General Discussion

On March 13, 1989, solar activity and the resultant geomagnetic disturbance (GMD) on the earth was responsible for widespread disturbances to the bulk electric systems in North America. This report will explain the GMD phenomenon and present in some detail the impacts of GMD on the electric systems.

This report contains the following sections:

1. General discussion of GMDs
2. Description of the March 13, 1989, Hydro-Québec blackout
3. Description of the damage to generator step-up transformers at the Salem generating station
4. Operating practices during a GMD
5. Chronologies of reported events on the bulk electric systems from the March 13, 1989 GMD in North America
6. Map of North America showing the states and provinces where the March 13, 1989 GMD events were reported

Introduction to Geomagnetic Disturbances

The solar wind is a continuous outflow of particles and magnetic fields from the sun that normally take several days to travel the 93 million miles to earth. Under solar storm conditions, coronal mass ejections create "gusts" of particles that can reach the earth in 2 to 3 days, and severely disturb the earth's magnetic field. Numerous solar storm conditions exist on the sun, but relatively few reach the earth with the appropriate attitude to the earth's magnetic field to cause a GMD on the earth's surface.

On March 10, a solar storm created a solar wind that reached the earth in approximately 54 hours. The result was the severe GMD of March 13, 1989, which is the subject of this report.

As the solar particles arrive at the earth, they cause rapid fluctuations of the earth's geomagnetic field. This, in turn, produces an induced earth-surface potential and geomagnetically induced currents, or GIC. GIC appears as a quasi-dc current (an ac waveform with a period of several minutes), and for all intents and purposes, appears as dc to the bulk electric system. The consequences of this dc current is to drive transformer cores into saturation. This, in turn, causes significant heating from stray flux, increases var losses that depress system voltages, and can damage the transformer itself. Core saturation can also generate harmonic distortion that impacts other elements in the electric system.

Effects of GIC on the Bulk Electric Systems

Harmonic currents injected into the ac system can precipitate a multiple-contingency incident, which, under certain operating conditions, can jeopardize the integrity of the bulk electric systems in North America. Specifically, harmonic currents can cause overcurrent relays to trip capacitor banks because capacitors offer a lower impedance path for harmonics. Similarly, static var compensators can trip for over-current or over-voltage protection. The consequences of tripping a large amount of reactive resources during a GMD is particularly critical because the effect is to further depress system voltages already reduced by transformer var losses.

Protection systems can operate in direct response to harmonic currents, and a distorted sinusoidal waveform can cause HVDC converter commutation failures. System frequency can become erratic, and generators, which are not immune to harmonic current, can be tripped by negative sequence protection systems. Units that do not trip are susceptible to damage from turbine blade vibration.

Chronology of Events from the March 13, 1989, GMD

The chronology of events from the March 13, 1989 GMD demonstrates the wide variety of system

General Discussion (cont.)

components affected by a severe GMD. The Hydro-Québec blackout shows the possible result of a multiple contingency event. A review of capacitor trippings during the day demonstrates the potential for a multiple event affecting the reliability of other control areas. Fortunately, on March 13, the transmission systems were lightly loaded, enabling them to compensate for the loss of reactive power. Under more heavily loaded conditions, system reactive margins may not have been sufficient to maintain a reliable voltage profile.

Effects of Location and Topography on GMD

The earth's magnetic field doubles in intensity as one traverses from the equator to the poles. Consequently, the effect of a GMD increases proportionately in the higher latitudes. Normally, the impacts at middle latitudes should not be sufficient to affect the electric systems. However, electric systems built on highly resistive igneous bedrock or in proximity to large bodies of water change the equation.

In 1968, the Edison Electric Institute Board of Directors authorized support of research by the University of Minnesota and the General Electric Company to study the effects of geomagnetic storms on electric systems. This study reaffirmed that geological conditions tend to override the effect of latitude. Igneous rock resists the ground dissipation of GIC. The result is for this current to superimpose on the transmission network. Figure 9 shows the states and provinces in the U.S. and Canada that reported electric system disturbances from the March 13, 1989 solar storm. Note the relationships of the igneous rock and coastline to the reported events.

Measuring Geomagnetic Intensity

Geomagnetic conditions can vary locally depending on the angle of incidence of the solar wind to the axis of the geomagnetic field, latitude, geological conditions, and the position of the auroral oval (the more visual aurora borealis or "northern lights," the more intense the storm). Magnetometers are used in the U.S. and Canada to measure the geomagnetic field intensity in nanoTeslas (nT). Figure 10 shows the magnetometer readings of the horizontal axis of the geomagnetic field as measured at four locations on March 13, 1989. Note the variation in pattern and intensity at each location. Note also the relative difference in field activity between the early morning hours during which Hydro-Québec's blackout occurred and the late afternoon when significant electric system disturbances were reported in the U.S. These magnetometer plots also show the limitations of the "K" index.

The K and A Indexes

The K index is an indicator of the average local geomagnetic activity over a three-hour period. It is based on a quasi-logarithmic scale that ranges from 0 to 9. A K9 disturbance is the minimum indicator of the most severe storm. It is also the maximum indicator, because the K scale is open-ended. There is nothing above K9.

Table 2 - *The "K" and "A" indexes for geomagnetic activity*

"K" Scale	"A" Scale
0	0
1	3
2	7
3	15
4	27
5	48
6	80
7	140
8	240
9	400

General Discussion (cont.)

On March 13, 1989, there were two periods where geomagnetic intensity registered K9. Graph 1 on page 55 shows the relationship between the K index and events recorded on the bulk electric system due to geomagnetic activity on March 13.

Table 2 on the previous page shows the relational scale that converts the three-hour K index into the 24-hour A index, which is also expressed in nT. In the U.S., the K and A indexes are measured in Boulder, Colorado. (Boulder is the headquarters of the National Oceanic and Atmospheric Administration's Space Environmental Services Center (SESC). In Canada, these measurements are taken in Ottawa by the Ministry of Energy, Mines, and Resources (EMR). Both national agencies issue K and A index alerts and warnings to each country. The March 13, 1989 GMD measured 248 nT on the A index in Boulder, second only to the November 13, 1960 GMD that measured 264 nT.

GMD Forecasting

Forecasting solar activity and its equivalent effects on local earth conditions is an art that is much less precise than local weather forecasting. Both the SESC and EMR concentrate on "alerts" that are reports of the K or A index of observed local GMD activity. Three-hour periods of K5 or greater, and 24-hour periods of A50 or greater are reported by SESC and the equivalent is reported by EMR.

"Warnings" are projections for the next three-day period. So imprecise is the art of predicting GMDs, it is extremely unlikely that an SESC or EMR forecaster would ever predict a solar storm in excess of A100. Precision in forecasting GMD is a critical need to the power industry.

On July 9, 1990, the NERC Board of Trustees approved a position statement urging that geomagnetic disturbance forecasting methods be improved (see page 40).

General Discussion (cont.)

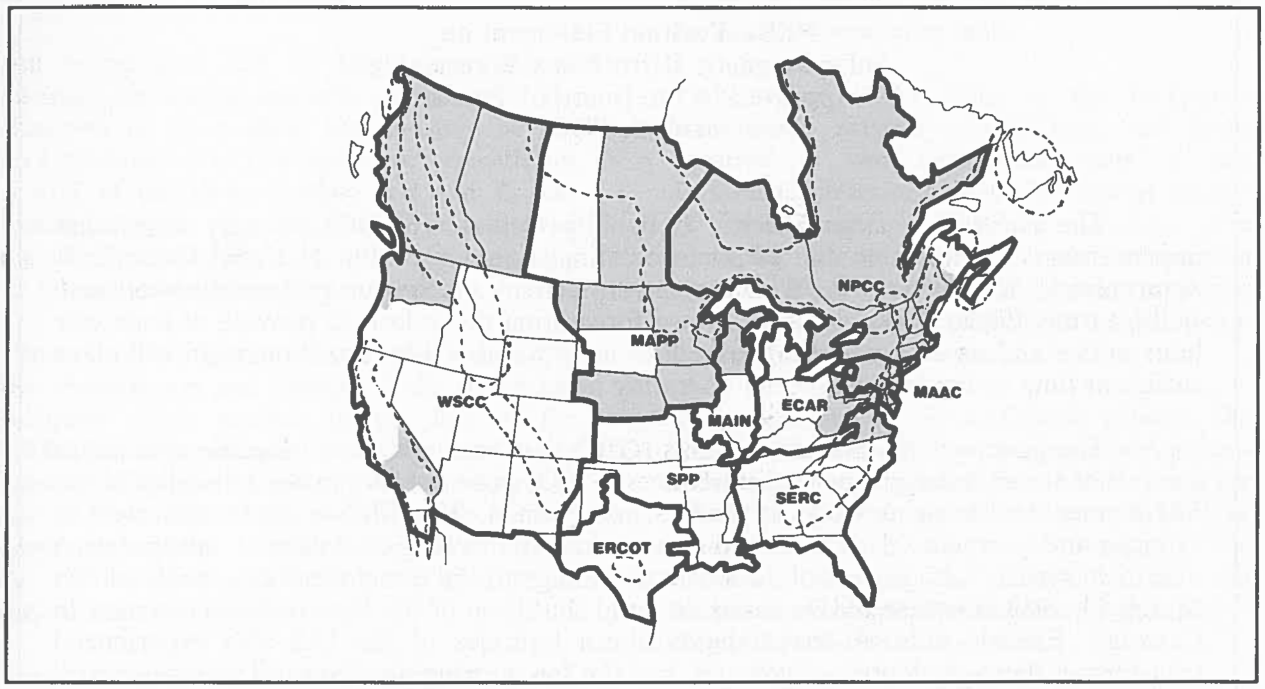


Figure 9 - *States and provinces affected by the March 13, 1989 geomagnetic disturbance are shaded. Areas of igneous rock formations also shown.*

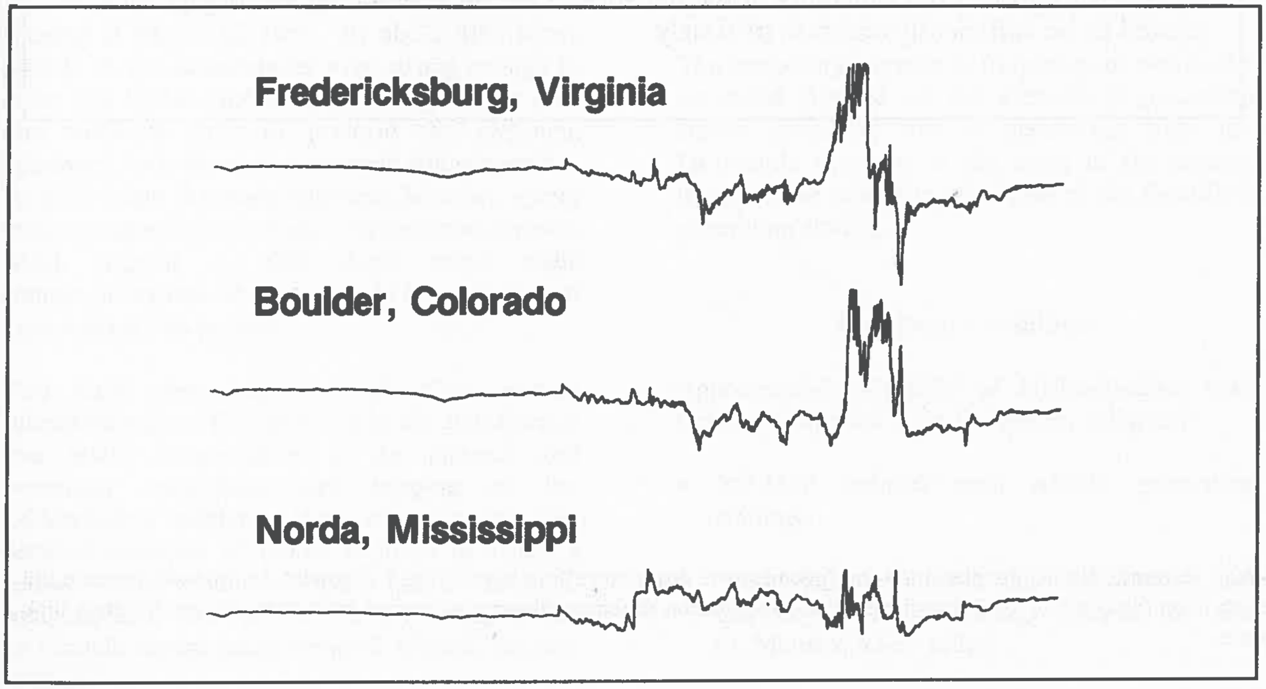


Figure 10 - *Magnetometer readings from March 13, 1989 geomagnetic disturbance*

NERC Position Statement on Solar Magnetic Disturbance Forecasting

Approved by the Board of Trustees
July 9, 1990

The North American Electric Reliability Council (NERC) strongly urges that improvements be made to the SMD forecasting accuracy of the National Oceanic & Atmospheric Administration. With the current activity on the sun projected to continue well into the 1990s, NERC believes that a forecasting procedure to provide at least one hour notice and an accuracy of at least 90% is required. This security margin will allow sufficient time to implement special operating procedures.

The geomagnetic induced currents (GIC) that are imposed on electric systems as a result of severe solar magnetic disturbances (SMD) pose a threat to the reliability of the interconnected electric networks in the U.S. and Canada. The GICs cause transformers to saturate and overheat. This results in depressed system voltages, failure or misoperation of critical system voltage control devices, and damage to the transformers themselves. On March 13, 1989, a severe SMD caused the total shutdown of the Hydro-Québec system in Canada. Electric utilities across the northern latitudes of the U.S also experienced transformer damage, depressed voltages, and the forced tripping of several voltage control devices. While no widespread blackouts have yet occurred, the incident demonstrated the potential damage to equipment and risk to system reliability. As a result, several control areas have established SMD operating guidelines and study groups.

The nature of the sudden onset of SMD requires that an effective SMD forecasting mechanism be in place to provide system operators with sufficient time to take preventive measures to protect the reliability of the network. Current forecasting technology has not proved to be sufficiently accurate or timely.

Note: Recently, NERC adopted the term "geomagnetic disturbance" in place of "solar magnetic disturbance" because the effect is on the earth's ("geo") magnetic field. The position statement above was drafted before this change in terms took place.

Hydro-Québec Blackout

Summary

Just before 0245 EST on March 13, 1989, an exceptionally intense magnetic storm caused the shutdown of seven static compensators on the La Grande network. This equipment is essential for control of the Hydro-Québec grid and its loss caused voltage to drop, frequency to increase, and the resultant instability caused the tripping of the La Grande transmission lines.

The rest of the Hydro-Québec system, supplied by the Manicouagan and Churchill Falls complexes, collapsed within seconds of the loss of the 9,500 MW of generation from the La Grande network. The general system blackout affected all but a few substations isolated onto certain generating stations; a total of 430 MW of load in the Abitibi, Hull, and St. Maurice River valley regions remained supplied.

Power was gradually restored over the next nine hours. The delay was due mainly to damaged equipment on the La Grande network.

Sequence of Events

Low intensity magnetic disturbances began on the evening of March 12, 1989. By about 0100 hours March 13, the disturbances were strong enough to affect the Hydro-Québec grid, but operating staff had sufficient time to perform the switching necessary for transmission network voltage control. At 0245 hours that same morning, however, a very intense magnetic storm generated harmonic currents which tripped or shut down seven static compensators one after another before any human intervention was possible.

Two static compensators at the Chibougamau substation tripped first, followed by the shutdown of four static compensators at the Albanel and Nemiscau substations and tripping of the La Verendrye substation static compensator. The detailed sequence of events is listed in Table 3 below. A few seconds after the loss of the static compensators, one of the 735 kV lines of the La Grande transmission network tripped, causing automatic rejection of the generation of two La Grande 4 generating units.

Three other 735 kV lines of the La Grande transmission network tripped next, and faults occurred in two single-phase units of two La Grande 4 transformers and in the surge arrestor of a shunt reactor at Nemiscau substation. The remaining line of the La Grande transmission network tripped next. Thus, the La Grande network was separated completely from the Hydro-Québec transmission network.

With separation of the La Grande network, the frequency fell rapidly. In response, automatic load-shedding systems tripped all loads but could still not offset the loss of approximately 9,400 MW of generation from the La Grande Complex. The network connecting the Churchill Falls and Manicouagan complexes with Montreal and Quebec City collapsed within six seconds.

Next, two lines of the Churchill Falls network tripped at the Montagnais station, and a remote load-shedding signal was sent to the System Control Centre in Montreal in response. Since all possible load shedding had already been performed, the result was the collapse of the remainder of the system.

The temporary increase in frequency, as well as the increased demand on the Gentilly 2 generating station given the loss of generation from the La Grande Complex at the onset of the outage, triggered the complete shutdown of the Gentilly 2 generating station.

Post-Event Conditions

Approximately 430 MW of Hydro-Québec load remained supplied after the system collapsed:

- 250 MW isolated onto Abitibi generating stations.
- 160 MW isolated onto the Grand-Mere and Shawinigan 2 generating stations in the St. Maurice River valley.

- 13 MW isolated onto the Hull 2 generating station.

Damaged transformers caused the unavailability of two-thirds of the generation of the La Grande 4 generating station (1,800 MW). A permanent shutdown deprived the system of the entire output of the Gentilly 2 generating station (685 MW).

Damaged equipment included damaged surge arrestors at La Grande 2, Nemiscau, and Churchill Falls, and a damaged shunt reactor at Nemiscau.

All dc interconnections and radial export loads tripped; total load loss was 1,376 MW, but neighboring systems remained unaffected since simultaneous load loss of this order is well below recognized limits.

All generation isolated on neighboring systems (573 MW) remained in service.

System Restoration

Close to full power was gradually restored over a nine-hour period:

- 5,000 MW (25%) restored after three hours.
- 10,500 MW (48%) restored after five hours.
- 14,200 MW (65%) restored after seven hours.
- 17,500 MW (83%) restored after nine hours.

The percentages are based on load forecasts and take into consideration that many industries did not resume full activity immediately after the outage.

In terms of the transmission network, restoration of power was delayed mainly because of the unavailability of strategic La Grande network equipment; indeed, major modification of the system restoration plan and hence additional switching was required because of the unavailability.

As for the distribution network, damaged equipment and load transfers delayed restoration of power. Given cold weather, the duration of the blackout and the power demands of the usual flurry of activity of a Monday morning, there were overloads when power was restored to customers.

The Ontario and New Brunswick systems provided emergency assistance during system restoration. Once power was restored, Québec's power demand was met with the help of the New York and New England systems, the Alcan and McLaren systems in Québec, and voluntary reduction of demand from certain industrial customers.

The system was gradually restored by connecting autonomous networks one after another to the basic grid.

Damage to Equipment

The loss of all static compensators on the La Grande network caused the system disturbance, damaged some strategic equipment and rendered other major pieces of equipment unavailable. As a result, it took over nine hours to restore 17,500 MW, that is, 83% of full power.

Among the major pieces of damaged equipment were two La Grande 4 generating station step-up transformers damaged by overvoltage when the network separated and a shunt reactor at Nemiscau that requires factory repair. The SVCs at the Albanel and Nemiscau substations suffered only minor damage: thyristors were damaged at Nemiscau and capacitor bank units failed at Albanel. The SVC phase-C transformer at the Chibougamau substation was also damaged by overvoltage following system separation.

Hydro-Québec's telecommunication network operated satisfactorily throughout the magnetic storm, as did all special protection systems.

Causes of the Static Compensator Tripping

The La Verendrye – Chibougamau Static Var Compensators

Figure 11 shows a typical one-line diagram of SVC installations at the La Verendrye and Chibougamau substations. These SVCs were subjected to severely distorted voltage caused by geomagnetically induced dc currents (GIC).

Hydro-Québec Blackout (cont.)

Spectrum analysis of the waveforms recorded indicates predominance of second- and fourth-order harmonics resulting from dc saturation of transformer cores. Table 3 below shows the harmonic distortion content of voltage and current at La Verendrye prior to system shutdown. The equipment protection scheme was originally designed for normal conditions and the possibility of intense geomagnetic storms was not considered. With the exceptional disturbance of March 13, 1989, overload protection systems of the capacitive branches initiated tripping of the SVCs at the Chibougamau site. Figure 12 and Figure 13 show the distorted current waveform measured in the thyristor-switched capacitor branch prior to protection system operation.

At the La Verendrye site, overvoltage protection on the 16 kV bus side was responsible for tripping the only SVC in service. The components most sensitive to ground-induced currents are the capacitors, the thyristor-switched capacitor (TSC) reactors and the power transformers. Because of the low impedance of the capacitors for higher order harmonics, exposure to harmonic current has a greater impact on the TSC branch than the TCR branch. Given the abnormal conditions, the relays had to be readjusted, since the protection systems were set to values that allowed only a fraction of inherent overload capacity to be used. Peak-value overload and overvoltage protection is, in fact, provided for in these installations, but when harmonics are present the risk margin for improper protection system operation increases.

Table 3 — *Harmonic distortion at La Verendrye*

Harmonic Order	ac Voltage at 735 kV	Secondary 16 kV Bus Voltage	Current (TSC)
1	100%	100%	100% (2371 A)
2	7.2%	16.7%	32%
3	2.1%	4.6%	1.8%
4	5.9%	0.9%	3.4%
5	1.8%	0.62%	3.4%

The Nemiscau – Albanel Static Var Compensators

Figure 14 shows a typical one-line diagram of SVC installations at the Nemiscau and Albanel sites. These SVCs were tripped by capacitor unbalance and resistor overload protection devices of the third harmonic filter branch.

As Table 4 shows, substantial second and fourth harmonic distortion was recorded on the 735 kV side of the Albanel substation. Figure 15 shows the resultant current waveform on the high-voltage side just prior to tripping.

Unfortunately, the lack of a reading for the secondary 22 kV side of the static compensators at the time of the collapse made exact assessment of the stress on the SVC components impossible. The impact of voltage and current distortions on the 22 kV side was, therefore, determined theoretically. The findings thus obtained indicate values in excess of the settings of the protection devices that operated.

Short-term Remedial Measures

New Protection Settings

An increase in harmonic currents can affect the operation of relays sensitive to harmonics. To maintain normal operation of Hydro-Québec's static var compensators during geomagnetic conditions, settings for certain protective systems have been adjusted upward (see Table 5 and Table 6 on the following pages.) The new settings are only a short-term remedial measure to allow full use of the equipment's overload capability without having to deal with the problem of replacing all the relays. However, higher protection settings may accelerate aging of some static compensator components and of power transformers.

Information on Forecasts of Magnetic Disturbances

Agreements have been made with Energy, Mines and Resources Canada, as well as with neighboring NPCC systems, to keep Hydro-Québec informed around-the-clock of forecasts of magnetic disturbance that could affect electric system operation. Such forecasts are essential tools for System Control Centre dispatchers, who can then position the transmission system within secure limits. A 10% safety margin has been included in maximum transfer limits.

Monitoring of ac Voltage Asymmetry

Ac voltage asymmetry is now monitored at four key locations: the Boucherville, Arnaud, La Grande 2,

Table 4 – *Harmonic distortion at Albanel*

Harmonic Order	ac Voltage at 735 kV	ac Current on the 735 kV Side
1	100%	100%
2	5.1%	145%
3	3.4%	39%
4	0.5%	90%
5	0.9%	28%
6	0.4%	8%
7	0.2%	3%

Table 5 – *La Verendrye – Chibougamau protection settings*

Type of Protection	Settings Before 3/13/89	Current Settings
H.V. XFO. O/C PROTECTION 1 p.u. = 250 A (rms)	1.4 p.u. (0.65s)	2.0 p.u. (0.65s)
Thyristor-switched capacitors O/C protection 1 p.u. = 4,000 A (rms)	1.5 p.u. (0.65s)	2.0 p.u. (0.65s)
TSC overload protection 1 p.u. = 2,300 A (rms)		
Chibougamau	1.08 p.u.[1](5s)	1.83 p.u. (10s)
La Verendrye	1.3 p.u. (5s)	1.83 p.u. (10s)
16-kV bus overvoltage		
Chibougamau	1.1 p.u (60s)	
La Verendrye	1.07 p.u.[2](5s)	Disconnected[3]

[1] This protection initiated tripping of the SVC at the Chibougamau substation. Measured circulating current in the delta branch was about 1.5 p.u.

[2] This protection initiated tripping of the SVC at the La Verendrye substation.

[3] This protection is not considered representative of voltage across the capacitor bank in the presence of harmonics; it is connected to the oscillograph for more detailed information during GIC conditions.

Table 6 — *Nemiscau — Albanel protection settings*

Type of Protection	Settings Before 3/13/89	Current Settings
H.V. XFO. O/C PROTECTION 1 p.u. = 236 A (rms)	1.27 p.u.	1.5 p.u.
Capacitor bank overload protection 1 p.u. = 2,200 A (rms)	1.35 p.u.	1.8 p.u.
Capacitor and 3rd harmonic filter overload protection 1 p.u. = 2,200 A (rms)	1.08 p.u.	1.8 p.u.
Third harmonic filter resistor overload protection	1.03 p.u.[1] TRIP	1.25 p.u.[2] ALARM ONLY
Capacitor unbalance protection for main and 3rd harmonic filter capacitor branch.	Alarm: Loss of 3 units in main capacitor bank Loss of 1 unit in 3rd harmonic filter branch Trip: Loss of 4 in main branch. Loss of 2C in the 3rd harmonic filter branch	Temporary adjustment for loss of 8[3]filter-branch capacitors Loss of 9[4]filter-branch capacitor

[1] This protection initiated tripping of the SVC at Albanel substation.
[2] Connected to the oscillograph for further analysis during GIC conditions.
[3] To take into consideration natural unbalance during normal conditions; compensating circuits will be installed in the near future.
[4] To comply with the 1.1 p.u. overvoltage limit on remaining units.

and Chateauguay substations. Upon detection of 3% voltage asymmetry at any one location, an alarm is sent to the System Control Centre so that immediate action can be taken to position system transfer levels within secure limits — if this has not already been done.

New Operating Limits for dc

Interconnections During Magnetic Disturbances

HVDC loading is to be adjusted to between 40% and 90% of normal full-load rating in response to magnetic disturbance forecasts. Loading can be adjusted to even lower levels if deemed necessary.

Future Actions

Analyses of the event of March 13, 1989 indicate that the main problem was overloading of static var compensators with the advent of low-order harmonic currents along the system. The remedial measures described above will minimize the likelihood of future SVC trippings.

GIC Monitoring

Monitoring of harmonic voltages and transformer neutral currents at various stations within the system is advisable to broaden the knowledge of such voltages and currents and to find out if certain parts of the system are more sensitive to geomagnetic disturbance than others.

GIC Computation

Digital programs such as EMTP can be used to compute GIC by assuming different earth surface potential (ESP) values at the neutral bus. The usual assumption that ESP varies linearly from south to north and from east to west is questionable, especially when a very large territory is involved. Research and development to determine ESP patterns during magnetic storms would be very helpful for system designers.

Estimation of Harmonic Voltages Resulting From GICs

If the GIC at each station can be determined with enough confidence, then a digital program can be used to compute the resulting harmonic distortion at ac buses. Two different approaches are possible: With the first approach, each transformer is represented as a source of harmonic currents with amplitudes proportional to GIC values; phasing of these sources of harmonic currents then becomes a major consideration. A harmonic analysis digital program is then used to compute harmonic components of voltage and current at different points along the system.

With the second method, the saturation characteristic of the transformer's magnetizing core is modelled with a program such as EMTP. Earth surface potential is then applied directly to the transformer neutral. The ac waveforms that result at the different buses are then subjected to Fourier analysis. This method can take up an enormous amount of CPU time, as the transformer may take seconds, indeed even minutes, to saturate. To reduce CPU time to an acceptable level, tricks and artifices to "accelerate" transformer saturation time in EMTP must be developed.

Impact of the Installation of Series Compensation

The scheduled installation of series compensation throughout the network in the near future will help to significantly reduce the impact of magnetic storms (see Figure 16). The series capacitors that are to be installed have a very high impedance for GICs and will thus block them. However, short lines and many tie lines will not be compensated, and this means creation of "loops" where GIC will continue to flow and to saturate transformers. This in turn will generate harmonics which will flow throughout the system, since they will not be blocked by series capacitors. The impact of series compensation is to be studied by evaluating GIC and harmonic voltages.

Neutral-Blocking Capacitor

Capacitors installed between transformer neutrals and grounds can be very effective in blocking ground-induced currents. Ideally, the capacitors should be very simple, should not increase voltage stress on transformer insulation, should not have to be bypassed during faults (eliminating the necessity for a complex bypass device) and should have a low 60 Hz impedance (to avoid any impact on the system grounding coefficient). The cost of such a device will, of course, have to be weighed against its simplicity, robustness, and reliability. Hydro-Québec is currently studying a capacitor of this sort and if findings are promising, a prototype will be installed for field testing and evaluation of long-term reliability and performance.

Impact of GIC on HVDC Control

Studies are to be conducted to find ways to improve inverter control under ac-bus waveform distortion conditions. The risks of commutation failure will be examined as will remedial measures such as improved firing control or automatic reduction of power.

Automatic Switching of Shunt Reactors

Transformer saturation tends to depress 60 Hz voltage. Static var compensators usually react by operating in the capacitive range, although this can be detrimental to system stability. One way to control ac voltage is to use circuit breakers to automatically switch shunt reactors connected to lines. The number of breaker operations required will have to be carefully assessed by considering the random oscillations induced by GICs.

Conclusions

The blackout of the Hydro-Québec system on March 13, 1989 was caused by an exceptionally intense magnetic storm. The storm induced dc ground current that saturated transformers and generated even-order harmonic currents that caused seven static compensators on the 735 kV network to trip or shut down. Loss of the static compensators gave rise to system instability that culminated in separation of the La Grande network. Automatic load shedding was not able to offset the loss of the 9500 MW of generation from the La Grande generating stations, and the rest of the system collapsed within seconds.

The La Grande's vast transmission network relies on static var compensators to maintain system stability and voltage control. Since this type of equipment is particularly sensitive to magnetic storms and we are approaching the peak of the solar activity cycle, Hydro-Québec has made great efforts to improve SVC performance under magnetic storm conditions. Remedial action was taken immediately to increase the reliability of the static compensators and two task forces were set up to make recommendations for the short as well as the long term. Indeed, some of these recommendations have already been implemented, guidelines for geomagnetic disturbance operating procedures have been developed and an automatic alerting system has been devised.

References

The Hydro-Québec System Blackout of March 13, 1989: System Response to Geomagnetic Disturbance

Presented at the EPRI Conference on Geomagnetically Induced Current
November 8 to 10, 1989
San Francisco, California
Messrs. P. Czech, S. Charo, H. Huynk, and A. Dutel

The Analysis of the Hydro-Québec System Blackout on March 13, 1989 (Report dated June 8, 1989.)

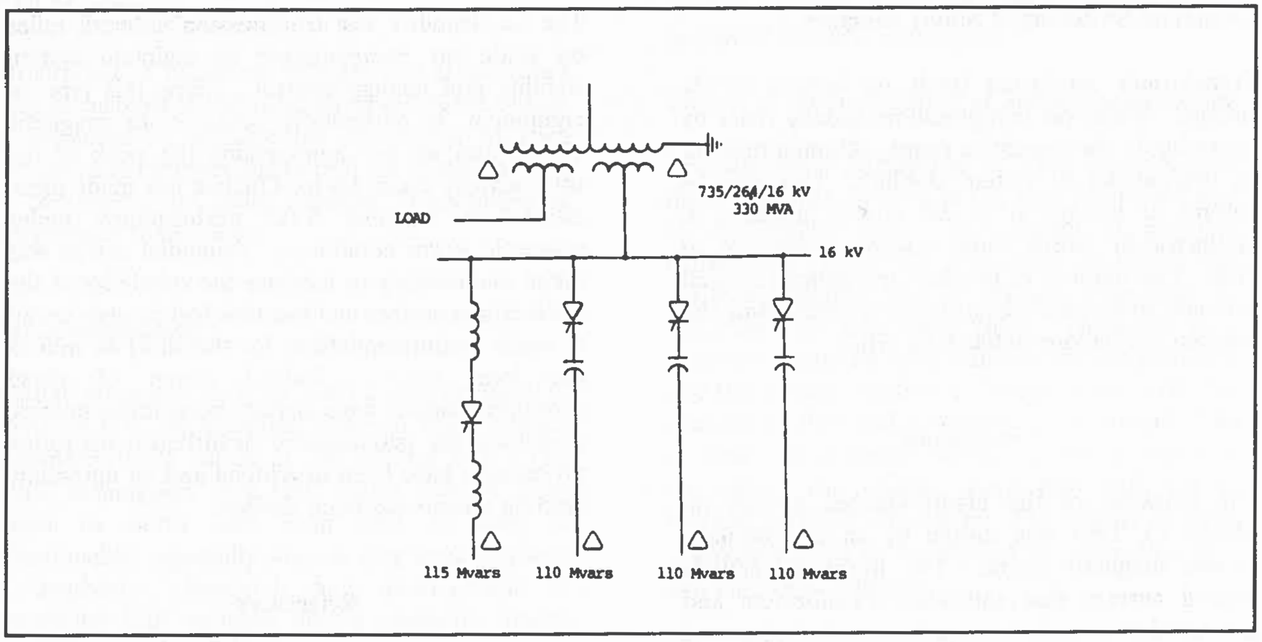
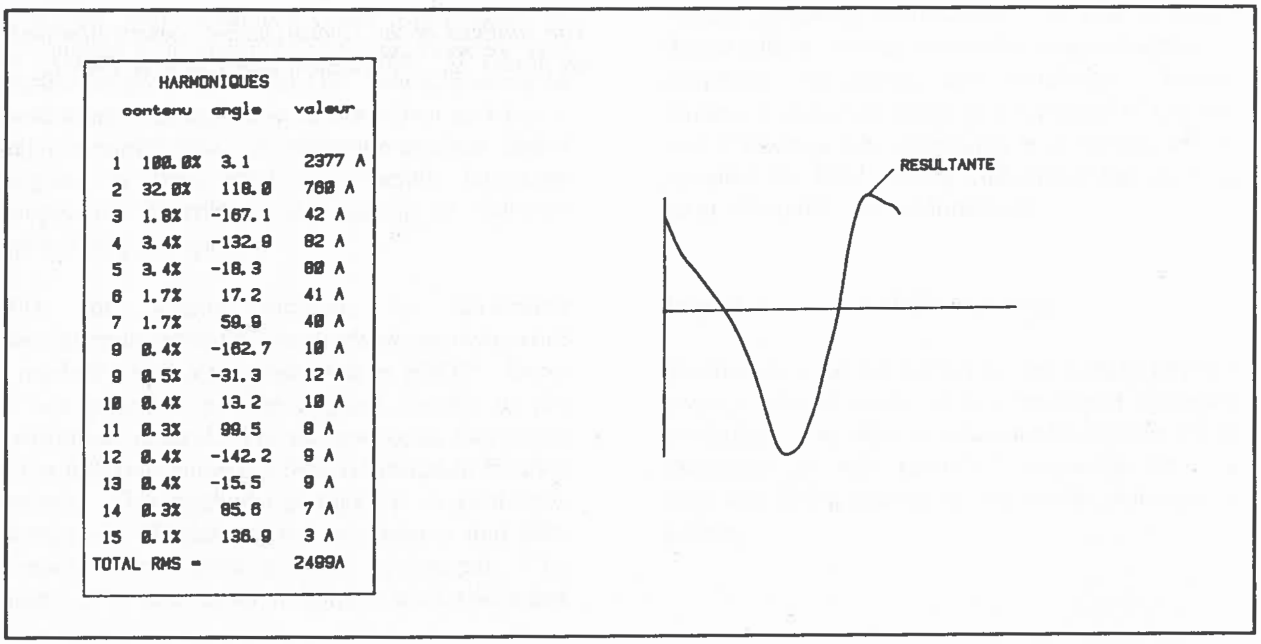


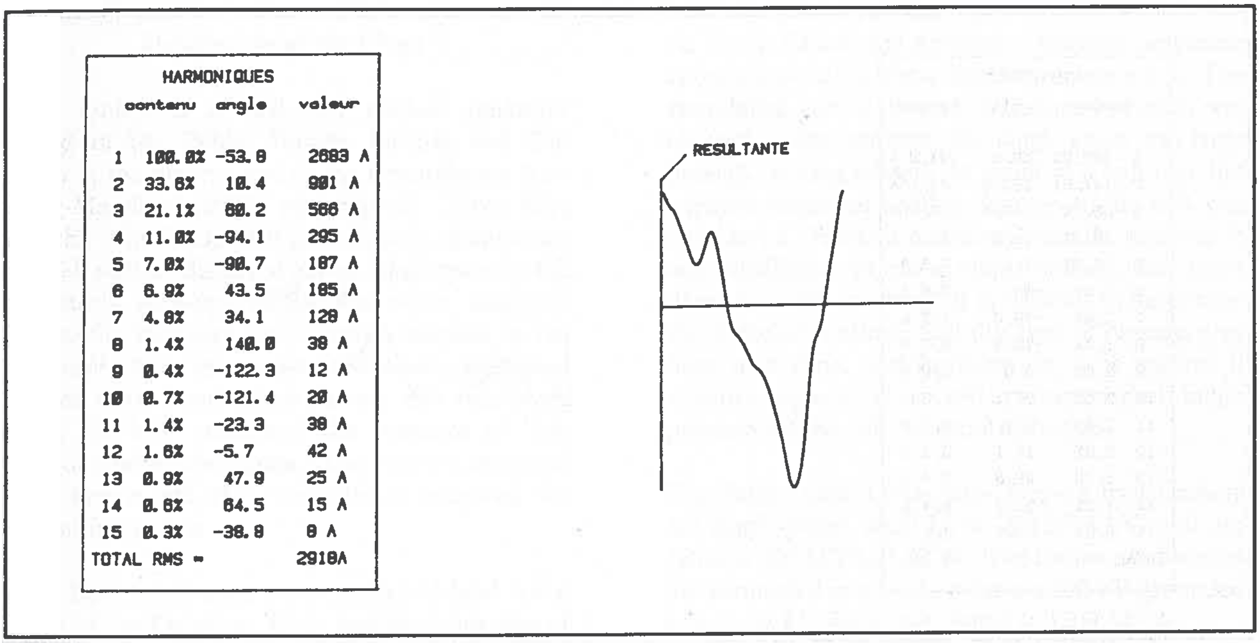
Figure 11 - *One-line diagram of La Vérendrye-Chibougamau SVCs*



```
         HARMONIQUES
    contenu  angle    valeur

  1  100.0%  3.1       2377 A
  2  32.0%   110.0     760 A
  3  1.8%   -167.1     42 A
  4  3.4%   -132.9     82 A
  5  3.4%   -18.3      80 A
  6  1.7%    17.2      41 A
  7  1.7%    59.9      40 A
  8  0.4%   -162.7     10 A
  9  0.5%   -31.3      12 A
 10  0.4%    13.2      10 A
 11  0.3%    99.5      8 A
 12  0.4%   -142.2     9 A
 13  0.4%   -15.5      9 A
 14  0.3%    85.6      7 A
 15  0.1%    136.9     3 A
TOTAL RMS =           2499A
```

Figure 12 - *Harmonic current at La Vérendrye*



HARMONIQUES

	contenu	angle	valeur
1	100.0%	-53.8	2683 A
2	33.6%	10.4	901 A
3	21.1%	60.2	566 A
4	11.0%	-94.1	295 A
5	7.0%	-90.7	187 A
6	6.9%	43.5	185 A
7	4.8%	34.1	128 A
8	1.4%	140.0	38 A
9	0.4%	-122.3	12 A
10	0.7%	-121.4	20 A
11	1.4%	-23.3	38 A
12	1.6%	-5.7	42 A
13	0.9%	47.9	25 A
14	0.6%	64.5	15 A
15	0.3%	-38.8	8 A
TOTAL RMS =			2918A

Figure 13 - *Harmonic current at Chibougamau*

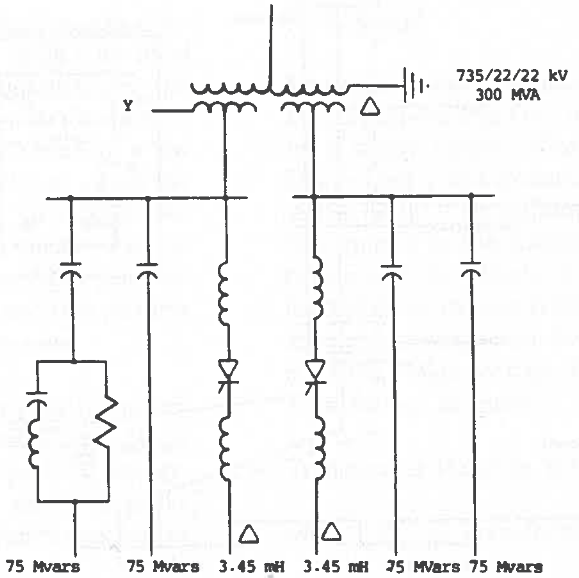
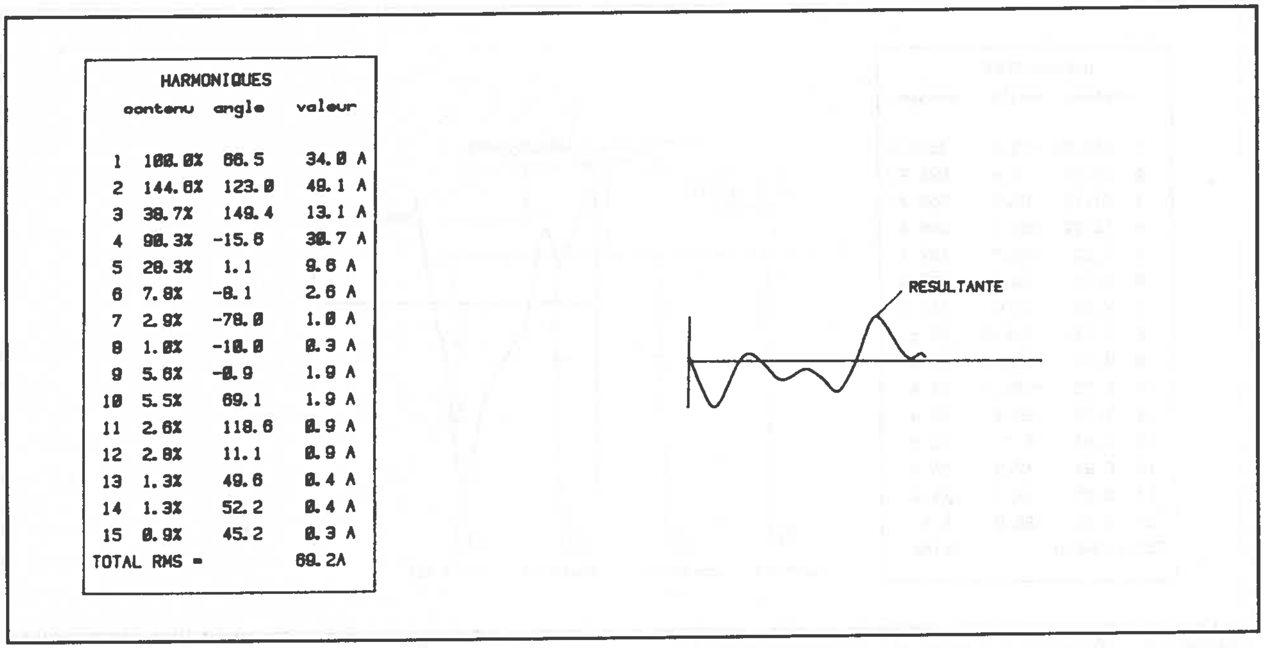


Figure 14 - *One-line diagram of Némiskau/Albanel SVCs*

Hydro-Québec Blackout (cont.)



HARMONIQUES

	contenu	angle	valeur
1	100.0%	66.5	34.0 A
2	144.6%	123.0	49.1 A
3	38.7%	149.4	13.1 A
4	90.3%	-15.6	30.7 A
5	28.3%	1.1	9.6 A
6	7.8%	-8.1	2.6 A
7	2.9%	-78.0	1.0 A
8	1.0%	-10.0	0.3 A
9	5.6%	-0.9	1.9 A
10	5.5%	69.1	1.9 A
11	2.6%	118.6	0.9 A
12	2.8%	11.1	0.9 A
13	1.3%	49.6	0.4 A
14	1.3%	52.2	0.4 A
15	0.9%	45.2	0.3 A
TOTAL RMS =			69.2A

Figure 15 - *Harmonic current at Albanel*

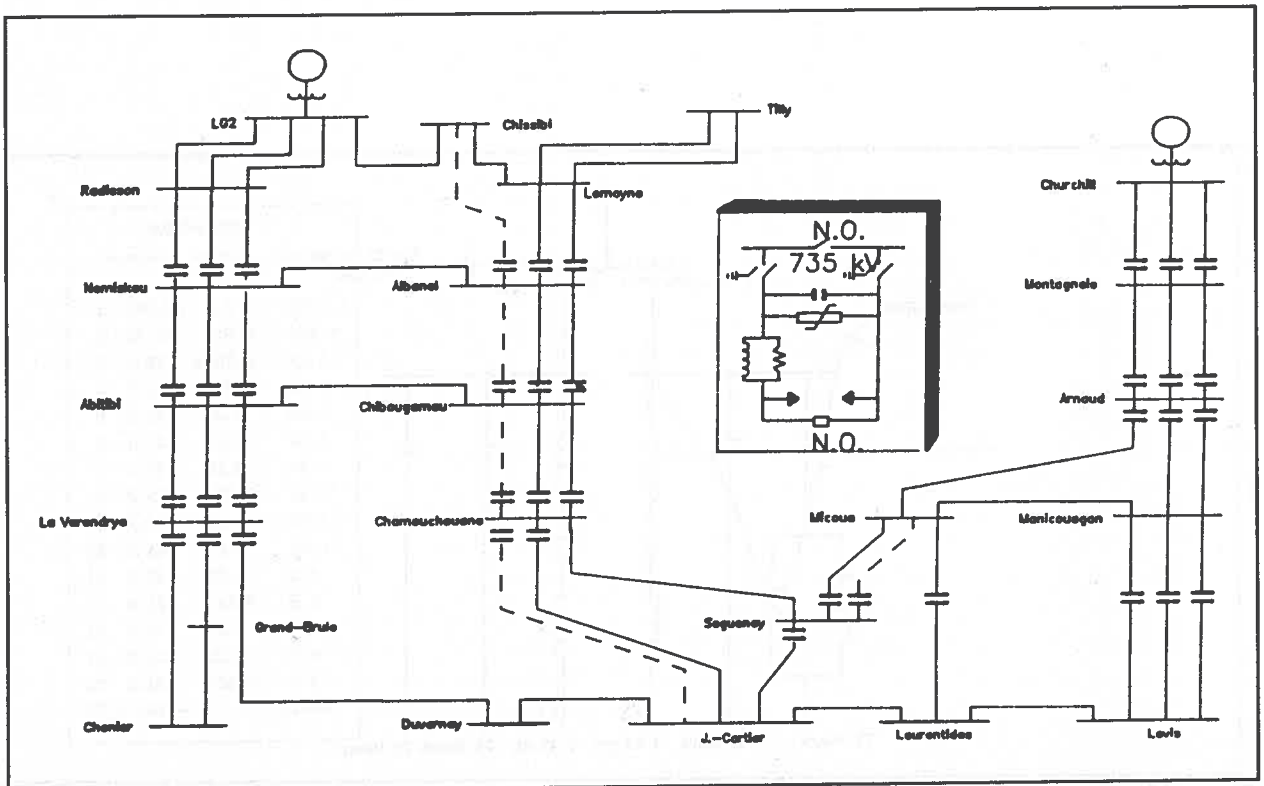


Figure 16 - *Addition of series compensation to the Hydro-Québec transmission system*

Effects of Geomagnetic Induced Current on the Salem Plant Step-up Transformers

Description of the Event

Salem Unit 1 is a 1160 MW nuclear generator located in the Public Service Electric and Gas system at the eastern end of the Pennsylvania-New Jersey-Maryland (PJM) power pool. Seven days after the March 13, 1989 geomagnetic disturbance (GMD), routine dissolved gas-in-oil samples for the generator's step-up-transformers were analyzed. The results indicated an alarming increase in the total combustible gas content of the oil. Additional samples were immediately drawn, and results on March 23, 1989 confirmed the presence of high levels of combustible gases. The unit was removed from service and the transformers prepared for internal inspection.

Salem Unit 1 is located on an artificial island at the mouth of the Delaware River and the beginning of the Delaware Bay. Also located on this island are two additional nuclear units, Salem Unit 2 and Hope Creek. Total generating capacity at this site is approximately 3450 MW.

Due to its location in a marshy area, the majority of the structures are supported on hundreds of steel piles, with average lengths of 100 feet. Since all these piles are connected into the station's ground grid, grounding of the station is excellent. This, coupled with the fact that this is the eastern end of the 500 kV PJM transmission system, provides geomagnetically induced currents (GIC) an ideal location to enter the electrical system from the Atlantic ocean. The flow of GIC is further enhanced at this point due to the location of a low ground conductivity, igneous rock region across the eastern end of Pennsylvania. Therefore, the grounded wye connection of the generator step-up transformers provides a favorable entrance point for GIC to easily flow past this region and into western Pennsylvania on the 500 kV system.

On March 13, 1989, the generator reactive power output (MVAR) charts for Salem 1 and Hope Creek indicated numerous uninitiated var swings. The var swings were significant, and had peaks exceeding 200 MVAR. (Salem Unit 2 was not in service at the time.)

At Hope Creek, the generator negative sequence current protection alarm operated many times. The cumulative period of time the alarm operated was more than five minutes. No single event was large enough, or long enough, to result in a unit trip, but negative sequence heating damage to the unit was considered. While it is believed that the magnitude was insufficient to cause major damage, any rotor damage is still concern. It is difficult to determine the cumulative effects that this type of damage may have over time, and furthermore, it is unclear if negative sequence relays will operate properly in the presence of the GIC current distortion.

The Salem Unit 1 generator step-up transformers are single-phase, shell form, 288.8/24 kV, and are rated at 406 MVA at 65° C. The three transformers are connected in a bank to form a 500 kV grounded wye to 24 kV delta unit, rated at 1209 MVA.

Visual inspection of the failed transformers showed severe damage to one of the two long series connections of the outer low-voltage winding paths. All three phases had severely thermally degraded insulation, and Phase A and Phase C had 20 - 25% conductor damage. The conductor damage varied from melted and fused strands, to large melted masses of copper and copper shot. Fortunately, the paper insulation contained the damage, which was not readily apparent until the series lead was unwrapped.

Investigation of the failures began immediately after the inspection, and GIC was quickly determined to be a major factor. During the magnetic storm, Salem Unit 1 had extended var excursions of 150 - 200 MVAR. The additional vars were assumed to be required by the transformers as they saturated, because of the effects of GIC. The approximate level of direct current (GIC) can be calculated using an empirical equation developed in EPRI Report EL-1949, "High Voltage Direct Current Convertor Transformer Magnetics."

$$\text{Transformer Reactive VA} = V(I_{exc} + 2.8I_{dc})$$

where I_{exc} = Transformer exciting current (no dc component)

Effects of Geomagnetic Induced Current on the Salem Plant Step-up Transformers (cont.)

I_{dc} = Direct current in the transformer winding

Solving this equation with actual conditions, yields a total direct current of 224 A, or 74.7 A per phase. Direct currents of this level, when compared to core material properties, will heavily, if not completely, saturate the core.

It is this saturation that produces the major effects on the transformer. They include increased eddy current losses, steel and tank heating, and enormous magnetizing currents. The increased eddy current losses result from distortion of the leakage field pattern within the winding and leads, a condition that is further aggravated by the increased harmonic content of the leakage field. In a similar manner, steel tank heating should have been impacted, however, no effects were observed on the units.

The most significant effect on the transformers was the tremendous increase in magnetizing current. It is estimated that during peak storm activity there was a 50 to 75% increase in the low-voltage winding current due to saturation. Unfortunately, due to the configuration of the low-voltage windings, the outer two parallel paths of the winding carried the majority of this increase. This is principally the result of the unequal self and mutual inductances of the outer and inner paths for this winding. The effective impedance presented to the magnetizing current is lower in the outer path, and therefore, carries the bulk of the current.

It is postulated that the combination of above-normal eddy current losses, and uneven distribution of the increased magnetizing current, produced the damage observed. The location of the damage in the long series connection of the outer low-voltage winding paths is consistent with the mechanisms described above.

Additional Failure

On September 19, 1989, a geomagnetic storm of intensity K6 was reported. Approximately three days later, a dissolved gas-in-oil detector on Salem Unit 2, Phase B, showed an increase of 50 ppm. Immediate samples were drawn, and depicted an alarming increase in combustible gases. At that point, a program of sampling the oil every day was initiated. Gassing continued to increase, but became unpredictable. The decision was made to remove the unit from service on October 13, 1989, three weeks after the initial problem was detected.

Internal inspection of the unit, which is identical to the failed units of Salem Unit 1, found the same winding series connection with similar damage. The damage was in the same location, but had not progressed as far. Only two strands showed signs of melting, but the area was severely thermally damaged.

Mitigation of GIC

Existing transformer relay protection does not respond to harmful GIC. As a result, a protection scheme was developed that monitors the total vars at the Salem Generating station 500 kV bus. During normal operating conditions, the total vars would ideally sum to zero. However, during a GIC disturbance, the generator step-up transformers would begin to saturate and create a large increased var flow.

The PSE&G Electric System Operating Center has automated this calculation, and provided an alarm. When the alarm setpoint is exceeded, and a magnetic storm has been announced, the generating station will be instructed to reduce the output of the unit. This system is in place and functioning and has been implemented in response to GMDs since that event. A neutral dc current measuring device is being installed to supplement this scheme.

Prevention

The consequences of failed transformers are too great to rely on protection alone. Therefore, mitigation of GIC effects by prevention, in addition to protection, were considered. At present, a blocking device to be installed in the neutral of the transformer is being studied and designed.

(Excerpted from *Geomagnetic Effects on a Bank of Single-Phase Generator Step-up Transformers*, by Peter M. Balma, P.E., Public Service Electric and Gas Company, Distribution Systems Department, Newark, New Jersey.)

Practices and Procedures for Dealing with Geomagnetic Disturbances

Several utilities have implemented procedures for dealing with geomagnetic disturbances. The following are excerpts from the procedures supplied to the NERC staff. These are for example only.

Northeast Power Coordinating Council

Operations Planning

On receiving notification of high GMD activity, review operating practices. Pay particular attention to those areas where voltages approach the limits of the operating range and where HVDC schemes are operating in excess of their nominal full-load rating.

Operating Procedures

1. Discontinue maintenance work and restore out-of-service high voltage transmission lines to service. Avoid taking long lines out of service.
2. Keep system voltage within an acceptable operating range to protect against voltage swings.
3. Adjust loading on HVDC circuits to be within 40% - 90% of nominal rating.
4. Reduce the loading on generators operating at full load to provide reserve power and reactive capacity.
5. Consider the impact of shunt capacitor banks and static var compensators that are connected to the high voltage transmission system being tripped out of service.
6. Dispatch reserve generation to manage system voltage, tie line loading and to distribute operating reserves.
7. Bring equipment capable of synchronous condenser operation on line to provide reactive power reserve.
8. Notify adjacent control areas of GMD problems.

Pennsylvania-New Jersey-Maryland Interconnection

Transformer Damage Mitigation

As a result of damage to the Salem main step-up transformers and its correlation with the geomagnetic disturbance, the following steps will be taken whenever there is a positive indication of geomagnetic activity as indicated by any two of the following:

1. Erratic MVAR output from the generating units.
2. Excess MVAR consumption by the generating unit step-up transformers (i.e., more then 80 MVAR for Salem or more then 60 MVAR for Hope Creek) monitored in the control center using SCADA.

Practices and Procedures for Dealing with Geomagnetic Disturbances

If any two of the above conditions occur, the generating units will reduce their power output as follows:

- Salem 1 and 2 – Reduce to 80% power
- Hope Creek – Reduce to 85% power

Note: These reductions address a specific problem identified with the Salem unit step-up transformers resulting from circulating currents in the four parallel low-side windings. Such reductions may have little or no effect in alleviating problems with other transformers which may react differently under geomagnetic disturbance conditions.

Western Area Power Administration

Operations Planning

3. Adjust negative sequence current relay settings on transformers.

4. Review harmonic unbalance relay settings.

5. Verify proper operation of ground backup and transformer differential relays (including harmonic restraint). If they are operating as desired, consider changing their settings to make them less sensitive to current transformer saturation effects by either increasing the CT ratio or adjusting the settings.

6. Install monitoring at selected points to monitor transformer neutral currents and provide a better record of geomagnetically induced current activity.

7. Simulate GIC effects on the electric system to predict which locations may be subject to transformer, or reactor, or both, thermal problems in the future.

Allegheny Power Service Corporation

Transformer Damage Mitigation

1. Increase frequency of gas-in-oil sampling to a monthly basis with additional samples taken based on dc or harmonic levels.

2. Install on-line hydrogen monitors set to alarm at a level of 200 ppm of hydrogen, and again at 1000 ppm of hydrogen dissolved in the oil

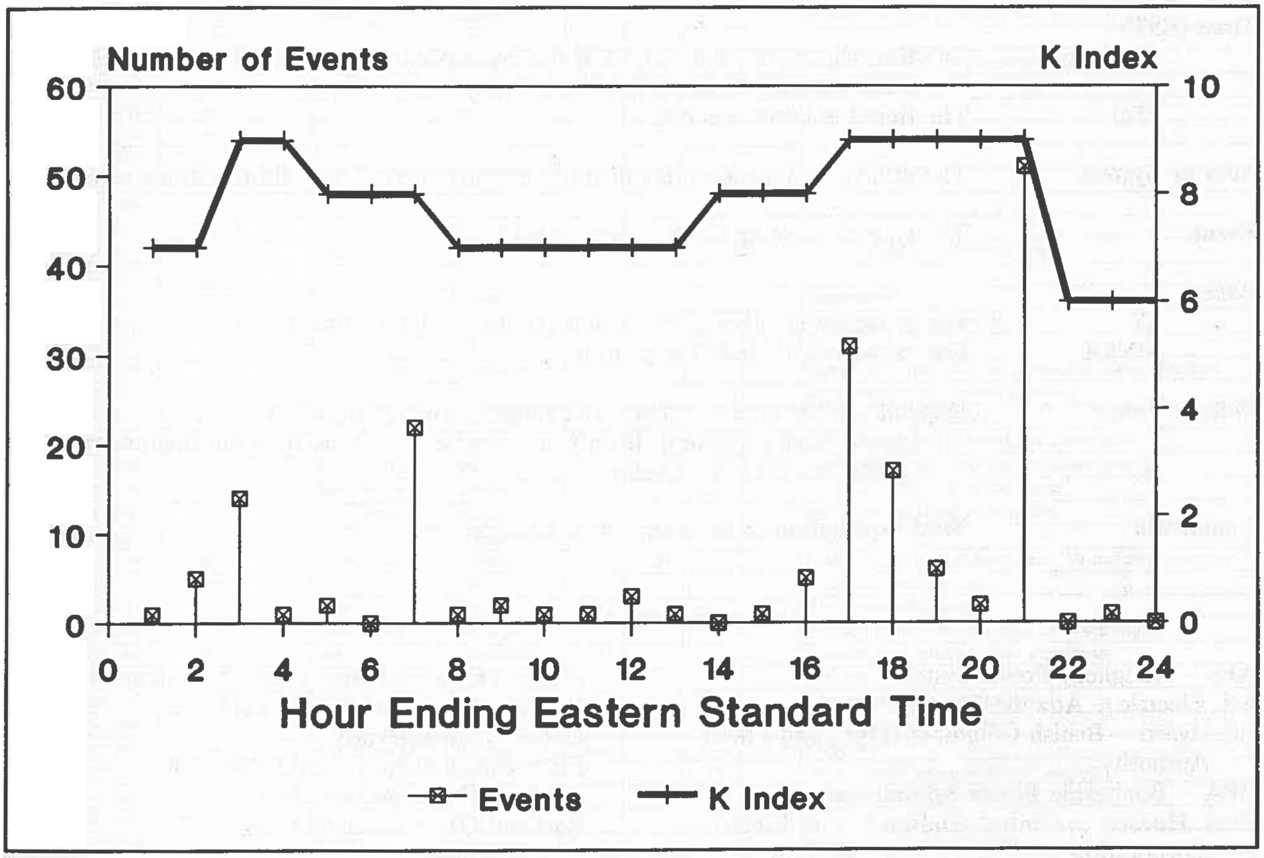
3. Trip the transformer for operation of the gas accumulation detector (200 cc of free gas).

4. Enable the transformer sudden pressure relay tripping during the periods of high solar disturbances.

5. Perform weekly inspections, particularly noting abnormal sounds, any tank discoloration due to heating, and the gas accumulator reading.

Chronology of Reported Events

Graph 1 is a histogram of the events that were recorded on March 13, 1989 related to the geomagnetic disturbance. These events are listed on the following pages.



Graph 1 - *Events and K intensity recorded during March 13, 1989 GMD*

Explanation of GMD Events Chronology

A chronology of events recorded during the period March 11-14, 1989 related to the geomagnetic disturbance is listed on the following pages. An explanation of each data column follows:

Event #	Reference number for each event.
Date	The date the event occurred.
Time (EST)	
At (From)	The time the event occurred, or, if the event occurred over a period, the time the event started. (Eastern Standard Time)
(To)	The time the event was over.
Area or System	The utility, pool, or area in which the event occurred. See abbreviations below.
Event	The type of event or the K value at that time.
Base	
kV	For capacitor or other transmission events, the base voltage.
MVAR	For capacitors, their MVAR rating.
Voltage Range	Depends on the type of event: The range of voltage or MVAR fluctuations from **Low** to **High** or values. If only one number is shown, then the fluctuation ranged from 0 to that value.
Comments	Brief explanation of the event or its location.

Area or System Abbreviations

APS — Allegheny Power System
Atl. Electric — Atlantic Electric
BC Hydro — British Columbia Hydro and Power Authority
BPA — Bonneville Power Administration
Cent. Hudson — Central Hudson Gas & Electric Corporation
CPA — Cooperative Power Association
East ND — Eastern North Dakota
HQ — Hydro–Québec
IIGE — Iowa–Illinois Gas and Electric Company
LILCO — Long Island Lighting Company
Man. Hydro — Manitoba Hydro
Minn. Power — Minnesota Power Company
Nebraska — Nebraska Public Power District
NEPOOL — New England Power Pool
NIMO — Niagara Mohawk Power Corporation
NSP — Northern States Power Company
NYPP — New York Power Pool
OH — Ontario Hydro
PE — Philadelphia Electric Company
PJM — PJM Interconnection
Portland GE — Portland General Electric Company
SC Edison — Southern California Edison Company
UPA — United Power Association
Va. Pwr. — Virginia Power
WAPA - Western Area Power Administration
WAPA-Fargo — Western Area Power Administration
WEP — Wisconsin Electric Power Company
WKPL — West Kootenay Power, Ltd.
WPL — Wisconsin Power & Light Company
WWPC — Washington Water Power Company

Chronology of Reported Events (cont.)

Event #	Date	Time (EST)		Area or System	Event	Base		Voltage Range		Comments
		At (From)	(To)			kV	MVAR	Low	High	
1	3/11/89	727		PJM	Oscillograph					Brandon Shores voltage below 224 kV
2	3/11/89	744		PJM	Oscillograph					Brandon Shores voltage at 232
3	3/11/89	1404		PJM	Oscillograph					Granite Substation
4	3/11/89	1422		PJM	Oscillograph					Brandon Shores
5	3/12/89	NA		SC Edison	Noise					115/55 kV transformer near Bishop CA
6	3/12/89	3		PJM	Alarm					Permissive trip & pilot relay alarms
7	3/12/89	100			K2					
8	3/12/89	119		PJM	Alarm					Backup permissive trip monitor alarms
9	3/12/89	138		PJM	Alarm					Alarms reset
10	3/12/89	400			K2					
11	3/12/89	700			K3					
12	3/12/89	1000			K3					
13	3/12/89	1300			K4					
14	3/12/89	1600			K3					
15	3/12/89	1900			K3					
16	3/12/89	2029		Man. Hydro	Alarm					Neg. seq. alarm at Dorsey station
17	3/12/89	2200			K6					
18	3/12/89	2215		OH	Oscillograph					Essa station
19	3/13/89	0	100	PJM	Noise					Calvert Cliffs GSU transformer
20	3/13/89	100			K7					
21	3/13/89	119		Minn. Power	Capacitor	230	70			Forbes substation. Tripped by neutral overcurrent relay
22	3/13/89	119		Man. Hydro	Alarm					Negative sequence alarms at Dorsey
23	3/13/89	119		NIMO	Capacitor					Reynolds Rd. capacitor trip
24	3/13/89	200		Man. Hydro	Alarm					Grand Rapids unit #1 phase unbalance alarm
25	3/13/89	239		Man. Hydro	MVAR			−140	280	Dorsey synchronous condenser output varying
26	3/13/89	239	247	Man. Hydro	Voltage			−2.5		Winnipeg voltage. Freq. −0.04 Hz
27	3/13/89	243		Minn. Power	Capacitor					Numerous banks switched on line
28	3/13/89	243		Minn. Power	Voltage	235		226		
29	3/13/89	245		Minn. Power	Capacitor	115	37			Lost capacitor bank at Nashwauk. Neut overcurrent relay
30	3/13/89	245		HQ	SVC					Hydro–Quebec blackout
31	3/13/89	245		PJM	MVAR					MVAR generation swing
32	3/13/89	245		Man. Hydro	Generator					Brandon station. Ghost marks on #5 slip rings.
33	3/13/89	245		OH	Generator					Harmon Hydro trips on phase unbalance
34	3/13/89	245		WAPA–Fargo	SVC					SVC trip
35	3/13/89	246	255	WAPA	SVC					Tripped on harmonic unbalance
36	3/13/89	246		OH	Generator					Harmon phase unbalance
37	3/13/89	255		WAPA–Fargo	Voltage	230		−8	14	Fargo bus
38	3/13/89	258	303	Man. Hydro	MVAR			−130		Dorsey synchronous condenser varying
39	3/13/89	335	340	Man. Hydro	MVAR			−125	25	Dorsey synchronous condenser varying
40	3/13/89	400			K9					
41	3/13/89	458		NYPP	Generator					Poletti unit tripped (700 MW)
42	3/13/89	458		NYPP	Generator					Poletti trips on lost exciter control
43	3/13/89	606		NIMO	Capacitor					Rotterdam capacitor trip
44	3/13/89	608		Cent. Hud.	Capacitor	69				Pulvers Corners capacitor trip
45	3/13/89	610	630	PJM	Voltage	500		−6	14	Voltage swings at Whitpain
46	3/13/89	613		NIMO	Capacitor					Reynolds Rd. capacitor trip
47	3/13/89	615		APS	Capacitor	138	44			7 Capacitors tripped
48	3/13/89	615		Va. Pwr.	Capacitor	230	162			Loudoun
49	3/13/89	617		PJM	Oscillograph					Peach Bottom and Whitpain
50	3/13/89	618		NIMO	Capacitor					Cortland and Teall Ave. capacitor trip
51	3/13/89	618		PJM	Recorder					Alburtis fault recorder
52	3/13/89	618		PJM	MW					Safe Harbor and Brunner generation swings
53	3/13/89	618		Va. Pwr.	Capacitor	230	162			Carson
54	3/13/89	618		Va. Pwr.	Capacitor	115	54			Virginia Beach
55	3/13/89	619		Va. Pwr.	Capacitor	230	117			Chuckatuck
56	3/13/89	619		PJM	Recorder					Wescosville fault recorder for no reason
57	3/13/89	619		Cent. Hud.	Capacitor	115				Hurley Ave. capacitor trip
58	3/13/89	620		Va. Pwr.	Capacitor	230	117			Yadkin
59	3/13/89	624		Va. Pwr.	Capacitor	230	164			Elmont
60	3/13/89	624		Va. Pwr.	Capacitor	230	162			Dooms
61	3/13/89	624		OH	Oscillograph					Essa and Bruce A
62	3/13/89	625		Va. Pwr.	Capacitor	230	162			Valley
63	3/13/89	630		Atl. Elec.	MVAR					Increase in MVAR generation
64	3/13/89	700		HQ	Restoration					25% load restored (5,000 MW)
65	3/13/89	700			K8					

Chronology of Reported Events (cont.)

Event #	Date	Time (EST) At (From)	(To)	Area or System	Event	Base kV	MVAR	Voltage Range Low	High	Comments
66	3/13/89	800	1015	PJM	Noise					Calvert Cliffs GSU transformer
67	3/13/89	825		WWPC	Radio					Radio problems
68	3/13/89	900		HQ	Restoration					48% load restored (10,500 MW)
69	3/13/89	926		Man. Hydro	Line	230				Radisson-Churchill line trip by 50N relay
70	3/13/89	1000			K7					
71	3/13/89	1100		HQ	Restoration					64% load restored (14,200 MW)
72	3/13/89	1102		Man. Hydro	Line	230				Radisson-Churchill line trip by 50N relay
73	3/13/89	1151		Man. Hydro	Line	230				Radisson-Churchill line trip by 50N relay
74	3/13/89	1159		Man. Hydro	Line	230				Radisson-Churchill line trip by 50N relay
75	3/13/89	1300			K7					
76	3/13/89	1300		HQ	Restoration					83% load restored (17,500 MW)
77	3/13/89	1405		Portland GE	Noise					360 Hz noise at Boardman
78	3/13/89	1528		Man. Hydro	Line	230				Radisson-Churchill line trip by 50N relay
79	3/13/89	1545		Cent. Hud.	Capacitor					Hurley Ave. capacitor trip
80	3/13/89	1600	2200	Atl. Elec.	Voltage					
81	3/13/89	1600			K8					
82	3/13/89	1600	2200	Atl. Elec.	MVAR					
83	3/13/89	1602		Va. Pwr.	Capacitor	230	162			Valley
84	3/13/89	1610		PJM	Noise					Calvert Cliffs GSU transformer
85	3/13/89	1615		PJM	Generator					Mickleton CT trip (related to SMD?)
86	3/13/89	1625		PJM	Oscillograph					TMI oscillograph on 230 kV
87	3/13/89	1626		PJM	Oscillograph					Whitpain
88	3/13/89	1630		SC Edison	Current					Elevated neutral current at 220/66 kV transformer
89	3/13/89	1630		SC Edison	Current					Neutral current of 15–30 A at 500/220 transformer
90	3/13/89	1630		SC Edison	Noise					500/220 kV transformer at Mira Loma
91	3/13/89	1640	1700	PJM	Voltage	500		–18	18	Whitpain
92	3/13/89	1644		PJM	Alarm					Conastone substation general alarm
93	3/13/89	1644		PJM	Capacitor					All capacitors tripped at Hosensack and TMI
94	3/13/89	1645	2000	WPL	Voltage	138		–2	2	Various voltage problems. Regulators hunting
95	3/13/89	1649		PJM	Recorder					Alburtis-Wescosville fault recorder
96	3/13/89	1651		NIMO	Capacitor					Cortland, Teall Ave, Porter caps. trip
97	3/13/89	1653		NIMO	Capacitor					Reynolds Rd. capacitor trip
98	3/13/89	1654		PJM	Alarm					Conastone substation general alarm
99	3/13/89	1655	1715	Minn. Power	Voltage	230		237	240	System voltage
100	3/13/89	1655		Atl. Elec.	Voltage	69		–2		
101	3/13/89	1655		Atl. Elec.	MVAR					
102	3/13/89	1658		BC Hydro	Voltage	500		–20	20	4% voltage fluctuation
103	3/13/89	1658		OH	Demand					Demand fluctuating by 200 MW
104	3/13/89	1658	1700	WAPA	Converter					Miles City converter tripped
105	3/13/89	1658		BPA	Noise					Ross Substation (near Vancouver, WA)
106	3/13/89	1658		WAPA	Line					Miles City–Custer. By neg. seq. relay
107	3/13/89	1658		WKPL	Alarm					Negative sequence alarms
108	3/13/89	1658		BPA	Capacitor	115				Tripped by neutral time ground at 4 substations
109	3/13/89	1658		BPA	Transformer					Hunting between taps 14 and 6
111	3/13/89	1700		UPA	Voltage	230				Fluctuations at Wilmer substation
112	3/13/89	1700		LILCO	Voltage					Voltage fluctuations
113	3/13/89	1700		IIGE	Voltage					Minor system fluctuations
114	3/13/89	1700	2100	WEP	Noise					Low frequency noise at Point Beach Plant
115	3/13/89	1701		PJM	Capacitor	500				Hosensack capacitors tripped
116	3/13/89	1701		NIMO	Capacitor					Cortland capacitor trip
117	3/13/89	1701		Va. Pwr.	Capacitor	230	117			Chuckatuck
118	3/13/89	1701		Va. Pwr.	Capacitor	230	162			Carson
119	3/13/89	1701		OH	Voltage					Overvoltage alarms on Waubaushene
120	3/13/89	1701		OH	Oscilligraph					Essa station
121	3/13/89	1703		Va. Pwr.	Capacitor	230	108			Idylwood
122	3/13/89	1708		UPA	Capacitor					Cap at Milaca sub switched in automatically
123	3/13/89	1709	1725	WAPA	Converter					Miles City converter tripped
124	3/13/89	1709		WAPA	Transformer					Trip
125	3/13/89	1709		WAPA–Fargo	Voltage	230		–8	14	Fargo bus
126	3/13/89	1709		WAPA	Line					Miles City–Custer. By neg. seq. relay
127	3/13/89	1709	1827	WAPA	Relay					Boie substation isolated by diff relay
128	3/13/89	1711		NIMO	Capacitor					Porter capacitor trip
129	3/13/89	1720		UPA	Voltage	230				Swings on Willmer 230 kV system
130	3/13/89	1723		Va. Pwr.	Capacitor	230	164			Elmont

Chronology of Reported Events (cont.)

Event #	Date	Time (EST)		Area or System	Event	Base		Voltage Range		Comments
		At (From)	(To)			kV	MVAR	Low	High	
131	3/13/89	1742		PJM	Alarm					500 kV line carrier low signal alarm
132	3/13/89	1827		Va. Pwr.	Capacitor	230	162			Carson
133	3/13/89	1829		Va. Pwr.	Capacitor	230	162			Yadkin
134	3/13/89	1830		PE	Voltage	500		−10		Peach Bottom
135	3/13/89	1832		NEPOOL	Capacitor					Blown fuse at Orrington
136	3/13/89	1840		Atl. Elec.	MVAR					
137	3/13/89	1858		NEPOOL	Oscillograph					Maxcys substation
138	3/13/89	1900			K9					
139	3/13/89	1910		Va. Pwr.	Capacitor	230	164			Elmont
140	3/13/89	2000		NEPOOL	MVAR					Connecticut Yankee 50 MVAR increase
141	3/13/89	2010	2024	NEPOOL	MVAR					Merrimack units MVAR swings
142	3/13/89	2010	2020	NEPOOL	Voltage	230		228	234	Comerford 230 kV station voltage swing
143	3/13/89	2010	2020	NEPOOL	Voltage	230		232	236	Moore 230 kV station voltage swing
144	3/13/89	2010	2024	NEPOOL	MVAR			100	200	Newington MVAR and voltage swing
145	3/13/89	2010	2020	NEPOOL	Voltage	345		351	354	Vermont Yankee 345 kV voltage swing
146	3/13/89	2010	2100	LILCO	Voltage					Severe voltage fluctuations
147	3/13/89	2010	2030	NEPOOL	MVAR					Salem Harbor & New Boston minor swings
148	3/13/89	2010	2020	NEPOOL	MVAR			4	8	Schiller station
149	3/13/89	2010	2024	NEPOOL	Voltage	345		350	336	Maine Yankee voltage drop
150	3/13/89	2010	2030	NEPOOL	Voltage	345		357	360	Mystic 345 kV stations voltage swing
151	3/13/89	2011		NIMO	Capacitor					Reynolds Rd. capacitor trip
152	3/13/89	2011		Va. Pwr.	Capacitor	230	162			Dooms
153	3/13/89	2012	2020	NEPOOL	Voltage			111.6	109.8	Bennington voltage fluctuations
154	3/13/89	2012	2016	NEPOOL	Voltage			355	352	Long Mountain voltage drop
155	3/13/89	2012	2020	NEPOOL	Voltage			232	227	Bear Swamp voltage fluctuations
156	3/13/89	2012	2024	NEPOOL	MVAR			100	300	Maine Yankee MVAR output swing
157	3/13/89	2012	2016	NEPOOL	Converter					Comerfored filter bank tripped
158	3/13/89	2013		NEPOOL	MVAR					Mystic 100 MVAR swing
159	3/13/89	2014		PJM	Recorder					Alburtis–Wescosville fault recorder
160	3/13/89	2014	2028	NEPOOL	Voltage			355	352	Berkshire voltage drop
161	3/13/89	2014		NYPP	Voltage					Voltage decline at Goethals, Rainey, Gilboa, Edic
162	3/13/89	2015	2030	NEPOOL	MW					Deerfield generation swings
163	3/13/89	2015	2030	NEPOOL	MVAR					Brayton Pt reactive output
164	3/13/89	2015	2030	NEPOOL	MVAR					Canal Station 20 MVAR swing
165	3/13/89	2015		PJM	Alarm					Juniata
166	3/13/89	2015	2030	NEPOOL	MVAR			190	325	Millstone Unit 3 MVAR swings
167	3/13/89	2015	2030	NEPOOL	Voltage	345		358	359.5	Millstone Station voltage swings
168	3/13/89	2015	2030	NEPOOL	Voltage	345		350	353	Brayton Pt voltage dip
169	3/13/89	2015	2030	NEPOOL	Voltage					Webster St. voltage dip and swings
170	3/13/89	2015	2030	NEPOOL	MVAR					Middletown #4 20 MVAR
171	3/13/89	2016		OH	Generator					Phase unbalance at Bruce
172	3/13/89	2016		OH	Capacitor		32			Belleville capacitors trip
173	3/13/89	2017		NEPOOL	Converter					Madawaska dc tie run–back
174	3/13/89	2017		NEPOOL	Voltage	345		−24		Voltage on Orrington 345 kV bus
175	3/13/89	2017		NEPOOL	Capacitor	115	67			Orrington capacitors (1,2,&3) opened and would not close
176	3/13/89	2017		NEPOOL	Voltage					General voltage instability
177	3/13/89	2017		NEPOOL	MVAR					Yarmouth reactive output exceeded 300 MVAR
178	3/13/89	2018		Va. Pwr.	Capacitor	230	162			Ox
179	3/13/89	2019		WEP	Alarm					Point Beach plant
180	3/13/89	2019		UPA	Alarms					Rush City MW and MVAR alarms
181	3/13/89	2020	2030	Atl. Elec.	MVAR		85			
182	3/13/89	2020		APS	Transformer					Autotransformer at Meadowbrook damaged. 9.2 THD
183	3/13/89	2020	2030	Atl. Elec.	Voltage	138	−2.5			
184	3/13/89	2020		OH	Generator					Chats Falls MW and MVAR fluctuations
185	3/13/89	2020		UPA	Converter					Coal Creek pole #2 at 375 kV
186	3/13/89	2021		PJM	Capacitor					TMI capacitors tripped. Returned at 2139
187	3/13/89	2022	2024	UPA	Line	230				Benton Co.–Milaca line opened
188	3/13/89	2022		PJM	Alarm					Conastone
189	3/13/89	2024	2054	CPA	Voltage					Voltage fluctuations
190	3/13/89	2024	2054	CPA	Capacitor					Capacitor banks switched on
192	3/13/89	2032		PJM	Capacitor	69				Nazareth capacitors tripped
193	3/13/89	2200			K9					
194	3/13/89	2300	2400	PE	Voltage	500		−10		
195	3/14/89	100			K6					

Chronology of Reported Events (cont.)

Event #	Date	Time (EST)		Area or System	Event	Base		Voltage Range		Comments
		At (From)	(To)			kV	MVAR	Low	High	
196	3/14/89	153		Nebraska	Alarm					Unexplained frequency alarms
197	3/14/89	233		Nebraska	Alarm					Unexplained frequency alarms
198	3/14/89	240		Nebraska	Alarm					Unexplained frequency alarms
199	3/14/89	240	250	East ND	Voltage	230		–3	15	
200	3/14/89	400			K8					
201	3/14/89	628		PJM	Recorder					Wescosville fault recorder
202	3/14/89	700			K4					
203	3/14/89	819		PJM	Alarm					Juniata miscellaneous alarms
204	3/14/89	1000			K4					
205	3/14/89	1300			K4					
206	3/14/89	1600			K6					
207	3/14/89	1720	1730	East ND	Voltage	230		–3	15	
208	3/14/89	1900			K7					
209	3/14/89	2020	2040	East ND	Voltage	230		–3	15	
210	3/14/89	2104		Man. Hydro	Alarm	500				SMD alarm at Dorsey station
211	3/14/89	2200			K5					