The 1989 Blackout

By: Ben Hutchins, WPP

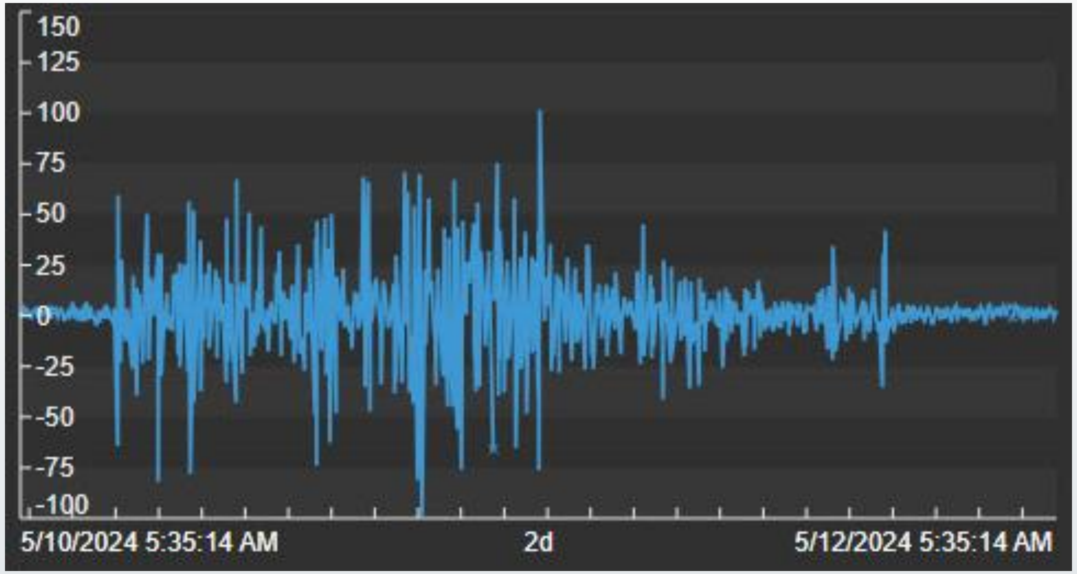
For: WECC RAC, July 10th, 2024

EOP-010-1
TPL-007-4

Relevance

May 10th – 12th Geomagnetic Storm

100 amps recorded on a BPA transformer neutral!



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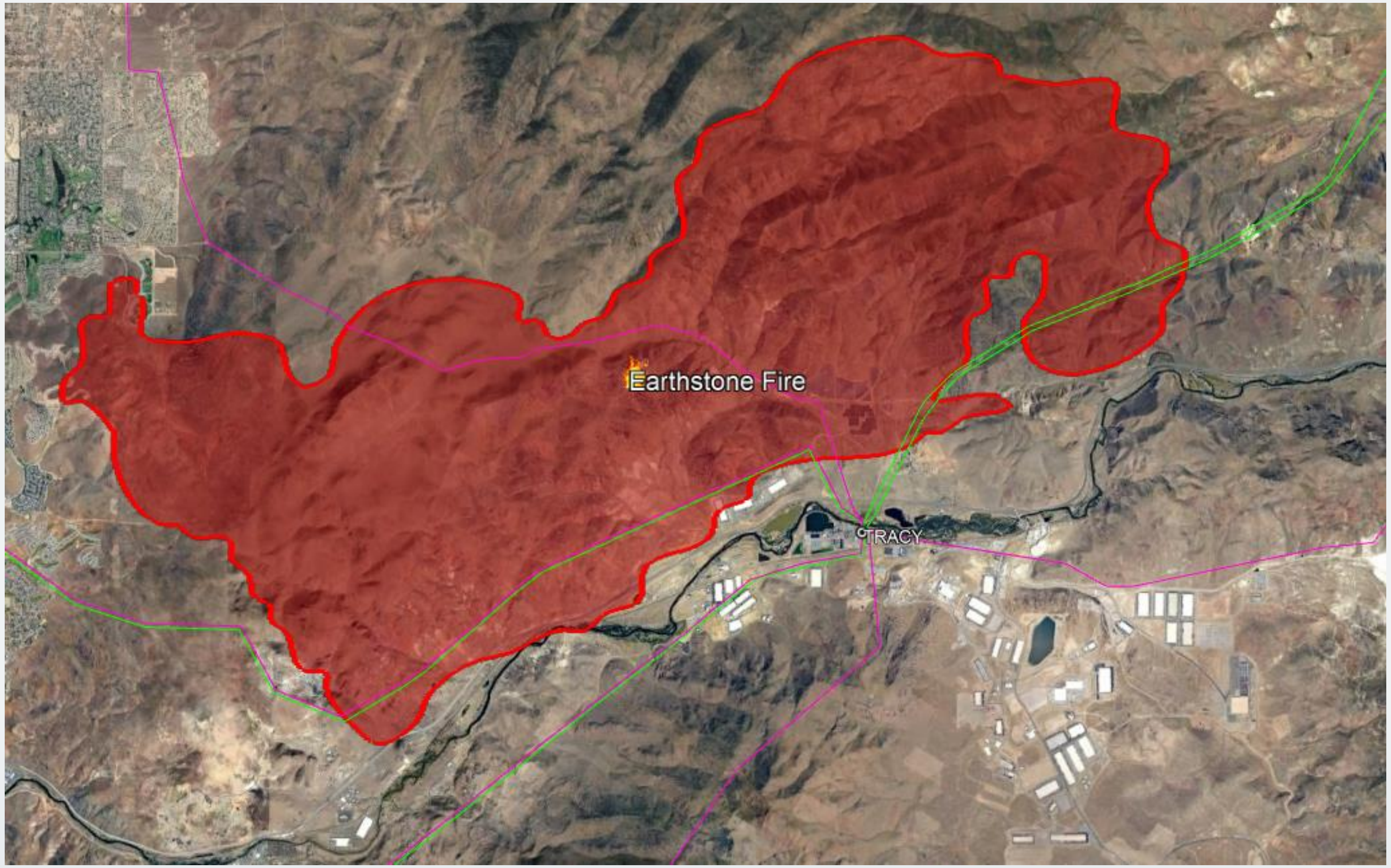
Note: Sometimes in Operations… [Single Event] >> [N-1]



*Public Substations and Lines Layers by EIA
Google Earth KML with Colors by Ben Hutchins (Link)

2017 Earthstone Fire Boundary from KOLO TV (Link)

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A Day In The Office

1989 - You Work at Hydro Quebec

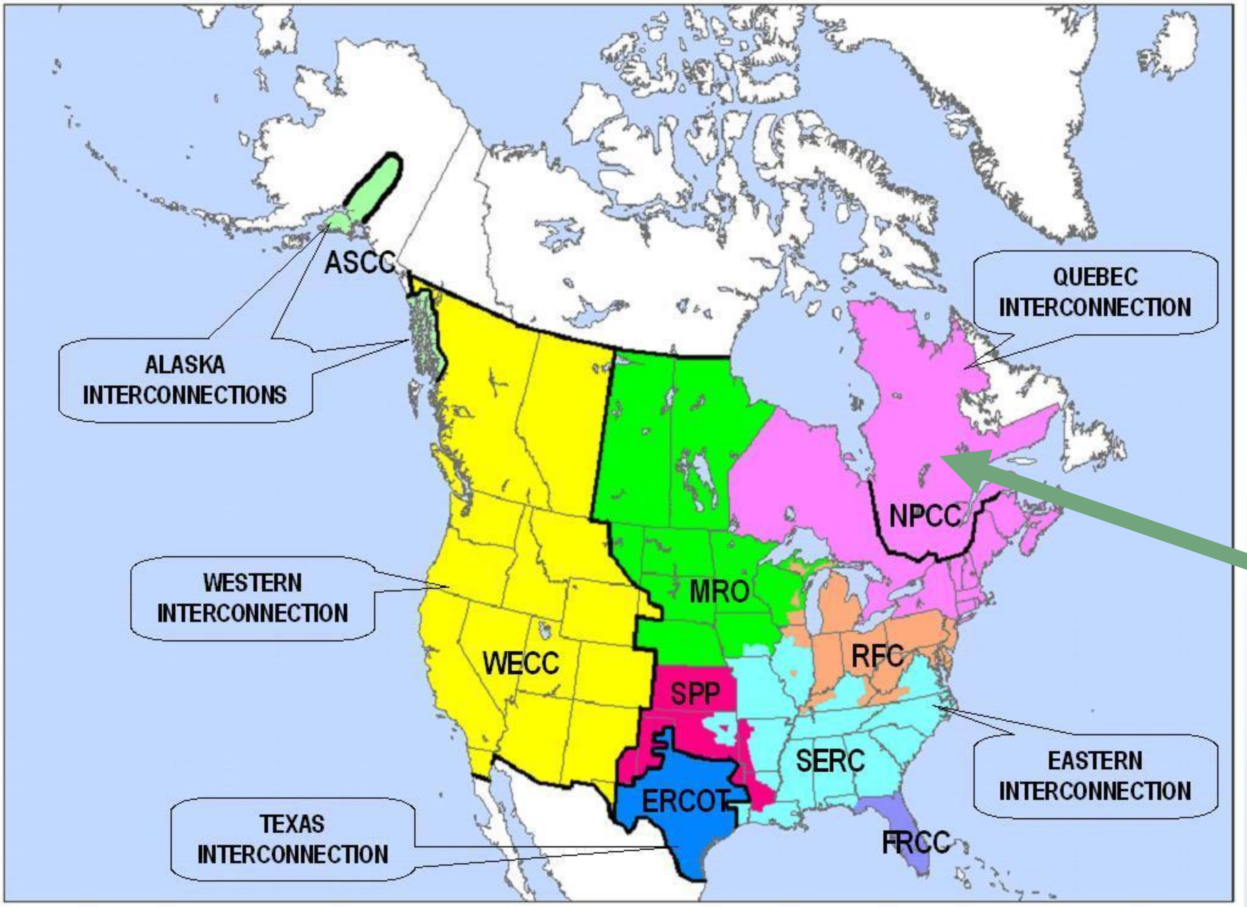
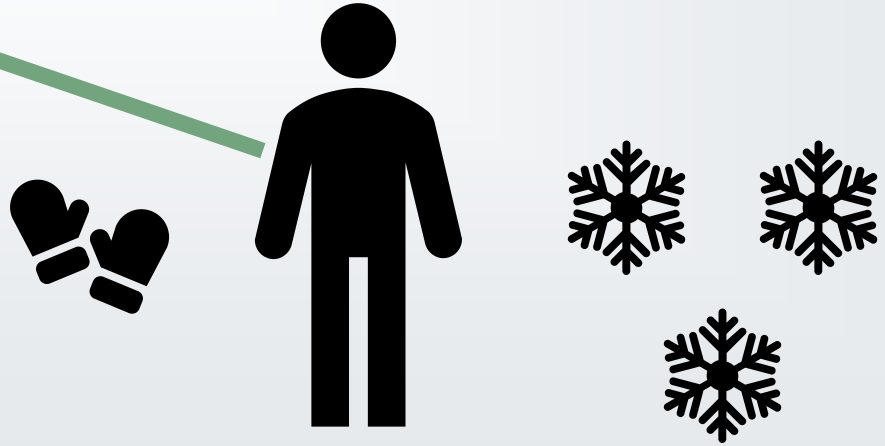


Image from Wikipedia

The Date is Sunday, March 12th, 1989.
You are a new operator at Hydro Quebec, with a 12AM to 8AM shift.

Your alarm wakes you up at 10 PM, so you get up and get ready.
You leave your house for work at 11 PM.
It's 19F outside, so you bring your jacket and gloves.



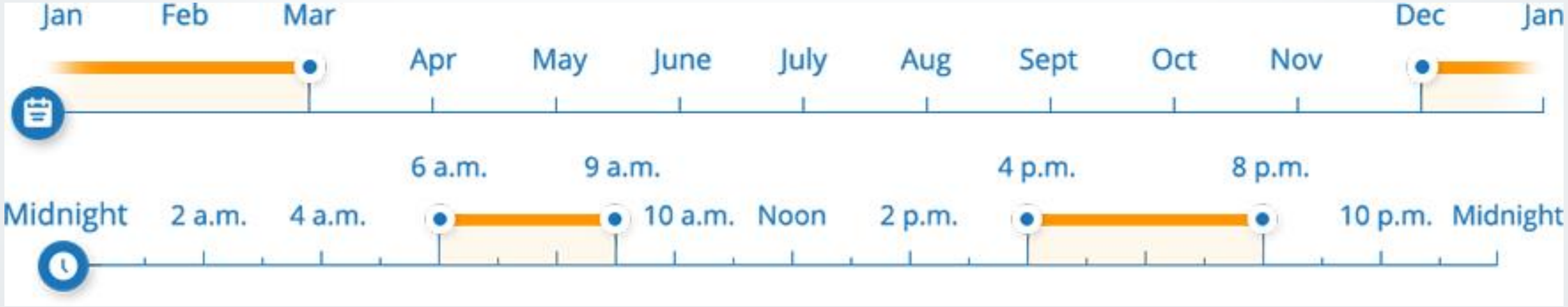
1989 – Night Shift

You get to the office a little bit early, take off your jacket and gloves, say “hi” to you co-workers.

Start up the coffee pot. Get a big cup-o-Joe.
Sit down, start looking at the state of the system.

March 13th, 1989

- Your training says that load-peaks during cold weather will happen around 6A-9A every morning, and 4P-8P every night.
- You’re expecting a load peak sometime this morning, but there’s plenty of time to prepare.



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March 13th, 1989

Event #	Date	Time (EST) At (From)	(To)	Area or System	Event	Base kV	MVAR	Voltage Range Low	High	Comments
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

12:00 AM

You sit down and review present logs.

- PJM had a couple events, but nothing particularly unusual.

- Everything for your area seems totally normal.

6 AM to 9 AM you expect load to pickup, but so far load isn't very high. It's the middle of the night.

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March 13th, 1989

Event #	Date	Time (EST)		Area or System	Event	Base		Voltage Range		Comments
		At (From)	(To)			kV	MVAR	Low	High	
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

02:35 AM 

Slow shift so far.

Voltage got a little low, so your team switched on some more capacitors. Fairly normal.

Only a couple items seem out of place.

- Negative sequence alarm at Dorsey.
- Phase unbalance at Grand Rapids.

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March 13th, 1989

Manitoba

Minnesota Power

Hydro Quebec

PJM

The events seem far away so far

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March 13th, 1989

Event #	Date	Time (EST) At (From)	Time (EST) (To)	Area or System	Event	Base kV	Base MVAR	Voltage Range Low	Voltage Range High	Comments
19	3/13/89	0	100	PJM	Noise					Calvert Cliffs GSU transformer
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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

2:45 AM 

10 Minutes go by.

Events in Minnesota Power and Manitoba Hydro (Far away)

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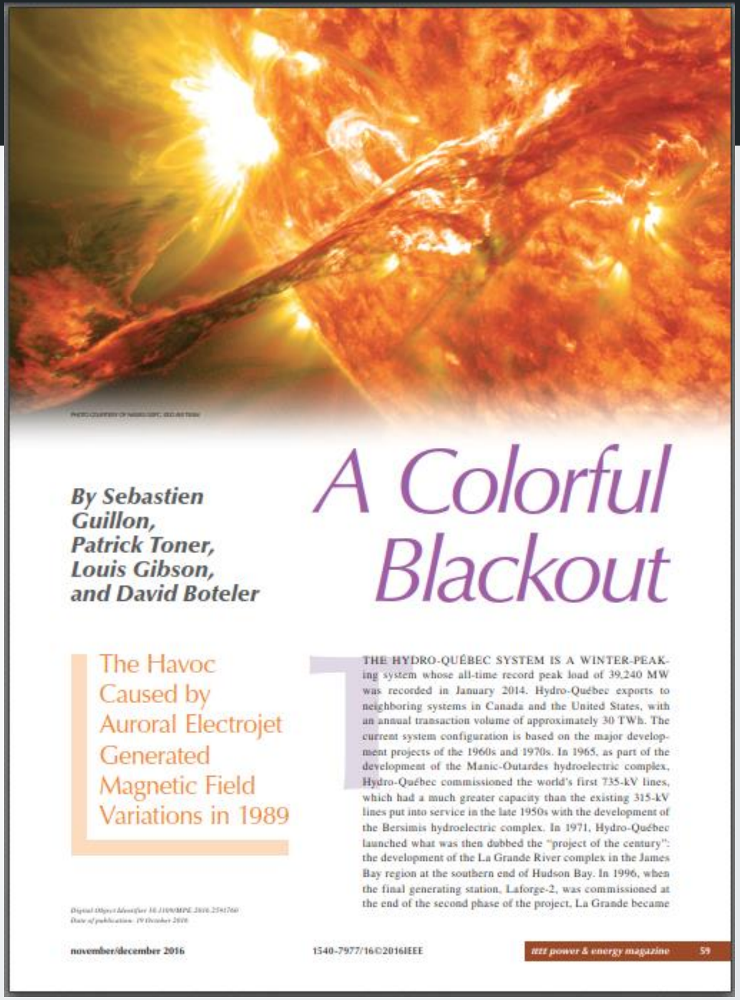
Everything goes dark.

Your emergency lighting kicks on in the office.
You have spilled your coffee.

"At 02:45 a.m. eastern standard Time (EST), Bolduc ventured outside to find complete darkness and silence everywhere. He watched in awe as a fantastic light show swirled in the sky, a dazzling performance of light with colors flourishing and dancing in the night. From 3:00 to 4:30 a.m., Montreal resident Brian Maged watched in amazement at what he said looked like thousands of meteor showers."



A Colorful Blackout

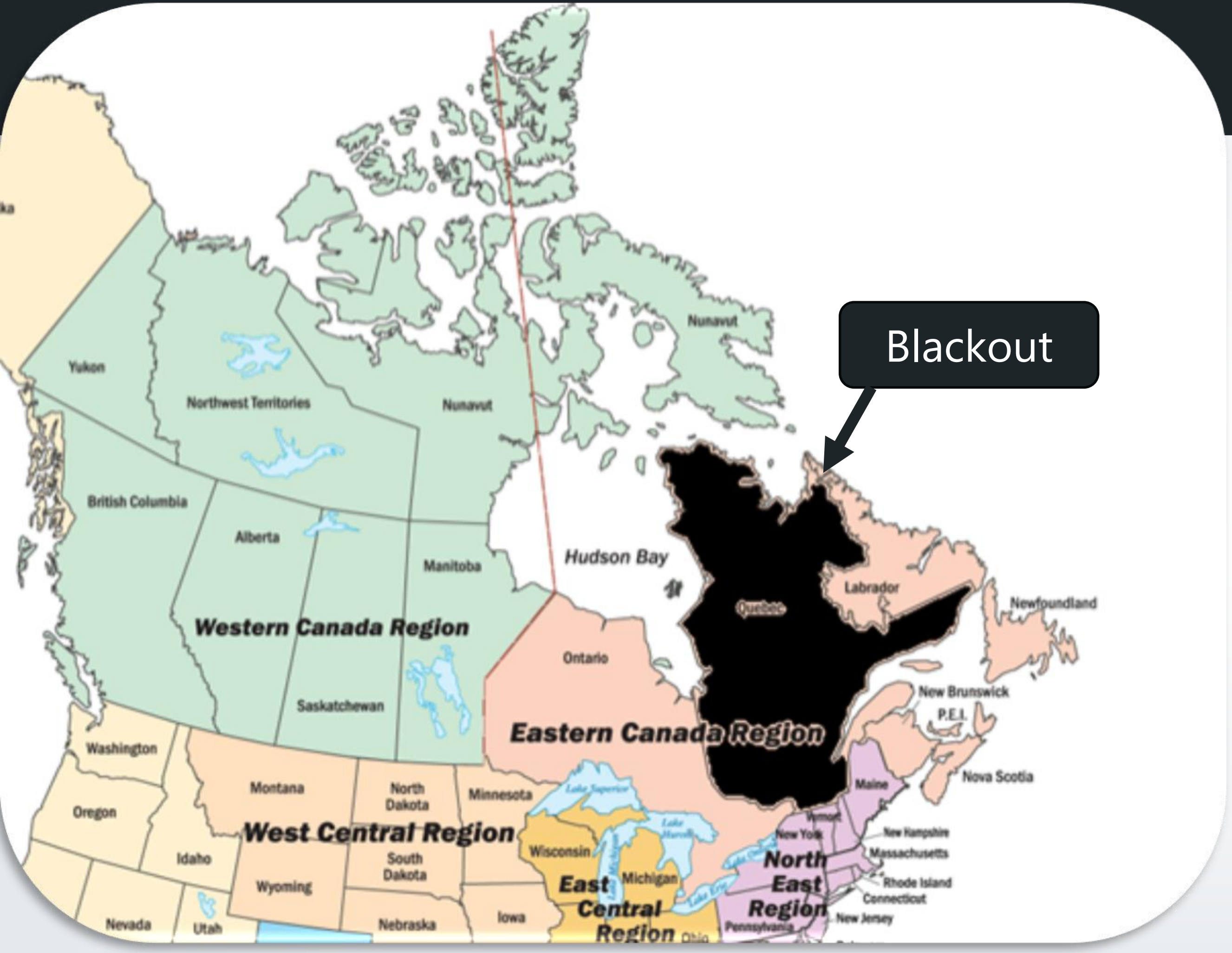
By Sebastien Guillon, Patrick Toner, Louis Gibson, and David Boteler

The Havoc Caused by Auroral Electrojet Generated Magnetic Field Variations in 1989

THE HYDRO-QUÉBEC SYSTEM IS A WINTER-PEAKing system whose all-time record peak load of 39,240 MW was recorded in January 2014. Hydro-Québec exports to neighboring systems in Canada and the United States, with an annual transaction volume of approximately 30 TWh. The current system configuration is based on the major development projects of the 1960s and 1970s. In 1965, as part of the development of the Manic-Outardes hydroelectric complex, Hydro-Québec commissioned the world's first 735-kV lines, which had a much greater capacity than the existing 315-kV lines put into service in the late 1950s with the development of the Bersimis hydroelectric complex. In 1971, Hydro-Québec launched what was then dubbed the "project of the century": the development of the La Grande River complex in the James Bay region at the southern end of Hudson Bay. In 1996, when the final generating station, Laforge-2, was commissioned at the end of the second phase of the project, La Grande became

november/december 2016 1540-7977/16©2016IEEE ieee power & energy magazine 59

IEEE: [A Colorful Blackout: The Havoc Caused by Auroral Electrojet Generated Magnetic Field Variations in 1989]



Your team starts putting together how much has been lost, and planning how to recover.
Everything just got very busy in your office.

You dropped 21 GW of load, and you don't know why.
You're working overtime to black start the system, when you see the news playing in your office.


MARCH 13, 1989
SOLAR FLARE CAUSES
QUEBEC BLACKOUT
CBC NATIONAL NEWS

NERC's Report

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.

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.

*Note: Map is much more recent than 1989 and may have more facilities than existed at that time.

Event	Time	Duration
1	2:44:17	
2	2:44:19	2 s
3	2:44:46	27 s
4	2:45:16	30 s
5	2:45:25	9 s
6	2:45:31	6 s
7	2:45:49	18 s

(4) – (5)
8 Seconds of Rapid Voltage Collapse

(5) – (6)
With generation separated, voltage jumped up, causing faults at:
La Grande-4 T1 Phase C
La Grande-4 T3 Phase A
Némiscau Shunt Reactor's Surge Arrestor

(6) – (7)
Rapid frequency collapse. UFLS schemes picked up, but could not prevent full system collapse.

(7) 2:45:49
Entire System Collapses, in 92 Seconds
21 GW of Load Lost

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Hydro Quebec Map (Link) – Timeline Reference (Link)

Albanel SVC

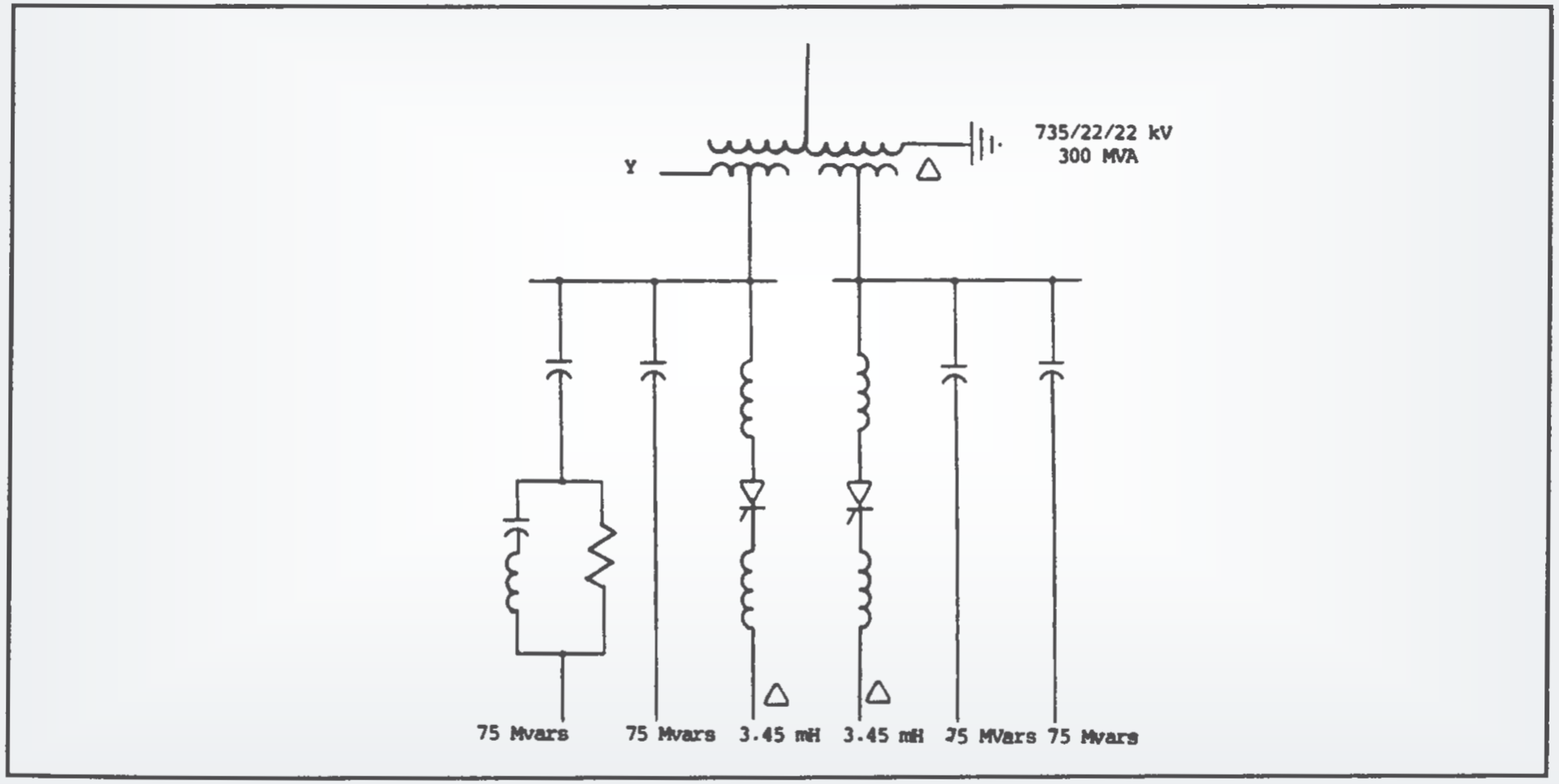

Figure 14 - *One-line diagram of Némiskau/Albanel SVCs*

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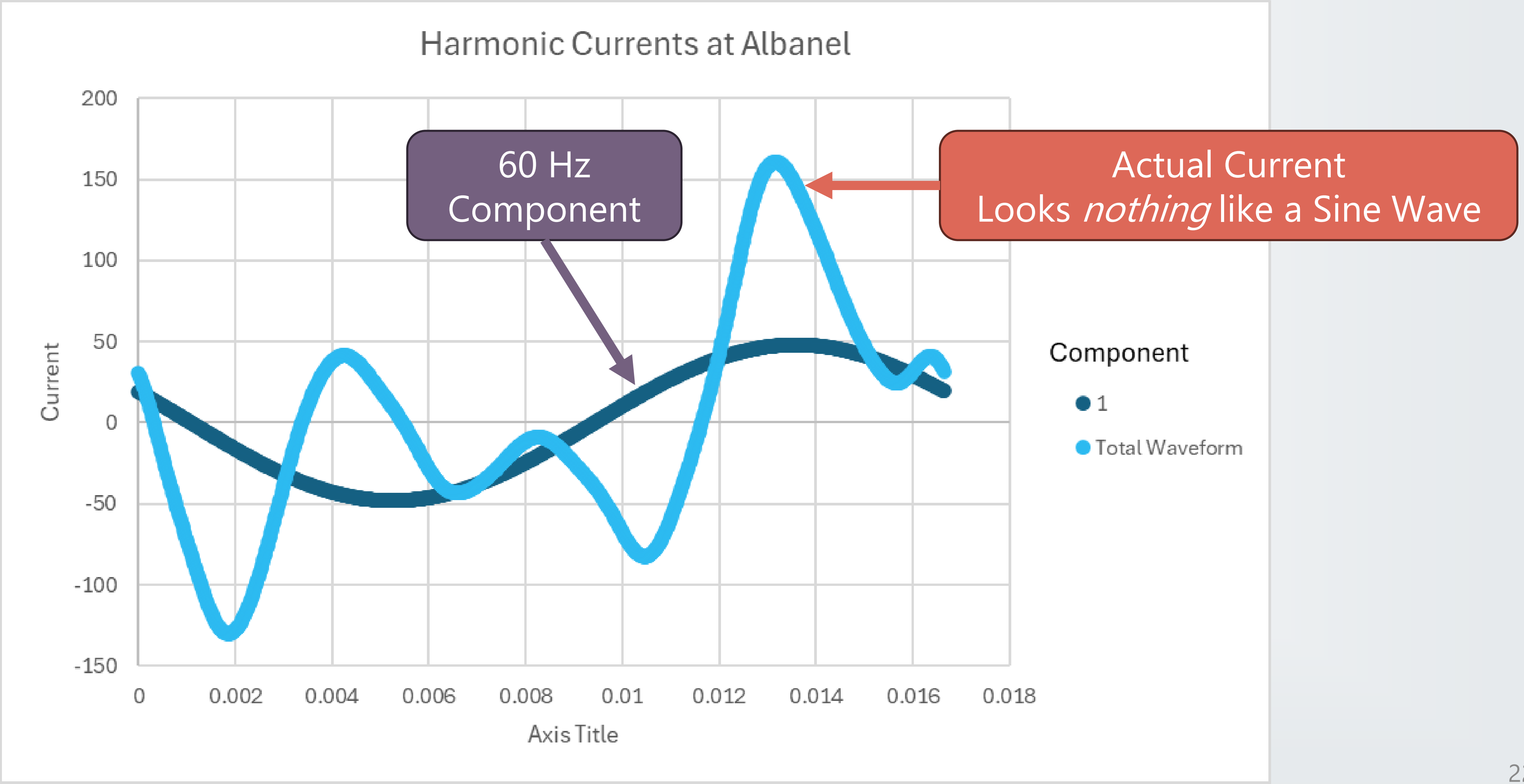
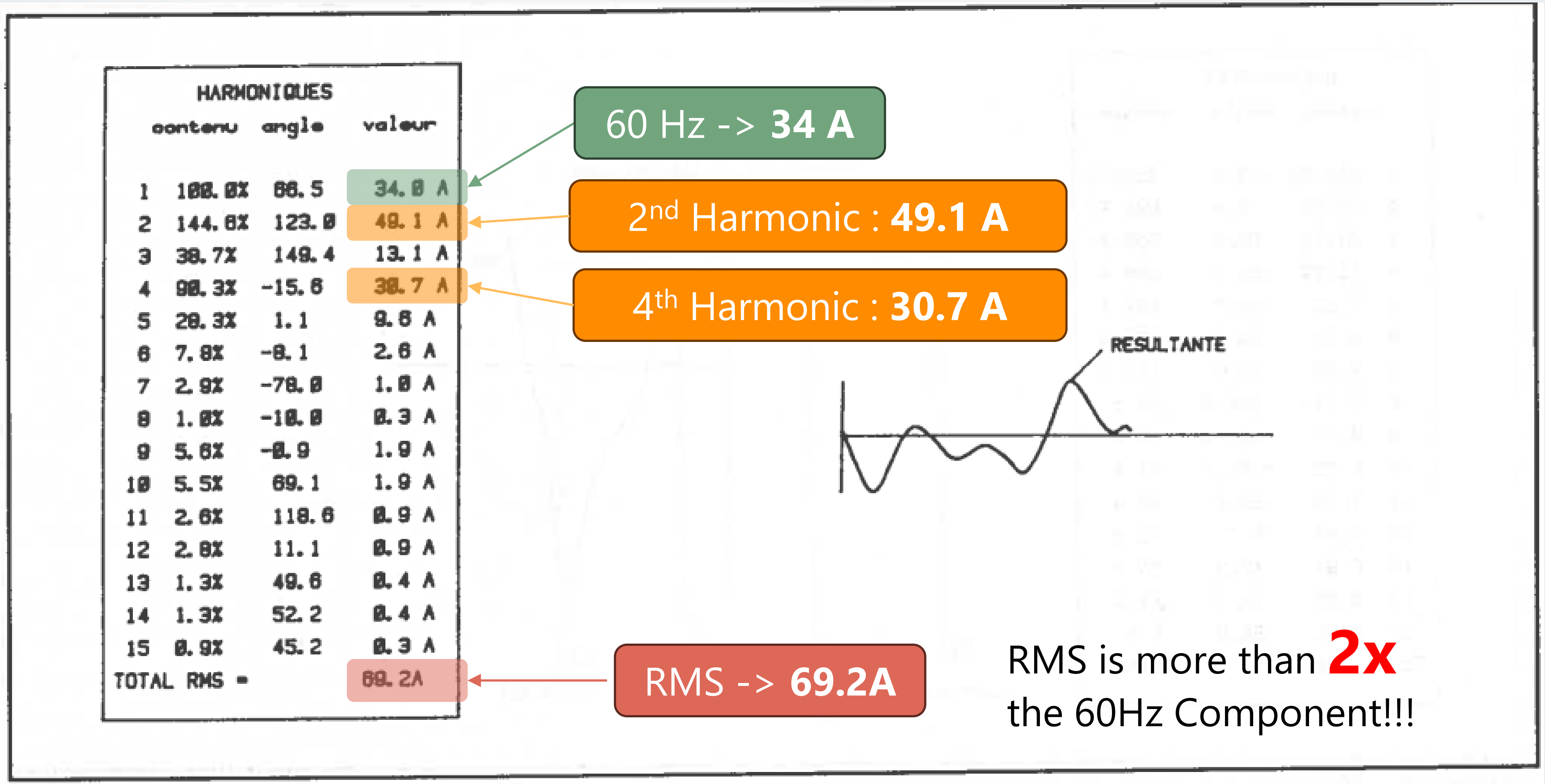
Albanel SVC
Primary (60Hz) vs Total Waveform



Albanel SVC Harmonic Currents

$$Z_c = \frac{1}{j\omega C} = \frac{1}{2\pi f C}$$

Capacitors have lower impedance at higher frequencies



	contenu	angle	valeur
1	100.0%	80.5	34.0 A
2	144.6%	123.0	49.1 A
3	38.7%	140.4	13.1 A
4	90.3%	-15.6	30.7 A
5	28.3%	1.1	9.6 A
6	7.6%	-0.1	2.6 A
7	2.9%	-70.0	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%	110.6	0.9 A
12	2.0%	11.1	0.9 A
13	1.3%	40.6	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*

RMS is more than **2x** the 60Hz Component!!!

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EPRI Guide on GMD Harmonics

Screening Criteria by EPRI (Link)

Shunt Capacitors (Not SVCs)

But similar principles at work

SHUNT CAPACITORS		
Thermal failure, fuse melting, or overload protection trip due to overcurrent.	Capacitors are likely to have high currents where they form resonances with the transmission system at integer harmonic frequencies.	$I_{rms} > 1.35$ p.u. (fundamental and harmonics)[2]
Dielectric failure due to excessive voltage.	Capacitor voltages may have highly amplified harmonic components due to resonances. Peak voltage is dependent on the phase relationship between harmonic and fundamental voltage components.	$THD_V > 10\%$, and $\Sigma V_n > 20\%$.[2,3] Total harmonic distortion (THD)
Capacitor bank protection false trips due to harmonic currents.	Certain protection schemes, such as zero-sequence overvoltage and ground overcurrent	Evaluate in detail any capacitor banks using zero sequence overvoltage or ground

1.35 I_{RMS} PU

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Damaged Equipment

Salem, MA Nuclear Station
Unit 1, 1160 MW
3x406 MVA 1-Phase GSUs

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.

Hydro Quebec

Two La Grande 4 GSUs
Damaged by Over Voltage during separation

La Grande 2 Surge Arrestors

Nemiscau Shunt Reactor
Required factory repair

Albanel SVCs
Capacitor Bank units failed

Nemiscau SVCs
Thyristor Damage

Chibougamau SVC
Phase-C transformer damaged by overvoltage during separation

Widespread Tripping

SVCs!

Capacitors!

Generators!

HVDC!

Lines!

March 1989 Event

- Seven static var compensators (SVCs) tripped in rapid succession in the Hydro Quebec system, resulting in system instability and total blackout of that system. Post-event analysis revealed that harmonic distortion was the direct cause of the SVC trips.
- Widespread capacitor banks trips, including 16 bank trips in the Virginia Power system, 12 in the New York Power Pool (predecessor to NYISO), four at Bonneville Power, seven in the Allegheny Power system, and at least three in the PJM system (including 500 kV capacitor banks).
- Generator trips due to negative sequence or phase imbalance protection in the Manitoba Hydro and Ontario Hydro systems (including one major nuclear unit).
- Static var compensator trip in the WAPA system.
- HVDC system trip at the WAPA Miles City station and an HVDC filter trip at the Comerford converter station in the New England system.
- Transmission line trips at Manitoba Hydro and WAPA.

7 www.epri.com EPRI ELECTRIC POWER RESEARCH INSTITUTE

EPRI Harmonic Assessment Presentation (Link)

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Blackouts, Damaged Equipment, Tripped Equipment

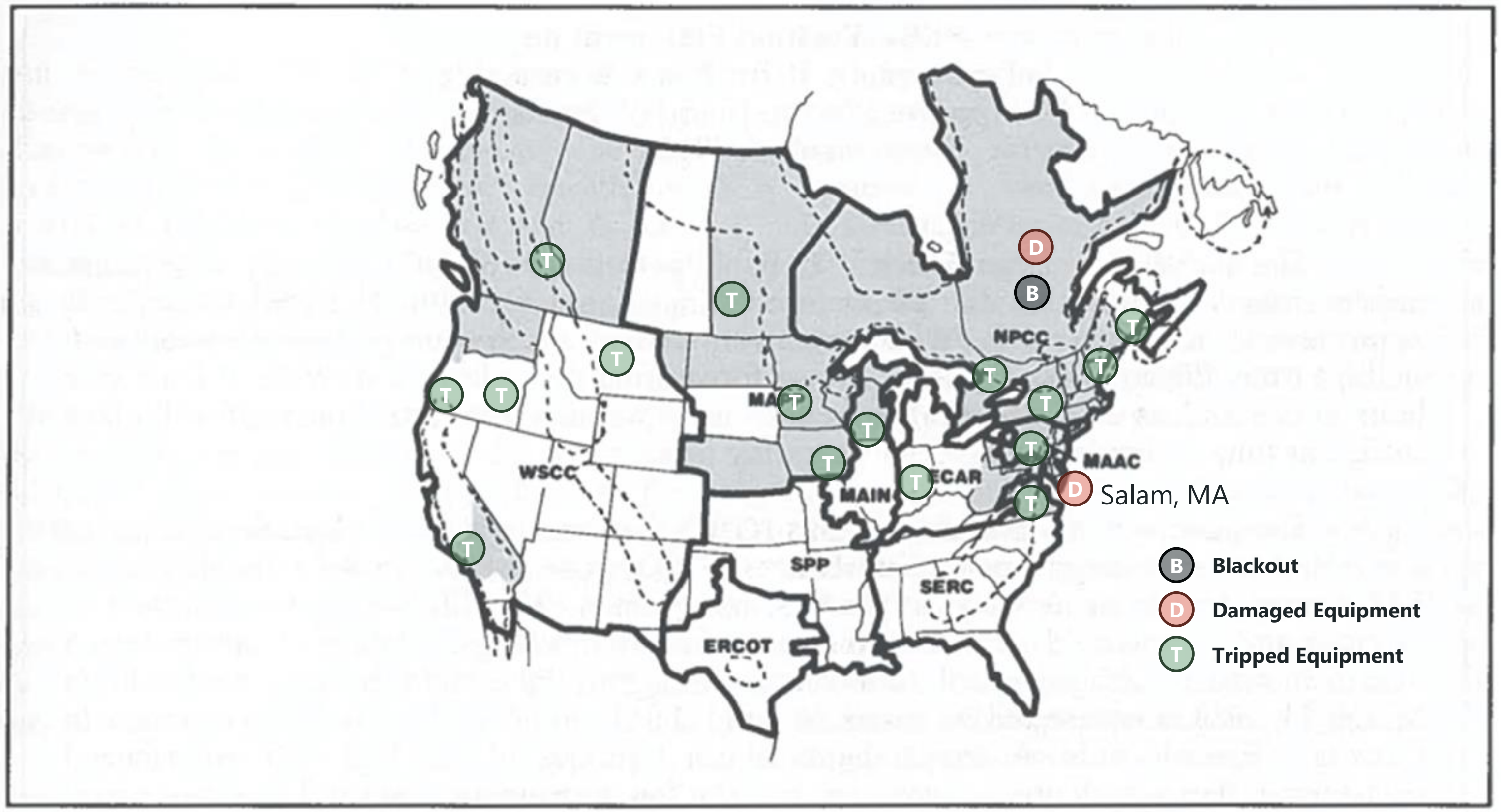


Figure 9 - *States and provinces affected by the March 13, 1989 geomagnetic disturbance are shaded. Areas of igneous rock formations also shown.*

A Couple Notes

1. It wasn't just Quebec impacted by the storm.

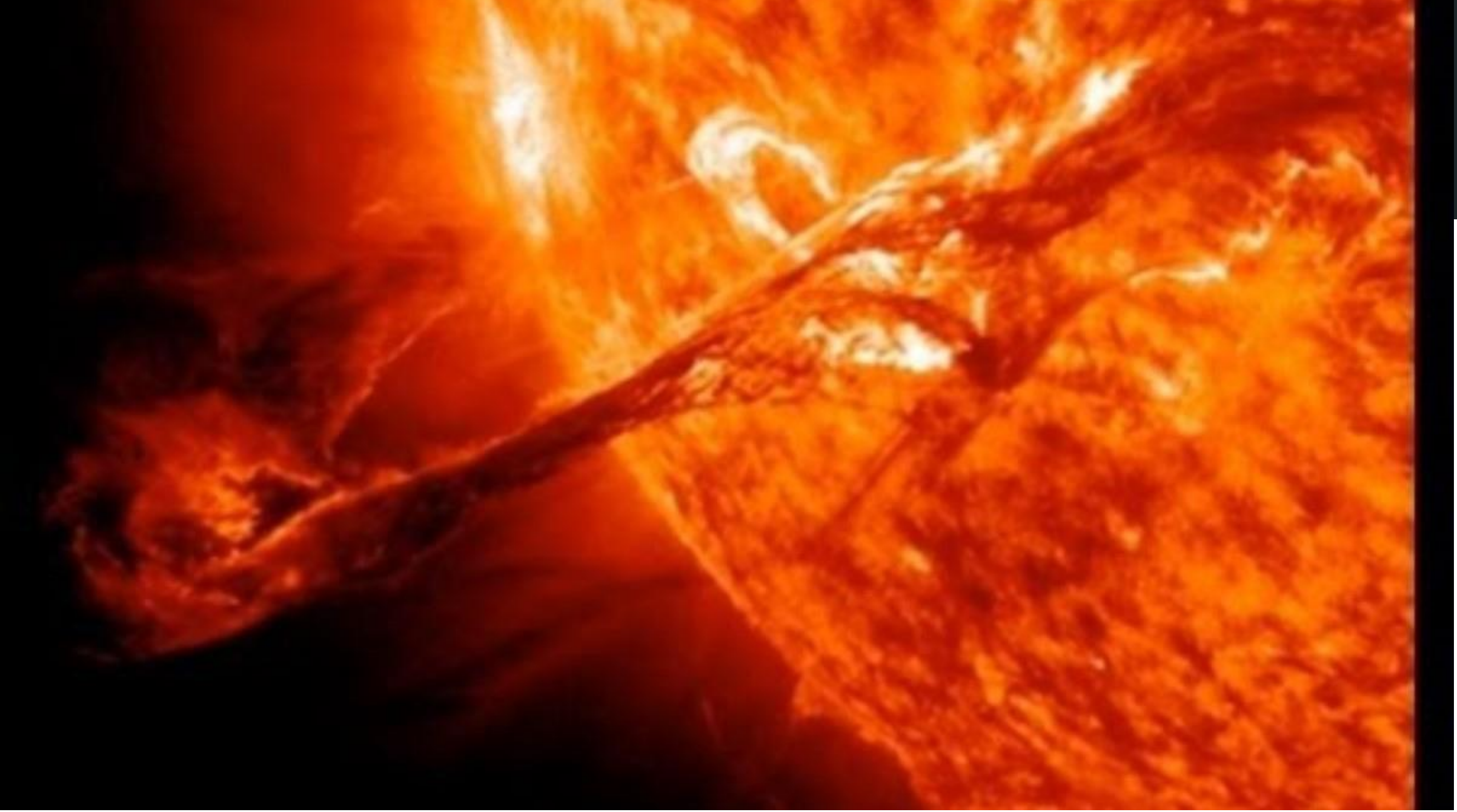
2. It can be hard to fully restore a system, when you're missing some critical pieces of equipment.

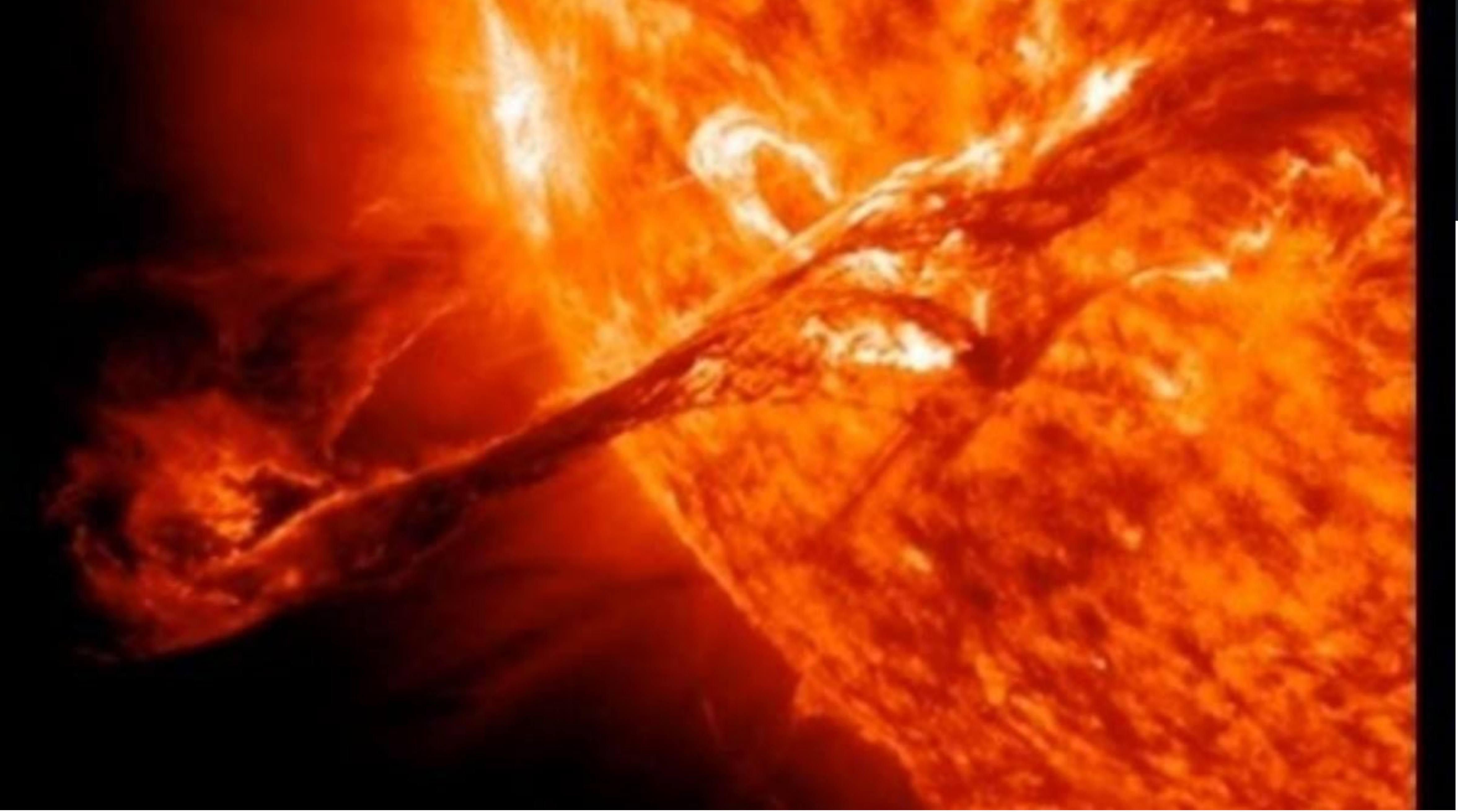
Markup based on: (Link by Ben Damsky)

Fact-Check Note

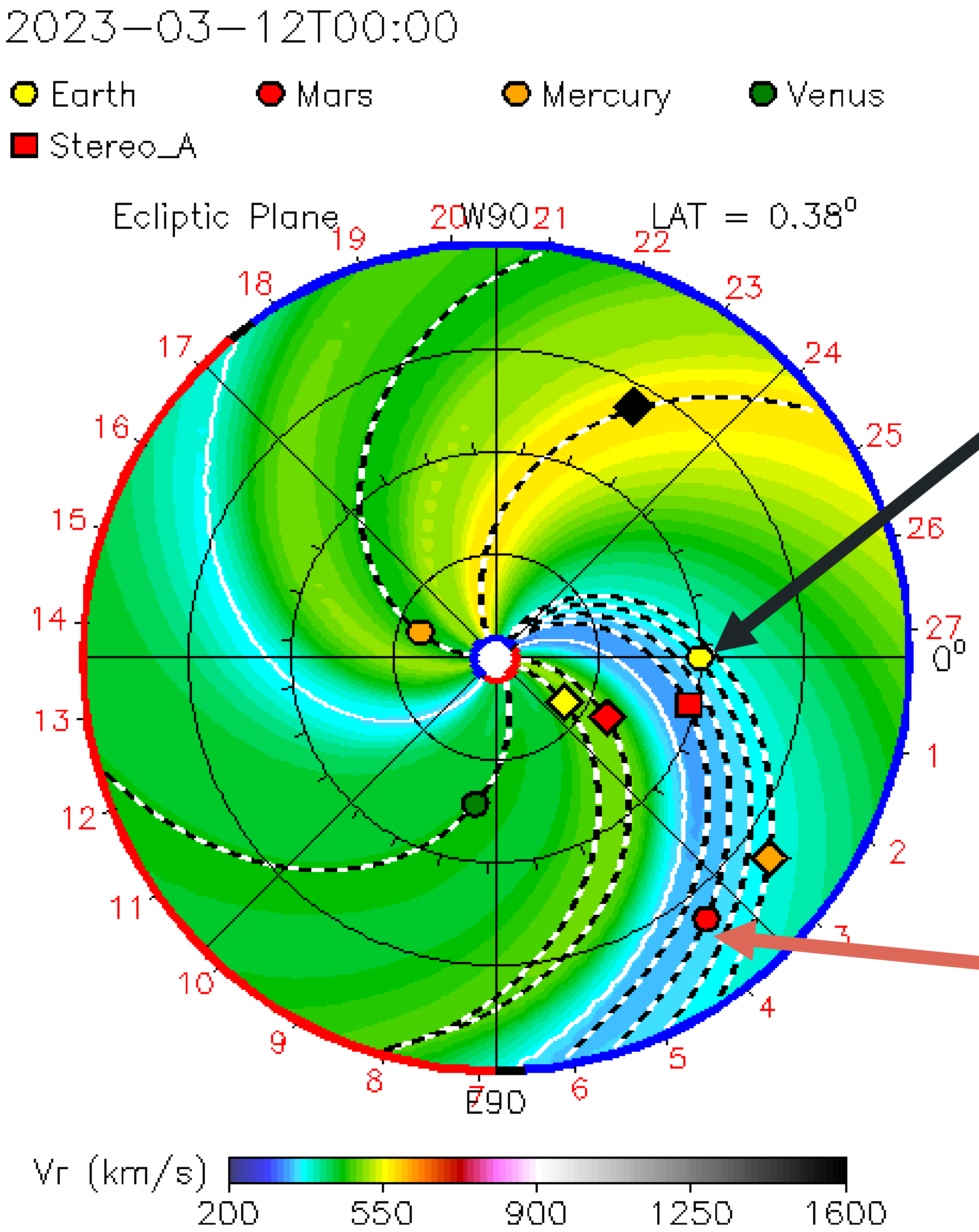
- For story telling purposes above, we presented as though the Hydro Quebec operators had access to all of the logs which were displayed in the NERC 1989 report.
- The fact is, I don't know how much of this information they had access to at that time.

Mechanism
Coronal Mass Ejection (CME)





Example from 2023



Earth!
Home sweet home…

Mars

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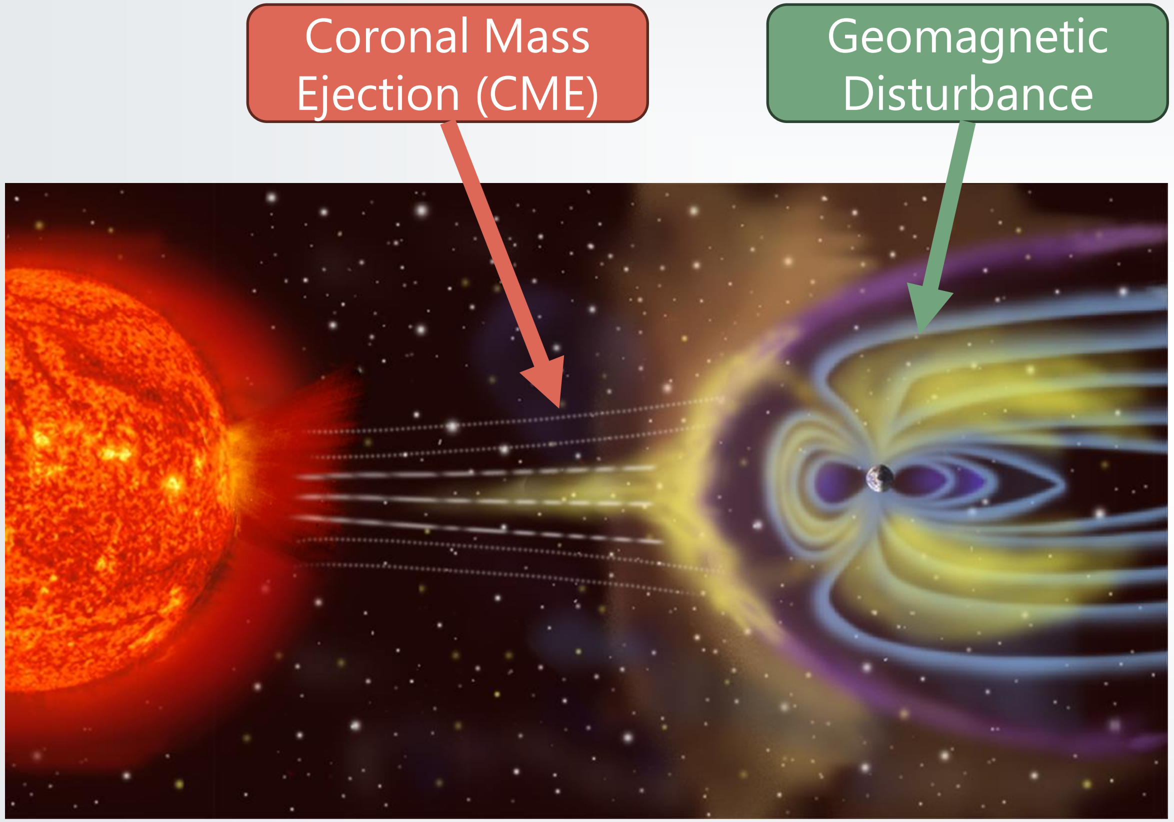
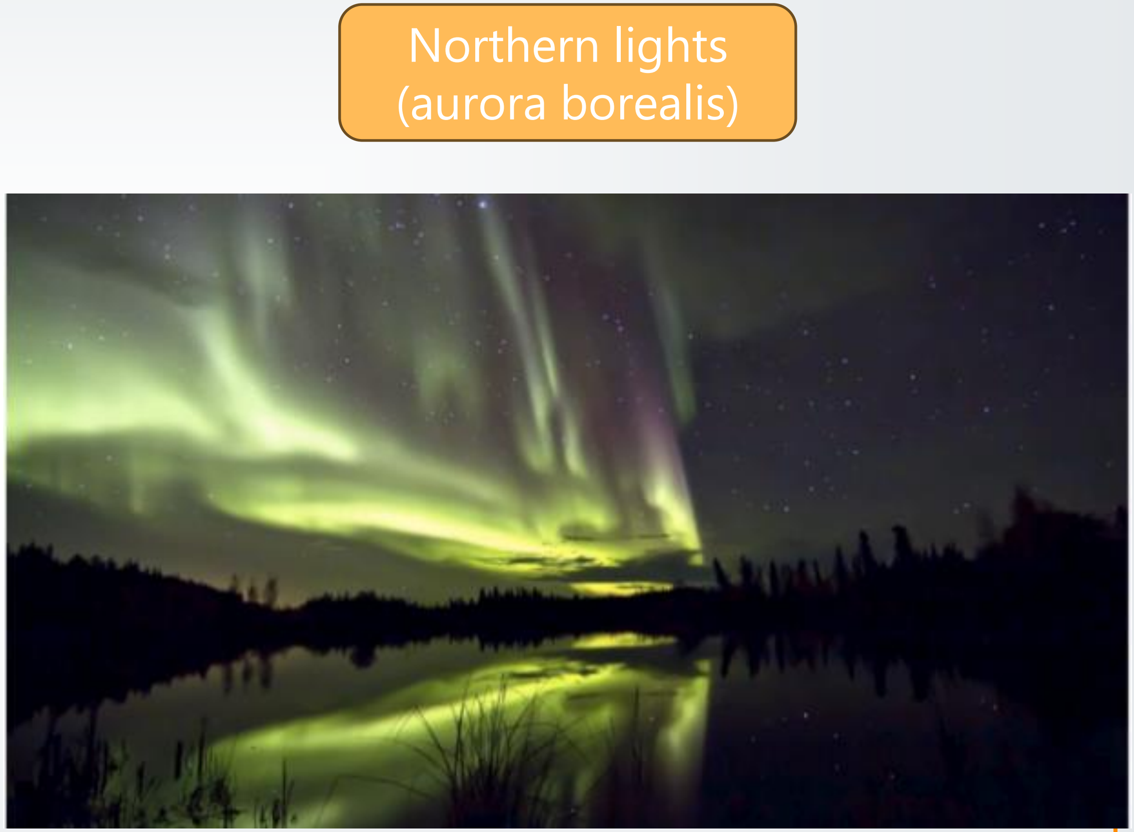
Coronal Mass Ejection



https://en.wikipedia.org/wiki/Geomagnetic_storm



https://www.maine.gov/mema/maine-prepares/preparedness-library/geomagnetic-storms

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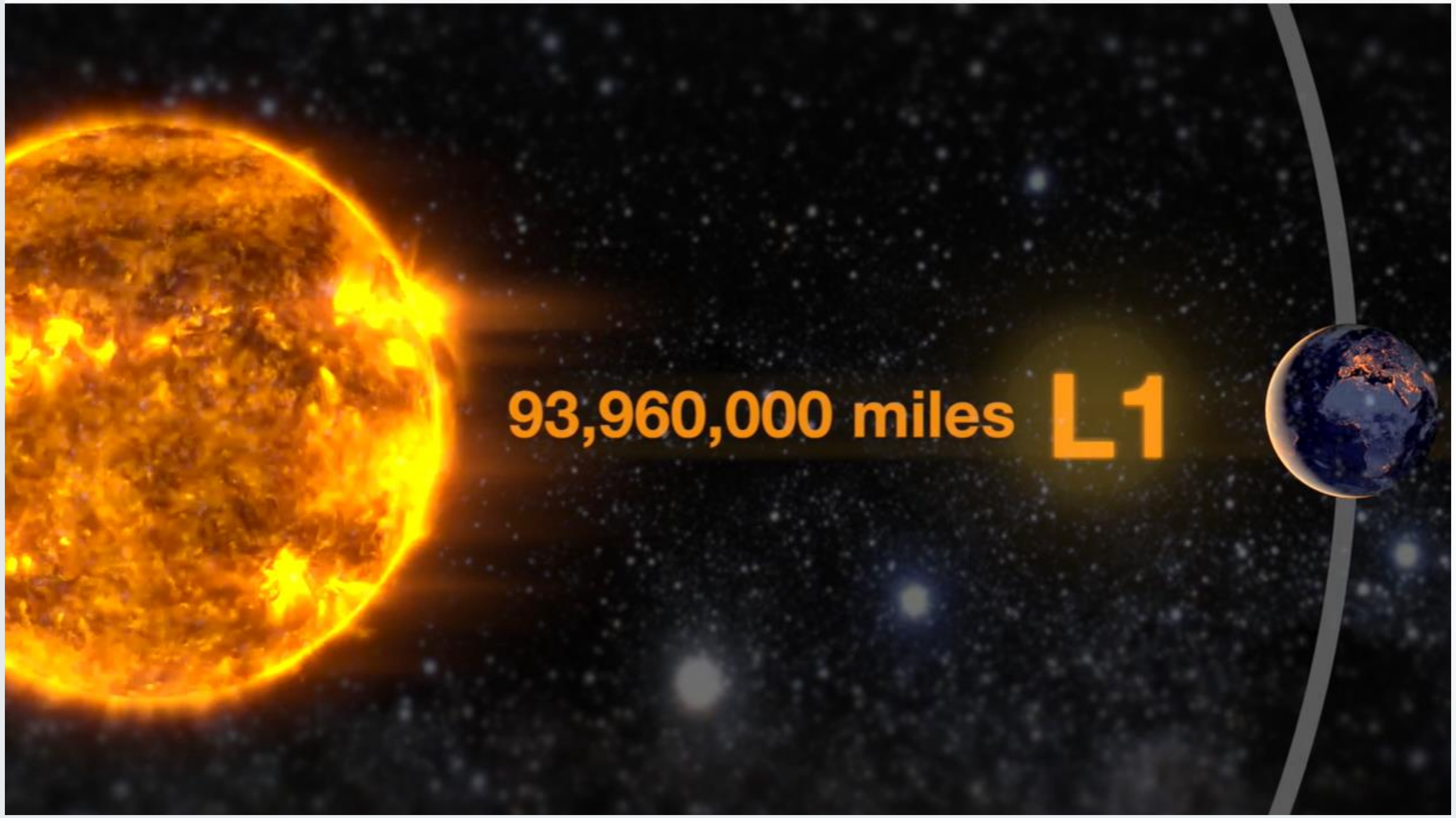
Notifications - NOAA

NOAA notifies RCs, whom notify BAs & TOPs



CME Travel Time (NOAA): Link

CME — We see it coming. "**Watch**"

15 Hours to 3 Days

CME Size Measurement — It's a big one! "**Warning**"

15 Minutes

CME Upon Earth — There's a storm! "**Alert**"

1-2 Days Later

The Storm Passes

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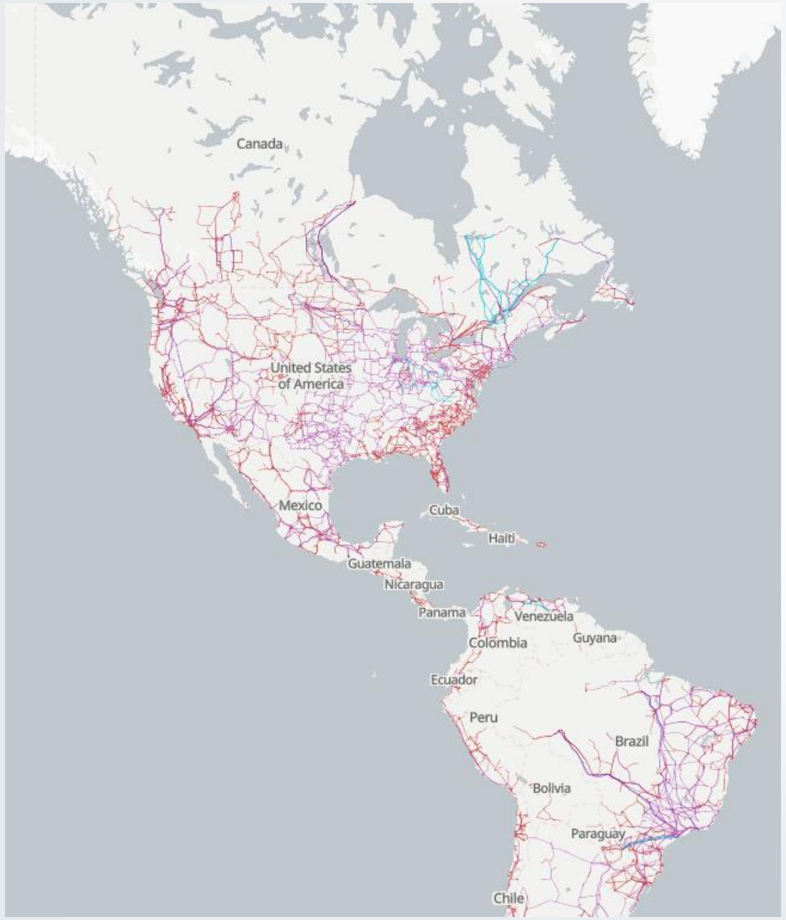
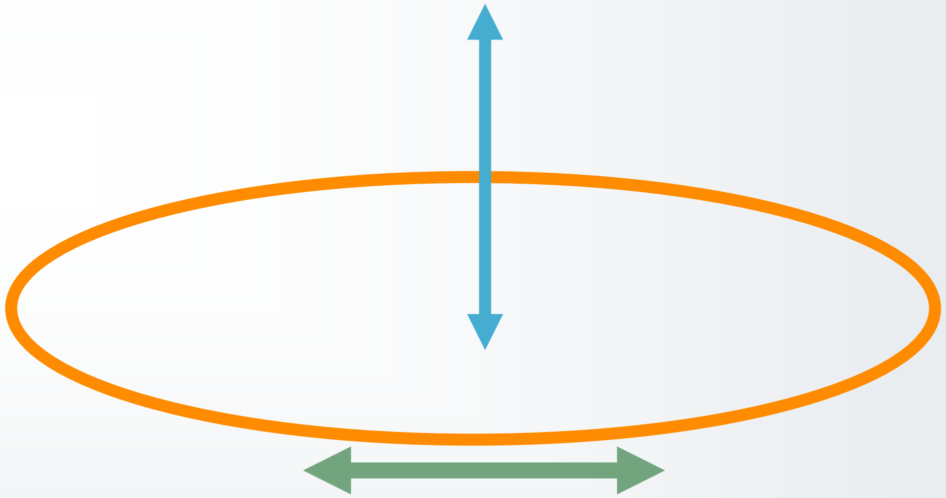
Changing Magnetic-Field



https://openinframap.org/

Changing ***B*** (Magnetic Field)



Induced ***E*** (Electric Field) in V / km
Induced ***I*** (Current)

Benchmark Event – Magnetic Field

Magnetic Field Recordings

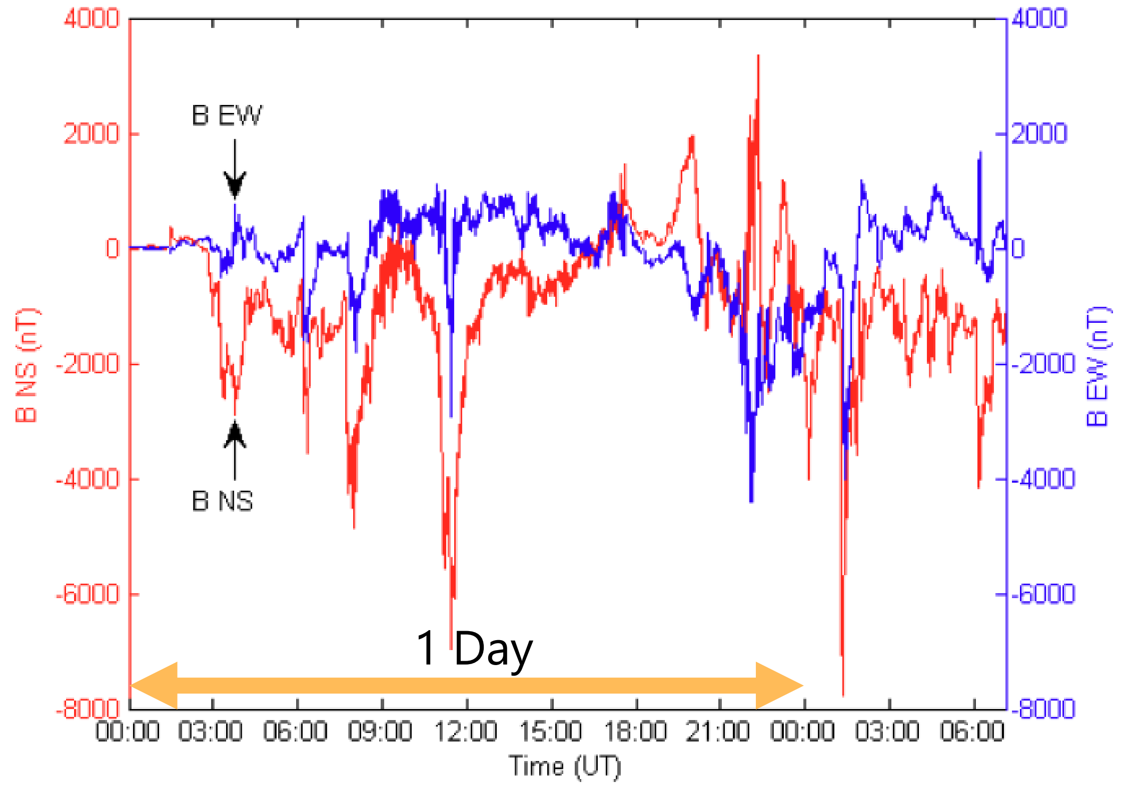


Figure 3: Benchmark Geomagnetic Field Waveform
Red B_n (Northward), Blue B_e (Eastward)

*"The geomagnetic field measurement record of the **March 13-14, 1989 GMD event**, measured at the NRCan **Ottawa** geomagnetic **observatory**, is the basis for the reference geomagnetic field waveform to be used to calculate the GIC time series, GIC(t), required for transformer thermal impact assessment for the supplemental GMD event."*

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Benchmark Event
Electric Field During the Storm

Electric Field (mV/km) East to West

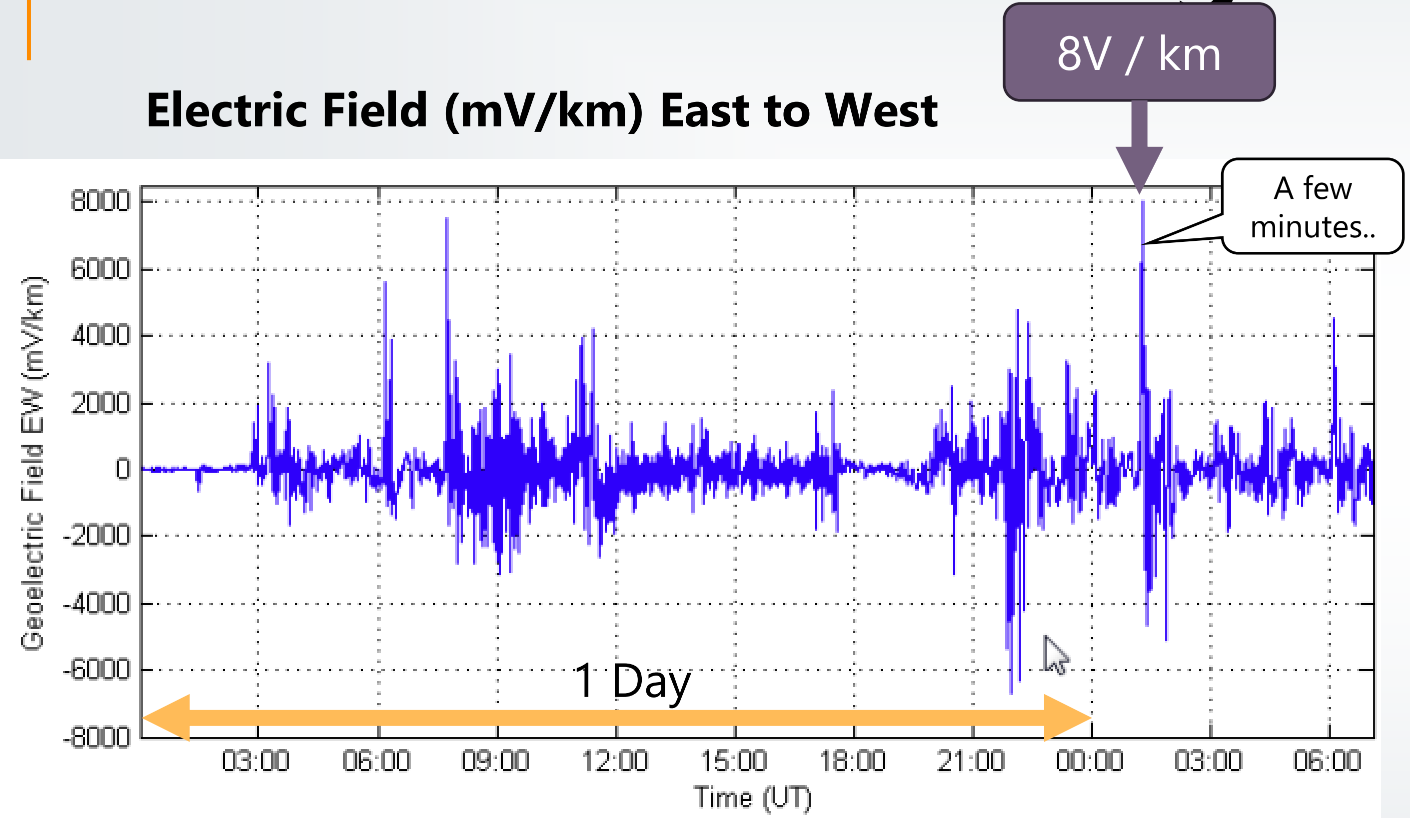
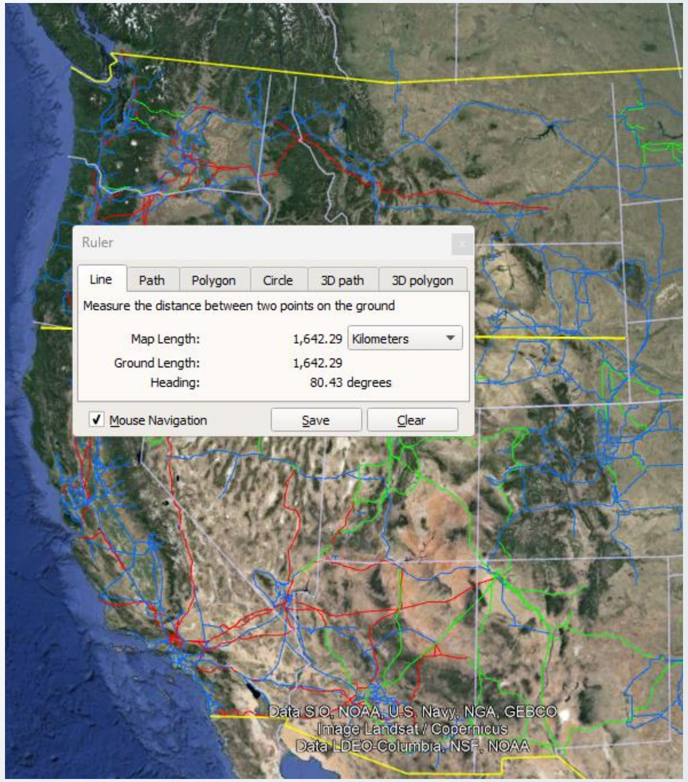


Figure 4: Benchmark Geoelectric Field Waveform
E_E (Eastward)

WECC Width? ~1600-1700 km.



8V/km * 1700 km = 13.6 kV

(Just as a reference for numbers-scale only)

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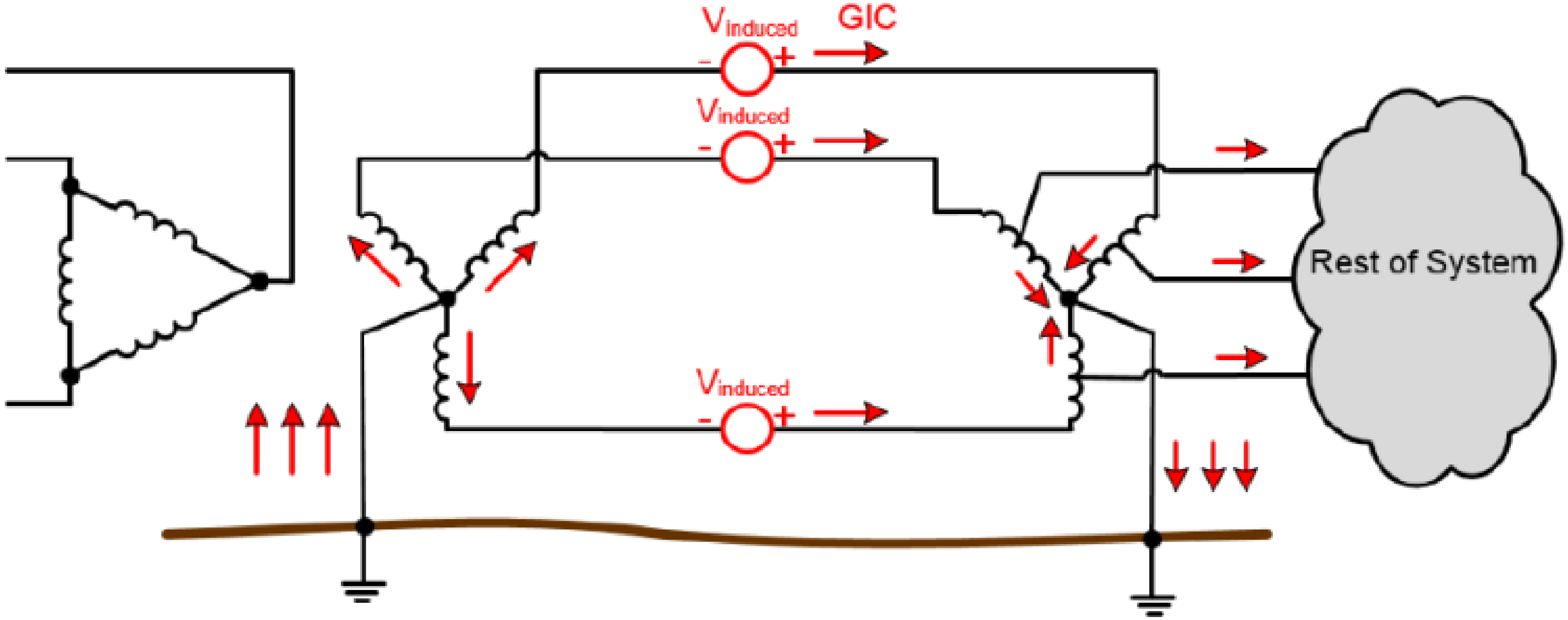
GMD Background

During geomagnetic disturbances, variations in the geomagnetic field induce quasi-dc* voltages in the network which drive geomagnetically-induced currents (GIC) along transmission lines and through transformer windings to ground wherever there is a path for them to flow

Figure 1: GIC flow in a simplified power system



NERC Application Guide: Computing Geomagnetically Indued Current in the Bulk Power System, Dec 2013

* an AC waveform with a period of several minutes

MISO

GMD Background, cont…

- The flow of GICs in transformer windings can cause half-cycle saturation of transformer cores leading to
  - increased transformer hotspot heating
  - harmonic generation
  - increased reactive power absorption
  - depressed voltages
- Core saturation can generate harmonics, which
  - Can cause overcurrent relays to trip cap banks and SVCs
  - Can further aggravate voltage issues

Half-Cycle Saturation

NASA YouTube Video

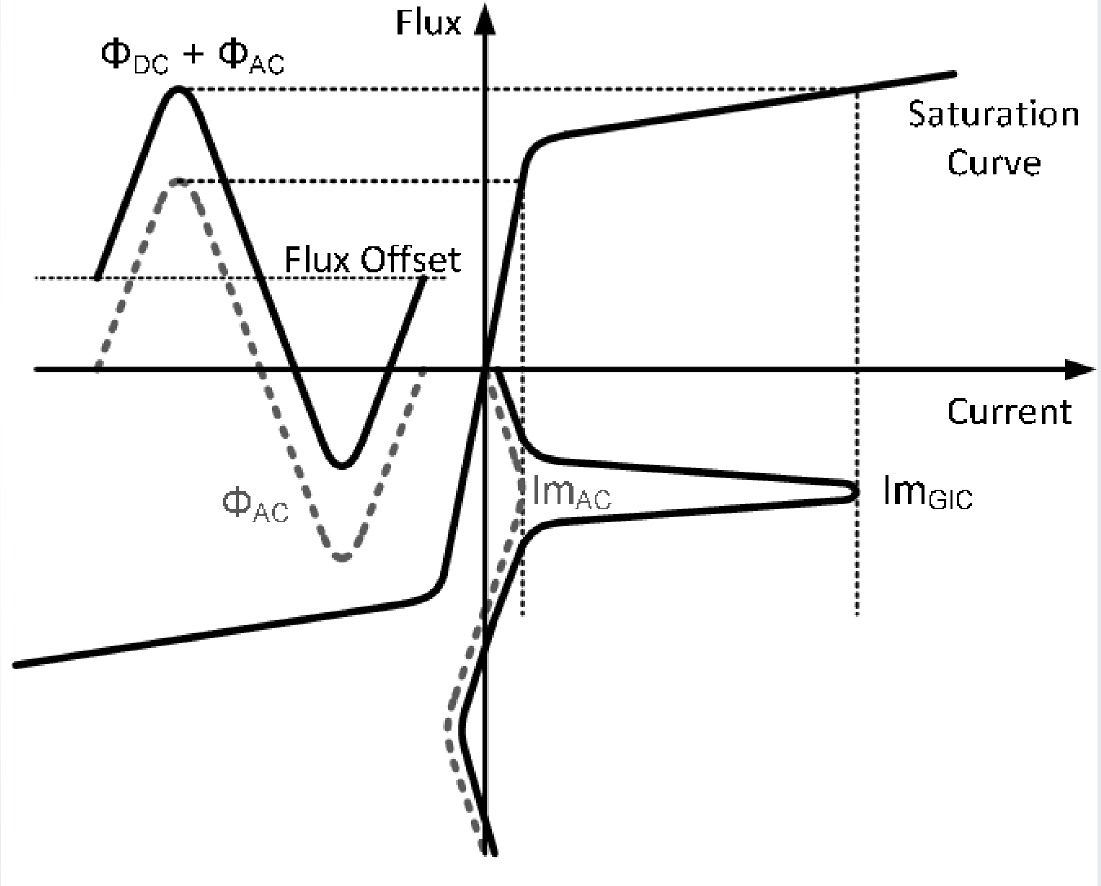


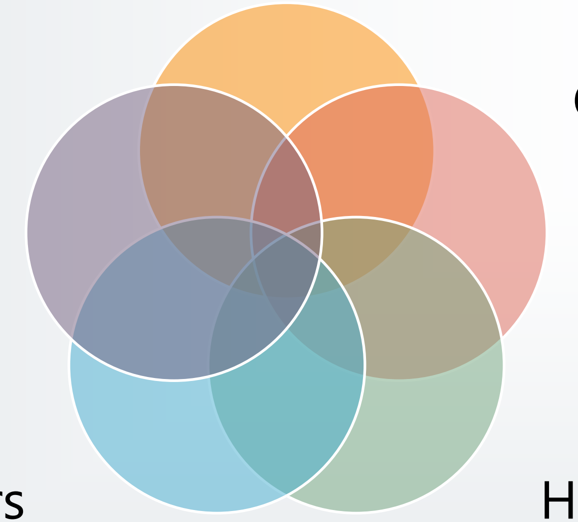
Fig. 1. Half-cycle saturation of the transformer core due to GIC

Graphic Source

GIC Impacts

Transformers → **Half Cycle Saturation**

- **Heating**
  That can melt your transformer!
- **VAR Losses**
  Suppress System Voltage!
- **Harmonics**
  Impact other equipment!



Old Relays

Capacitors & SVCs

Generators

HVDC Lines

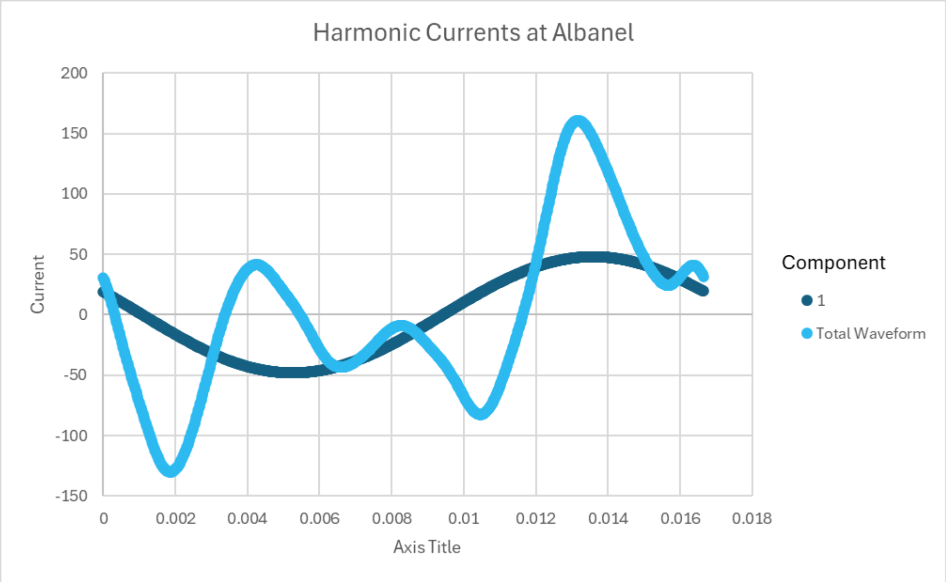
Utilities should focus on all the impacts, not just the transformers

Harmonics

Harmonics Study

- Does TPL-007 require a harmonics study?
- Without a harmonics study, could you catch the 1989 blackout?

- Loss of Seven (7) SVCs within 60 seconds due to harmonics. N-7+ System State.
- Subsequent full system collapse, losing 21 GW of load.



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TPL-007-1 Language:

Table 1 –Steady State Planning Events				
Steady State: a. The System shall remain stable. Cascading and uncontrolled islanding shall not occur. b. Consequential Load Loss as well as generation loss is acceptable as a consequence of P8 planning event. c. Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings. d. System steady state voltages shall be within acceptable limits as established by the Planning Coordinator and the Transmission Planner in accordance with Requirement R4.				
Category	**Initial Condition**	**Event**	**Interruption of Firm Transmission Service Allowed**	**Non-Consequential Load Loss Allowed**
P8 GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation during the GMD event[3]	Yes[4]	Yes[4]

Table 1 – Steady State Performance Footnotes

1. The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information.
2. The GMD conditions for planning event P8 are described in Attachment 1 (Benchmark GMD Event).
3. Protection Systems may trip due to the effects of harmonics. P8 planning analysis shall consider removal of equipment that the planner determines may be susceptible.
4. The objective of the GMD Vulnerability Assessment is to prevent instability, uncontrolled separation, Cascading and uncontrolled islanding of the System during a GMD event. Non-Consequential Load Loss and/or curtailment of Firm Transmission Service may be needed to meet BES performance requirements during studied GMD conditions but should not be used as the primary method of achieving required performance. GMD Operating Procedures should be based on predetermined triggers from studied GMD conditions so that the likelihood and magnitude of Non-Consequential Load Loss or curtailment of Firm Transmission Service is minimized during a GMD event.

3. Protection Systems may trip due to the effects of **harmonics**. P8 planning analysis shall consider removal of equipment that the planner determines may be susceptible.

WPP

TPL-007-4 R4/R8 Table 1

Table 1: Steady State Planning GMD Event

Steady State:

a. Voltage collapse, Cascading and uncontrolled islanding shall not occur.

b. Generation loss is acceptable as a consequence of the steady state planning GMD events.

c. Planned System adjustments such as Transmission configuration changes and re-dispatch of generation are allowed if such adjustments are executable within the time duration applicable to the Facility Ratings.

Category	Initial Condition	Event	Interruption of Firm Transmission Service Allowed	Load Loss Allowed
Benchmark GMD Event – GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes[3]	Yes[3]
Supplemental GMD Event – GMD Event with Outages	1. System as may be postured in response to space weather information[1], and then 2. GMD event[2]	Reactive Power compensation devices and other Transmission Facilities removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Yes	Yes

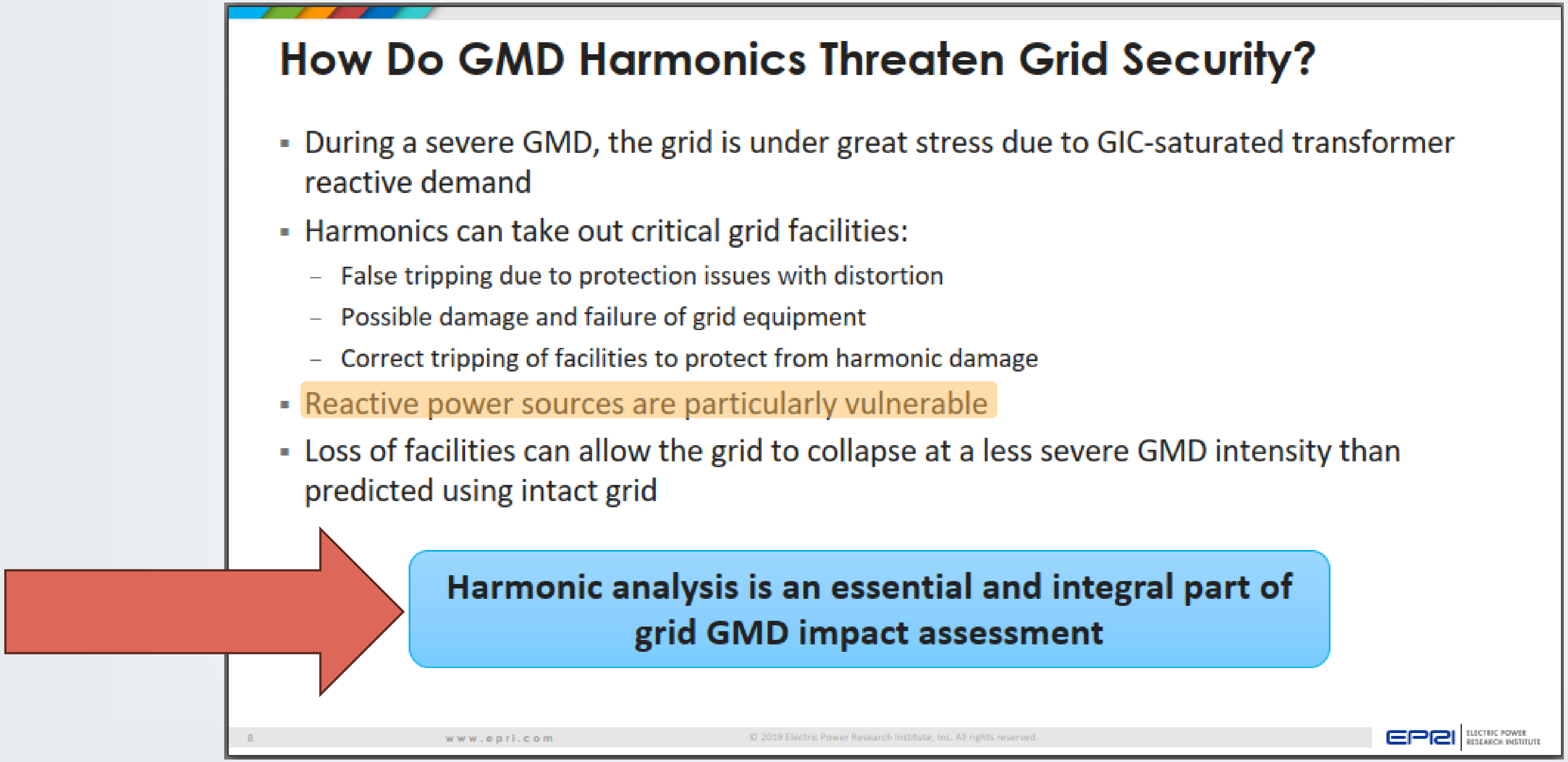
Table 1: Steady State Performance Footnotes

1. The System condition for GMD planning may include adjustments to posture the System that are executable in response to space weather information.
2. The GMD conditions for the benchmark and supplemental planning events are described in Attachment 1.
3. Load loss as a result of manual or automatic Load shedding (e.g., UVLS) and/or curtailment of Firm Transmission Service may be used to meet BES performance requirements during studied GMD conditions. The likelihood and magnitude of Load loss or curtailment of Firm Transmission Service should be minimized.

Harmonics
Mentioned in Table 1

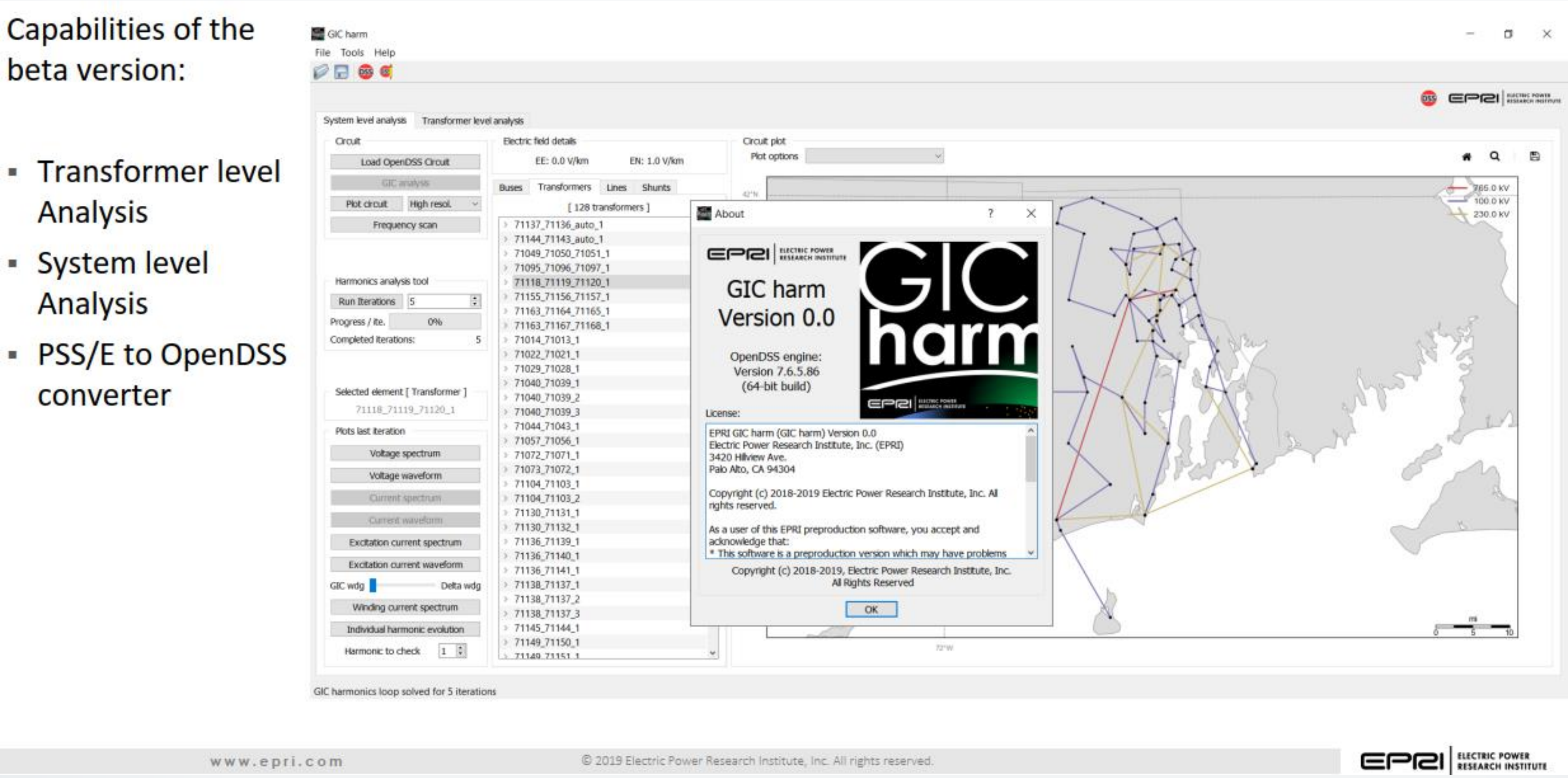
WPP

EPRI Harmonic Assessments



EPRI Harmonic Assessment Presentation (Link)

EPRI GICHarm



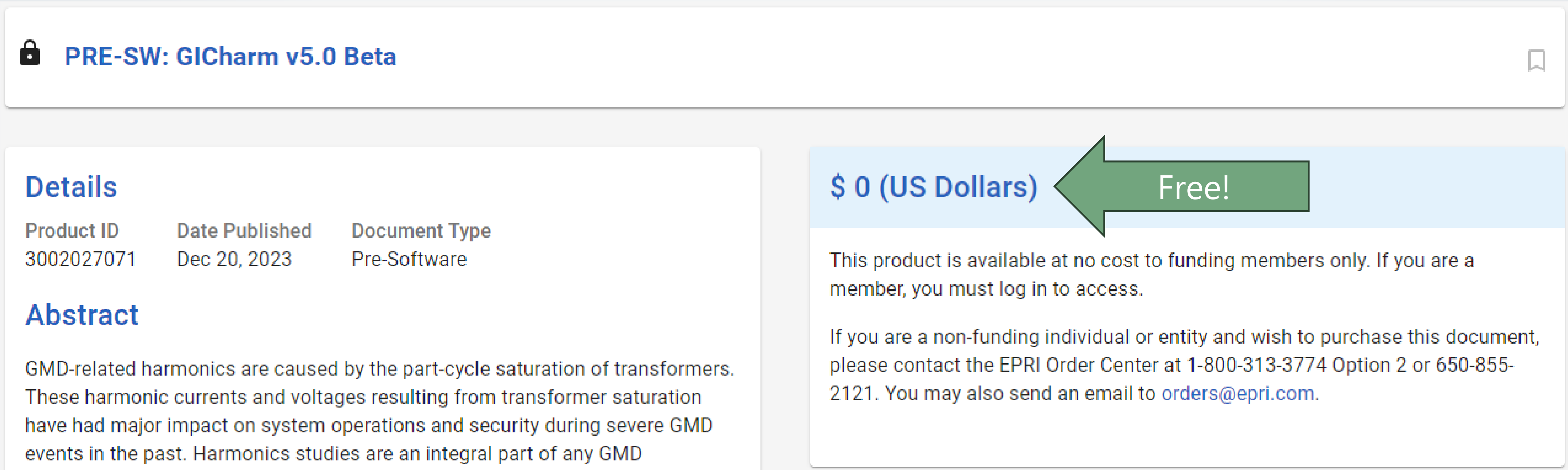
[PRE-SW: GICharm v5.0 Beta]

Takes input in PSS/E format.
*.raw & *.gic.

PowerWorld is able to export in this format.

WPP

EPRI GICHarm is Free!



PRE-SW: GICharm v5.0 Beta

$ 0 (US Dollars)

Free!

Details

Product ID	Date Published	Document Type
3002027071	Dec 20, 2023	Pre-Software

Abstract

GMD-related harmonics are caused by the part-cycle saturation of transformers. These harmonic currents and voltages resulting from transformer saturation have had major impact on system operations and security during severe GMD events in the past. Harmonics studies are an integral part of any GMD

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EPRI Guide on GMD Harmonics

Screening Criteria by EPRI (Link)

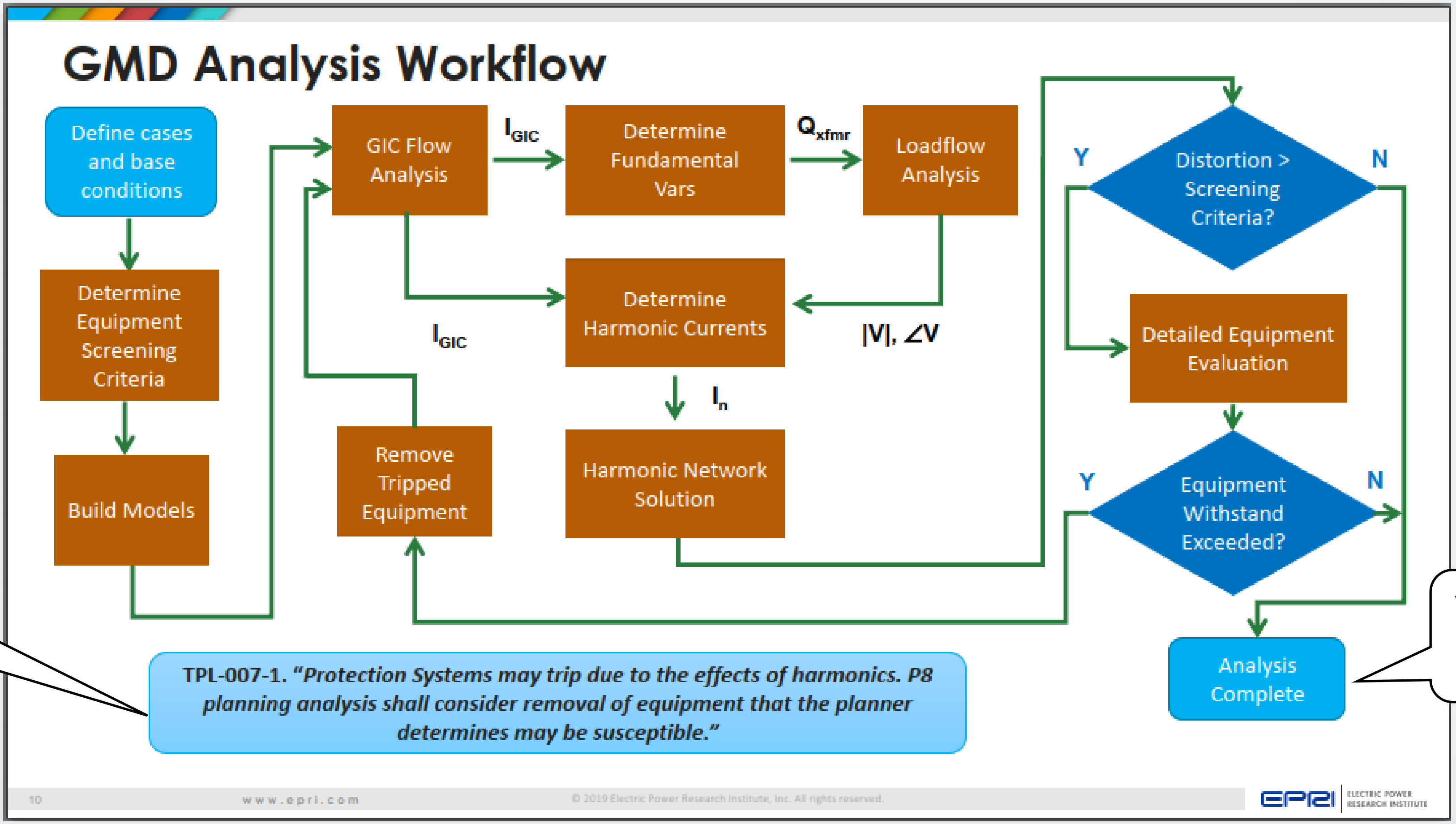
SHUNT CAPACITORS		
Thermal failure, fuse melting, or overload protection trip due to overcurrent.	Capacitors are likely to have high currents where they form resonances with the transmission system at integer harmonic frequencies.	$I_{rms} > 1.35$ p.u. (fundamental and harmonics)[2]
Dielectric failure due to excessive voltage.	Capacitor voltages may have highly amplified harmonic components due to resonances. Peak voltage is dependent on the phase relationship between harmonic and fundamental voltage components.	$THD_V > 10\%$, and $\Sigma V_n > 20\%$.[2,3] Total harmonic distortion (THD)
Capacitor bank protection false trips due to harmonic currents.	Certain protection schemes, such as zero-sequence overvoltage and ground overcurrent	Evaluate in detail any capacitor banks using zero sequence overvoltage or ground

GENERATORS		
Harmonic current into stator can cause excessive rotor heating.	The thermal time constant of the generator rotor significantly reduces the potential impact. Generators are largely unprotected from this potential impact.	< 350 MVA, $THD_i > 0.107$ p.u. 350 – 1250 MVA, $THD_i > 0.107 - 0.00447 \times (MVA-350)$ > 1250 MVA; $THD_i > 0.067$ p.u.

WPP

EPRI Harmonic Assessments

Language is no longer in TPL-007-4



Would this study process catch the 1989 blackout? **Probably**!

EPRI Harmonic Assessment Presentation (Link)

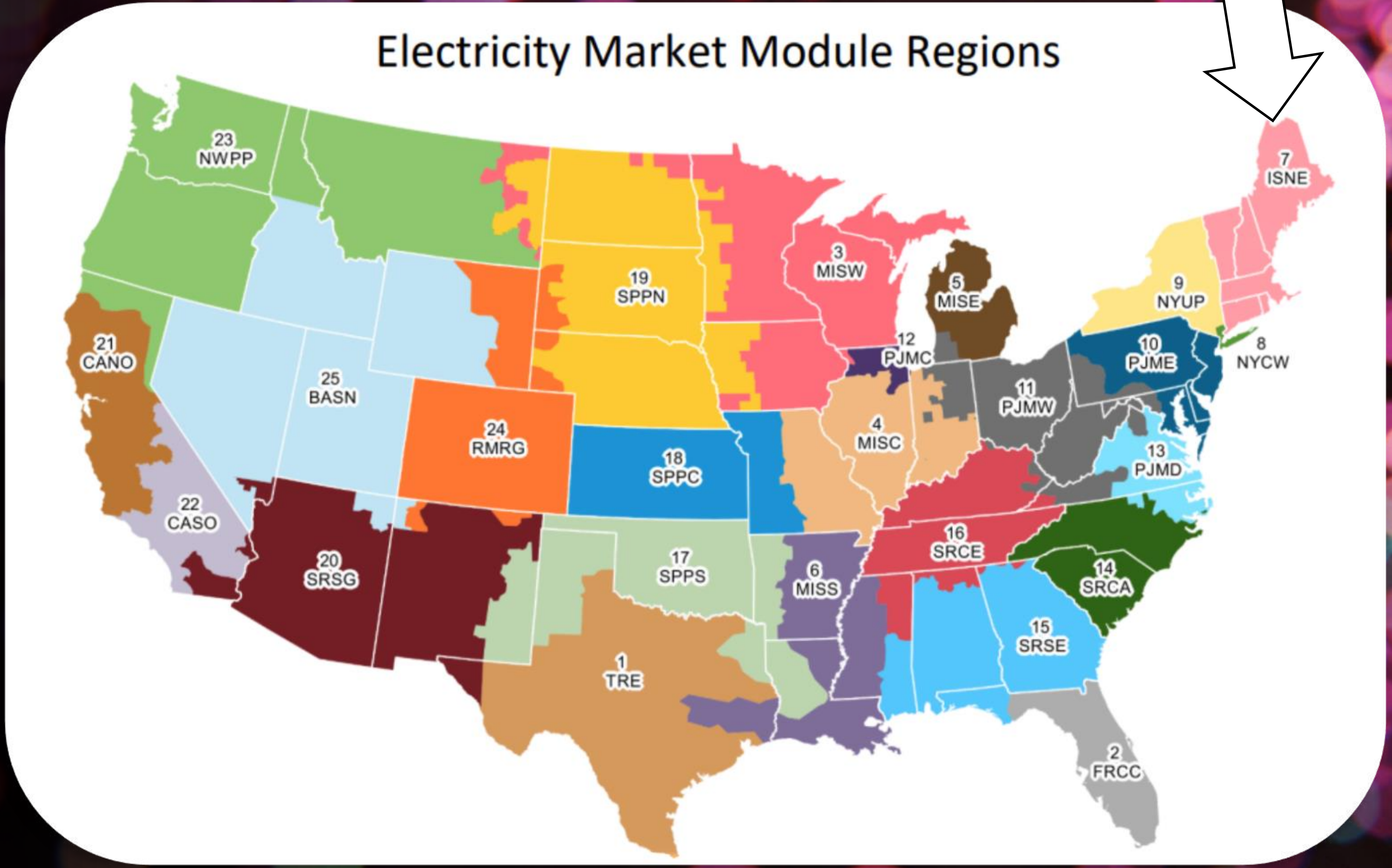
Review of Various Procedures

Procedure Question

Would this procedure have caught the 1989 Blackout?

Note

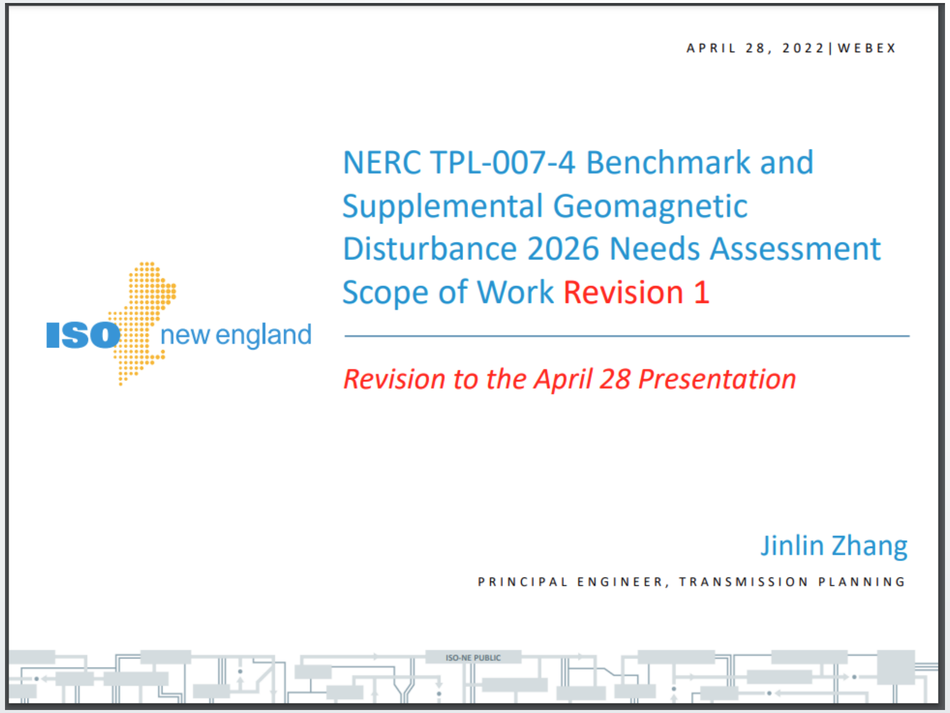
We don't have access to everyone's TPL-007 study reports, only what has been published publicly online!


Electricity Market Module Regions
23 NWPP
21 CANO
22 CASO
25 BASN
24 RMRG
20 SRSG
19 SPPN
18 SPPC
17 SPPS
1 TRE
3 MISW
4 MISC
5 MISE
6 MISS
12 PJMC
11 PJMW
10 PJME
13 PJMD
16 SRCE
14 SRCA
15 SRSE
2 FRCC
9 NYUP
8 NYCW
7 ISNE

ISO-NE TPL-007

» Link 1

» Link 2


APRIL 28, 2022 | WEBEX

ISO new england

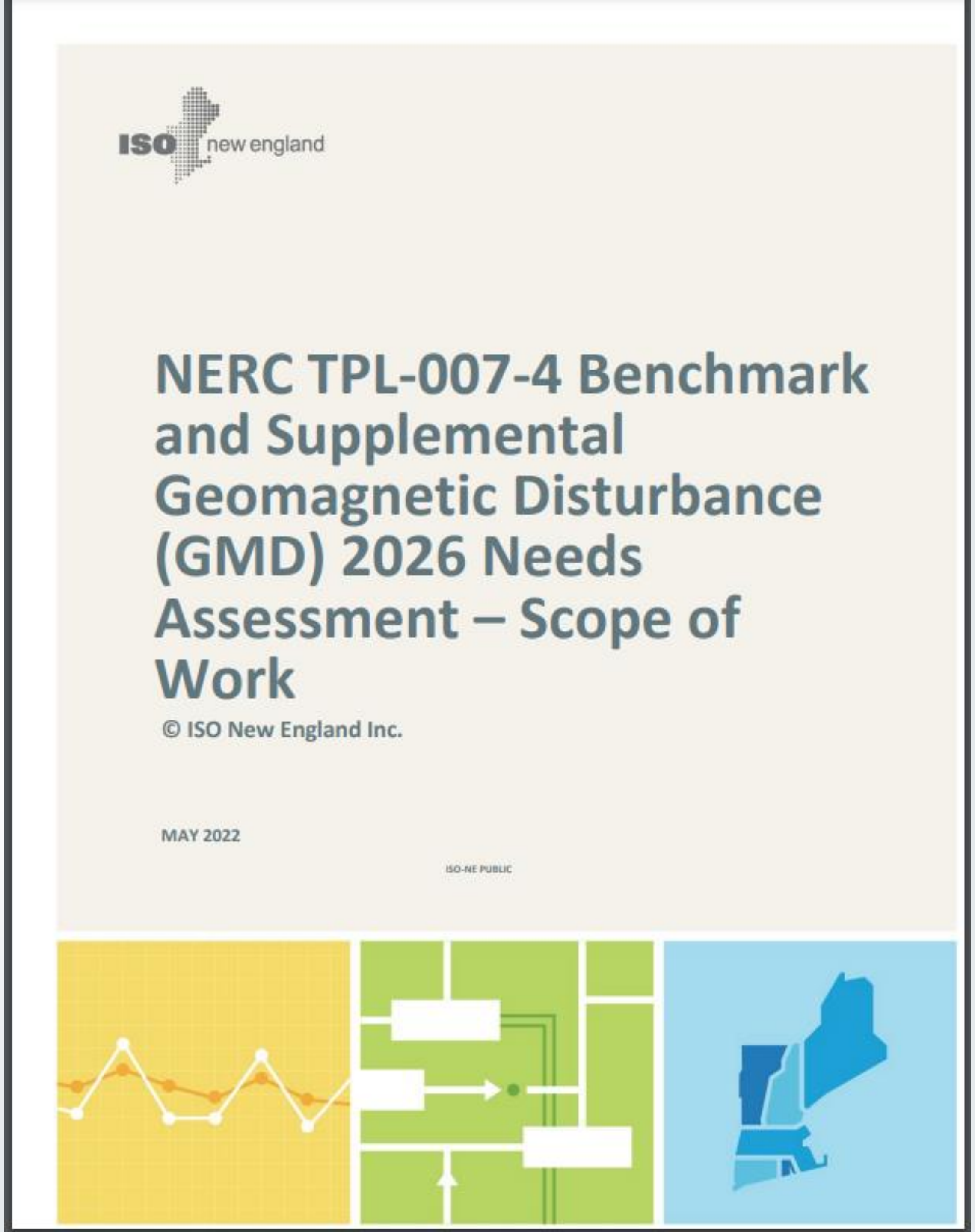
NERC TPL-007-4 Benchmark and Supplemental Geomagnetic Disturbance 2026 Needs Assessment Scope of Work Revision 1

Revision to the April 28 Presentation

Jinlin Zhang

PRINCIPAL ENGINEER, TRANSMISSION PLANNING

ISO-NE PUBLIC


ISO new england

NERC TPL-007-4 Benchmark and Supplemental Geomagnetic Disturbance (GMD) 2026 Needs Assessment – Scope of Work

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MAY 2022

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ISO-NE

Modeling Assumptions, cont.

- Additional AC Model Assumptions for GMD study
  - Summary of the GMD Needs Assessment AC Cases

Case Number	Case Description*
#1	Peak case with no reactive power losses
#2	Off-peak case with no reactive power losses
#3	Benchmark GMD event peak case w/ maximum reactive power losses
#4-#9	Benchmark GMD event peak case w/ corresponding reactive losses for geoelectric field orientations at 0°, 30°, 60°, 90°, 120°, 150°
#10	Benchmark GMD event off-peak case w/ maximum reactive power losses
#11-#16	Benchmark GMD event off-peak case w/ corresponding reactive losses for geoelectric field orientations at 0°, 30°, 60°, 90°, 120°, 150°
#17	Supplemental GMD event peak case w/ maximum reactive power losses
#18-#23	Supplemental GMD event peak case w/ corresponding reactive losses for geoelectric field orientations at 0°, 30°, 60°, 90°, 120°, 150°
#24	Supplemental GMD event off-peak case w/ maximum reactive power losses
#25-#30	Supplemental GMD event off-peak w/ corresponding reactive losses for geoelectric field orientations at 0°, 30°, 60°, 90°, 120°, 150°

* Reactive power losses noted in each of the case descriptions refer to the transformer saturation during GMD events.

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ISO-NE

Study Methodology, cont.

- Contingency Development
  - The ISO relied on the TOs to identify facilities that should be included in the contingency list to be used in the study. The facilities were broken up into five groups. For the purpose of the first GMD Needs Assessment, the ISO focused the contingency selection on transmission elements that are protected by electromechanical and solid state electronic relays, since these relays are considered more susceptible to the effects of GICs*
    - Group #1: 200 kV or higher transmission lines protected by at least one electromechanical and/or solid-state relaying package with a line length greater than 10 miles between terminals
    - Group #2: Grounded-wye shunt capacitors protected by electromechanical and/or solid-state relaying;
    - Group #3: Static VAR compensators (SVCs) and static synchronous compensators (STATCOMs);
    - Group #4: HVDC Installations;
    - Group #5: Power transformers with a high side, wye-grounded winding with terminal voltage greater than 200 kV
  - In addition, the TOs were relied on to identify those facilities on the contingency list that were considered at risk for protection system operation and mis-operation due to harmonics during GMD events
  - Generator contingencies are not included in the contingency list because GICs are isolated from the transmission system due to the delta-wye connection of the generator step-up transformer

* For Groups #2 through #4, the focus was to identify facilities connected to the transmission system at 200 kV or higher. However, the TOs were asked to include facilities below 200 kV, if including the data is appropriate and could potentially impact the results observed at facilities connected at 200 kV and above.

WPP

ISO-NE

A comprehensive set of contingencies/facilities removed due to harmonics during a GMD event, provided by the TOs and listed in Table 3-4, will be tested individually.

Table 3-4:
Contingencies/Facilities Removed due to Harmonics during a GMD Event

Contingency Number	Contingency (kV level)
1	Orrington 345/115 kV transformer #2 (345 kV)
2	Chester SVC (345 kV)
3	Dogtown SVC (115 kV)
4	Coopers Mills STATCOM (345 kV)
5	Sanford Capacitor (115 kV)
6	Vermont 345/115 kV transformer (345 kV)
7	Coolidge 345/115 kV transformer (345 kV)
8	West Rutland 345/115 kV transformer #1 (345 kV)
9	West Rutland 345/115 kV transformer #2 (345 kV)
10	New Haven 345/115 kV transformer #1 (345 kV)
11	New Haven 345/115 kV transformer #2 (345 kV)
12	Vernon 345/115 kV transformer (345 kV)
13	Newfane 345/115 kV transformer (345 kV)
14	Granite 230/115 kV transformer and phase shifter #1 (230 kV)
15	Granite 230/115 kV transformer and phase shifter #2 (230 kV)

Steady state thermal and voltage analysis will be performed, for N-0 (all-facilities-in), N-1 (all-facilities-in, first contingency), for the described set of Benchmark and Supplemental GMD events.

The general industry understanding is that generators are normally isolated from GICs because of the delta-wye transformer connection of the generator step-up transformer with the power systems. Therefore, generator contingencies are not included in the contingency list. However, generators are susceptible to the voltage imbalance and harmonics coming from the step-up transformer. Without actual investigation on the harmonic impact to the generators, the generator owners are not able to provide this information.

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ISO-NE

» No GMD:

- » **0.95** – 1.05 PU

» GMD Event:

- » **0.8** – 1.05 PU

Study Methodology, cont.

- Steady state thermal and voltage analysis was performed, for N-0 (all-facilities-in) and N-1 (all-facilities-in, first contingency)* for the described set of benchmark and supplemental GMD events
  - The list of first contingencies were provided by the TOs and were tested individually

Needs Assessment Analysis Results

- N-0 Violations
  - There were no N-0 thermal or voltage violations in New England for both Benchmark and Supplemental GMD events
- N-1 Violations
  - There were no N-1 thermal or voltage violations in New England for both Benchmark and Supplemental GMD events

Study Methodology

- As part of the TPL-007-4 R3 requirement, the following steady state voltage criteria were established and applied*

Facility	Voltage Level (kV)	Bus Voltage Limits		
		Normal Conditions (N-0) (p.u)	GMD Event (Post-Contingency)	
			Pre-Switching (p.u)	Post-Switching (p.u)
Transmission/Generation	200 and above and less than 345	$0.95\overline{0} - 1.05\overline{0}$	$0.8\overline{0} - 1.05\overline{0}$	$0.8\overline{0} - 1.05\overline{0}$
	345	$0.95\overline{0} - 1.0492\overline{0}$	$0.8\overline{0} - 1.0492\overline{0}$	$0.8\overline{0} - 1.0492\overline{0}$
Millstone/Seabrook	345	$1.\overline{0} - 1.0492\overline{0}$	$1.\overline{0} - 1.0492\overline{0}$	$1.\overline{0} - 1.0492\overline{0}$

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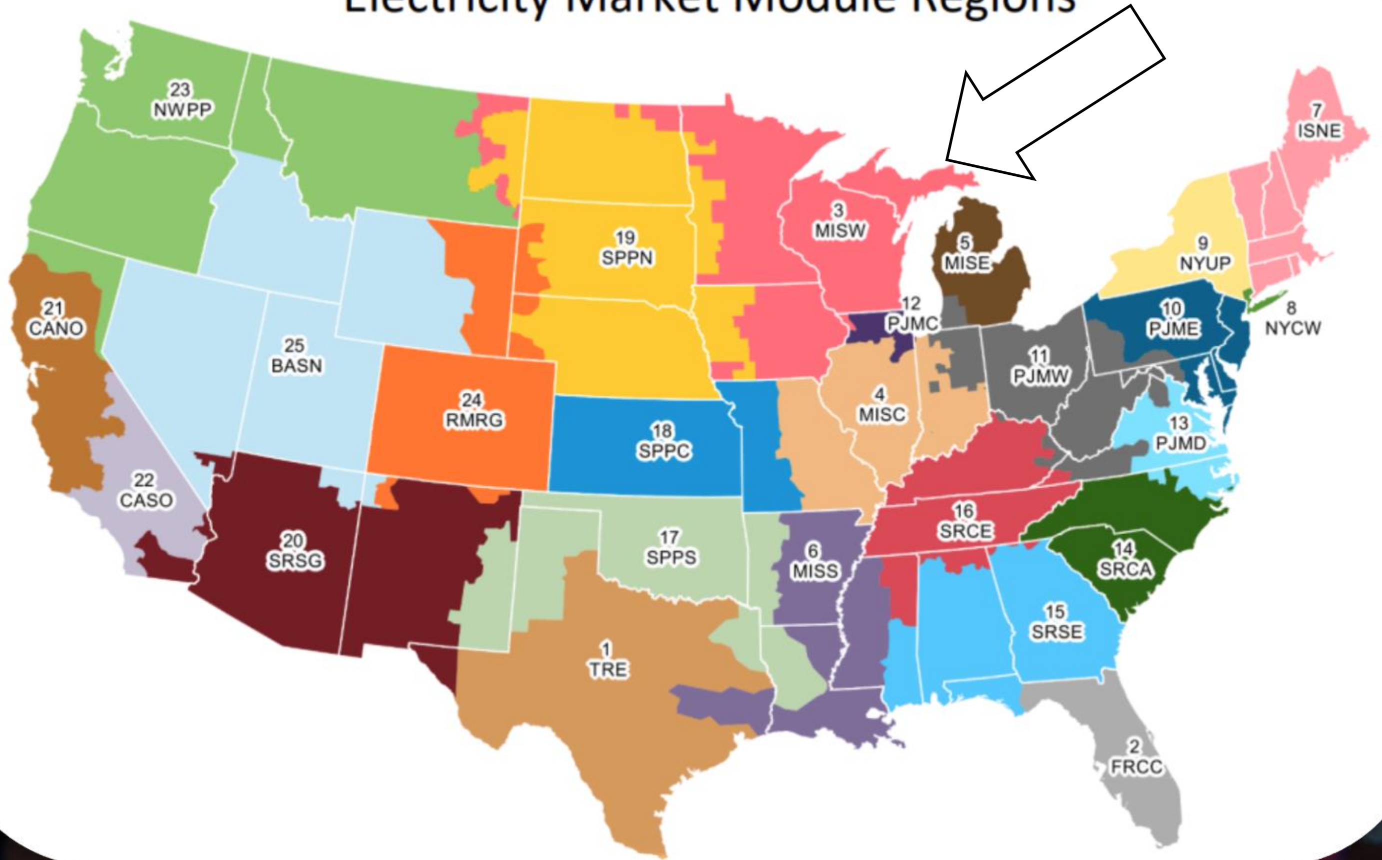
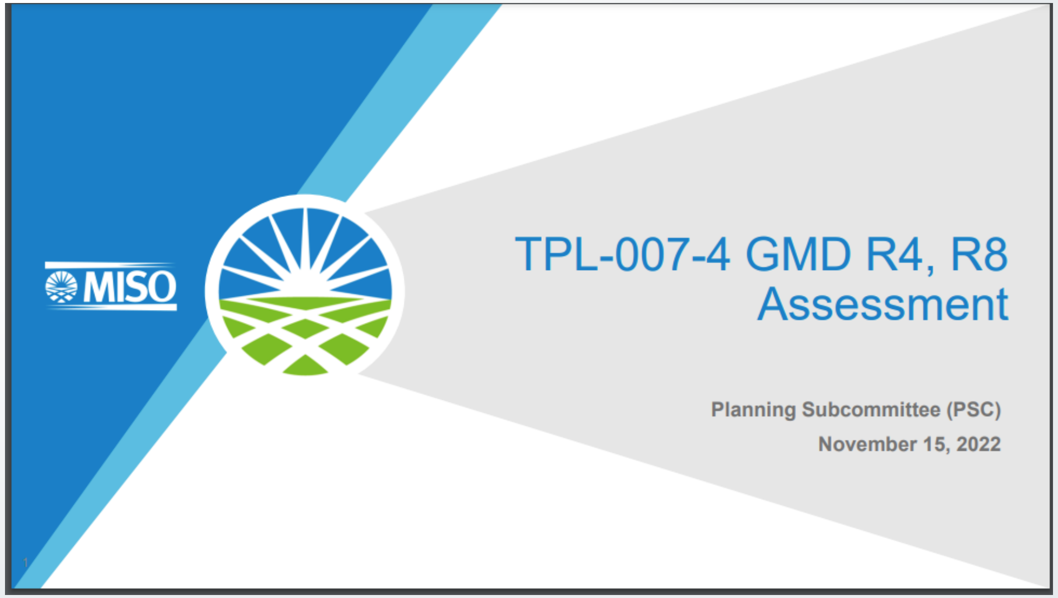
Q: Would this study have caught the 1989 blackout?

Electricity Market Module Regions

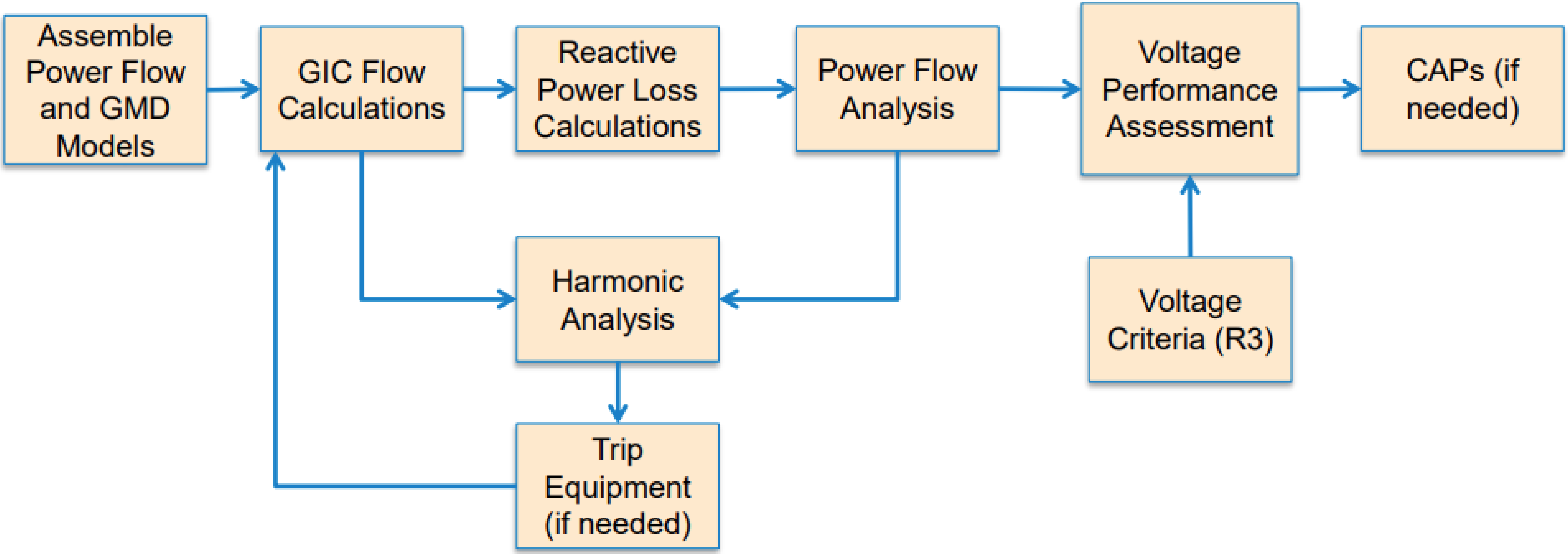


MISO TPL-007 Procedures

- Highly recommend MISO’s TPL-007 Presentations:
  - Link 1
  - Link 2



TPL-007-4 R4, R8 Assessment-- High Level Work-Flow



Voltage Criteria for GMD Assessment (R4, R8)

- MISO proposes to monitor against Transmission Planners' Emergency voltage thresholds listed in TPs' Local Planning Criteria (LPC)
- If LPC absent, MISO's Default Planning Criteria's Emergency voltage thresholds to be used:

Steady State Voltage	Threshold (p.u.)
Normal Low Voltage	0.95
Normal High Voltage	1.05
Emergency Low Voltage	0.90
Emergency High Voltage	1.10

Criteria from MISO BPM

- Emergency voltage thresholds to be applied post-GMD event, but prior to the loss of any BES elements due to harmonics
- Monitored facilities: 100 kV and above
- Facilities with violation will also be monitored for voltage deviation of more than 0.05 p.u.
- Nuclear Plants to follow voltage criteria per existing NPIRs
- MISO will share the post-event voltage results from R4, R8 assessment with the TPs if emergency thresholds are violated
- TPs don't need to provide CAPs unless there is voltage collapse, cascading or uncontrolled islanding
- MISO expects TPs to determine when voltage collapses in their system

Q: Would this study have caught the 1989 blackout?


Blackout
Yukon
Northwest Territories
Nunavut
Nunavut
British Columbia
Alberta
Manitoba
Hudson Bay
Quebec
Labrador
Newfoundland
Western Canada Region
Ontario
Saskatchewan
Eastern Canada Region
New Brunswick
P.E.I.
Nova Scotia
Washington
Oregon
Montana
North Dakota
Minnesota
West Central Region
Idaho
South Dakota
Wyoming
Wisconsin
Michigan
East Central Region
Maine
New York
North East Region
New Hampshire
Massachusetts
Rhode Island
Connecticut
New Jersey
Pennsylvania
Nevada
Utah
Nebraska
Iowa

NPCC TPL-007

Link

NPCC, Inc.

NORTHEAST POWER COORDINATING COUNCIL, INC.
1040 AVE. OF THE AMERICAS, NEW YORK, NY 10018 (212) 840-1070 FAX (212) 302-2782

Approaches for Meeting Requirements R3, R4, and R8 of NERC Reliability Standard TPL-007-4

Prepared by:
SS-39 Working Group on Geomagnetic Disturbance

TFSS Approved
January 25, 2022

WPP

NPCC Methodology

Table 3-1: TPL-007 Criteria Recommendation for Steady State Planning GMD Event

Event ID	Stage/Time Horizon (per Table 1 in TPL-007)	Description	Suggested Criteria	Rationale
A	Initial Condition: 1. Posturing	After system has been postured in response to GMD/space weather information	Equal to TPL-001 P0 voltage criteria (TPL-001 'No Contingency' Planning Event performance criteria)	No events have occurred yet so system normal criteria should be maintained even if operating conditions are worse due to posturing made to the system
B	Initial Condition: 2. GMD event	During GMD event, but prior to any elements being removed per Event description in Table 1	Not more relaxed than TPL-001 P1-P7 voltage criteria (TPL-001 post contingency Planning Event performance criteria)	After the inclusion of reactive losses, there could be significant voltage drops; however, system should be postured in preparation. Criteria can be more relaxed than the recommended P0 criteria. However, the addition of system wide reactive losses should not merit voltage criteria for a greater severity than a TPL-001 P1-P7 event.
C	Event: Loss of Facilities	After Reactive Power compensation devices and other Transmission Facilities have been removed as a result of Protection System operation or Misoperation due to harmonics during the GMD event	Not more relaxed than TPL-001 extreme event performance criteria (which should identify voltage collapse, Cascading, and uncontrolled islanding)	Could range from no system Misoperation to system wide issues; For this reason, we recommend P1-P7 criteria, but depending on severity (i.e., beyond equivalent Planning Event contingencies), Extreme Event performance criteria may be appropriate to identify voltage collapse, Cascading, and uncontrolled islanding. Load loss as a result of manual or automatic Load shedding (e.g., UVLS) and/or curtailment of Firm Transmission Service may be used . If Extreme Event performance criteria are violated, a Corrective Action Plan (CAP) will be required.

WPP

NPCC Guidelines

Harmonic Levels During Geomagnetic Storms

Using only fundamental frequency analysis (e.g., load flow and dynamic stability) for assessing the performance of power systems subjected to GMD events may underestimate the risks of severe GMD events. Therefore, a complete assessment should consider the possible harmonic effects, and to do so the appropriate harmonic content for each planning area or sections of the planning area should be evaluated. Planners can use harmonic level information to determine if problems can be anticipated on different equipment on the network, and they can consult protection experts, with these levels, for a more thorough analysis if needed.

Evaluation of harmonic effect during a GIC event in a power system can be performed with:

1. Tools to evaluate the total level of voltage harmonic distortion (THD); e.g., EPRI GICHarm [8].
2. Time-domain electromagnetic transient simulation studies with appropriate models that have all the details necessary to capture the behavior of the network with GICs.
3. Use of existing measurements from GMD events and extrapolation of data based on engineering judgment.

The measurement-based approach (item #3 above) providing an order of magnitude estimate of the level of harmonic can also be used to decide the need (or not) to perform further analysis with harmonic analysis tools and if further evaluation should be considered in case no harmonic effects are foreseeable based on engineering judgment.

WPP

NPCC Methodology

System Margin Considerations

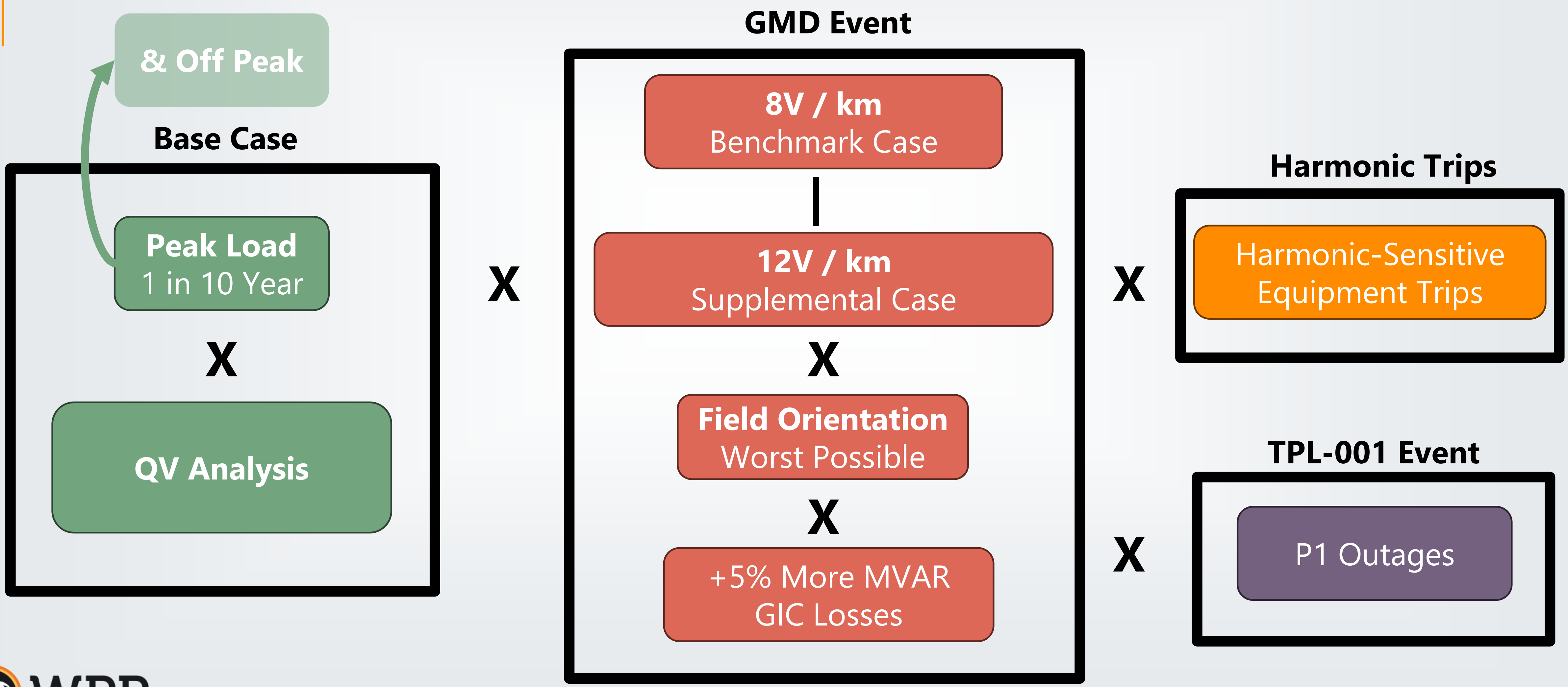
The SS-39 members determined that voltage magnitude, by itself, is not a good indicator or sufficient to ensure that voltage collapse, Cascading, or uncontrolled islanding shall not occur and suggest that consideration be given to evaluating a combination of voltage limits, stability margins, and Reactive Power reserve requirements, although not mandated by TPL-007.

There are various methods to determine system margin, and each entity will determine how much margin is considered acceptable in the Event (loss of Facilities) state, i.e., under event ID C above, and which methodology to use. In typical voltage transfer P-V analysis performed as part of NPCC Area Transmission Reviews (ATR), transfer limits are set to ensure at least 5% Reactive Power margin[3] from the point of maximum loadability (voltage collapse point). A similar % margin can be adopted for this analysis. To determine this margin, an entity may consider using one of the three methods described below:

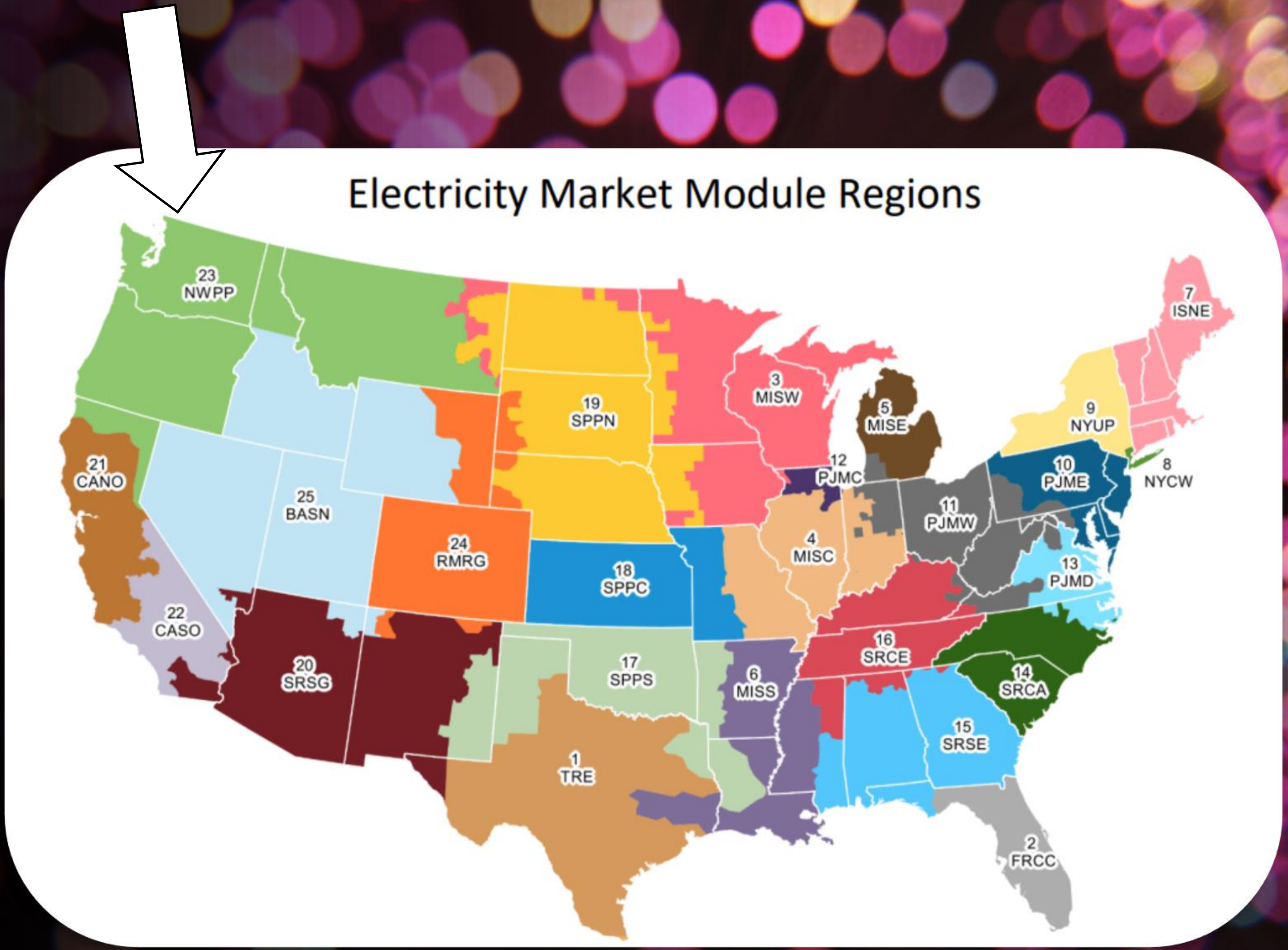
a. Run a sensitivity analysis that:
   i. Assumes the Misoperation of one Facility (a P1 event after Event ID C), or
   ii. Assumes a slightly more severe storm that increases reactive loss by 5% (this is beyond the supplemental GMD event since this is to determine how much margin is available beyond what is expected from the standard)

b. Q-V analysis[4] that captures how quickly voltage changes for step increases in MVAr losses. A single reference bus can be assumed for voltage or a collection of representative bus voltages can be monitored. If the voltage significantly decreases for a step increase in reactive losses, it is an indication the system is approaching a collapse condition.

NPCC Methodology



Q: Would this study have caught the 1989 blackout?



Very Similar to Previous WECC Methodology

2022 PowerWorld/WPP Study

Transmission Topology

WPP provided a set of transmission facilities that could be lost or inoperable as a results of protection system operation or misoperation due to harmonics during GMD events, as follows:

- [illegible]
- [illegible]
- [illegible]
- [illegible]

These outages are simultaneously applied to the system models for purposes of assessing worst-case transformer and steady-state voltage stability.

Q: Would this study have caught the 1989 blackout?

Suggested Improvements

Suggested Improvements

Harmonics Assessment: EPRI GICHarm

Use EPRI's Screening Thresholds

Model a simultaneous outage of ALL harmonics-impacted equipment

Questions?

References

The public references used for this presentation are shared for your reading pleasure <Here>