High Power Electromagnetic (HPEM) Threats to the Smart Grid

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This paper is focused on the threats and impacts of High Power Electromagnetic (HPEM) environments on the U.S. Power Grid and further introduces the implications of making the power grid “smarter” through the introduction of additional electronics. These Smart Grid electronics may introduce additional vulnerabilities if the grid is exposed to the high power EM threats of High-altitude Electromagnetic Pulse (HEMP) from a nuclear detonation in space over the U.S.; Intentional Electromagnetic Interference (IEMI) from terrorists or criminals who wish to attack and create regional blackouts using electromagnetic weapons; and, finally, from an extreme geomagnetic storm (initiated by solar activity) that could create damage to the high-voltage electric grid. This author has previously referred to these three electromagnetic environments as a “triple threat” [1].

This paper will briefly introduce the basic electricity delivery system as it exists today with an explanation of the trends that are underway to make the grid “smarter”. Some discussion of the impacts of electromagnetic interference on the existing grid will be mentioned, including the fact that standards have been developed to protect existing power grid electronics from these “standard” electromagnetic threats. Next, the relationship of these HPEM threats to the existing EM environments will be explained, including work initiated by the EMP Commission where tests were performed to determine vulnerability levels of the existing grid.

The next portion of this paper discusses an approach to be taken to protect both the current power grid and the future Smart Grid from these HPEM threats. This paper will then conclude with a summary of the activities of various national and international organizations working to develop HPEM procedures and standards to protect power grids and other critical infrastructures throughout the world.

WHAT IS THE SMART GRID?

The electric power grid consists of basic elements of generation, transmission, distribution and users. Currently, power generators are dispatched based on the projected power needs for each day, and in some states auctions are held to achieve the best price and reliability outcome for the consumer. Each large power company has a control center that works to keep the power generated and used in balance, through diverse communications networks. In addition, they use communications networks to keep track of the health of the control electronics within substations to react in case of faults or equipment failures. Figure 1 illustrates a basic power grid example with three types of power-generating plants illustrated and three types of users (residential, commercial and industrial). It should be noted that the terminology of transmission, subtransmission and distribution in the figure may vary with respect to particular voltage levels in different parts of the U.S. and the world. In addition, the IEC [3] defines a.c. high-voltage as above 100 kV, low voltage as below 1 kV, and medium voltage as in between these two levels. Additionally, the term EHV (extra high voltage) is usually defined above 345 kV, and a new term of UHV (ultra high voltage) is defined above 800 kV, both for a.c. power flow.

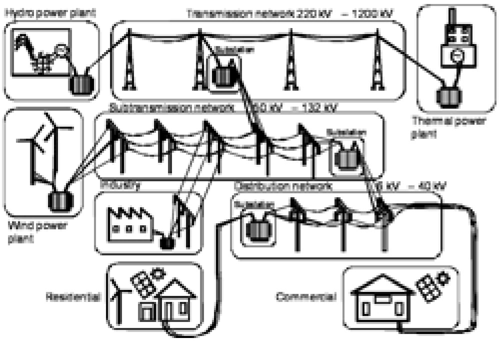


Figure 1. *Basic elements of a power grid [2].*

With regard to the trends for Smart Grid, there are several aspects to consider. Due to the emphasis put on renewable sources of energy, there are large numbers of wind turbines and solar farms being built by power companies. As these forms of generation become a larger portion of the power generation availability, sensors to track the actual flow of power over short periods of time become more important (as is the reliability of the communications networks to provide this information to the control centers). In addition, forecasting of wind velocity over hours and even minutes may become important in the future. If the wind generation drops suddenly, the control center needs to have this information in order to bring up alternate power generators (or drop load) to avoid a power blackout.

Another area of Smart Grid activity is to upgrade the electronics in high voltage and medium voltage substations and to develop new rapid communications methods to relay status information and to take actions when necessary. Another area of power company activity is to increase the monitoring in the distribution network to determine the location of local outages if they occur and to command the opening of sectionalizing switches if needed.

A final area of Smart Grid activity involves the actual consumer of electricity through the rollout of Smart Meters. These electronic meters can communicate back to the control center through a new communications network providing information regarding the use of electricity. In addition, consumers may be given alerts regarding the use of power and changes in the price of electricity during different times of the day. There is even a concept to build in control chips for consumer appliances that would allow particular items to be turned off remotely by the power company (presumably with the permission of the consumer, with a possible benefit of lower power rates). There is work ongoing now in the Smart Grid community to develop the communications protocols for this aspect of appliance control. It should be noted that this "demand response" aspect of Smart Grid is viewed as a way to avoid building too many power plants by reducing the margin between the peak power required and the peak power available.

In reviewing the paragraphs above, it is clear that the main aspect of Smart Grid is to introduce new electronics in large numbers with new ways to communicate to them. It is of some concern that with a small operational margin, if the ability to communicate is disturbed or if Smart Grid equipment is damaged, then the smaller margin that we have today would likely result in a lower reliability of operation of the power grid. As described below it will be clear that severe (yet infrequent) electromagnetic threats have the capability to both damage and disrupt the current and future power grids.

HPEM THREATS

IEMI background

To refresh the reader regarding the terminology employed here, the term Intentional Electromagnetic Interference (IEMI) refers to the deliberate attempt to produce electromagnetic radiated and/or conducted disturbances to interfere with the operation of commercial equipment or to create damage to that equipment [4-6]. This could be done for criminal or terrorist purposes, although the purpose of the technical work is to determine the feasibility of such attacks and to determine ways to detect an attack and/or to protect against the types of disturbances that might be generated. As shown in Figure 2, the IEMI environments are split into two categories known as wideband and narrowband, with both normally produced at frequencies above 100 MHz. In the time domain, the peak electric fields exposing equipment are typically higher than 10 kV/m. Standardization work dealing with IEMI is moving forward in the IEEE EMC Society, IEC SC 77C, Cigré and ITU-T and will be discussed later in this paper.

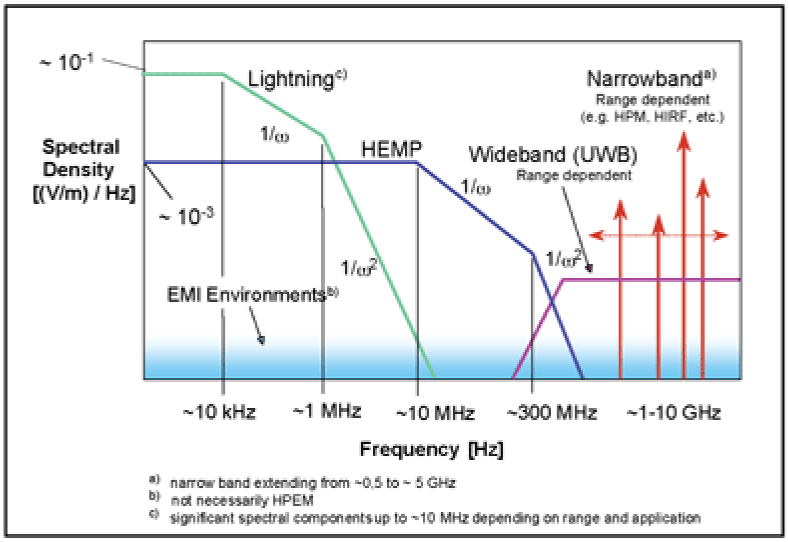


Figure 2. *Comparison of IEMI wideband and narrowband threats with the early-time HEMP and lightning electromagnetic fields [4].*

HEMP BACKGROUND

The terminology of the electromagnetic pulse has evolved over the years, but today the generic term for all types of nuclear generated electromagnetic transients is EMP. Sometimes one will see the term NEMP, which clearly identifies the particular pulse of interest as being generated by a nuclear detonation. Of interest here is the EMP created by a high-altitude burst, generally defined as one occurring at a burst height greater than 30 km. For this altitude regime, the radiation produced by the nuclear burst does not reach the Earth's surface, but several types of intense electromagnetic signals will. Because the burst is at high altitudes (in space), this type of EMP is usually referred to as HEMP. The HEMP has three time (and frequency) portions with the early-time (E1) HEMP reaching field levels of 50 kV/m within 10 ns, the intermediate-time (E2) HEMP reaching 100 V/m between 1 microsecond and 1 second, and the late-time (E3) HEMP reaching 40 V/km for times between 1 and several hundred seconds [1,7]. Based on research performed over the years, it has been concluded that the E1 and E3 HEMP are the biggest concerns to the power system due to their high peak field levels and efficiency in coupling to power and control lines. They both have an area coverage that can exceed several thousand kilometers from a single burst.

The concern is that these high-level electromagnetic fields and their area coverage will create simultaneous problems for computers and other electronic systems on the Earth's surface, including the critical infrastructures (power, telecommunications, transportation, finance, water, food, etc.). This was the focus of the U.S. Congressional EMP Commission studies [8, 9].

EXTREME GEOMAGNETIC STORM BACKGROUND

The first two high-power threats and environments discussed above are man-made. There is, however, a natural environment known as an extreme geomagnetic storm that has strong similarities (spatial distribution and time variation) to the late-time (E3) portion of the HEMP [10]. Because of this, the protection methods are also very similar, although the specification levels of protective devices may vary. It should be noted that the term extreme geomagnetic storm is used here to indicate that the level of the storm exceeds the usual description by NOAA of a severe geomagnetic storm, which may occur more than once during a solar cycle (11 years). The extreme geomagnetic storm is defined as a 1 in 100 year storm [8].

In brief, a large increase in charged particles ejected from the Sun and into the solar wind can interact with the Earth's magnetic field and produce a significant distortion of the geomagnetic field at the surface of the Earth. This rapid variation of the geomagnetic field (on the order of seconds to minutes) induces time varying electric fields in the Earth, which through the neutrals of transformers create time-varying (yet quasi-dc relative to 60 Hz) currents in the high-voltage power network. These currents induce severe harmonics, increase inductive load and produce heating in each exposed transformer. This can lead to voltage collapse of the network as experienced by the power grid in Quebec in March 1989 and damage to highly exposed transformers. Figure 3 illustrates the contours of the B-dot environment at the Earth's surface (in nT/min), minutes after the collapse of the Quebec power network. The spatial extent of the severe fields is quite large, and the footprint can move (and has moved) further south during other storms. For additional information about geomagnetic storms and their impact on power grids, one should consult the literature [11, 12].

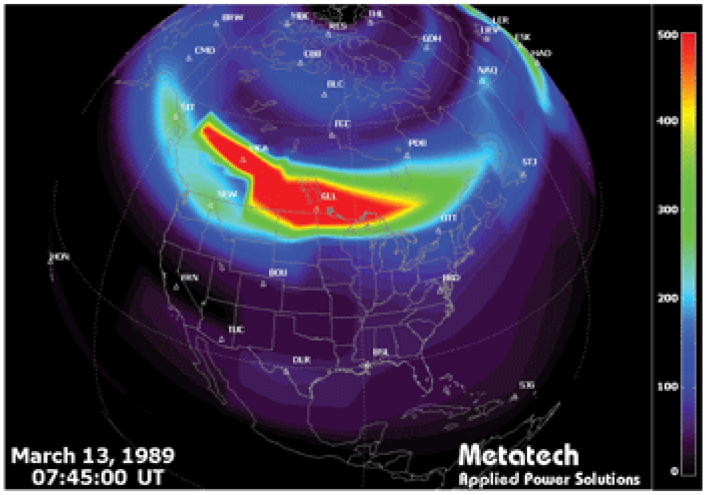


Figure 3. *Level of B-dot disturbance (measured) from the severe geomagnetic storm that created the blackout in the Quebec power system a few minutes earlier [8]. (Source: Metatech Corporation Applied Power Solutions)*

POTENTIAL IMPACTS OF HPEM WITH THE POWER GRID

Early-time (E1) HEMP impacts

The early-time (E1) HEMP produces a fast rising and narrow electric field pulse (2.5/25 ns) that propagates at the speed of light from the burst point. Figure 4 illustrates that the area coverage depends on the burst height. Due to the rapid rise of the E1 HEMP in the time domain, the frequency content is much higher in magnitude and frequency than lightning electromagnetic fields and normal substation electric fields produced by switching events in the high voltage yard. These electromagnetic fields can couple to low voltage control cables in a substation and propagate levels on the order of 20 kV to the control house electronics. This presents a severe disturbance to existing substation solid-state protective relays. In addition, the EM fields are high enough also to penetrate the walls of most substation control houses, as the walls are not designed to attenuate EM fields significantly (as shown in Table 1). As more Smart Grid electronics are placed in substations, these E1 HEMP fields become a significant concern to their performance. Also the placement of new Smart Grid communication antennas and electronics in substations should consider the threat of E1 HEMP. It is noted that microwave towers with their long cables extending to the ground are an ideal pickup geometry for E1 HEMP fields, and unless good grounding practices (circumferential bonding) are employed at the entrance of the cables to communications buildings, the high-level induced E1 HEMP currents and voltages will propagate efficiently to the cable connections of the electronics, creating likely damage.

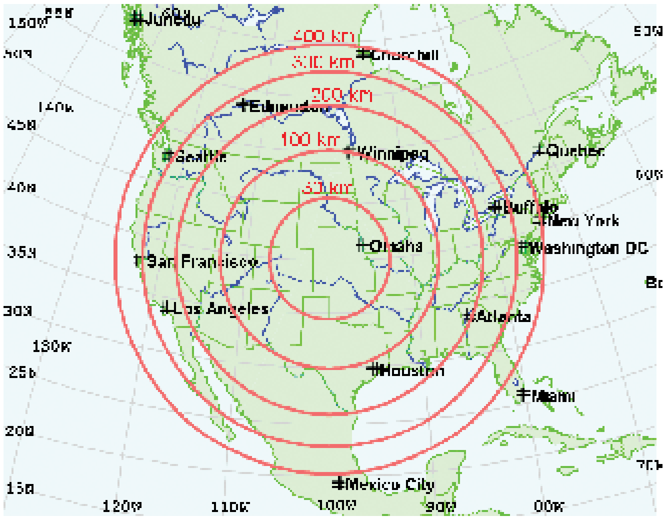
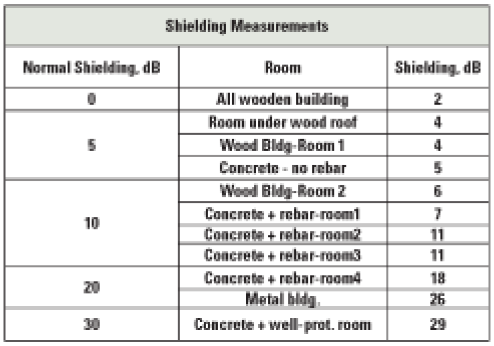


Figure 4. *Indication of the area exposed to E1 HEMP from a high-altitude burst over the central United States for various burst altitudes given in km.*



Shielding Measurements		
Normal Shielding, dB	Room	Shielding, dB
0	All wooden building	2
5	Room under wood roof	4
	Wood Bldg-Room 1	4
	Concrete - no rebar	5
10	Wood Bldg-Room 2	6
	Concrete + rebar-room1	7
	Concrete + rebar-room2	11
	Concrete + rebar-room3	11
20	Concrete + rebar-room4	18
	Metal bldg.	26
30	Concrete + well-prot. room	29

Table 1. *Shielding effectiveness measurements for various power system buildings and rooms.*

E1 HEMP will also couple efficiently to aboveground medium and low voltage power lines that are typical for the distribution grid and also to the low voltage drop lines to homes or businesses. While burial of distribution lines is becoming more common in the U.S., there are still on the order of 70% of U.S. distribution lines at medium voltage that are above ground. The problem with this is that the E1 HEMP can couple voltages up to 1 MV common mode with a rise time of 10 ns and a pulse width of 100 ns [13]. These levels will create insulator flashover on many distribution lines (simultaneously) and can cause mechanical damage to some insulators [14]. For the shorter drop lines to homes, levels on the order of several hundred kV are possible that could seriously damage solid-state Smart Meters. As for distribution sensors and electronic controls, these would also be fully exposed to the E1 HEMP environment; without protection for the sensors, cables, electronics and communications, damage could be expected.

Another concern is the protection of the control center for each power company that consists of computers/terminals and displays to keep track of the status of the power system under control and the supporting computer and communications rooms to send and receive data to and from substations. Currently there is some variation in the building construction quality used at different power companies (Table 1), but the best approach to avoid problems is to place the control center in the middle of the building on a low floor or in the basement. This is because soil and concrete provide some protection from high frequency EM fields. Locating the control center on the top floor with outside walls and windows increases the penetration of EM fields inside the building where they can interact directly with the computers and their ubiquitous Ethernet cables (which are extremely vulnerable to high levels of pulsed EM fields). In the context of Smart Grid, it is likely that more electronics and communications will be added to the control centers, increasing the likelihood of damage or upset to equipment that are required to operate at a higher data rate than today's equipment.

In terms of power generation, E1 HEMP is a threat to the low voltage controls of power plants, including those SCADA systems that control the flow of fuel to the generator. If additional communications are added to the generators to update the power control center periodically for Smart Grid, then these communication antennas, cables and electronics should be protected at least against damage (upset can be handled more easily as personnel are present). For the issue of distributed generation, the proliferation of variable generators such as wind turbines will require new communications for Smart Grid applications to keep track of the amount of power being generated on a shorter time basis. Both wind and solar power generators will be exposed to E1 HEMP fields, and additional test data are needed to determine whether the turbine electronics and power converters themselves will be able to survive the effects induced by E1 HEMP.

Intentional electromagnetic interference (IEMI) impacts

As indicated in Figure 2, IEMI environments tend to be present at somewhat higher frequencies than the E1 HEMP. The typical field levels are also on the order of 10s of kV/m (depending on the location of the attacker relative to the sensitive electronics), but because of the higher frequency content, most electronics appear to be slightly more vulnerable than when exposed to E1 HEMP. This is due to the fact that the penetration of EM fields into an equipment case is typically more efficient as the frequency increases. Also the ability to upset electronics is increased when the frequencies of the EM environment are similar to the operational frequency of a microprocessor (typically in the GHz range). E1 HEMP has most of its field energy below 100 MHz.

While the IEMI threat field level is similar to E1 HEMP, it does not resemble a plane wave field that is propagating downward from space. Since the attacker for IEMI is likely within 100 meters, the EM field propagating away from the weapon tends to decrease as 1/r. This variation in field level with distance (unlike E1 HEMP) does not allow significant coupling to lines with length on the order of 100 meters or more. Therefore, IEMI is not a significant threat to insulators on medium voltage power lines. On the other hand, the IEMI threat to Smart Meters, distribution electronics, substation electronics, substation communications, control rooms and power generating facilities (including wind and solar facilities) is the same as for the E1 HEMP. Of course only one facility at a time is exposed by IEMI, but a team of criminals or terrorists could expose a significant set of assets in a city or town by using a weapon mounted inside a vehicle.

Late-time (E3) HEMP impacts

The late-time (E3) HEMP produces a disturbed geomagnetic field beneath the burst that induces slow rising (rise time on the order of 1 second) electric fields in the Earth up to 40 V/km. The area coverage beneath the nuclear burst is on the order of several thousand kilometers and long transmission lines (e.g. 100 km) can couple 4000 V between the grounded neutrals of their transformers. With a typical line/transformer/grounding resistance of 5 ohms, this results in a quasi-dc current flow of approximately 800 A (for this example). This is more than enough to create severe levels of transformer saturation, leading to the creation of high levels of even harmonics in the a.c. waveform and also heating and potential damage to the large transformer itself. As these transformers are very expensive and for voltages of 500 kV and higher are manufactured off shore, the loss of a significant number of transformers could create a long-term power outage in the exposed area (months or more). Also a blackout situation is likely to result even where transformers were not damaged, and it would take significant time and effort to restart the grid where assets were not damaged.

A second aspect of the E3 HEMP is the fact that the severe harmonics would propagate throughout the grid and create malfunctions and potential damage to building backup power systems. Harmonic immunity is built into most UPS and backup diesel generator systems; however, the harmonics generated by an E3 HEMP (and also an extreme geomagnetic storm) will greatly exceed those normal immunity levels. As for Smart Grid, there are already concerns that the harmonics normally present in many power systems create accuracy problems for Smart Meters. The IEC is working to add tests to the International Smart Meter standard to cover this problem. The IEC immunity tests do not cover the enhanced levels due to E3 HEMP or geomagnetic storms, so the impact to Smart Meters is not currently known.

Finally the low-frequency HEMP environment occurs immediately after the early-time, high-frequency E1 HEMP. This raises the prospect that control electronics, including high voltage protection relays, may not operate properly due to the E1 HEMP, and this could result in additional damage that would occur due to the E3 HEMP. This is different than the case of the geomagnetic storm that only produces the low frequency environment similar to E3 HEMP.

Extreme geomagnetic storms

While geomagnetic storms are an act of nature (the Sun), they vary in intensity and location on the Earth. Through evaluations of the probability and magnitude of a worst-case geomagnetic storm, Kappenman studied the Carrington storm in 1859 [15] and has estimated that an extreme geomagnetic storm could produce electric fields on the order of 20 V/km, although the spatial extent would likely be larger than that of E3 HEMP (by two to three times). The particular types of impacts on the U.S. power grid would be similar to the E3 HEMP impacts discussed above, although the area coverage would likely be larger, depending on the latitude of the storm and its longitudinal coverage (see Figure 3).

The major difference between the geomagnetic storm and the E3 HEMP is that there is no early-time, high-frequency electric field that precedes the geomagnetic storm. It is therefore likely that in the region of HEMP exposure, the total impacts will be more significant.

HPEM PROTECTION APPROACH

Protection from electromagnetic fields is strongly dependent on the frequency range and magnitude of the environment. This is due to the fact that high frequency transients penetrate more easily through gaps in metal shields or through dielectrics such as windows; they also couple well to “floating” wires, which act as antennas. Also high-frequency conducted transients usually have high power but modest energy, allowing the use of surge protection devices that do not require a high-energy handling capability.

In the case of low-frequency electromagnetic fields, grounding is very important and conducted transients with low voltages can be isolated by relatively small gaps.

For these reasons we will discuss the protection concepts for the high-frequency HPEM threats (E1 HEMP and IEMI) together and the low-frequency HPEM threats (E3 HEMP and Extreme Geomagnetic Storms) together. While there are great similarities within the two groupings, care must be taken to ensure that protective devices are properly sized for both threats within each group.

High-frequency HPEM protection approach

The basic approach for protecting from high-frequency HPEM threats is to first take advantage of the EM shielding that may be available in your installation. This is applicable to cases where the sensitive electronics are inside of a substation building, a power control center building, a generator control building, or a communications control building. Many building materials will attenuate high frequency fields from the outside to the inside. For cases in which the attenuation is insufficient (see examples in Table 1), then one can consider an augmentation of the shielding through external building additions, internal room wall shielding, or even moving equipment to a newly built shielded enclosure.

For electronics that are fully exposed to the E1 HEMP or IEMI (e.g. Smart Meters, distribution system sensors and communications, and antenna systems on substations, control center buildings and power plants), it will be necessary to evaluate by analysis and test the ability of connected electronics to withstand the E1 HEMP or IEMI environment when high-frequency grounding is improved and filters and surge arresters are added.

In both cases, it is necessary to perform detailed assessments that include evaluations of the shielding effectiveness, coupling to cables, consideration of fiber optic cabling, evaluation of existing filters and surge arresters and vulnerability of the equipment before protection is added. This approach is discussed in some detail for E1 HEMP and IEMI in a recent conference paper that provides additional details beyond those given here [16].

Low-frequency HPEM protection approach

The basic approach for protecting against the two low-frequency HPEM threats described here, is to prevent the electric fields induced in the Earth from coupling to the neutral connections of the high voltage transformers in substations. This can be done with neutral capacitors (to block) or resistors (to reduce), but the difficulty is that a fast bypass must be provided to allow for lightning surges and faults to flow safely to ground without damaging the neutral “blocking” device. While these types of devices have been successfully applied in large numbers at lower transformer voltages than we require for the EHV power grid, some techniques have been developed that should work for EHV transformers. The next step is to develop and test prototypes, write standards and then field the devices. If the reader has further interest in this area of protection, see [17].

ORGANIZATIONS DEALING WITH THE THREATS OF HEMP AND IEMI

IEC SC 77C (EMC: High Power Transient Phenomena)

Since 1989, the International Electrotechnical Commission (IEC) headquartered in Geneva, Switzerland has been publishing standards and reports dealing with the HEMP and IEMI threats and methods to protect civilian systems from these threats under IEC SC 77C. As these are electromagnetic threats, it was decided from the beginning that this work would be closely integrated with the EMC work being performed by the IEC and other organizations throughout the world. In fact IEC Technical Committee 77, the “parent committee” of SC 77C, has the title “EMC”. There are several recent papers that provide details on the 20 IEC SC 77C publications that can be applied to the definition of the threats, the coupling to systems and the protection of systems [6, 18]. It is noted that these are basic standards and as such do not describe the resultant recommended immunity levels for particular types of equipment. This means that the standards must be applied on a case-by-case basis.

ITU-T Study Group 5

The International Telecommunications Union – Telecommunications Standardization Sector (ITU-T) has been working since 2005 to protect telecommunications and data centers from disruption from HPEM threats, which include HEMP and IEMI. They have relied a great deal on the basic publications of IEC SC 77C to prepare their recommendations. As of 2011 they have completed two recommendations for protecting against the E1 HEMP and IEMI [19, 20].

IEEE P1642

The IEEE EMC Society with the support of TC-5 (High Power EM) has been developing the "Recommended Practice for Protecting Public Accessible Computer Systems from Intentional EMI [21]." The purpose of this work is to provide guidance to businesses and government agencies that are operating computer systems in close proximity to public access. The concern is that criminals and terrorists could use small electromagnetic weapons to disrupt or destroy important computer systems without any trace of an attack. The focus on this work is to establish appropriate threat levels, protection methods, monitoring techniques and to recommend test techniques to ensure that installed protection is adequate. This document is scheduled for publication in early 2012.

Cigré C4 Brochure on IEMI

The International Council on Large Electric Systems has formed a working group WG C4.206 entitled, "Protection of the high voltage power network control electronics against intentional electromagnetic interference (IEMI) [22]." This working group is preparing a brochure that will recommend IEMI protection methods for the control electronics found in high voltage substations. The work is expected to be completed by the end of 2011.

SUMMARY

In this paper we have introduced three severe HPEM threats and discussed their likely impacts on the current and future U.S. power grid (Smart Grid). While we cannot be sure of all of the features of the eventual Smart Grid, there is enough information to evaluate the trends. In addition to pointing out the likely impacts on particular aspects of Smart Grid, assessment methods and protection measures have been described with references to more detailed studies. It is expected that efforts to assess and protect Smart Grid electronics and communications from electromagnetic interference (EMI) from "everyday" threats will continue; it is also recommended that assessments and protection be considered for these "low probability" HPEM threats.

Any readers who are interested in contributing to this research or standards, please contact this author at wradasky@aol.com.

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