

GEOMAGNETIC DISTURBANCE HARDENING AND OPERATION OF POWER SYSTEMS

Geomagnetic Disturbance Hardening of power systems involves a multi-faceted approach that includes modifying the equipment and design of the system, installing equipment, and augmenting the procedures for system operation and contingency preparation in order to mitigate the negative effects on power system operation that can be caused by solar storms.

Geomagnetic Disturbances

The normal activity of the sun causes a solar wind – high energy charged particles streaming outward from the sun in all directions. The sun is so active that there is almost constantly a noticeable level of solar wind at any time. One consequence of solar wind is the aurora borealis seen in the northern hemisphere and the aurora australis seen in the high southern latitudes.

From time to time, more intense solar storms or solar flares occur on the surface of the sun, again as part of its normal processes. These storms and flares often eject large amounts of very energetic particles into space, events which can be likened to ‘sparks’ being thrown off by the sun. They travel outward at speeds of up to 2 million miles per hour, taking roughly two days to reach the earth. Only a few will be aimed squarely at the earth. However, those that come close can have a significant, even dramatic effect on the earth’s magnetic field, leading to unusual electrical activity on the earth, and in the atmosphere. Such an event is called a geomagnetic disturbance (GMD).

GMDs generally last for two or four days, although their period of greatest intensity is generally much shorter. An intense GMD will cause much more spectacular and colorful auroras. In addition it can also have adverse effects on manmade equipment and systems including air traffic control systems, pipelines, and electric power systems through Geomagnetic Induced Current (GIC). Although geomagnetic storms are part of the constant activity of the sun they vary in frequency with the sun’s roughly 10.5 year average sunspot cycle. During periods of peak sunspot activity the number of events and the chance that a particularly severe one will occur increases significantly although the risk is not eliminated in the non-peak periods.

Intensity, Phases and Storm Categories

The intensity of a GMD is indicated by Dst, a measure of the horizontal component of the earth’s magnetic field that is determined as an estimated average over the whole planet. Normally Dst is in the range ± 20 nt (nano Teslas). During a storm it can deviate far above this norm.

A geomagnetic storm typically goes through three distinct phases: initial, main, and recovery. In the initial phase, which may not occur in some events, Dst at first shoots upward to perhaps +50 nT or more at an accelerated rate – perhaps in less than half an hour. In the main phase, Dst drops to less than -50 nT and may continue to plunge far below that for a period of hours, during which it will reach the most intense period of the storm. During the recovery period Dst does just that, returning to normal values, usually over a period that may be less than half a day or as long as a week. Geomagnetic storms were historically categorized astronomically as shown in the table below.

<u>Type of GMD</u>	<u>Range of nT</u>	
Normal (no storm)	+ 20	-20
Moderate storm	-50	-100
Intense storm	-100	-250
Super storm	-250	and above

More recently, the Space Weather Prediction Center uses the K index to track and record the intensity of geomagnetic activity. K categories 0-3 are considered normal activity. K is measured on a three-hour rolling basis. A K score over 4 is considered a solar storm. NOAA (National Atmospheric and Oceanographic Administration) classifies solar storms into five categories by severity. NERC uses the K scale for rating GMDs that affect power systems and their operation.

<u>K Rating</u>	<u>Range of nT </u>	<u>NOAA Storm Class</u>
0	0-5	} G0
1	5-10	
2	10-20	
3	20-40	
4	40-70	} G1
5	70-120	
6	120-200	
7	200-300	
8	330-500	
9	>500	G5

The most intense geomagnetic storm ever recorded was a G5+ event that occurred over a four-day period centered around September 1, 1859. Named the Carrington event, after the British scientist who observed and cataloged its effects, modern estimates put the most extreme Dst levels reached at around -1750 nT. Aurora were visible as far south as Cuba and Italy. Magnetic interference with telegraph lines created electrical shocks to operators, ignited fires, and damaged some equipment.

In more modern times GMDs have caused noticeable disturbances to power systems around the world. A G5 geomagnetic storm, estimated to have reached an extreme Dst of -575 to -600 nT, occurred around March 13, 1989, the result of a “solar mass ejection” (solar flare) on March 9-10. This GMD’s initial phase on earth began on March 12, and by midnight it was causing vivid aurora that were visible as far south as Dallas, TX. A few hours after midnight, the magnetic field in the northern hemisphere fluctuated wildly, leading to anomalous readings and flows in the Hydro Quebec’s 735 kV transmission system. Protective equipment opened circuit breakers to protect the regional power grid, disconnecting Quebec load centers from 9,400 MW of generation and leading to a regional blackout that left six million people without power for nine hours. Other utilities in Canada and in the US as far south as Nebraska and Virginia experienced noticeable, and at times significant effects, including lasting damage to a large generator step up transformer on the PJM system. A total of over 210 anomalous events were cataloged in North America during this solar storm,

Understanding the Effects of GMDs on the Earth

An intense GMD causes a twenty- to one-hundred-fold increase in the strength of the magnetic field near the earth. This increase fluctuates. While storms vary greatly in characteristics, typically peak Dst levels are reached over a period of several minutes or half an hour. Intensity may vary up and down for some time thereafter. This is a significant increase, but it must be kept in perspective. The most powerful permanent magnets made have a field strength of about five (5) billion nT. The most intense GMD ever recorded was about 1,750 nT. GMD magnetic fields are orders of magnitude weaker than those produced in normal electrical machinery. Strong as they are at their most intense, GMD magnetic fields are far too weak to directly create any significant flows or changes in voltage on power system equipment. At times such effects can be measured, but they are minor.

The adverse electrical effects caused by GMDs are due to the effect their magnetic field fluctuations have on the earth. The field strength of a GMD may be several orders of magnitude weaker than man-made magnetic fields, but the field is massive - perhaps larger than the entire planet. It is acting on tens of millions of square miles of dirt and rock. And while dirt and rock are not particularly efficient conductors of electricity nor normally highly magnetism, in sufficient quantity they can get the job done. In this case the fluctuating GMD field, the earth’s magnetically active core, and the earth’s mass of dirt and stone form a type of electrical generator, creating noticeable differences in ground potential over distances of many miles, and creating very significant ground currents that travel within the earth’s surface.

GMD Impacts on Power Systems

These GMD-induced ground currents create significant disturbance on power systems. As noted above, dirt and rock are not highly efficient conductors of electricity. Therefore, where they can,

GMD-induced ground current will travel through grounding onto high voltage electric power lines in the area and use them for transport. Particularly in regions where the underlying rock is igneous, the current flow onto regional power lines can be significant (igneous rock is far less conductive than many other types of rock, or dirt). Generally, GMD electric power system effects are more extreme nearer the earth's poles, due to the shape of the earth's magnetic field and the orientation of the earth's surface to that field (at the equator the earth's surface is more in line with the field and thus the fluctuations produce very little lateral flow across the earth's surface, whereas at the pole the field is at a 90° angle). Power lines are not alone in being effected: metal pipelines also can see very heavy induced currents under the right conditions and those cause damage by accelerating corrosion and burn out in extreme cases.

GMD fluctuations in electric fields occur over periods of several minutes. As a result, the frequency of GMD induced voltages and current flow is on the order of .001 Hz – what is often called *quasi-DC*. From the standpoint of the power system it is effectively DC current and voltage. As a result:

- *Neutral currents may be quite high* and neutral voltage difference across the region very noticeable
- *Significant harmonic flows will occur* as a result. Often the 2nd and 4th harmonics are higher than the 3rd, but regardless a significant harmonic content flows on the EHV system.
- *Stray flux created in transformers can lead to significant core heating* and damage or destruction of the unit. In some cases core saturation will also lead to generation of more harmonics, only further exacerbating the situation.
- *Increased VAR losses result* from this and this can lead to a need for more system VAR support.
- *VAR support may trip off line*. Since capacitors and VAR compensators provide low impedance paths for harmonic flow, they can experience current flow sufficient to activate protective equipment. The loss further compounds the potential for loss of system voltage support at a time when more than normal is needed.
- *Protection and control systems may take actions that jeopardize system integrity*. Potentially, GMD induced currents could be so high as to directly lead to the tripping of breakers and activation of other protective measures for what are basically legitimate reasons. Negative sequence generator protection may trip generators off line to protect them from damage due to harmonics.
- *Damage to transformers, due to heating from saturation by induced quasi-DC flows* is perhaps the most common adverse consequence of GMDs.

- *Underground cable can potentially be affected. Ground currents can induce very high currents in that sheath.*

Taken in combination, the above effects can “bring down” a major regional power grid in a matter of minutes, and cause damage enough to equipment as to make quick restoration impossible.

In addition, local geology shapes the severity of the impact on the power system. In particular, igneous rock has a much higher resistance to electric flow than other types of stone and dirt. As a result, in areas where subsurface earth is largely igneous, much more of the GMD-induced ground current will flow onto the power system.

Geomagnetic storms vary from one to the other – as mentioned earlier some completely lack the initial phase. A few have steady and relatively slow increases in Dst while others have much more rapid and extreme fluctuations. In addition, the impact on any one transmission line depends on the exact orientation of the GMD’s path through space and alongside the earth, as well as the route and location of the power line. It is worth noting that not all gradient electric fields from solar storms are oriented north – south. Ground currents and interaction with the power system depend on the local geology and how that interacts with the earth’s magnetic field. Finally, more than one line – often every power line – in a grid can be affected at one time. Put all these issues together and the impact of a GMD is difficult if not impossible to predict accurately and in detail.

Intense GMDs can severe power system operating problems and even damage or destroy major equipment. The Hydro Quebec blackout occurred during a GMD that was well into the “super storm” category, but GMDs nearly three times as powerful (the Carrington event) are known to have occurred and would have devastating consequences if their effects were not mitigated and controlled. This is because there are more and in many cases longer and higher voltage lines today than in 1989, modern power grids are potentially even more vulnerable today than they were then. A geomagnetic storm like the Carrington event, could conceivably cause multiple regional blackouts around the world and put significant amounts of capacity out of service for some time.

Qualitatively, all of the effects outlined above can occur during a GMD on any particularly power system, under the right conditions. However, the severity and even the type of impacts expected on a power system will vary substantially depending on the type of equipment and its design (transformer core type, wye or delta configurations), system characteristics (grounding, amount and type of VAR compensation and VAR support need, types of transmission lines and regional EHV overlay, and protection and control schemes), as well as on the local geology and topology of the system.

Eliminating and Mitigating Power System Impacts of GMDs : Treat It Like Any Other Storm

Solar storms are planetary in scale, and they interact with power systems through the action of basic natural physical effects that cannot be stopped. For this reason, a “defense in depth” strategy is best, using a number of approaches from tactical to strategic in a layered, coordinated way.

Significant reinforcement of power system equipment to withstand the higher currents of major GMDs is often not effective, and may make certain effects worse (larger capacity → lower impedance → even high GMD-current flow). Similarly, shielding is not particularly effective. The only way to completely protect equipment and systems from the effects of geomagnetic storms is to fully encase them in Faraday cages or the equivalent. This is feasible only for critical substation and control equipment. Such protection is practically impossible for overhead power lines and major substation equipment. Underground cable in metal pipe ducts is effectively shielded.

Best practice approach for geomagnetic disturbance hardening is a defense in depth approach similar to the best practice approaches electric utilities take to prepare for other major storms, such as hurricanes: study the characteristics of the events (GMDs) that are likely occur in the utility service area, anticipate the types, nature, and location of problems and identify system vulnerabilities, “harden” equipment and protection where feasible and cost justifiable, develop a “storm operation” plan with special guidelines and processes to be executed when a storm is likely including system separation, then execute that plan in anticipation of the storm when you see it coming. The basic steps are:

Step 1: Study and Anticipation Study the nature, expected characteristics and most probable impacts of possible GMDs and the types of effects that could be seen on the particular power system. Although GMD’s generally affect much of the earth at one time, the particular location and characteristics of the utility service area and its specific system will lead to a few unique needs and a situation that could be considerably different from that seen by other utilities. A good study thus begins with an assessment of any particular weaknesses of unique characteristics of the power system itself, of the local geology, and its location that may be of importance. Such a study will also allow for the identification of appropriate locations for monitoring Geomagnetic Induced Currents to alarm operators and take appropriate actions.

Step 2: Make an assessment of system changes including hardening, for equipment, grounding, blocking, filtering, monitoring, or of equipment type or circuit/buswork configuration and switching including system separation, that can cost-effectively reduce vulnerability or improve the system’s ability to protect itself or recover once affected.

Neutral blocking capacitors can be effective at protecting key power and GSU transformers from saturation, protecting them from damage as well as greatly reducing GMD-induced saturation increases in system VAR support needs during the event. Series compensation on long transmission lines can reduce or nearly eliminate GMD-induced ground currents on them. Coordination of the application of these devices is critical, or we create a “whack-a-mole” effect where the current simply redirects to the neighboring system equipment. In addition, monitoring of transformer neutral currents may be recommended for some transformers.

Step 3: Similarly make an assessment of the role that “strategic operating” procedures may play in the utility’s solar storm operations and in the reduction of the systems vulnerability to GMD effects. Part of this should include assessment of the potential of “logical islanding” operation or removal of certain equipment highly susceptible to GMD effects during severe solar disturbances. This basically segments the system to avoid putting long electric transmission in parallel with GIC paths or removes susceptible equipment, thus reducing the expected impact. Such operation is not always feasible and creates a number of issues that have to be examined (contingency operation in that mode, etc.).

Step 4. Review protection and develop list of steps and options that could be used for a “solar storm protection coordination plan” that includes revised protection schemes and settings to be used only during solar storms or during periods when they are thought to be likely. This should be done for all equipment. Review particularly the harmonic sensitivity of the system specific to solar storms: normal harmonic analysis, which focuses on “third-harmonic heavy” situations keyed to large amounts of rectifier loads, may miss important characteristics of GMD effects.

Revised protection schemes for key equipment may include adding monitoring and relaying based on VAR totals or VAR mis-matches at key points in the system and potentially revise harmonic and negative sequence protection settings for generators. The utility should determine if possible the nature of any asymmetrical waveforms that might be seen on major lines that could lead to breaker actions that are undesirable during a GM. Make changes to protection to avoid those. The storm protection plan should include all such revisions along with criteria for when and how they are implemented (and when a return to normal settings is to be done).

In particular, as part of a solar storm hardening plan, the utility should consider increasing harmonic over-current tripping levels for capacitors and static VAR compensation during storms. Higher flows permitted during GMDs may contribute to accelerated loss of life, but the intense period of a GMD is measured in minutes, not hours).

Step 5. Review FACTS and power electronics operating guidelines. Review particularly the expected performance and behavior of any FACTS equipment associated with DC flows and or VAR control and voltage support. Review and determine if operating limits for DC or other FACTS equipment need to be revised for operation during solar storms or periods when GMDs are highly likely. Coordinate these changes with those for system and equipment protection.

Step 6: Develop a coordinated system plan for both changes to the system and operations.

Develop a coordinated system plan for change to the system, both permanent and only for the duration of storms, along with revised operating guidelines and a “solar storm” operating mode to be used during severe storms.

Step 6a: System aspects of solar storm plan. Combine the results of Steps 2 – 5 above into a final for changes and additions needed to equipment, system configuration, protection schemes and coordination and programming, and FACTS, along with revised control equipment needed.

Step 6b: Operating aspects of solar storm plan. Produce a coordinated operating plan that fully utilizes the capabilities provided by the changes and additions made in 6a and addresses all of the considerations that should be included in a GMD solar storm operating plan.

- a) Track solar activity and forecasts of “space weather” as predicted by the Space Weather Prediction Center. The Center tracks solar activity and uses the Advanced Composition Explorer (ACE) satellite, which is permanently positioned between the sun and the earth, to provide early warning of Geo-magnetic storms approaching the earth providing up to 45 minutes warning.
- b) Monitor and alarm for increasing Geomagnetic Induced Currents in locations identified as susceptible. With sufficient knowledge about where the current is likely to be detected, monitoring and alarming for system operators can be put in place to allow for preventive measures to be taken before the solar storm reaches levels that could be potentially detrimental to the equipment or system
- c) Go into “storm operating mode” at an appropriate time and in an appropriate way in advance of the storm.
 - o Prepare contingency operation and restoration plans. Put restoration resources on notice.

- Move to storm operation mode which might include logical islanding and other measures that put the system in a mode in which it is less likely to conduct GIC across major lines.
- As is the case for all types of storms, suspend routine and scheduled maintenance work and restore all equipment that can be put back in service
- Temporarily shift to “solar storm” protective settings and permissible operating limits of equipment (see 3 and 4 above).
- Reduce loading on DC lines in anticipation of increased flows due to GMS induced currents.
- Bring units that can act as synchronous condensers on line to provide additional reactive power. Reduce loading on generators that are at or near full capacity to provide additional reserve power and reactive capacity. In expected severe GMD situations, consider bringing additional generators on line.
- Move into a dispatch and operating mode that has been determined to be especially tolerant of tie loading and operating reserve margins, and that anticipates any contingencies thought likely in the GMD.
- After, the storm, return to normal status in a planned, controlled manner that avoids immediately putting high levels of stress on transformers susceptible to GMD induced saturation currents, or depends on such equipment too much
- Immediately after the storm, perform comprehensive DGA and acoustic diagnosis other diagnostic evaluations of major transformers. Periodically re-perform such tests, looking for increases in gassing that could be a sign of GMS damage to the core.
- Evaluate all aspects of the storm plan and revisions and make adjustments and continuous improvement as needed.

Step 7: Use and React to Space Weather Forecasts. The National Oceanographic and Atmospheric Administration (NOAA) provides forecasts of solar storms. It is very similar to forecasts of hurricanes. There is no serious likelihood that at least a day or two of warning will not be given, along with a qualitative estimate of storm strength and characteristics. A utility must not only make a solar storm plan (Item 5 above), but as part of normal operations, when a serious storm is forecast, it must always activate its plan.

Hardening Against Electromagnetic Pulse Weapon Effects

A high-altitude electromagnetic pulse (HEMP) weapon is a nuclear warhead detonated hundreds of miles above the earth’s surface. Although the detonation causes no blast effects at ground

level it can lead to even greater disabling devastation to a nation below. Through several simultaneous interactions with the earth and its atmosphere and magnetic fields, the HEMP will cause intense voltage spikes and electric interference with power system equipment, machinery and electronics over an area 1000 miles wide below it. Voltage potentials as high as 25,000 volts/meter will cause flashovers and instant failures of solid state and some analog equipment and systems in that region.

Many national security evaluations consider the use of HEMP weapons highly likely at the start of any war, particularly if “rogue nations” are involved. The reason is that a limited technology nuclear weapon system stands a good chance of creating significant damage when used as a HEMP. Even a small warhead detonated at the right altitude can create disabling damage, and the guidance system need only be crude enough to put long-range rocket somewhere high above the continent to assure disabling damage to a major nation’s infrastructure below.

Some of the measures that are effective for GMD protection also are useful as mitigation methods against the effects of high-altitude electromagnetic pulse (HEMP) weapons, particularly those aimed at driving high-frequency harmonics to ground. However, GMD-hardening power systems will not make the system immune to major damage from a HEMP attack. The major disabling impact on a power system would be to destroy all solid state and much electromechanical control and protection equipment, making it inoperable. Thus, substation control and operations center equipment and systems need to be put in Faraday cages to protect them from the pulse energy, and other “electromagnetic sealing” measures taken in all cases. A power system so protected is still somewhat vulnerable to being knocked out of operation by a HEMP attack, but enough equipment and control will likely survive for operation on at least a limited basis to be restored in a matter of hours, at least if the weapon was a first generation technology nuclear weapon such as a rogue nation would possess. It is far less likely that such measures can protect against a weapon designed by a major military power specifically to have an optimal HEMP profile: a purpose-built HEMP of advanced design would create an especially high-frequency pulse create much greater shielding and protection challenges.

Geomagnetic Disturbance Hardening Studies

Geomagnetic Disturbance Power System Operation

Quanta Technology provides a range of services from quick initial studies of a utility or industrial system’s GMD vulnerability to comprehensive projects in which our experts partner with the utility’s experts and a management to develop detailed plans for system change and new and very explicit operating guidelines. We can also provide assistance with project management in execution of the plan once developed, including coordination of the manifold changes and complexities that have to be put in place and verification that they are both made as intended and their actions coordination appropriately. In addition, “audits” of GMD operating plans provide a

systematic and complete review of the revised GMD operating plan to verify its quality and order and coordination of actions and expectations.

Training and Professional Development

Quanta Technology offers several short on-site courses and workshops that focus on Geomagnetic Disturbances and Power Systems. These range from a half-day summary course that provides a quick overview to a comprehensive seminar workshop provides more technical details and depth, followed by a workshop that works through all of the various system changes and operating approaches that can be deployed to eliminate and mitigate adverse GMD effects on a power system.

For more information, contact Dave Hilt, Mark Kruger, or Lee Willis at Quanta Technology.