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SPACE WEATHER AND UTILITY INFRASTRUCTURE

JULY 2011 ▪ ipu.msu.edu

Albertson, V. D., and van Baelen, J. A. (1970). Electric and Magnetic Fields at the Earth's Surface Due to Auroral Currents. *IEEE Transactions on Power Apparatus and Systems, 89*(4), 578–584. [link]

Abstract: "The horizontal components of the electric and magnetic fields due to auroral atmospheric currents are calculated at the surface of the earth. For sinusoidal changes in the earth's magnetic field (Fourier frequency components of actual nonsinusoidal variations), a lower limit of the corresponding earth-surface potential is obtained by considering a line-type auroral current over a nonuniform stratified earth. An upper limit of the earth-surface potential is obtained by considering a current-sheet model of the auroral current, and the same model of the earth. A diagram is constructed that allows calculation of the earth-surface potential for given variations in the earth's magnetic field. Finally, the influence of the earth-surface potential on electric power systems is discussed."

Barnes, P. R., Rizy, D. T., and McConnell, B. W. (1991). Electric Utility Industry Experience with Geomagnetic Disturbances. *Oak Ridge National Laboratory*. [link]

Abstract: "A geomagnetic disturbance (GMD) by its nature occurs globally and almost simultaneously. Severe geomagnetic storms cause problems for electric power systems. The vulnerability of electric power systems to such events has apparently increased during the last 10 to 20 years because power system transmission lines have become more interconnected and have increased in length and because power systems are now operated closer to their limits than in the past. In this report, the experience of electric utilities during geomagnetic storms is examined and analyzed. Measured data, effects on power system components, and power system impacts are considered. it has been found that electric power systems are susceptible to geomagnetically induced earth-surface potential gradients as small as a few (2 to 3) volts per kilometer, corresponding to a storm of K-6 intensity over an area of high earth resistivity. The causes and effects are reasonably well understood, but additional research is needed to develop a better understanding solar-induced geomagnetic storms and the responses of power systems to these types of storms. A better understanding of geomagnetic storms and the power systems' responses to GMDs is needed so that migration measures can be implemented that will make power systems less susceptible to sever geomagnetic disturbances. A GMD caused by a large high-altitude nuclear detonation is similar in many ways to that of solar-induced geomagnetic storms except that a nuclear-caused disturbance would be much more intense with a far shorter duration."

Bolduc, L., Langlois, P., Boteler, D., and Pirjola, R. (1998). A Study of Geoelectromagnetic Disturbances in Quebec, I. General Results. *IEEE Transactions on Power Delivery, 13*(4), 1251–1256. [link]

Abstract: "With the aim to better understand the flow of geomagnetically induced currents in power systems and to be able to prevent GIC inconveniences in the future, Hydro Quebec (Canada) carried out measurements of the geoelectromagnetic field in Quebec at five sites, spread over 250 km, from 1992 to 1994. This included magnetometers and the use of 25 km long phone cables to measure the electric field, The largest disturbances were found to occur when the auroral electrojet moved close to the recording sites. The magnetic disturbances varied little over the five sites, but the electric fields varied greatly from site to site due to changes in the local geology. An analysis of events with electric fields $E \geqslant 1$ V/km found an approximate linear relationship between E

and horizontal dB/dt. The directions of these electric fields were roughly East-West, consistent with the electrojet as the cause of the disturbances."

🗋 Bolduc, L., Langlois, P., Boteler, D., and Pirjola, R. (2000). A Study of Geoelectromagnetic Disturbances in Quebec, II. Detailed Analysis of a Large Event. *IEEE Transactions on Power Delivery, 15*(1), 272–278. [link]

Abstract: "As part of investigations of geomagnetically induced currents in the Hydro-Quebec power system, the geoelectromagnetic field was recorded at five sites in western Quebec in 1992 to 1994. A description of the measurements and some general results are presented in an accompanying paper. This paper concentrates on an analysis of a disturbance on February 21, 1994, that produced one of the largest electric fields recorded. The magnetic recordings are used to determine the intensity, location, and orientation of the auroral electrojet that is the cause of the disturbance. By tracking these parameters we show that dB/dt is due to both the changing intensity of the electrojet and due to movement of the electrojet. The resulting electric fields are found to be anti-parallel (parallel) to the electrojet when the magnetic field is increasing (decreasing)."

🗋 Commission Report (2010). *High-Impact, Low-Frequency Event Risk to the North American Bulk Power System*. North American Electric Reliability Corporation. [link]

Executive Summary: "As these proposals for action are considered, it is important to place HILF risks in context of the larger landscape of risk and concerns facing the electric sector over the coming years. NERC's 2009 Long-Term Reliability Assessment2, for example, identified nine emerging issues expected to impact reliability by 2018 including climate legislation, smart grid, cyber security transmission siting, variable generation issues, workforce issues, and reactive power. Several of these are reflective of other legislative and regulatory priorities. In addition, the sector is expected to require significant infrastructure additions3 to meet demand as economic recovery continues over the coming years."

🗋 Committee on the Societal and Economic Impacts of Severe Space Weather Events (2008). *Severe Space Weather Events—Understanding Societal and Economic Impacts: Workshop Report.* The National Academies Press. [link]

Description: "The adverse effects of extreme space weather on modern technology--power grid outages, high-frequency communication blackouts, spacecraft anomalies--are well known and well documented, and the physical processes underlying space weather are also generally well understood. Less well documented and understood, however, are the potential economic and societal impacts of the disruption of critical technological systems by severe space weather."

🗋 Daglis, I. A. (ed.). (2004). Effects of Space Weather on Technology Infrastructure. *Kluwer Academic Publishers: Netherlands.*

Preface: "The 17 chapters of this book provide an update of the existing knowledge on dynamic physical processes at the Sun, the interplanetary space and the geospace, as well as thorough reviews of the major mechanisms in which space weather disturbances influence technological systems. The book moreover reports recent advances in monitoring and predicting space weather and its impacts on technology systems and introduces new tools and methods for accurate predictions of space weather disturbances."

🗋 Eroshenko E. A., Belov A. V., Boteler D., et al. (2010). Effects of strong geomagnetic storms on Northern railways in Russia. *Advances in Space Research*, *46*(9), 1102-1110. [link]

Abstract: "Seventeen severe magnetic storms occurred in the period 2000 through 2005. In addition there was a major magnetic storm in March 1989. During each of these storms there was an anomaly in the operation of the system of Signalization, Centralization and Blockage (SCB) in some divisions of the high-latitude (similar to 58 to 64 degrees N) Russian railways. This anomaly was revealed as false traffic light signals about the occupation of the railways. These signals on the Northern railways appeared exactly during the main phases of the strongest part of the geomagnetic storms characterized by high geomagnetic indices Dst and Kp (Ap). Moreover, the durations of these anomalies coincided with the period of the greatest geomagnetic disturbances in a given event. Geomagnetically induced currents (GICs) during significant strengthening of geomagnetic activity are concluded as the obvious reasons for such kind of anomalies."

🗋 Freeman, J. W. (2001). Storms in Space. *Cambridge University Press.*

Preface: "The purpose of this book is to provide a brief glimpse of an astounding and beutful aspect of nature known only to a relative handful of space scientists and yet which is capable of disrupting human technical systems ranging from communications satellites to electric power grids-storms in space.

The Problem faced by a specialist writing for a general audience encompasses several challenges: first, he or she must draw connections to everyday experiences that lead the reader into the realm of the new phenomenon along familiar and enticing paths; second, the writer must avoid technical jargon and translate the description into understandable word images; and last, the unveiling of new concepts must be layered and progressive as the reader's comprehension matures.

The problem of describing storms in space is doubly challenging because the majority of the phenomenon is invisible to the human eye. This is why little progress could be made studying the phenomenon until the space age when in-situ satellite investigations became possible. It is also why space physicists are continually jealous of astronomers who can show marvelous images of the objects of their studies.

🗋 Ilonidis, S., et al. (2011). Detection of Emerging Sunspot Regions in the Solar Interior. *Science 333*, 993-996. [link].

Abstract: "Stathis et al. detected subsurface signatures of emerging sunspot regions before they appeared on the solar disc. Strong acoustic travel-time anomalies of an order of 12 to 16 seconds were detected as deep as 65,000 kilometers. These anomalies were associated with magnetic structures that emerged with an average speed of 0.3 to 0.6 kilometer per second and caused high peaks in the photospheric magnetic flux rate 1 to 2 days after the detection of the anomalies. Thus, synoptic imaging of subsurface magnetic activity may allow anticipation of large sunspot regions before they become visible, improving space weather forecast."

🗋 ISO New England. (2011). *System Operating Procedures: Implement Solar Magnetic Disturbance Remedial Action*. Holyoke, MA.

"The objective of this procedure is to provide a guide for operating the New England Bulk Power System during a Solar Magnetic Disturbance (SMD) and maintain the reliability of the bulk power system."

Kappenman, J. G. (2006). Great geomagnetic storms and extreme impulsive geomagnetic field disturbance events - An analysis of observational evidence including the great storm of May 1921. *Advances In Space Research, 38*(2), 188-199. [link]

Abstract: "Impulsive geomagnetic field disturbances are an important aspect of the geomagnetic storm environment for electric power grids and other ground-based infrastructures that can be impacted by geomagnetically induced currents (GIC). Significant power grid impacts in present day networks have been observed at relatively low levels of intensity, for example the Quebec grid blackout during the March 1989 storm occurred at a peak intensity of similar to 480 nT/min and permanent damage to large power transformers have occurred at even lower intensity levels. An analysis of both contemporary and historic storm data and records indicates dBh/dt impulsive disturbances larger than 2000 nT/min have been observed at latitudes of concern for power grid infrastructures. In extreme scenarios available data suggests that disturbance levels as high as similar to 5000 nT/min may have occurred during the great geomagnetic storm of May 1921. A comparative evaluation of this storm using morphology-based techniques indicates that large electrojet intensifications exceeding those observed during the March 1989 superstorm were present, further that the Dst range for the May 1921 storm could be as much as -900 nT or similar to 50% larger than the March 1989 Dst ranking which is the largest on record."

Kasinskii, V. V., Pititsyna, N. G., Lyahov, N. N., et al. (2007). Effect of geomagnetic disturbances on the operation of railroad automotive mechanisms and telemechanics. *Geomagnetism and Aeronomy, 47*(5), 676-680. [Link]

Abstract: "Geomagnetic variations generate electric currents in long conductors such as high-voltage lines, pipelines, and telecoms cables. The aim of our work is to study the possible effect of geomagnetic disturbances on the operation of automated systems and telemechanics of a midlatitude railroad based on the data on the malfunctions and breakdowns registered in 2004 on the East Siberian railroad (VSZhD). It has been obtained that the total daily duration of malfunctions and breakdowns (T) during disturbed periods is controlled by geomagnetic activity. When a peak of geomagnetic activity is reached during a storm, T increases about three times. Moreover, a correlation between T and the local index of geomagnetic activity (A), measured at Podkamennaya Tunguska Siberian observatory, is high during disturbed periods. Specifically, the correlation coefficient (K) is equal to 0.83 and 0.71 for the strongest two storms of 2004 that occurred in July 17–August 2 and November 4–18, respectively."

Lam, H. L., Boteler, D. H., and Trichtchenko, L. (2002). Case studies of space weather events from their launching on the Sun to their impacts on power systems on the Earth. *Annales Geophysicae, 20*(7), 1073-1079. [link]

Abstract: "Active geomagnetic conditions on 12-13, 15-16, and 22-23 September 1999 resulted in geomagnetically induced currents (GIC) measurable in power systems. in Canada and the United States. Different solar origins for these three events gave rise to dissimilar interplanetary signatures. We used these events to present three case studies, each tracing an entire space weather episode from its inception on the Sun, propagation through the interplanetary medium, manifestation on the ground as intense magnetic and electric fluctuations, and its eventual impact on technological systems."

Northeast Power Coordinating Council. (2007). *Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems*. New York.

Introduction: "Solar Magnetic Disturbances (SMD) are events that occur on the sun which can ultimately affect man-made systems on earth, including power systems. Voltage potentials are induced in the earth's crust which in turn cause geomagnetically induced currents (GIC) to flow in transmission lines. The resulting GICs are predominantly direct currents in nature and are typically more prevalent in the more northerly latitudes and in those regions in which the resistivity of the earth's crust is high to a considerable depth. This is notably the case in areas of igneous rock deposits. Those utilities most affected by solar activity since 1989 have developed procedures which establish a safe operating posture and which are initiated by criteria for their respective systems."

Pulkkinen, A. (2003). *Geomagnetic Induction During Highly Disturbed Space Weather Conditions: Studies of Ground Effects*. Ph.D. dissertation, University of Helsinki, Finland. [link]

Abstract: "It is shown that GIC can be modeled accurately with rather simple mathematical tools requiring that the topology and the electrical parameters of the conductor system, the ground conductivity structure and either the ionospheric source current or the ground magnetic field variations are known. Data-based investigations revealed that from the geophysical viewpoint, the character of GIC events is twofold. On one hand, large GIC can be observed at the same time instant throughout the entire auroral region. On the other hand, spatial and temporal scales related to these events are rather small making the detailed behavior of individual GIC events relatively local. It was observed that although substorms are statistically the most important drivers of large GIC in the auroral region, there are a number of different magnetospheric mechanisms capable to such dynamic changes that produce large GIC."

Scherer, K., Fichtner, H., Heber, B., and Mall, U., eds. (2005). Space Weather: The Physics Behind a Slogan *Lecture Notes in Physics* (Springer).

Review: "The aim of this book is to give an in-depth look at the physics behind the space weather phenomena … This book has … succeeded in its aim of providing the reader with an in-depth look at the physics involved in space weather…Grammatically, the book is excellent throughout … All the chapters have illustrative figures and … include very interesting reference lists… I found this book in general quite interesting and educational." (Norma B. Crosby, Surveys in Geophysics, 2006).

Skoug, R. M., Gosling, J. T., Steinberg, J. T., et al. (2004). Extremely high speed solar wind: 29-30 October 2003. *Journal of Geophysical Research-Space Physics, 109*(A9), A09102. [link]

Abstract: "On 29 - 30 October 2003 the Solar Wind Electron Proton Alpha Monitor (SWEPAM) instrument on the Advanced Composition Explorer (ACE) spacecraft measured solar wind speeds in excess of 1850 km/s, some of the highest speeds ever directly measured in the solar wind. These speeds were observed following two large coronal mass ejection (CME) driven shocks. Surprisingly, despite the unusually high speeds, many of the other solar wind parameters were not particularly unusual in comparison with other large transient events. The magnetic field reached - 68 nT, a large but not unprecedented value. The proton temperatures were significantly higher than typical for a CME in the solar wind at 1 AU (> 10(7) K), but the proton densities were moderate, leading to low to moderate proton beta. The solar wind dynamic pressure was not unusual for large events but, when coupled with the large negative B-z, was sufficient to cause intense geomagnetic disturbances."

Solar Terrestrial Dispatch. (2002). *A Guidance Report for the Power Industry: Geomagnetic Storms During the Decline of Solar Cycles.* Stirling, Alberta. [link]

Introduction: "At the request of NYISO, we have prepared the following report. It is hoped this report may help guide the electrical power industry toward a better understanding of the relationship between solar cycles and severe geomagnetic storm intervals capable of producing significant Geomagnetically Induced Current (GIC) activity. It was requested that we assemble a list of historic geomagnetic storm events that occurred during the declining phase of the solar cycles, to better illustrate the fact that the occurrence of significant geomagnetic storms are not limited to the sunspot maximum phase of the solar cycle. Refer to Appendix A for the complete list of storm events that occurred in the declining phases of the previous solar cycles. Appendix B contains an entire list of all storm events during all phases of the solar cycle that were associated with severe storm intervals."

🗋 Wik, M, Pirjola, R., Lundstedt, H., et al. (2009). Space weather events in July 1982 and October 2003 and the effects of geomagnetically induced currents on Swedish technical systems. *Annales Gepphysicae, 27*(4), 1775-1787. [link]

Abstract: "In this paper, we analyse in detail two famous space weather events; a railway problem on 13-14 July 1982 and a power blackout on 30 October 2003. Both occurred in Sweden during very intensive space weather storms and each of them a few years after the sunspot maximum. This paper provides a description of the conditions on the Sun and in the solar wind leading to the two GIC events on the ground."

Additional References

- NOAA Space Weather Prediction: http://www.swpc.noaa.gov/
- ESA Space Weather: http://www.esa-spaceweather.net/
- Australian Space Weather Agency: http://www.ips.gov.au/
- Solar Dynamics Observatory: http://sdo.gsfc.nasa.gov/