Learning to Live in a Dangerous Solar System

Advanced Geomagnetic Storm Forecasting Technologies allow the Electric Power Industry to Manage Storm Impacts

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As the new millenium dawns, many new sophisticated and highly integrated technology systems hold great promise for providing unparalleled advances in services and societal needs. In particular, new advances in communications, transportation, and energy production are key infrastructures that provide much of the underpinnings for the anticipated evolutions. As the new millenium arrives, it is also accompanied by the peak of Solar Cycle 23, (the 11 year sunspot cycle) which brings with it *Space Weather* and evolving threats to many of the same previously referenced technology infrastructures. The recurring theme and irony of Space Weather, unlike other natural phenomena, is that the heaviest impacts will occur to the most technologically advanced industries and societies of the world.

Power Systems and the Foot Prints of a Super Storm

The evolution of the electric power industry and its evolving vulnerability to Space Weather provides a case-in-point. The use of electricity has grown from its early inception at the turn of the century as a nonessential convenience, to a major resource necessary to meet the most essential needs of society. The requirements for security and reliability of the electric supply are exceedingly stringent. As a result, the present day electric power networks are arguably the most complex systems ever conceived by man.

Space Weather threats to power system integrity became a reality with the Great Geomagnetic Storm of March 13, 1989. In fact, the entire Hydro Quebec power system (a system serving more than 6 million customers) was plunged into a blackout triggered by geomagnetically induced currents (GICs) which caused voltage collapse and equipment malfunction. The impact of this particular storm was simultaneously felt over the entire North American continent with most of Hydro Quebec's neighboring systems in the US coming uncomfortably close to experiencing the same sort of voltage collapse/cascading outage scenario. Power industry designers witnessed the unintended consequences of a threat that had never been considered on a simultaneous and system wide scale. Further, designers had neglected to fully take into account the coincident interaction dynamics of such a large scale while considering the new generation of voltage regulation devices combined with the tight-knit continental networks.

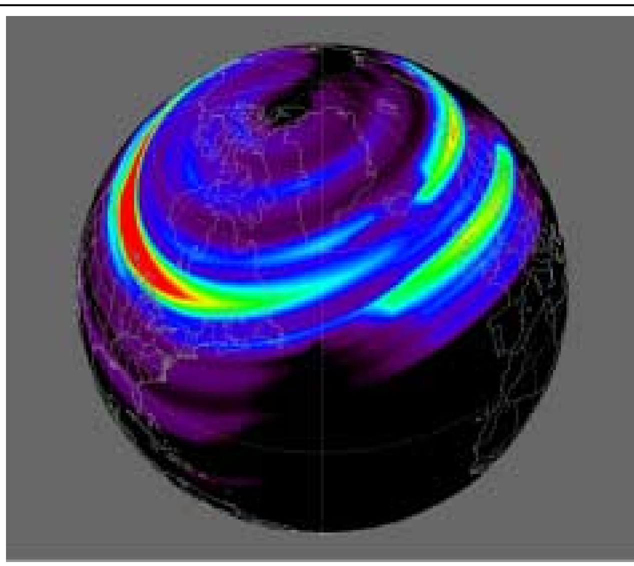

Figure 1: The Footprints of a Superstorm. The level of geomagnetic field disturbance at 7:45UT on March 13, 1989 is shown above. It is at this moment when a sudden impulse was observed over the US-Canada border that precipitated the collapse of the Hydro Quebec power grid. The planetary scale of a large geomagnetic disturbance is also quite evident, as large and intense magnetic field disturbances are simultaneously observed over extensive portions of northern Europe. It is the level of local geomagnetic field disturbance (or rate of change) that causes geomagnetically induced currents that can disrupt power system operations.

The known scale of the geographic footprint and the intensity of such Space Weather disturbances are enormous and anecdotal evidence from the past suggests even larger scales may be possible. It has

Figure 2: Large rate of change magnetic field disturbances (dB/dt in nT/min) observed during the March 13, 1989 storm were extensive and illustrative of a large storm. The largest dB/dt observed occurred at a Danish magnetic observatory BFE with a 2000 nT/min rate of change of local magnetic field. This Iso-Telluric chart describes equivalent locations worldwide had the same 2000 nT/min impulsive disturbance occurred at other local times (as shown in red). The locations depicted would follow the geomagnetic latitudes rather than geographic latitudes, hence the large low-latitude excursion over North America. For perspective the level of dB/dt that precipitated the Hydro Quebec collapse was only 400 nT/min. Levels this high were observed at very low latitudes, which would encompass most of North America and Europe (as shown in green). Levels of 200 nT/min can easily produce significant power system impacts which for this storm extended to even lower latitudes (as shown in blue).

always been understood that high latitude regions are the most frequently exposed to geomagnetic storms. Surprisingly the scale appears to be much broader; investigators that have sought to measure disturbances on their systems, such as Geomagnetically-Induced-Currents (GICs), have observed them, wherever in the world they have looked. These observations have ranged from extreme levels such as 200 Amps of GIC in the neutral of a transformer in Sweden to significant currents as far south as Texas, Australia and even the southern island of Japan. The sudden and rapid onset of storm activity is also problematic, as the Hydro Quebec system collapse evolved with a total elapsed time of less than 90 seconds. Therefore, impacted electric systems that need a "Lead-Time" of storm onset conditions cannot achieve it with the use of ground-based monitoring, as the impulsive events of a large storm are too rapid and intense to guarantee survival once disturbances have been locally observed.

Those impacted systems that have undertaken a comprehensive review of the Space Weather threat have, not surprisingly, determined that the impacts from a severe storm may be a defining disturbance benchmark in establishing the important system design and operational constraints in the network. The evolving susceptibility of the industry has occurred because large interconnected power networks have developed and become equivalent to a large efficient antenna that is electromagnetically coupled to the disturbance signals produced by fluctuations of the Earth's normally quiescent magnetic field. In this solar cycle, those trends still hold but are compounded with the uncertainties and increasing complexities of the ongoing operational management of the network reliability related to unfolding worldwide deregulation in the electric power industry.

This solar cycle also ushers in new monitoring capabilities, which combined with better understandings of storm processes will allow in this solar cycle, unlike others preceding, the ability to make highly accurate and detailed forecasts of severe storm conditions. These forecasts will provide meaningful "lead-time" for those systems potentially impacted by a disturbance to operationally prepare to better their odds of coping with the stress of the storm.

Satellite Monitoring & Forecast Models Advance Forecast Capabilities

Geomagnetic storm forecasting is difficult because the storm processes can be extremely dynamic. Observations have confirmed that planetary-wide eruptions of intense storm conditions can occur within the span of a few minutes, unlike the thermodynamic processes that largely govern the behavior and rules of terrestrial weather forecasting. The plasma and electromagnetic coupling processes that are inherently instantaneous drive Space Weather and associated impacts to ground-based systems. To further add to the degree of difficulty, the rapid manifestation processes of Space Weather also demands a requirement to rapidly and continuously update the complex forecast models. For forecast systems developed by the authors for the electric power industry, the forecast is in fact updated on a continuous one-minute cadence.

Also, unlike the terrestrial weather conditions that are monitored routinely at thousands of locations worldwide, the conditions in space are much more difficult to monitor. As a result only a handful of space-based and ground-based monitoring stations are available. In early 1998, a NASA satellite called ACE "Advanced Composition Explorer" began continuous real-time monitoring and transmission of the Solar Wind conditions at a point in space upwind from the Earth's magnetic field. Monitoring from this point in space (an orbital position called L1, about 1.6 million km toward the Sun from Earth) provides data fundamental to enabling the formulation of highly accurate forecast techniques and the subsequent issuance of alerts and warnings of impending major geomagnetic disturbances. Because it takes a disturbance in the solar wind about an hour to travel from where ACE is to Earth, telemetry from ACE will allow alerts of imminent, severe geomagnetic storms to be issued nominally an hour in advance of their onset.

The extreme under-sampling of the diverse, coupled regions of space demands that numerical models be utilized to provide continuous quantitative assessment and prediction of the geospace environment. Solar wind velocity and density and the direction and magnitude of the interplanetary magnetic field provide the basic inputs to magnetospheric and ionospheric models and as such provide an equivalent "Lead-Time" for the processes modeled. These measurements and models are increasing our capability to predict not only on a global scale, but also more importantly for concerned transmission grid operators an ability to provide a projection of region and time-specific meso-scale processes of concern. Further, these can be provided with the expectation that major events can be forecast with a low false alarm rate. The key for the fusion of these systems into a *forecast capability* has been the recent availability of real-time solar wind data.

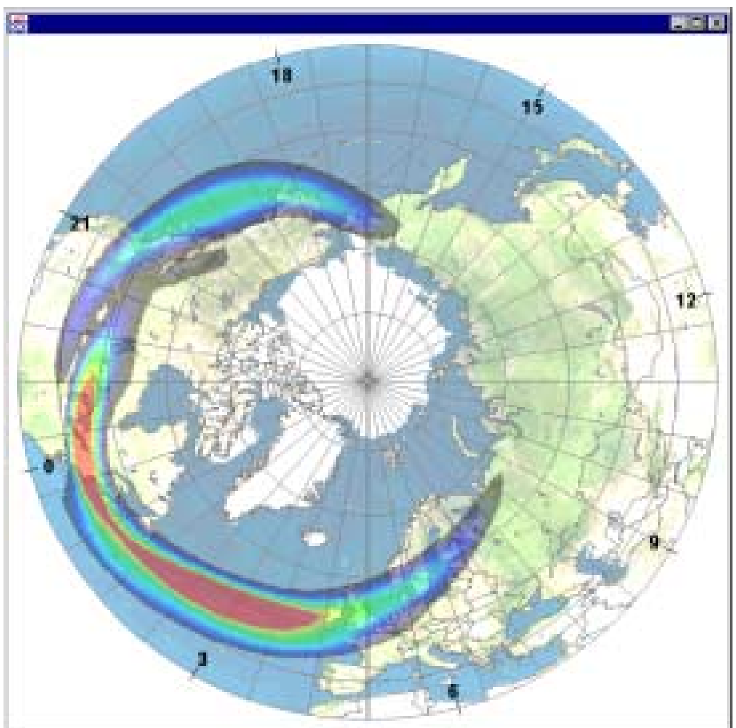

Figure 3: The above shows the Northern Hemisphere display of the Electrojet Current pattern that is produced by the SpaceCast magnetospheric and ionospheric model. As shown above at this time-step, a large Westward Electrojet current extends from approximately local midnight to local dawn spanning from mid Canada to Western Europe. The storm also creates an Eastward Electrojet current that typically spans from local midnight to local dusk. This SpaceCast model uses real-time solar wind data from the NASA ACE satellite to forecast the expected electrojet current conditions at an altitude of approximately 100km worldwide. The model provides important details on the electrojet current density, the equatorward boundaries of the electrojet and temporal variations that are used in the PowerCast model to estimate ground-level magnetic field disturbances and GIC flows. The Electrojet Current estimate is made nominally 45 minutes in advance, which allows important lead-time for impacted systems. Because large-scale changes can occur rapidly, this model recalculates the electrojet current continuously at a one-minute cadence.

Defining New Standards for Storm Forecast Capabilities

As previously noted, the coupling of the solar wind with the Earth's magnetosphere sets in motion a complex set of interactions that can produce rapid planetary manifestations of a geomagnetic storm. The electrojet current (a hall-effect current that can intensify to more than a million amperes) is created during the storm process at an altitude of 100 km in the ionosphere. It is simultaneously centered over both magnetic poles and is the principal source of ground-level disturbances in the geomagnetic field. The electrojet is a large-scale structure that can rapidly intensify and expand equatorward during a storm. Forecasting the temporal and spatial variations in location and intensity of the electrojet is key to predicting the impulsive ground-level disturbances of importance to power system operators. For accurate impact assessment to operational power system forecast users, the forecast needs to provide a lead-time of onset of the most severe portion of the storm event, and an intensity prediction of the magnetic field deviation and resulting electric field which produces GIC. Further to provide client-specific impact assessment, the forecast specification of the positional and intensity variation of the electrojet current structure can then be linked with a model computing the electromagnetic coupling from the ionosphere to ground-based networks to determine the geomagnetically-induced currents (GICs) entering the distributed grounding points of those power systems. Modeling techniques for estimating the impact of geomagnetic disturbances on the flow of GICs in large complex interconnected networks have been developed over the past 22 years and now achieve accuracies that can be readily benchmarked.

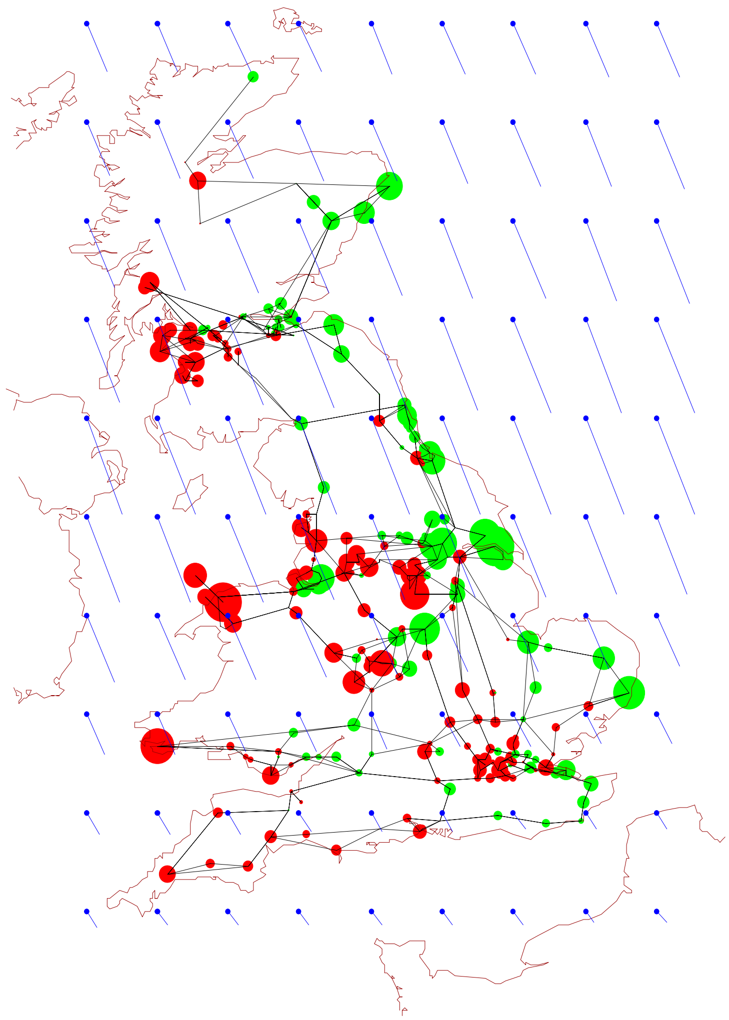

Figure 4: The storm visualization shown above is designed to provide a clear and concise picture of the location and intensity of storm impacts across the transmission network as provided by PowerCast. In this example the storm conditions are displayed over England and Scotland. The 400kV and 275kV transmission system is displayed with small circles indicating the magnitude (circle size varies) and polarity (circle color changes) of the GIC at each transformer. Also shown are the vector icons of the magnitude and direction of the local magnetic field during the storm, which is responsible for the GIC flows. Text and graphic summaries can also be provided on System or Region reactive power demands, numbers of transformers in saturation and other important system impact details. This PowerCast calculation is made in a Forecast and Nowcast mode and both are recalculated on a one-minute cadence. The Forecast mode utilizes data from the Electrojet model output of SpaceCast and effectively provides a nominal 45-minute warning of storm impacts. The Nowcast mode utilizes locally sensed magnetic field data and provides a system-wide assessment of current conditions.

Space Weather, unlike terrestrial weather, is not easily sensed by the available human senses. Therefore, one of the most important challenges is to present forecast disturbances in a clear and descriptive manner to impacted users of the data. The presentation of the information must not only be accurate, but also to-the-point. The operators of these impacted systems have no desire to fully comprehend all of the space-physics, therefore tailoring the data in a manner in which the operator is provided a clear picture of expected impacts is important. Figures 3 & 4 are examples of presenting the conditions of exposure of a bulk power system in a way that is readily intuitive without inundating the operator with superfluous details. These data visualizations mimic the familiar terrestrial weather projections that most power system operators currently use and are quite familiar with in the management of operation of their networks. The primary difference amounts to supplanting the ordinary weather imagery with the pertinent Space Weather equivalent of a weather-radar tracking system. In fact, no large power system operator in the world would dream of not having continuous, high-quality weather data available in managing the operational control of their networks. The same criterion needs to become the standard for Space Weather.

For many in the electric utility business, it is difficult to comprehend that one of their most pressing operational challenges arrives from space. They are yet to fully reconcile that solar activity 93 million miles away needs to be considered, and yet there is no denying that to this extent they have unwittingly entered the space age. To progress in this age, operators and designers will have to acquire new skills and employ new tools to successfully manage the ever-present risk posed by the space environment. For nature has presented a number of difficult challenges with Space Weather to impacted systems. However, nature has partially compensated for these challenges with one important gift, the ability to accurately forecast with a meaningful "lead-time" the onset of geomagnetic storm conditions. Now it is up to those operating impacted systems to make use of this important gift.