during peak demand periods will continue to diminish through 2016.[4] Less slack in the grid will mean that SCADA functions will be more critical than ever in preventing major power outages. Therefore, it is important to understand how these systems work and what their vulnerabilities are. A collapse in the major SCADA systems that control the power grid could cause a catastrophic power failure. These systems control all aspects of the grid, including generation facilities, transmission networks, and distribution facilities. The systems that were once confined to the relatively small world of power transmission and generation facilities have now been expanded to connect to the outside world through the internet. This provides opportunities for additional efficiencies that were not previously possible; however, it also creates vulnerabilities that the industry did not previously have to consider.[5]

Evolution and History of SCADA Systems:

There are two dominant types of SCADA systems: traditional SCADA systems that function over a wide geographic area, and Distributed Control Systems (DCS) which tend to function over a small geographical control area; for example, a single generating facility. In the past, DCS systems controlled processes in real time and SCADA systems did not control processes in real time; however, most modern SCADA systems now have the capability to

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[3] Eric Lerner, "What's Wrong with the Electric Grid?", Industrial Physicist, 2003.

[4] North American Electric Reliability Corporation, *Annual System Disturbance Reports*, North American Electric Reliability Corporation, 2008, p. 14.

[5] Barnes, Johnson, and Nickelson, p. 3.

control systems in real time. This causes the line between the capabilities of a DCS system and a SCADA system to become blurred. There are very few aspects of SCADA systems that are universal; systems currently used on the U.S. power grid are diverse in function and technical capabilities. With modern telecommunications technology, real-time processes can be completed over wide geographical areas. The difference between SCADA systems and DCS systems has become more philosophical than task-based, due to the increased sophistication in SCADA systems. In this paper, DCS systems are defined as systems that control processes in a small geographical area such as a single generation facility, instead of a SCADA system defined as a system that controls processes over a large geographical area.[6]

SCADA systems, including DCS systems, all have a few basic components that are required for the system to function. These four components are the Human Machine Interface (HMI), Remote Terminal Unit (RTU), Programmable Logic Controller (PLC), and the central host computer or central master station (CMS). The HMI displays the information used to alert operators to problems within the system. This system presents processed data to the human operator and allows the human operator to control processes. The HMI often provides logistics information for a certain sensor, detailed schematics, and maintenance procedures or troubleshooting guides. Almost all HMI systems present information to operators graphically, showing schematics and diagrams. Operators obtain their decision-making information from the HMI, which can consist of a single computer monitor or multiple computer monitors, depending upon the type of SCADA system and the complexity of the system. The HMI is generally part of an operator workstation; however, in some small SCADA systems the HMI can be connected directly to the CMS.[7] Some small municipal utilities are configured in this way. These small scale systems are proprietary in nature and are only connected to the outside world through a

[6] Communication Technologies, Inc. "National Communications System Technical Information Bulletion 04-1." *Supervisory Control and Data Acquiition (SCADA) Systems.* Arlington, Virginia: National Communications System, 2004, p. 8.

[7] Ibid.

manual switch that allows the vendor to install updates. These systems are generally only used for transmission and distribution power networks that have a small geographical footprint, most often in a rural area without much complexity. The primary function of the HMI is to convey the information the CMS has received to the operator.

The CMS is the processing unit of field data and commands field devices to take action. These actions can be automatically initiated such as closing a relay when voltage rises above a predetermined level or opening a relay when it drops below a predetermined level. The CMS acts as a server for the SCADA application. In all but the most basic SCADA applications, the CMS is connected to operator workstations which act as terminals to the CMS. The terminals send and request information from the CMS. The CMS usually host the SCADA software and terminals they also have a subset of this software installed on them. Most CMS systems use Windows or UNIX-based operating systems; however, some SCADA vendors have proprietary systems that use only vendor-specific operating systems and applications. Depending on the vendor, the software may come as a package and require all other components of the SCADA system to originate from that specific vendor, in order to interface with field components of the SCADA system, or it may be commercial off-the-shelf software (COTS) package. COTS software packages generally have more flexibility and can often interface with field components from different vendors.[8] This is a trend in SCADA systems that gives the utility more flexibility to mix and match components, which can provide significant cost savings. SCADA systems that use COTS software packages are often less expensive to implement because the cost of developing the software can be divided among multiple industries. These software systems are often more customizable and scalable. They use standard protocols and can be deployed over commercial communication systems.[9]

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[8] Ibid.
[9] U.S. House of Representatives Committee on Goverment Reform, op. cit., p. 45.

The components mentioned above are the command posts of SCADA systems, while the field components are the eyes, ears and hands of the system. Field components are composed of voltage and temperature monitors, actuators, and motor control switchboards. Before an automatic process can occur, information must be passed from the field device to the CMS. Once obtained by the field device, this information must be converted into the digital SCADA language to be understood by the SCADA software. The Remote Terminal Unit (RTU) is a microprocessor that connects physical objects to the SCADA system.[10] The RTU provides the language translation from the field device to the protocol that the SCADA system can understand. Most modern RTU's can send as well as receive signals. Therefore, they can be used to close or open a relay remotely, thus significantly reducing the number of personnel required for a task. RTU's also provide the CMS with information about the system. Programmable Logic Controllers (PLC's) are used to facilitate electromechanical processes such as engaging or disengaging switches. PLC's are used to acquire analog or digital data and execute a program loop while scanning inputs. The PLC then takes action based upon the inputs that they receive from the system they are monitoring.[11]

The difference between PLC's and RTU's has been blurred with the advancement of technology and requires some additional background information to fully understand. PLC's were developed in the automation industry and were initially used in manufacturing and processing industries. Initially, the need for PLC's to connect to external sources of communication was not very important, as these devices were used to replace relay logic systems and pneumatic controllers, whereas SCADA systems trace their origins back to early telemetry applications where it was important to know basic information about remote locations. Initially, RTU's connected to these systems to provide the function of connecting these devices to communications and had no need for control functions. The control functions were held by the

[10] Ibid., p. 45.
[11] Ibid., p. 6.

relay switching logic. It then became more efficient to influence the programming of the PLC through the use of a remote signal. This is the supervisory aspect of a SCADA system: the function where the PLC can be supervised from afar. PLC's store the program locally and only used the local program; as technology advanced, it became possible to store this program in the RTU. While RTU's were essentially performing the functions of PLC's, the makers of PLC's started to include communications modules in their product. This led both PLC and RTU manufactures to manufacture a product that had the same functions and allowed them to compete with each other for market share.[12] Over the past decade, RTU's and PLC's have evolved to become the same product. There are still limitations to this evolution, because the products may complete the same tasks in different ways. In practice, PLC usage is geared toward localized fast controls of discrete variables. RTUs are usually designed for remote monitoring and have integrated control functions designed in them; they have a higher demand of application communications which results in more protocol flexibility.[13] As a result of this trend, RTU's tend to have faster processors, more programming flexibility and broader communication capabilities. Due to the nature of the power grid, and the importance placed on reliability of communications, redundant communication capabilities are important to utility operators. RTU's can communicate via dial-up phone lines, medium speed RF systems, and broadband (wired and wireless).[14] This makes RTU's very flexible and they can perform in remote areas that lack commercial communication. In remote areas, radio communications may be the only economically feasible solution. PLC's performance advantage is demonstrated in sequential logic control applications with high discrete data counts. PLC's tend to have specialized designs which limits their CPU horsepower and hinders communication flexibility.[15] Due to specialized design, PLC's tend to not be easily scalable or modular in nature. Because the difference between PLC's and RTU's

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[12] Ibid.
[13] Motorola, *SCADA Systems*, Schaumburg, IL: Motorola, 2007.
[14] Ibid.
[15] Ibid.

has become increasingly blurred, I will refer to the interface between a PLC and the SCADA system as an RTU, and a PLC as an automation programming device for the sake of clarity.

As a whole, SCADA systems have evolved over the years together with the electric power industry's business model. As the electric industry began to develop in the 20th century, generating facilities were only associated with local loads. Municipalities that had electricity usually generated that electricity within or very close to the municipality. They consumed the electricity they generated and had very little need to transport electricity over large distances. When a system failure occurred, electricity for the entire region was lost. As the nation began to rely on electricity for lighting and other vital functions, the need for grid reliability increased, requiring additional safeguards to ensure reliable power. Over time, the grid became interconnected. Nearby towns would connect their grid to increase reliability and lower generation requirements. Over time, substations were built and labor costs started to escalate as did the number of substations and other grid components. This brought about the need for additional technology to provide real-time monitoring. SCADA systems could monitor and eventually control parts of the grid, which reduced the number of operationally ready personnel needed to operate a utility company.[16]

The first generations of SCADA systems were "monolithic" and were operated by mainframe computers. There were two identical mainframe computers: the primary mainframe did all the processing, while the standby systems monitored the primary function for failure and took over if a failure was detected. When the standby computer was in "standby" mode, no processing took place except for the processing required to monitor the primary system for failures. Monolithic SCADA systems were developed before networks. Therefore, they only connected to proprietary components of the SCADA system. The power companies installed their own cable network throughout the systems that they needed to control remotely. These early systems used proprietary protocols and were very specific to the utility system they were

[16]Alcaraz, Lopez, Zhou, and Roman, op. cit.

intended to control. Local area networks were implemented to communicate with RTU's - the network's sole purpose. The lines that controlled the SCADA system were managed and only utilized by the local utility company. The interfaces were proprietary and connectivity to the master system was limited to equipment manufactured by that vendor. Connections to the master system were done at the bus level by a proprietary adaptor plugged into the CPU.[17]

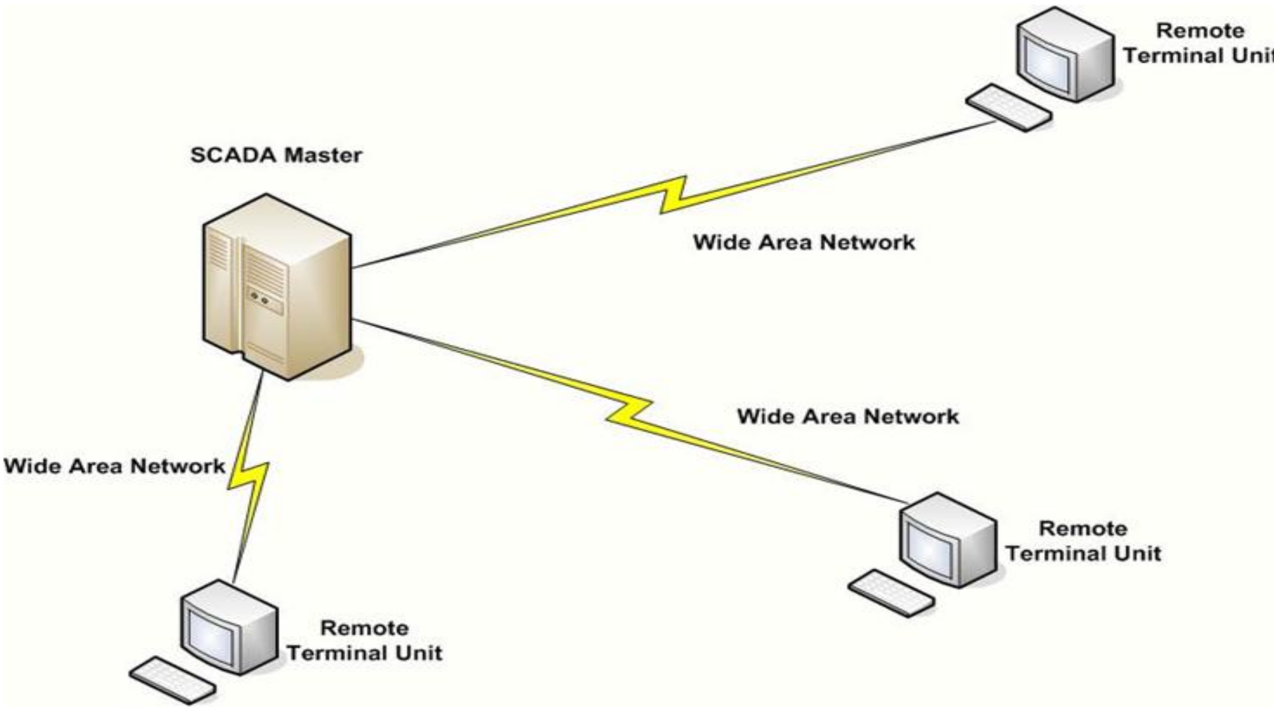

Figure 20: Monolithic First-Generation SCADA System[18]

Second-generation SCADA systems were distributed. They introduced networking technology which enabled the CMS to process multiple systems and used multiple mini computer stations. In a distributed system, each station had a specific function. The systems were connected to a local area network (LAN) and were able to share data in real time. The mini computer stations were more cost-efficient and scalable than mainframe systems. Each station had different functions, such as communicating with RUI's or providing HMI's. This system was

[17] Communication Technologies, Inc., op. cit., p. 10-11.
[18] Ibid., p. 11.

much more complex and added additional capabilities that first-generation systems lacked. Most second generation SCADA systems had dedicated mini computers devoted to calculation, processing, and database servers. The multiple processors used in distributed SCADA systems provided more processing power than the single processors used in mainframe systems. Generally, communication was limited to the LAN. These systems were not connected to the outside world and remained tied to cables installed by utilities for communication. The LAN protocols were often proprietary to the vendor to allow the vendor to optimize that protocol for real-time traffic. This technique prevented different SCADA systems from interacting with each other and limited connectivity. These systems relied on hardware and software provided by their particular vendor. Distributed systems are generally considered more redundant than monolithic systems, because all systems remain online at all times. In the event that a system failed, such as the HMI, another station could take over the failed systems task. The system did not have to wait for a standby system to detect the failure and take over the tasks.[19]

[19] Ibid., p. 11-12.

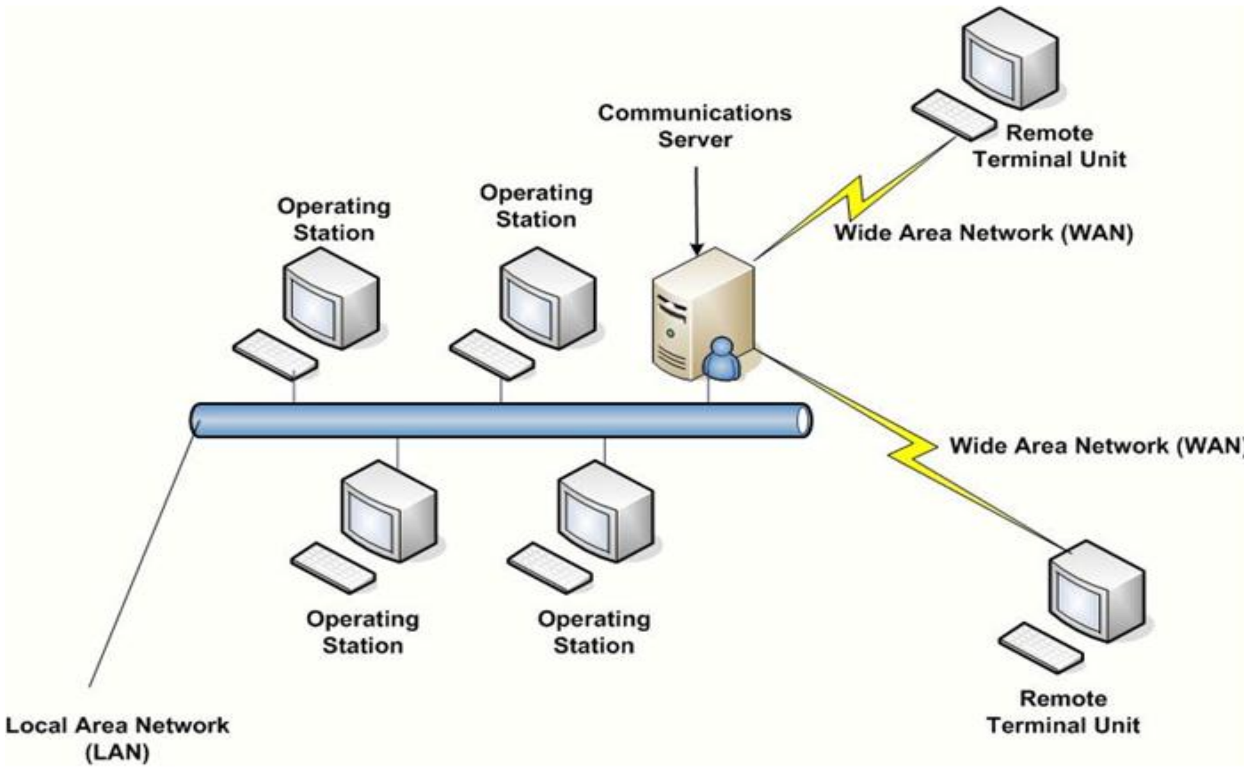

Figure 21: Distributed Second-Generation SCADA System[20]

Third-generation SCADA systems use architecture that is similar to second-generation systems. The primary difference between the two systems is the open-source architecture used in third-generation systems. Both systems share master functions and use similar RTU's. The open standards used in third-generation SCADA systems eliminate many of the limitations imposed by the second-generation's use of proprietary protocols. Current SCADA systems can be distributed across a wide area network (WAN). The open standard and COTS software makes it easier to connect to third party devices such as peripherals[21]. Although RTU's are still proprietary to the software, in a few situations there are third party solutions to link these to open sourced RTU's.[22] Vendors that have traditionally manufactured complete SCADA systems have gradually exited the hardware business to focus on software. Computer hardware manufacturers such as HP, Sun

[20] Ibid., p. 12.
[21] Ibid., p. 13.
[22] Motorola, op. cit., p. 7.

Microsystems, and Lenovo have taken over this segment of the business. The most significant improvement over previous SCADA systems is the addition of WAN protocols such as IP (Internet Protocol) for communication between the master station and communication equipment. This allows the part of the master station that is responsible for communications with field devices to be separated from the master station protocol across other communication devices such as back office systems. Vendors are now producing RTU's that can communicate with master stations, utilizing multiple forms of communication to create additional redundancy in the system. Additionally, networked SCADA systems have the benefit of disaster survivability.[23] Due to distributed processing across physically separate locations, SCADA systems can be constructed to survive a total loss of any one location. This can be critical for large transmission system operators due to the enormous size of their footprint. Hydro-Quebec would fit this criterion because their transmission system provides power for a large portion of the population in the north east U.S, making system continuity critical.[24]

[23] Communication Technologies, Inc., op. cit., p. 14.

[24] Ian Dobson, "Where Is the Edge for Cascading Failure? Challenges and Opportunites for Quantifying Blackout Risk." *IEEE Power Engineering Society General Meeting.* Tampa, FL: IEEE, 2007, p. 7-9.

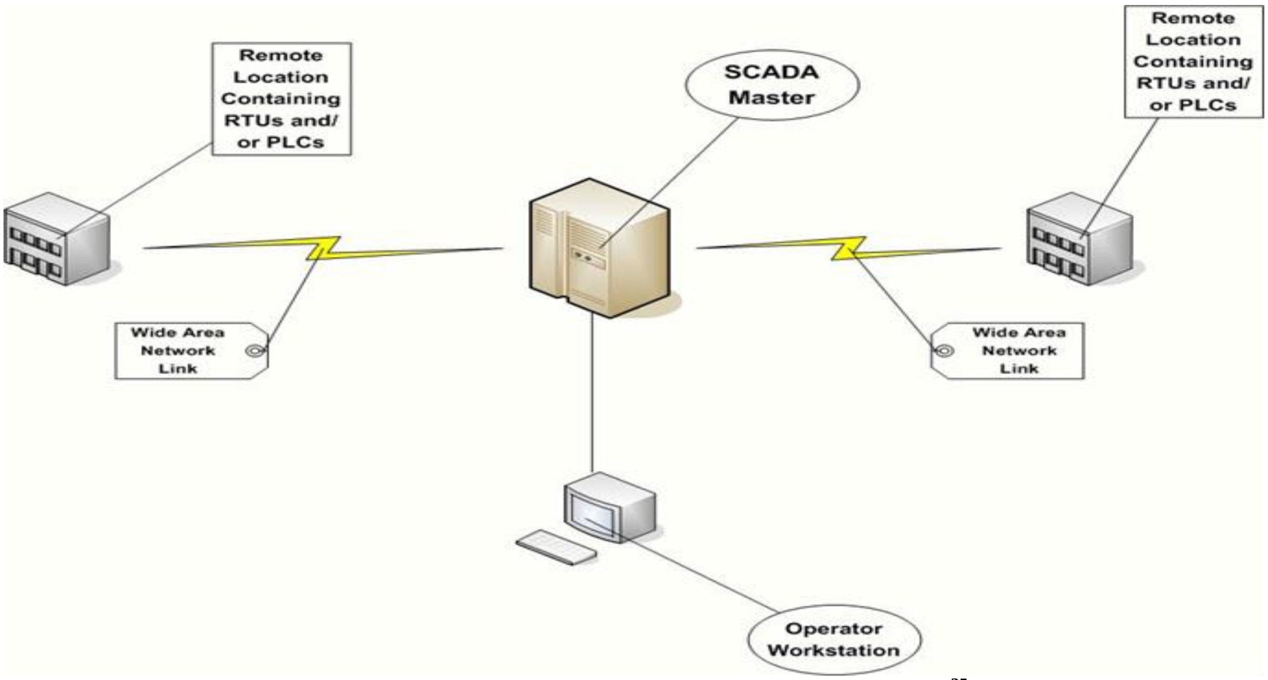

Figure 22: Networked Third-Generation SCADA System[25]

SCADA systems can be used by transmission operators to control parts of the grid that are hundreds of miles away; due to the increased capability of these systems, deployment in the power industry has rapidly declined over the years. At one time, lineman and substation operators were switching relays across the grid by physically going to a location and flipping a switch, and each substation required almost daily visits to check that systems were operating correctly. This is no longer the case: these systems can be monitored from far away and switchgear is almost exclusively operated from afar. Generation facilities often use distributed control systems (DCS) which are typically used within a single generating plant over a small geographic area. These systems are used in generating facilities of varying size from small gas-fired turbines to large-scale nuclear facilities. Given the nation's current dependence on SCADA systems, the grid would become inoperable if a large scale SCADA failure were to occur.[26]

[25] Ibid.
[26] U.S. House of Representatives Committee on Government Reform, op. cit., p. 14-20.

EMP and Solar Storm Effects on SCADA Systems:

SCADA systems are likely to be the weakest link in the event of a EMP event or solar storm.[27] These systems can contribute to cascading failures during both EMP events and solar storms. EMP events and solar storms will affect SCADA systems differently; however, both will contribute to the failure of the grid and hinder blackstart attempts. These systems are becoming more complex and increasingly depend on leased communication lines and wireless technology to remain functional. In the event of an EMP event, the power grid is vulnerable to first-order SCADA malfunctions such as damage to SCADA components and overcorrection. Additionally, due to the dependence on leased commercial lines, the grid would also be vulnerable from second-order malfunctions, such as failure of land line and wireless communications that would prevent remote controllers and sensors from communicating with central operations.[28]

EMP events cause direct damage to the microelectronics used by SCADA systems. The various localized communication lines used by SCADA systems in substations and generation stations have the ability to induce voltages between 100 and 700 amperes into components. The microelectronics used in these components would be rapidly destroyed by induced current of this magnitude. [29] The limited testing that has been completed has confirmed that induced current will severely damage these components. When these systems fail, other components of the system automatically react to the false signals sent out by failed components. There are many microelectronic devices in SCADA systems, some located at remote, unmanned locations. If the SCADA systems failed, these remote locations would be impossible to control until personnel could be sent to the location to physically monitor the situation and manually take control. Due to the interconnectedness of the power grid, this could cascade through large portions of the power grid, causing failure and damage to transmission and generating equipment. Most modern SCADA systems rely on commercial communication systems to control equipment located in

[27] Communication Technologies, Inc., op. cit., p. 15.
[28] Dobson, op. cit., p. 9.
[29] Commission, “Report of the Commission to Assess the Threat,” op. cit., p. 14.

remote locations. In the event of an EMP event, these systems would likely not be available, causing the system to fail.[30]

During the 1989 Hydro-Quebec solar storm event, SCADA systems contributed to the failure of the Hydro-Quebec grid. The SCADA systems reacted rapidly to the induced current in the transmission lines, which caused voltage regulation equipment to shut down and escalated the cascading effect of the Hydro-Quebec power grid. Eventually, the failure of the voltage control systems allowed the harmonics to cascade through the entire Hydro-Quebec grid. Several major components were damaged beyond repair during this incident. Since this event, SCADA systems have been utilized to an even greater degree in the power grid. These systems are not typically hardened against EMP events. For the most part, it is not known how modern systems will behave during an EMP event.[31]

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[30] Riswadkar and Dobbins, p. 8.
[31] Ibid., p. 15.

Appendix 2: Reactive Power

Reactive power occurs when the current waveform is "out of phase" with the voltage waveform due to inductive or capacitive loads. Single lines in an AC power system oscillate at a frequency of 60Hz in North America.[32] When voltage and current fluctuate (go up and down) at the same time, only real power is being generated. When voltage and current fluctuate at different times, they are "out of phase" and reactive power is being generated. Real power is the product of current and voltage and thus is maximized when they are in phase. Reactive power is equivalent to the real power lost due to these phase differences and is stored in the electric and magnetic fields within capacitors and inductors. This stored energy can actually be useful in sustaining power delivery during short interruptions of power delivery such as momentary trips of circuit breakers. System operators use capacitor or inductor banks to create "reactive reserves" to handle such system contingencies. Reactive power is measured using the volt-ampere reactive (var) unit.

Solar storms induce quasi-DC currents in transformers that push them off their normal balanced operating point and create phase instabilities between the current and voltage waveforms in the transformer, leading to large amounts of reactive power being stored in the transformers themselves. This stored energy is dissipated in the transformer windings and structure causing heating and, in some cases, damage to the transformer. The absence of normal operation also generates harmonic frequencies that cause problems with grid control systems affecting grid stability. With all transformers on the grid doing this at the same time, there is a significant risk of grid collapse.[33]

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[32] Peter Sauer, *What is Reactive Power?* Champaign, IL: University of Illinois, 2003.
[33] Kappenman, *Geomagnetic Storms*, op. cit., p. 49.

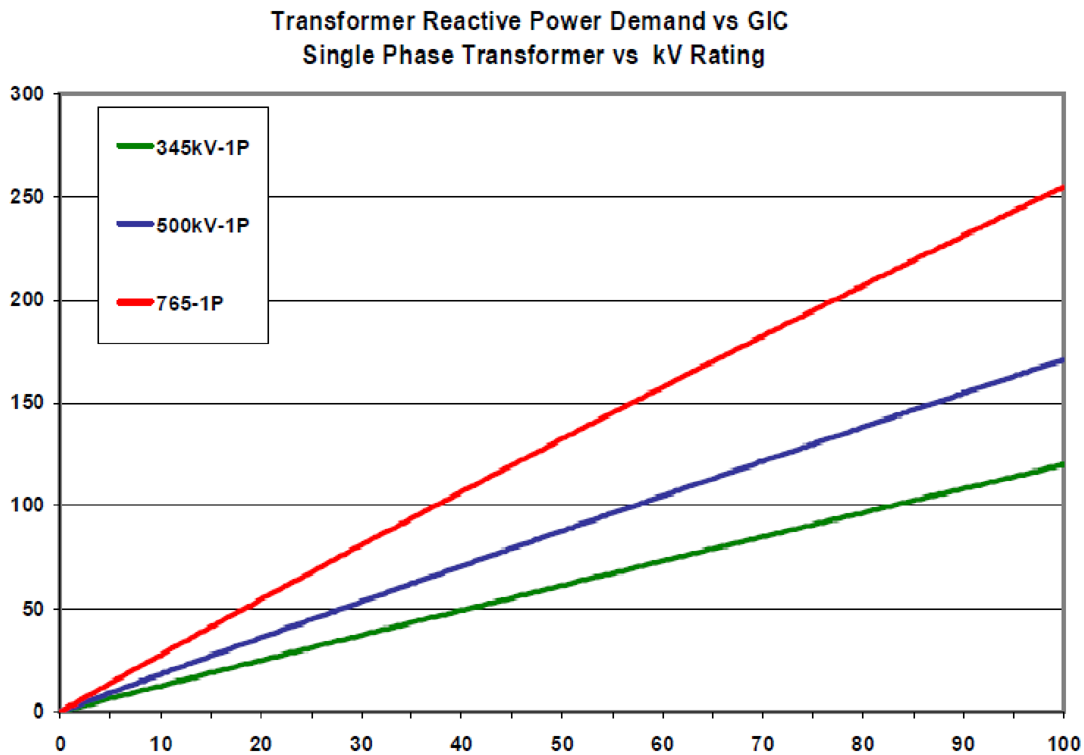

Figure 23: Transformer Reactive Power Demand vs. GIC[34]

[34] Ibid., p. 50.

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