Richard L. Garwin
IBM Fellow Emeritus[1]
IBM Thomas J. Watson Research Center
P.O. Box 218, Yorktown Heights, NY 10598
www.fas.org/RLG/
Email: RLG2@us.ibm.com

Prepared testimony for the hearing, "Protecting the Electric Grid from the Potential Threats of Solar Storms and Electromagnetic Pulse"

The spectacular images of Pluto this week from the NASA New Horizons probe provoked great public interest in our solar system. But our solar system is a matter for concern, as well. The 1200 people injured February 15, 2013 at Chelyabinsk, Russia, from a bolide (meteor) brought substantial focus on low-probability, high-consequence events. Among these are particularly intense magnetic storms from space-weather events or coronal mass ejections (CME), possibly even more intense than the 1859 Carrington Event in the pre-electric-grid era

Another potentially great impact on the electrical grid and modern societies is the high-altitude electromagnetic pulse (HEMP) from high-altitude nuclear explosions—HANE—on the order of 100 km or more above the Earth's surface.

The United States has been a leader in long-distance transmission of electrical power, but its system differs in characteristics, management, and organization from those of other advanced states. Nevertheless, there is much to be learned from and by the United States in working to make our electrical grid robust and economical in the modern era of technological threats and opportunities.

I begin with my recommendations to ease and essentially solve the severe problem posed by geomagnetic storms induced by space weather—specifically by the routine ejection from the sun of enormous blocks of plasma that travel out within the solar system and reach the Earth typically in a couple of days[2]. These cause displays of the "Northern Lights" (and Southern Lights as well). More importantly, the magnetized plasma and its incorporated magnetic field merge with the magnetic field of the Earth and change it by a relatively small amount, which, however, can create large currents on long electrical conductors such as pipelines, telegraph wires in the old days, and the electrical power transmission system—the Bulk Power System.

---

[1] Affiliation given for identification only.
[2] See *"Impacts of Severe Space Weather on the Electric Grid,"* JSR-11-320 of November 2011, sponsored by DHS, of which I was an author—available at https://fas.org/irp/agency/dod/jason/spaceweather.pdf A broad set of recommendations may be viewed on pp. 3-5 of that report.

Very serious consequences are estimated for such an event of a magnitude that can be expected to occur at random once per century, with greater events occurring with lower probability and lesser events more frequently[3].

I emphasize that a “once per century” event might occur next week; it has a probability of 10% of occurring within the next ten years—a time in which we can and should take measures to reduce and essentially eliminate its impact on the Bulk Power System of the United States. But events expected to occur once in 20 years can cause significant damage and disruption.

My recommendations regarding the Bulk Power System[4].

Missing in Federal policy and practice is a program to

1. *train and equip utility and transmission operators to bring down within seconds (switch off) transmission lines that are at risk of being damaged.*
2. *implement “rapid islanding” of the grid, to maintain a large fraction of the power consumers in operation by the use of whatever island generation capacity exists; this also facilitates restoring the Bulk Power System to operation, in contrast with a “black start.”*
3. *fit transmission lines on a priority basis with "neutral current blocking devices" (capacitors) in the common neutral-to-ground link of the 3-phase transformers of EHV transmission systems at one end of the line-- whether 3-phase transformers or 3 single-phase transformers. Where transformers at both ends are autotransformers this may not be possible, in which case series-blocking capacitors in the power lines themselves should be installed (even if shorted until an EMP event is recognized).*
4. *alert grid operators and others to a high-altitude nuclear explosion within milliseconds of the event (by detection of the unambiguous very brief E1—pronounced “Ee-one”--pulse).*

In my supplemental testimony submitted for the record, I provide support for these recommendations and explain why they would largely and immediately also eliminate long-lasting damage to the EHV transmisions system that might otherwise result from a high-altitude nuclear explosion.

** End of prepared oral testimony **

---

[3] It is important to understand what can and can not be done to mitigate damage from events that we wish would never happen, as was done in exemplary fashion in the FEMA-sponsored publication *"Key Planning Factors: Response to an Improvised Nuclear Device [explosion] in the National Capital Region"* November 2011, http://www.fas.org/irp/agency/dhs/fema/ncr.pdf

[4] I note that these recommendations are similar to those of the “E-PRO HANDBOOK” Executive Summary 2014 and the INTERNATIONAL E-PRO REPORT of September 2013, e.g.,

GIC current blockers
Series Capacitance
Reducing Transformer Loads
Real-time, Threshold-based Transformer Protection

** Beginning of supplemental Garwin testimony for the record **

Permanent and severe damage to the Bulk Power System occurs largely from the destruction of the extremely high voltage—EHV—transformers that are used to transmit the high-voltage alternating current three-phase power over distances of hundreds of miles. The electricity in our houses, offices, and factories is delivered from the wall plug at a voltage of 120 or 240 V, and large motors, trains, and other system generally consume electrical power at a voltage of some hundreds of volts. But because power is voltage multiplied by current—specifically watts equal volts-times-amperes, and megawatts equals kilovolts-times-kilo-amperes, the only way to transmit electrical power economically over a distance of 100 miles or more is to use a *transformer* to step up the voltage from the convenient generating level of a few thousand volts—kilovolts or kV—to EHV levels exceeding 500 kV.

The Earth's magnetic field changes irregularly over a period of minutes and hours and even days in the course of a geomagnetic storm, and by Faraday's law of magnetic induction produces small voltages in potential electrical circuits—voltages that are totally imperceptible to people and that in our automobiles, homes, or offices are of no concern. But according to Faraday (and this is the principle upon which all electrical motors and transformers are made) the voltage induced is proportional not only to the change of magnetic field per second of time, but to the area of the electrical circuit (and to the number of "turns" of wire around that circuit).

In the case of long-distance power lines that may be 50 meters (164 ft)—above ground, there is a substantial area of the circuit that might be expected to be the height of the power line above the ground, multiplied by the length of the transmission line in hundreds of kilometers. in fact, the area is far greater because, for these slow changes of magnetic field, the voltage around the closed circuit that is composed of the power lines on the transmission towers, and completed by the return of electrical current through the "ground," does not flow along the surface of the Earth. Rather it flows along the higher conductivity regions that are found at depths of 100-200 km or more in regions of the continents overlain by highly insulating crystal and rock such as granite. Much of the geology of eastern Canada and the northeast United States is of this nature, and so the "circuit" area for the changing magnetic field to do its dirty work may be 1000 km long by 100 km high--the size of a small state tipped on its side; the area is not 1000 km by 50m but 2,000 times as large!

The resulting voltage around the one-turn circuit is often expressed as the length of the line multiplied by the "electric field" expressed in volts per kilometer—V/km, and a geo-electric field as small as 5 V/km can cause serious damage because over a line of length 1000 km it would amount to 5,000 V. The particular vulnerability of transformers on the Bulk Power System arises when they are connected on the three-phase line so that the three fat aluminum power cables at the top of the poles enter three separate transformers that are "Y-connected," with their common point connected to a grounding mat or a field of metal stakes driven into the ground. Two such sets of Y-connected transformers at either end of the 1000-km line thus establish a circuit for the geomagnetic storm to induce current.

Despite the fact that EHV transmission occurs at voltages of 500 kV, and we have estimated 5 kV for the voltage due to the geomagnetic storm, the geomagnetic storm voltage is akin to "direct current" like that from a battery, whereas the power carried by the EHV system is alternating current, changing direction (twice) 60 times per second—at 60 hertz (Hz).

Over a period of many seconds or minutes, the dc current drives the transformers into "half-cycle saturation" allowing unprecedented amounts of power to flow from the generators or the source of electrical power, and overheating the copper windings and steel structure of the transformers.

It is essential to understand that geomagnetic storms cause no problems when the transmission systems are de-energized, as they would be following the downing of a transmission tower. Hence the first recommendation.

The second is to avoid collapse of the entire economy—blackout due to the loss of the most vulnerable line from the effect of geomagnetic storm, HANE, sabotage, or other problem. There is a big difference in the recovery time of the electrical power system between the blackout of an area covering many states and eastern Canada, and the loss of EHV transmission lines that only supplement more local generation capacity.

In fact, all but the most intense geomagnetic storm can be countered and Bulk Power Transmission continued if the Y-connected transformers are not connected from their common "neutral" terminal directly to the grounding mat, but instead through a "neutral current blocking device" that is designed to accept for a few minutes or hours steady voltages that could be expected from the 100-year geomagnetic storm. There have been several successful trials of such blocking devices in the United States, Canada, and elsewhere, and they are now offered for sale to the industry.

Their cost is on the order of $100,000 per tranformer[5], but they protect transformers that at a high-power terminal may cost $10 million[6] and can preserve the economy of a million Americans that would otherwise suffer from temporary disruption if the power line needed to be shut off, and severe economic loss and even loss of employment and life if the geomagnetic storm or HANE is allowed to destroy many transformers that would take months or years to replace.

Finally, essentially all transformer damage from a high-altitude nuclear explosion could be avoided by the installation of these blocking devices, or even where no such devices were installed, by manual or automatic shutdown of that EHV line for a minute or so following the detection of a HANE.

---

[5] http://www.powerworld.com/files/06Emprimus.pdf

[6] http://energy.gov/sites/prod/files/Large%20Power%20Transformer%20Study%20-%20June%202012_0.pdf A single-phase 500 MW large power transformer is quoted at $4.5 million.

Protection of U.S. society against a high-altitude nuclear explosion.

Such a high-altitude nuclear explosion—HANE—provides disturbances to long-distance power transmission systems by virtue of the high-altitude electromagnetic pulse—HEMP—through mechanisms that are complex and fascinating, but can be understood in broad outline and that have been the subject of much analysis over the decades since they were observed in fragmentary form in 1962.

A nuclear weapon exploded 100 km or so above the surface of the United States or above its shores would have "line of sight" out to 1000 km or so. This applies to a "normal" first-generation nuclear weapon as well as to a megaton-class nuclear explosive such as possessed by the United States, China, and Russia.

The geomagnetic-storm-like effect of a HANE arises from the liberation of large amounts of energy in a small (say one ton) mass of bomb and rocket materials in the weak magnetic field of the Earth. A magnetic bubble, 100-km or more in diameter, forms and is squeezed by the diverging magnetic field—the motion of these field lines in some sense mimics the disturbance formed by the incorporation of a portion of the magnetized plasma from the coronal mass ejection into the Earth's magnetosphere. The details of the resulting magnetic and electric disturbances on Earth are exquisitely complex because the bomb itself, before the expansion can take place, has liberated most of its energy in the form of vast amounts of soft x-rays that increase the ionization at the top of the atmosphere and serve largely to shield against the magnetic field variation from the "bubble" and "heave" of the bomb plasma in the magnetic field of the Earth. The resulting slow component of the electrical field from a HANE is dubbed E3. The time scale is typically ten seconds or more.

As might be suspected, there is an E1, which comes from the prompt gamma rays from the fission process. Within less than a nanosecond of an individual fission, a couple of percent of the energy release is emitted as the equivalent of extremely high voltage x-rays such as those used for radiography and radiotherapy. In a nuclear explosive—warhead or bomb—most of the gamma rays are absorbed, but those high-energy gamma rays that do emerge travel radially from the explosion above the atmosphere, although more might travel up or down or sideways depending upon the detailed internal design of the bomb. The bulk of the gamma rays may emerge over a few-nanosecond interval.

In 1962 the effect of the resulting E1 was observed in Hawaii, 1000 km from the explosion in space of a 1.4 megaton hydrogen bomb at an altitude of 400 km.

In contrast to earlier predictions of a modest electromagnetic pulse from a space nuclear explosion, on the order of 1 V/m at 1000 km[7], the detected EMP in this very fast-time (high frequency) range was of the order of 5,000 V/m, which was unexplained for many months after it

---

[7] R.L. Garwin, "*Determination of Alpha by Electro-magnetic Means*," Los Alamos Scientific Lab., Report LAMS-1871, (1954), S-RD.

had been observed, until Los Alamos physicist Conrad Longmire, in preparing for a talk at the Air Force weapons lab in Albuquerque, thought of the mechanism by which such efficient conversion of gamma ray energy to electromagnetic pulse could be achieved.

Although an observder anywhere on Earth within line of sight to the space explosion receives this radio pulse as if it came directly from the explosion itself, it really originates in the upper atmosphere on the line of sight from the bomb to the observer. As the gamma rays produce fast electrons from the molecules of air, the electrons travel initially along the line of sight outward from the bomb, but their paths are *curved* by the weak magnetic field of the Earth. These curved paths radiate, but it seems at first thought impossible that electrons materializing over a path length of 10 km (flight time of 30 microseconds) could add their signals in the nanosecond range, but that is exactly what happens--because the electrons travel at nearly the speed of light, and the gamma rays, which materialize all along this 10 km path, travel at the speed of light in vacuum so that the radio wave is strengthened until the gamma rays are extinguished by absorption in the air atoms.

The result can be the conversion of 10% of the gamma ray energy into electromagnetic pulse, and clever bomb designers can make this pulse even shorter than is natural for an ordinary fission bomb.

However, the EHV transmission system has no special vulnerability to this E1 fast pulse. It was thoroughly addressed and emphasized by the EMP Commission Report of 2008,

Impact of *E1* on critical infrastructure

No mechanism has been identified and there is no experimental or theoretical reason to judge that even the most intense *E1* field will cause direct harm to humans or animals. Furthermore, there is a much shielding of sensitive electronics to electric fields in this range. The EMP Commission arranged for experimental tests of exposure of various kinds of electronics to EMP simulators—specifically *E1*.

Of 37 gasoline-fueled automobiles, 3 stopped running when exposed to simulated *E1*, but all restarted without incident. No effects were observed on cars not running during the EMP exposure. Similar results were obtained for trucks.

With regard to the electrical grid, electromagnetic relays that sense current and voltage by means of the forces produced by their magnetic fields, were immune to E_1. About the more modern electronic relays, the full unclassified 2008 EMPC report, “Critical National Infrastructures” states (p. 40):

> “*Electronic protective relays.* These devices (see figure 2-5) are the essential elements preserving high-value transmission equipment from damage during geomagnetic storms and other modes of grid collapse. Fortunately, these test items were the most robust of any of the electronic devices tested. However, test agencies reported that they are subject

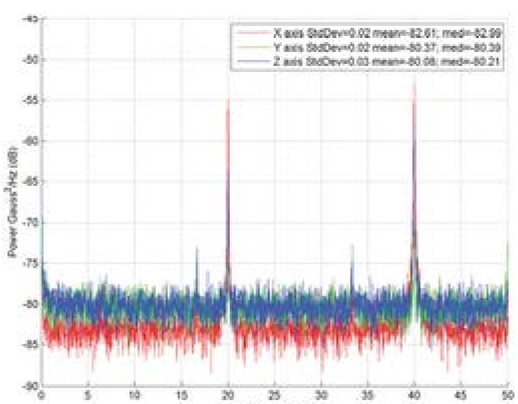
to upset at higher levels of simulated EMP exposure. We believe that altering the deployment configurations can further ameliorate the residual problems."

Thus, relatively simple field retrofits would preserve the electronic protective relays; however, the power grid is imperiled by unnecessarily weak links.

Consumer electronics in operation will suffer upset or damage at E1 fields of some 10kV/m. The EMPC report cites the RS-232 ports of PCs (personal computers) as particularly vulnerable, and PCs are used in the SCADA (systems control and data acquisition) facilities of the electrical grid and other industries, so a robust Bulk Power System will require protective filters on the control computers.

Other nations have taken more seriously improving the resilience of their Bulk Power Systems against geomagnetic storms (and hence E3 from a high-altitude nuclear explosion), as detailed in (4). In this effort there are major technological opportunities to reduce cost of protection and prediction.

One of the substantial lacks in planning and operation to reduce space weather impact on the grid is adequate and continuous magnetic field data, as well as corresponding measurements of GIC. GIC measurements must be obtained from the power transmission companies, and that is in process, but particularly in the United States is bureaucratically difficult. On the other hand, magnetometer data has become easier and cheaper to obtain, as the result of the universal deployment of SmartPhones containing a compass, which is a three-component magnetometer. So here is a reference to and a trace in frequency of the background magnetic noise from anisotropic magneto resistance (AMR) sensor in a typical SmartPhone.



Magnetometer B

These SmartPhones can be programmed to record the magnetic field in an intelligent way, and to transmit it over the Web, either as a typical data call, or via WiFi in case the magnetometer is located close to some facility.

So rather than think of deploying classical magnetometers, one should include the possibility of the SmartPhone magnetometer produced by the millions and correspondingly cheap and robust.

Furthermore, some of the approaches to eliminating geomagnetic-storm-induced current (GIC) are not well appreciated—for instance the use of series capacitors in the three-phase power lines themselves, where blocking the path from transformer "neutral" to ground is not feasible—as in the case of autotransformers. As described in (2), a trio of series blocking capacitors might have only 1% the cost of the series capacitors used for power-factor correction of long lines. The series blocking capacitors could be maintained shorted until potentially harmful GIC was detected, at which time the capacitors could be automatically and gracefully unshorted by silicon controlled rectifiers or other switches operating at the instant the voltage across the capacitor passes through zero.

Can the market provide a more resilient bulk power system?

FERC—the Federal Energy Regulatory Commission—and NERC—the North-American Electric Reliability Corporation—have a complex relationship themselves and with the organizations that generate, transmit, and distribute electric power in the United States and Canada. Thus far, the national interest in a more resilient bulk power system has not resulted in incentives or initiatives that would sufficiently advance that goal. The technical considerations discussed in this paper are important elements, but economic and organizational changes must be sought to result in the adoption of best world-wide practices in the North American Bulk Power System, and to advance beyond those best practices, where it is justified in the national interest.