The Robust Electrical Grid?

Discussion for the Rotary Club meeting
Moscato Restaurant,
Scarsdale, NY
January 19, 2016

Richard L. Garwin
1 Christie Place Unit 402W
Scarsdale, NY 10583
RLG2@us.ibm.com
URL: www.fas.org/RLG/

This is intended to be a low-key discussion of some facts regarding the widespread transmission of electrical power in the United States, and, in particular, in the Northeast.

We have been subject to half a dozen serious blackouts over the last half century, some of them caused by hurricanes or storms and leaving much of Scarsdale without power for days at a time.

In addition, three very serious blackouts of the Northeastern United States and Canada occurred in November 1965, March 1989, and August 2003. Two of them were caused by cascading failures of long-distance power transmission lines, and the other (1989) by a geomagnetic storm produced by "space weather"—more precisely a coronal mass ejection (CME).

Coronal mass ejections are in part correlated with sunspot activity and consist of billions of tons of solar matter ejected from the Sun's surface into space. This blob of plasma is sufficiently conductive electrically that a portion of the magnetic field of the Sun's corona remains embedded in the CME as it goes outward from the Sun—essentially radially. At the 93-million mile standoff of Earth from Sun, a CME may be a million miles in extent, but there is a high probability that any particular CMS will miss the Earth.

If it does engulf the Earth, the consequences differ depending upon whether the magnetic field embedded in the CME blob is more-or-less aligned with that of the Earth, or in the opposite direction. If the first, the magnetized blob essentially bounces off the Earth, but if the second, magnetic field lines "close"IS and the blob is essentially incorporated into the Earth's magnetosphere, with the trapped charged particles causing intense auroral displays. How long this persists depends in part on the size of the blob and on its speed. For a blob that takes two days to reach the Earth and is 1% of the Earth-Sun distance in extent, it would be absorbed in the Earth's magnetosphere in less than an hour. And then the fun begins.

Perhaps the most intense geomagnetic storm on record occurred in the first few days of September, 1859 (yes, 155 years ago!) with spectacular aurorae, illuminating the night sky to the extent that birds began to chirp, one could read a newspaper, and the like. Human beings and animals were not affected by the relatively small changes in the Earth's magnetic field, about 1% of the total that is evident by the orientation and vibrations of the compass needle, and, indeed, that is how the permanent record of that event was obtained—by a trace recorded on smoked paper at the Royal Observatory in England. The amateur astronomer Richard Carrington had briefly noticed two intense spots (fireballs) on the surface of the Sun, but the electrical effects on

Earth were limited to the disruption of telegraph service and, indeed, setting of fires in some telegraph offices because of the large currents induced in the telegraph lines that ran uninterrupted for many hundreds of kilometers.

Now, of course, the inhabitants of the Earth are dependent upon electrical power generated thousands of km from where it is used, and transported almost universally by the high-voltage lines on towers that dot the countryside. In particular, we in downstate New York import much of our power from hydroelectric sources in Quebec. Each home draws an average of about one kilowatt (kW) from the grid, via the fat transformer on the "telephone pole" nearby in Scarsdale's residential district, or similar transformer underground in the center of town. These transformers, in turn, are connected to lines that have a voltage of about 10,000 V (10 kV) with the local transformer converting that with extremely high efficiency to the power that enters our homes at 110/220 V.

In turn, the distribution of electrical power at 10 kV, which requires only modest-size insulators on the local power poles, is fed by large transformers in substations that step down the transmission voltage from the EHV (extremely high voltage) of 500 kV or so to the 10-kV level for distribution.

Long-distance transmission lines link various suppliers and consumers, and are operated by transmission companies and controlled by an ISO—independent system operator—in the United States in recent decades.

Although in our homes the "ground" plays an important role—the green wire in the wiring that comes to each of our outlet boxes, together with the white wire that is "neutral," and the black wire that is "hot", the ground is there for safety purposes and not to carry current under normal circumstances.

For reasons of economy, electrical power transmission is universally done with a "three-phase" system, in which the 60-times-per-second (or 60-Hz) oscillation of the electric voltage occurs out of phase on the three power transmission lines, ordinary household current is limited to a single phase. A transmission line serving a million homes thus carries on the average about a million kW or a thousand megawatts, and at 15 cents/kWh supplies power worth $150,000 per hour.

Bulk power is generated by the rotary motion of electrical coils through intense magnetic fields in the generator (more properly, "alternator") at a modest level of 20 kV or so and corresponding currents of 50,000 A. When transformed to 500 kV for economical long-distance transmission, the current is correspondingly reduced to about 2000 A.

Atop the transmission towers there is typically a relatively fine wire that is connected to the tower and to a grounding field, in order to intercept and to conduct lightning strikes to the Earth. Most of the EHV transmission in the United States is done with each of the three power-carrying wires connected to a separate "single-phase" transformer at the sending and receiving ends.

Recall, at the sending end the line is energized via a generator-step-up transformer from the three terminals on the generator, and at the receiving end, three substation transformers bring the EHV down to a voltage suitable for distribution on power poles or even underground cables to the local transformers that further step it down to the 110/220 V used in our households.

In a geomagnetic storm, the magnetic field of the Earth, typically about one gauss or one-ten-thousandth of a tesla—a more modern unit—may change by about 1%, but over a period of minutes. Contrast this with the typical almost two-tesla magnetic field used in the generator, and the change of that magnetic field with respect to the generator coil that happens 60 times each second (with significant change occurring in 1/400th of a second). One-millionth of the magnetic field intensity, changing 100,000 times more slowly doesn't sound as if it could be significant, but it is. That is because the geomagnetic storm has the disturbance in the Earth's field extend over thousands of km—a million times greater distance than that involved in the generator.

According to Michael Faraday, the voltage induced by the change or motion of a magnetic field relative to a conductor is proportional to the magnetic field and to the area of the "loop." If you figure the area of the loop as the length of the transmission line times the height of the transmission line, you get about 1/1000th the voltage observed on transmission lines because of the geomagnetic storm. This is because particularly in Northeastern Canada and United States, these slowly varying currents cannot return in the poorly conductive Earth just below the transmission towers, which overlies electrically non-conductive granite down to a depth of 100-200 km. Instead, the ground current has to make its way through that granite shield and return in the more highly conductive rock below it, so that the Faraday loop for geomagnetic storms is on the order of 1000 km long by 100 km high.

So the voltage induced by the geomagnetic storm on a long line may be on the order of 5 kV—still 100 times smaller than the EHV level of the 60-Hz power carried by the transmission lines.

Okay, so far we have:

1. Sun emits coronal mass ejection.
2. CME travels to Earth in an average of three days.
3. A portion of CME integrates with Earth magnetosphere, causing geomagnetic storm--GS.
4. GS induces voltages in long-distance power transmission lines.
5. Geomagnetic-storm induced current (GIC) provides relatively small, relatively steady current in EHV transformers connected to ground, producing "half-cycle saturation" of iron core of the transformer.
6. AC system power overheats copper winding of big transformer, may trip circuit breakers, etc.

Without cutting off transmission power, EHV transformers may be damaged or destroyed, costing tens of millions of dollars and requiring many months to replace. Terrible inconvenience if over in a day or few; disaster if power not restored within a month.

What to do? The GIC, even though it may be at a few percent of the level of the normal transmission current, because it is steady, is not compensated by current in other windings, and magnetizes the core so that it can no longer properly impede the flow of current uncompensated by current in the "other" winding of the transformer.

If this steady, almost "direct current," can be kept out of the transformer, essentially this problem to high-power transmission lines is eliminated. Technically, this is relatively easy to do for instances in which three separate transformers or one three-phase transformers connect to ground through a single wire, as is often the case. Here one needs to install a "neutral current blocking device" (NCBD) that with all safety and control elements costs about $100,000 and can be installed without interruption of service on the transmission line.

But even before that can be accomplished continent-wide, system operators can be instructed, or required to turn off their transmission lines when the transformers are heard to be humming loudly, or when monitors of GIC indicate hazard.

And for those cases in which a NCBD cannot be used (primarily "autotransformers" in the United States), one can install capacitors in each of the three power-carrying lines of the EHV system, to pass easily the AC power but to impede totally the GIC.

In fact, capacitors that are both much larger physically and more costly are often used in EHV lines in order to improve the "power factor" by compensating the line inductance, and they automatically provide protection against GIC, space weather, and geomagnetic storms. It turns out that the GIC-protecting series capacitors, although about 100 times the capacitance value, just because they have lower voltage across them due to the line current cost only about 1% as much as a PFC capacitor, and should be a primary tool in providing a robust electric grid—long before local generation or DC power transmission will be achieved.

I testified July 22, 2015, to the U.S. Senate Committee on Homeland Security and Governmental Affairs at a hearing titled "Protecting the Electric Grid from the Potential Threats of Solar Storms and Electromagnetic Pulse," just on this topic, making the same recommendations:

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).*

I leave for the discussion why more progress is not being made to protect against this truly significant hazard.

Then there is the problem of high-altitude nuclear explosions—HANE—that produce HEMP—high-altitude electromagnetic pulse. In addition to the so-called E1 component of the EMP that has absolutely nothing in common with geomagnetic storms and is not a special threat to the EHV system, there is an E3 component that for a powerful nuclear explosion above the atmosphere can lead to problems such as those of a geomagnetic storm due to a CME. Fortunately, damage to the EHV transformers takes many seconds to occur, and can readily be prevented by opening the circuit breakers and de-energizing the EHV lines. It makes sense to protect the nation to some extent against both E1 and E3, but it seems to me that enthusiasts for protection against HEMP produced by nuclear weapons exploded above the United States would do better to join in protection against geomagnetic storms, which automatically protects the EHV system against E3, and separately push the more difficult problem of protecting against the E1 component that threatens to destroy computers and other consumer electronics, such as furnaces and the like over a very large multi-state area.