



NORTHEAST POWER COORDINATING COUNCIL, INC.
1515 BROADWAY, NEW YORK, NY 10036-8901 TELEPHONE: (212) 840-1070 FAX: (212) 302-2782

Procedures for Solar Magnetic Disturbances Which Affect Electric Power Systems

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Table of Contents**

1.0	Introduction	1
2.0	Impacts on Power Systems	1
2.1	General Effects	1
3.0	NPCC Alerts of Solar Magnetic Disturbances	3
4.0	Recommended Procedures	4
4.1	Operational Planning	4
4.2	Operator Action With the Onset of a Solar Magnetic Disturbance	5
5.0	Back-Up Communications	5
5.1	Communications Failure	5
5.2	Conflicting Data	6

Appendices

- A** **Communication Paths**
- B** **Solar Alerts Issued by the Solar Terrestrial Dispatch**
- C** **Solar Alerts Issued by the Space Environment Services of the National
Oceanic and Atmospheric Administration (Boulder, Colorado)**
- D** **Solar Alerts Issued by the Geological Survey of Canada, Department of
Natural Resources Canada (Ottawa, Ontario)**
- E** **Time Conversion Reference Document**
- F** **Description of Solar Magnetic Disturbances**

Note: Terms in **bold typeface** are defined in the *NPCC Glossary of Terms* (NPCC Inc. Document A-07).

1.0 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.

A detailed technical description of SMDs may be found Appendix F.

2.0 Impacts on Power Systems

The flow of GICs in the transmission system may affect the following equipment:

2.1 General Effects

2.1.1 Power Transformers

The presence of GIC produces off-setting dc excitation in a transformer, resulting in some degree of core saturation. This can cause the production of **harmonic currents** which can distort system voltages and cause **protective relay** operation due to the flow of neutral current to ground. Core saturation can also result in internal localized heating of the core and windings, and degradation of winding insulation. Saturated transformers are **reactive power** sinks, using up system reactive capacity, resulting in voltage depression.

2.1.2 HVdc Systems and Static VAR Compensators

Operations at or near the minimum or maximum current **rating** of HVdc circuits increases the potential for **commutation failures**, jeopardizing continuity of service.

These systems require a sinusoidal voltage to properly commutate current transmission. Voltage distorted by **harmonics** may be severe enough to cause **commutation failures** and result in shutdown of such systems.

Filter banks, including capacitor banks, associated with these systems will tend to overload due to harmonic current and may result in tripping.

2.1.3 Shunt Capacitor Banks

Shunt capacitor banks will tend to overload due to **harmonic current**, typically the third **harmonic**.

2.1.4 Generators

Automatic voltage regulators (AVR) associated with generators require representative voltage signals to control the dc field current on generators. Distorted ac voltage input to the AVR may result in uncertain translation of the ac signals for control, possibly resulting in a cyclical level of excitation on the generator, and hence real and **reactive power** output may vary in an abnormal manner.

Overheating may occur in large generators due to imbalances in phase currents and **harmonic** distortion in voltages which result from the saturation of power transformers. Turbine mechanical vibration may be excited by the presence of increased **harmonic** rotor current.

2.1.5 Transmission Lines

Harmonic frequencies in the system voltage can increase the magnitude of the voltage required to be switched by circuit breakers. **Harmonics** increase transmission losses and cause interference to communications systems.

2.1.6 Overall System Impact

Transformer saturation results in increased VAR consumption and **harmonic** injection into the system. These **harmonic currents** can result in capacitor bank overloading and their tripping, generator tripping and misoperation of **static VAR compensators**. This could further deplete the system of reactive VAR support and impact the overall system performance and security. The power systems are becoming more vulnerable to GIC effects due to longer transmission lines, decreased reactive margins and greater dependence on **static VAR compensators** and high voltage dc control.

3.0 NPCC Alerts of Solar Magnetic Disturbances

The NPCC **Areas** receive, on a continual twenty-four by seven basis, the status of solar activity and geomagnetic storm alerts from the Solar Terrestrial Dispatch (STD). The primary mechanism for notification to the NPCC **Areas** is the Solar Terrestrial Dispatch's Geomagnetic Storm Mitigation System (GSMS), an active communications software package installed on the operator's console. Upon receipt of a geomagnetic storm alert from Solar Terrestrial Dispatch of level Kp 6 or higher, the GSMS simultaneously displays:

- a flashing dialog box advising the operator of a "Major or Severe Geomagnetic Storm Warning." At the discretion of the **Area**, audible warnings will also accompany the flashing dialog box. Both the flashing indicator and the audible warning (if utilized) will continue until the "Confirm Receipt" button is clicked in the dialog box. This sends a verification to Solar Terrestrial Dispatch that the storm alert was received by the NPCC **Areas**. After acknowledging receipt of the geomagnetic storm alert, the GSMS will immediately prompt the operator to specify any GIC activity that has been observed on the power grid. The operator responds by clicking one of the following four buttons, as applicable:
 - "No GIC activity has been observed yet."
 - "Weak GIC activity has been observed."
 - "Moderately strong GIC activity has been observed."
 - "Strong GIC activity has been observed."
- a main screen providing the operator with all information currently known about possible solar activity. The following information is presented:
 - the time of the notification in both Universal Time and the **Area's** local time in twenty-four hour format
 - the history of actual hourly Kp readings for the previous seven hours
 - the Kp prediction, together with the predicted time of its onset, and the predicted peak Kp reading for the next twenty-four, forty-eight and seventy-two hours periods
 - the maximum Kp prediction for both the auroral and sub-auroral zones

- the probability of occurrence of the predicted Kp level
- the probable duration of the geomagnetic storm
- a graphical presentation over time of both current historical Kp observations and projected Kp values
- the status of the receipt of the notification by all NPCC **Areas**.

After reviewing the available data, the operator may choose to enact protective measures. Such protective measures taken are to be promptly reported as soon as possible. This is done by clicking on the “Submit Notifications” tab and filling in the box labeled “Specify new actions being taken.” Then click on the red arrow to record the actions that are being taken. This permanently records the action taken on the GSMS display and transmits the action to all NPCC Areas. Upon the halting of a previous action taken, the operator is to similarly report these steps using the same interface.

In the event that an **Area** observes GIC activity absent the notification of a geomagnetic storm alert, the operator is to use the “Submit Notifications” feature of the Geomagnetic Storm Mitigation System to automatically notify the other NPCC **Areas** and the Solar Terrestrial Dispatch of the activity.

All time alerts issued by the Solar Terrestrial Dispatch are disseminated in Universal Time (Greenwich Mean Time), a constant scientific time reference. All references to Universal Time may be converted to the prevailing Eastern Time or Atlantic Time as described in Appendix E.

A summary of the levels of solar activity that are made available to the NPCC **Areas** by the STD are shown in Appendix B. Further details can be obtained through the Web site of Solar Terrestrial Dispatch at:

<http://www.spacew.com/>

4.0 Recommended Procedures

4.1 Operational Planning

On receiving from the Solar Terrestrial Dispatch a forecast of SMD activity expected to result in Kp levels 7, 8 or 9, operations should be reviewed for vulnerability to such storms. Actions should be considered which include, but are not limited to, those listed in Section 4.2.

4.2 Operator Action With the Onset of an SMD

On receiving from the Solar Terrestrial Dispatch a geomagnetic storm alert predicting at least a 40% probability of activity at levels of Kp 7, Kp 8 or Kp 9, or notification of significant GIC activity, **system operators** may evaluate the situation and consider the following actions where appropriate:

- 4.2.1 Discontinue maintenance work and restore out of service high voltage transmission lines to service. Avoid taking long lines out of service.
- 4.2.2 Maintain the system voltage within an acceptable operating range to protect against voltage swings.
- 4.2.3 Reduce the loading on interconnections, critical transmission facilities, and critical transmission interfaces to 90%, or less, of their agreed limits.
- 4.2.4 Reduce the loading on generators operating at full load to provide reserve power and reactive capacity.
- 4.2.5 Consider the impact of tripping large shunt capacitor banks and static VAR compensators.
- 4.2.6 Dispatch generation to manage system voltage, tie line loading and to distribute operating reserve.
- 4.2.7 Bring equipment capable of synchronous condenser operation on line to provide reactive power reserve.

5.0 Back-Up Communications

5.1 Communications Failure

Although significant redundancy is incorporated in the dissemination of the solar alerts provided by the Solar Terrestrial Dispatch, in the event that all communication is lost with STD, the NPCC will, in the interim, rely on the solar forecasts and alerts issued by the governmental agencies of the United States and Canada. These are, respectively, the Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA), located in Boulder, Colorado, referenced in Appendix C, and the Geological Survey of Canada, Department of Natural Resources Canada (NRCAN), located in Ottawa, Ontario, referenced in Appendix D. These communication paths are summarized in Appendix A.

5.2 Conflicting Data

All actions to be considered in section 4.2 are to be based on the forecasts and alerts disseminated by the STD. This data is tailored for the power system in general, and for the geographic subauroral region in which the NPCC transmission system is located. It is therefore unlikely that the STD would predict less solar activity than either the SEC or the NRCAN. However, should the forecasts or alerts of either the SEC or the NRCAN predict higher solar activity than those of Solar Terrestrial Dispatch, each NPCC **Area** will communicate this discrepancy with the STD through the “Submit Notifications” tab of the GSMS and request clarification.

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References:	<i>NPCC Glossary of Terms</i> (NPCC Inc. Document A-07)

Appendix A Communication Paths

Primary NPCC Notification:

Primary NPCC Notifications	
On a continual basis, through the Solar Terrestrial Dispatch Geomagnetic Storm Mitigation System (GSMS), solar activity is available to:	all NPCC Areas (IESO, ISO-NE, NBSO, NYISO and TE)
Upon the prediction of a geomagnetic storm alert of level Kp 6 or higher, the Solar Terrestrial Dispatch GSMS automatically provides alarms to:	all NPCC Areas (IESO, ISO-NE, NBSO, NYISO and TE)
For a prediction of Kp 7 or higher, the Solar Terrestrial Dispatch notifies by telephone:	the NYISO; the NYISO in turn notifies the IESO, the ISO-NE, NBSO, and TE.

Back-up NPCC Notification:

SEC (Boulder, Colorado) Forecasts and Alerts	
SEC-Boulder notifies:	New York ISO
New York ISO notifies:	PJM-ISO New England-IESO-TE-NBSO
New Brunswick System Operator notifies:	Nova Scotia Power Incorporated

NRCAN (Ottawa) Forecasts and Alerts	
NRCAN-Ottawa notifies:	IESO-TE
IESO notifies:	New York ISO
New York ISO notifies:	PJM-ISO New England-NBSO
New Brunswick System Operator notifies:	Nova Scotia Power Incorporated

Note: The North American Electric Reliability Council (NERC) also receives solar alerts from the Space Environment Center and transmits these alerts to the NERC Reliability Coordinators through the Reliability Coordinator Information System (RCIS).

Appendix B

Solar Activity Reporting Form

The predictive measure of solar activity reported by the Solar Terrestrial Dispatch is the Kp index, a scale divided into 27 zones of solar activity. A description of these zones and the relationship between the observed Kp index and typically observed GIC activity follows:

Kp Index	Solar Activity	GIC Activity
0o	Quiet	No GICs
1-		
1o		
1+		
2-	Unsettled	
2o		
2+		
3-	Active	
3o		
3+		
4-		
4o		
4+		
5-	Minor Storm	Low Level GICs
5o		
5+		
6-	Major Storm	
6o		
6+		
7-	Severe Storm	Moderate GICs
7o		
7+		
8-	Very Severe Storm	Strong GICs
8o		
8+		
9-		
9o		

Appendix C

Solar Alerts Issued by the Space Environment Services (SEC–Boulder, Colorado)

The Space Environment Center (SEC) of the National Oceanic and Atmospheric Administration (NOAA) is located in Boulder, Colorado, and provides warnings and alerts of geomagnetic activity to the New York ISO. The NYISO subsequently disseminates this information to the other operating Areas within NPCC.

SEC warnings and alerts are issued in the form of a daily "A" index up to three days in advance. The "A" index is a measure of the expected geomagnetic activity, based on solar observations, for Fredericksburg, Virginia. The classification of Major Storm (A index of 50 and above) is transmitted to the NPCC Areas. The SEC also includes a probability for “Major Storm” conditions to help users assess the confidence level of the forecast.

SEC warnings and alerts are also issued in the form of the Kp index, which is based on the maximum deviation of the horizontal magnetic field components of the earth relative to a quiet day, within a three hour time period. The Boulder Kp index is based on measurements from the Boulder magnetometer, and it is used at the SEC to define the alert thresholds. A warning or alert is issued for a Kp index of Kp 5 or greater. Most electrical power systems, however, are not affected until the Kp index reaches a level of 7 or higher.

The forecasts and warnings that are made available to system control centers follow:

Warnings

The following Warnings are issued by telephone from the SEC to the NYISO. Warnings are predictions for a certain period in the future. That is, warnings come before the specified period.

- A Index = 30
- A Index = 50
- Kp Index = 5
- Kp Index = 6
- Kp Index = 7 or above

Alerts

The following Alerts are issued by telephone from the SEC to the NYISO. Alerts are observations of activity that has already occurred. Generally, alerts are issued at the end of the specified period.

A Index = 30

A Index = 50

Kp Index = 5

Kp Index = 6

Kp Index = 7

Kp Index = 8

Rapid Alerts

The following Rapid Alerts are issued by telephone from the SEC to the NYISO. Rapid Alerts are observations of activity that has occurred, but they are issued immediately, without waiting for the end of the period.

Kp Index = 7

Kp Index = 8

Note: The SEC in some cases speaks of all of these messages, including warnings, alerts and rapid alerts, as “alerts,” and thus all of the messages can carry an alert code.

All time alerts issued by the SEC are disseminated in Universal Time (Greenwich Mean Time), a constant scientific time reference. All references to Universal Time may be converted to the prevailing Eastern Time or Atlantic Time as described in Appendix E

Further information can be obtained at:

<http://www.sec.noaa.gov/today.html>

Appendix D

Solar Alerts Issued by the Department of Natural Resources Canada (NRCAN– Ottawa, Ontario)

The Geological Survey of Canada, Department of Natural Resources Canada (NRCAN), located in Ottawa, Ontario, Canada, issues forecasts and warnings, based on magnetometer data from 12 observatories using the Canadian Automatic Magnetometer Observatory System (CANMOS) and on solar data received from sources around the world.

GSC forecasts are updated and issued every hour. They are based on hourly range predictions of geomagnetic activity for up to two days in the future for the subauroral zone, the geographic region in which most of the NPCC Areas are located. The classifications which are of concern to the NPCC Areas are "Stormy" (corresponding to an approximate Kp index of 5 or 6), and "Major Storm" (corresponding to an approximate Kp index of 7, 8, or 9). Several key observatories are continually monitored, and, when events are found that meet predefined criteria, a warning and updated forecast are issued. The forecasts and warnings that are made available to system control centers follow:

Warnings

Warnings issued by the NRCAN are based on actual conditions which have occurred and been observed:

WARNINGS-NRCAN (Ottawa)	
Kp Index	Hourly Range in Nanoteslas (nT)
0	0 to 7
1	8 to 14
2	15 to 29
3	30 to 59
4	60 to 104
5	105 to 179
6	180 to 299
7	300 to 499
8	500 to 749
9	750 and above

Forecasts

Forecasts issued by the NRCAN are projections for expected conditions:

FORECASTS-NRCAN (Ottawa)	
Activity Level	Kp Levels
Stormy	5 and 6
Major Storm	7, 8 and 9

NOTE: NRCAN data is measured at Ottawa, Ontario, Canada; forecasts are projections of conditions expected to occur in the subauroral zone in which most of NPCC is physically located.

All time alerts issued by the NRCAN are disseminated in Universal Time (Greenwich Mean Time), a constant scientific time reference. All references to Universal Time may be converted to the prevailing Eastern Time or Atlantic Time as described in Appendix E.

Further information can be obtained at:

forecast@geolab.nrcan.gc.ca
<http://www.geolab.nrcan.gc.ca/geomag>

Appendix E

Time Conversion Reference Document

The time reference used in the solar alerts disseminated by the Solar Terrestrial Dispatch, as well as the Department of Natural Resources Canada and the Space Environment Services, is the scientifically accepted Universal Time (UT), which is also equivalent to Greenwich Mean Time (GMT). The prevailing Eastern Time lags Universal Time / Greenwich Mean Time by five hours in the autumn and winter. The prevailing Eastern Time lags Universal Time / Greenwich Mean Time by four hours in the spring and summer. The prevailing Atlantic Time lags Universal Time / Greenwich Mean Time by four hours in the autumn and winter. The prevailing Atlantic Time lags Universal Time / Greenwich Mean Time by three hours in the spring and summer. The Universal Time / Greenwich Mean Time is a constant time reference and does not convert to accommodate daylight savings in the spring and summer. Conversion examples for the Eastern and Atlantic time zones follow:

Eastern Standard Time (EST)	Universal Time (GMT)
12:00 hour	17:00 hour

Eastern Daylight Time (EDT)	Universal Time (GMT)
13:00 hour	17:00 hour

Atlantic Standard Time (AST)	Universal Time (GMT)
13:00 hour	17:00 hour

Atlantic Daylight Time (ADT)	Universal Time (GMT)
14:00 hour	17:00 hour

Appendix F

Description of Solar Magnetic Disturbances

Solar Magnetic Disturbances (SMDs) are events that occur on the sun that can ultimately affect man-made systems on Earth, including power systems. The sun emits a stream of charged particles known as the solar wind that continuously moves outward from the sun past the Earth. Solar activity (solar flares, disappearing filaments and coronal holes) affects the intensity of the solar wind, varying from very quiet levels to very active levels during major storms. Extremely fast coronal mass ejection (CME) events associated with unusually energetic solar flares (known as Fast Transit Events [FTEs]) can reach the earth in as little as fourteen hours. However, most CMEs (including disappearing filament eruptions) require approximately two to three days to travel to the Earth. Coronal hole based disturbances typically take two to four days to reach the Earth. The quiet solar wind can take up to six days to reach the Earth.

The Earth has a magnetic field that is generated by a liquid metal core. This magnetic field penetrates the surface of the Earth and expands outward a large distance into space, effectively creating a cocoon or shield around the Earth that protects the Earth from harmful effects of the solar wind. The domain of the Earth's magnetic field is known as the magnetosphere. Pressure from the solar wind shapes the magnetosphere into a comet-like appearance with a "head" surrounding the Earth and a "tail" (known as the magnetotail) that extends a great distance in a direction that is opposite to the Sun (behind the Earth).

Strong magnetic fields on the Sun are dragged out toward the Earth by the solar wind. As these magnetic fields flow past the Earth, they can interact with the Earth's magnetic field. When the magnetic field lines in the solar wind are oriented in a direction that is opposite to the magnetic field lines from the Earth, the magnetic field lines from the Earth can reconnect with the magnetic fields in the solar wind. This opens up a conduit that allows solar wind momentum energy and particles to directly enter and energize the Earth's magnetosphere. The reconnected field lines are then convected across the Earth's polar regions and are dragged by the solar wind into the magnetotail region of the Earth's magnetosphere. The build-up of additional magnetic flux in the magnetotail can eventually trigger powerful magnetic field reconnection events in the Earth's magnetotail that both energize and accelerate particles and plasma from the magnetotail toward the Earth. Beams of energized particles are guided by the Earth's magnetic field into the ionosphere where they collide with atmospheric constituents and fluoresce as aurora (northern lights). The aurora are produced within a ring of activity that encircles the earth's geomagnetic poles, usually over the higher latitudes. This ring is known as the auroral zone.

Within the auroral zone ionosphere, powerful electrical currents (auroral electrojets) are forced to flow to help dissipate the tremendous energy that is released during the magnetotail reconnection events. Currents in the dusk regions flow eastward while currents in the dawn regions flow westward. These current systems converge near local midnight. The region where these currents converge is known as the Harang discontinuity region. Although the intensity of these currents can rapidly change during a geomagnetic storm, the most significant and hazardous changes typically occur near the midnight Harang discontinuity region where eastward-directed currents may suddenly change direction to westward directed currents. Significant changes in the intensity and / or the direction of these current systems can induce ground-based voltage (potential) differentials between locations spaced some distance apart. These ground potential differences can cause currents to flow through the grounded connections of transmission lines if the resistivity of the ground to a respectable depth is higher than the resistivity of the transmission line. This condition occurs more frequently and with greater magnitude in areas that overlie igneous rock.

The flow of these currents into transmission lines is known as geomagnetically induced currents (GICs). They are ostensibly direct currents in nature and are most often located toward the higher latitudes within the auroral zone during quiet to modestly active geomagnetic conditions. However, as geomagnetic storm activity intensifies, the size of the auroral zone expands. This expansion causes the equatorward boundary of the auroral electrojets (the southern-most location of the intense ionospheric electrical current systems) to migrate toward lower latitudes. During extreme events, the auroral electrojets can move at least into the central United States. This equatorward motion and the concurrent intensification of the ionospheric electrical currents during significant geomagnetic storms can therefore expose a considerable portion of the North American power grid to GICs that may be considerably stronger than those observed over the higher latitudes or during quieter geomagnetic intervals.