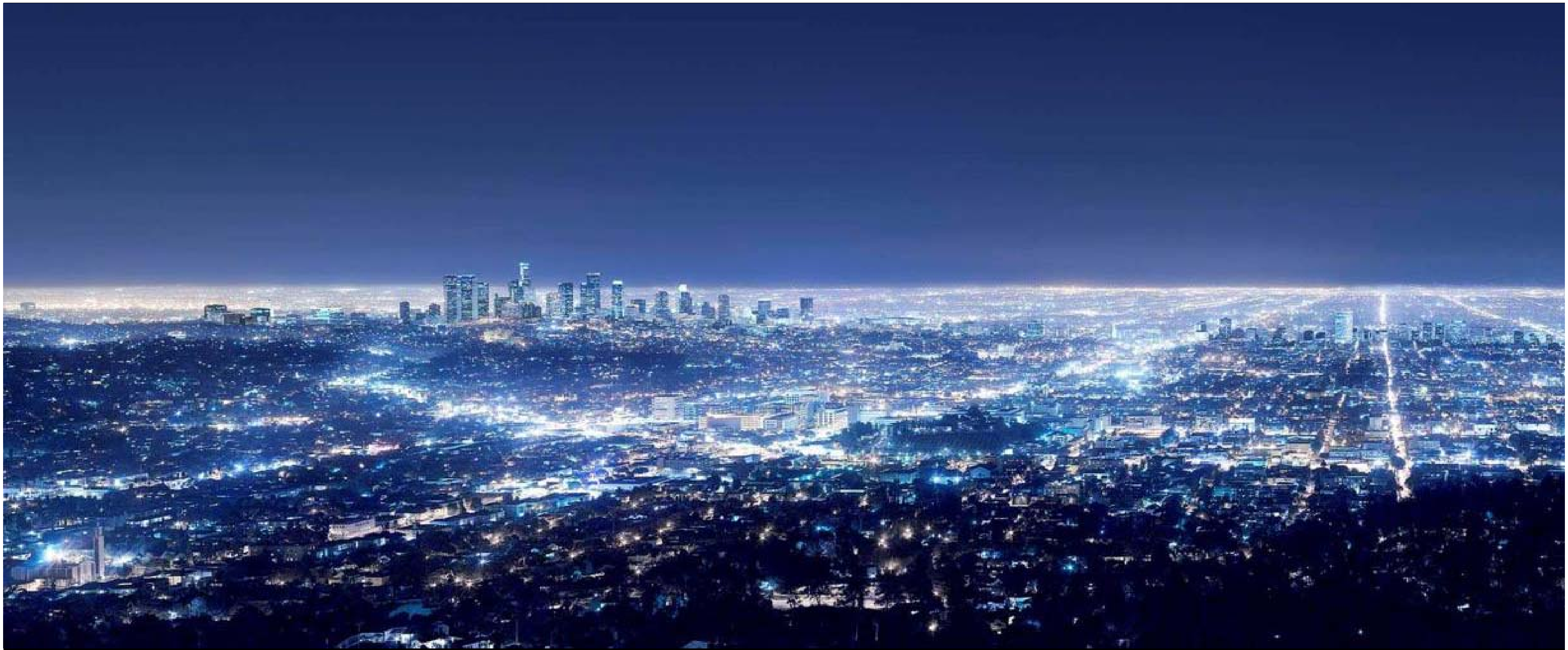

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Geomagnetic Disturbance and Risks to Electric Power Systems

Dr. Xiaoming Feng,
Executive Consulting R&D Engineer
ABB Corporate Research, Raleigh, NC, USA

Disclaimer

- This presentation is based on public information
- The views and opinions expressed in this presentation are those of the author and do not necessarily reflect the official opinion and position of ABB.

Growing interest in GMD in recent years

- Increased coverage in the news, IEEE Spectrum, 2/2012
- Executive Summary of FERC, DOE and DHS Detailed Technical Report on Electromagnetic Threats to the U.S. Power Grid, Oct, 2010
- FERC Report, "Geomagnetic Storms and Their Impacts on the U.S. Power Grid," FERC_Meta-R-319, January 2010
- NERC, "2012 Special Reliability Assessment: Interim Report: Effects of Geomagnetic Disturbances on the Bulk Power System," February 2012
- NERC, "Industry Advisory Preparing for Geo-Magnetic Disturbances," Initial Distribution: May 10, 2011
- FERC workshop on GMD effect, April 2012

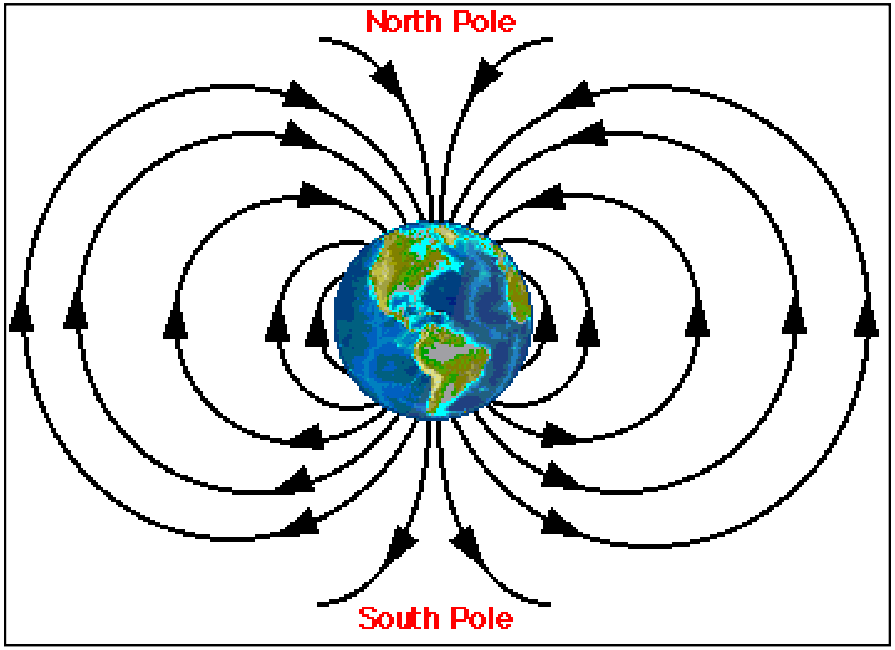
United States including destroying a major transformer at an east coast nuclear generating station. Major geomagnetic storms, such as those that occurred in 1859 and 1921, are rare and occur approximately once every one hundred years. Storms of this type are global events that can last for days and will likely have an effect on electrical networks world wide. Should a storm of this magnitude strike today, it could interrupt power to as many as 130 million people in the United States alone, requiring several years to recover.

Outline

- GMD, its relationship to solar flares, solar cycles,
- Historical and recent solar flares, classifications
- Current explanation of GIC in power systems and its effect
- Analysis of GIC and data uncertainty
- Mitigation strategies
- Current industry practice
- Summary

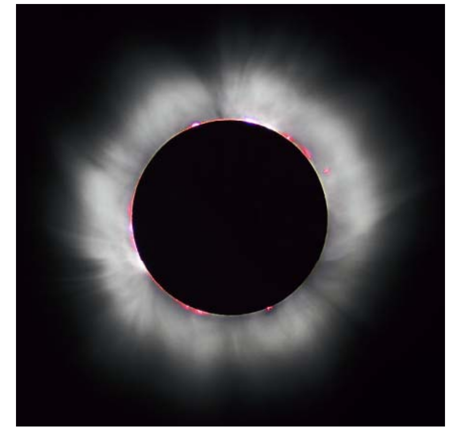
Geomagnetic Disturbance (GMD)

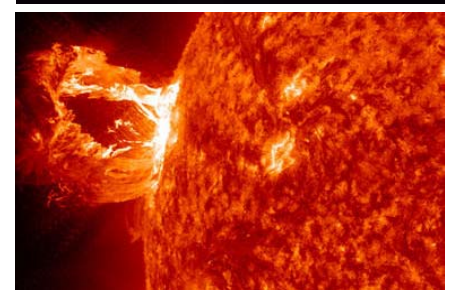
- Geomagnetic disturbance is the significant and abnormal fluctuations in the magnetic field (nT/minute) near the surface of the Earth caused by space weather
- GMD is also called geomagnetc storm



Cause of GMD

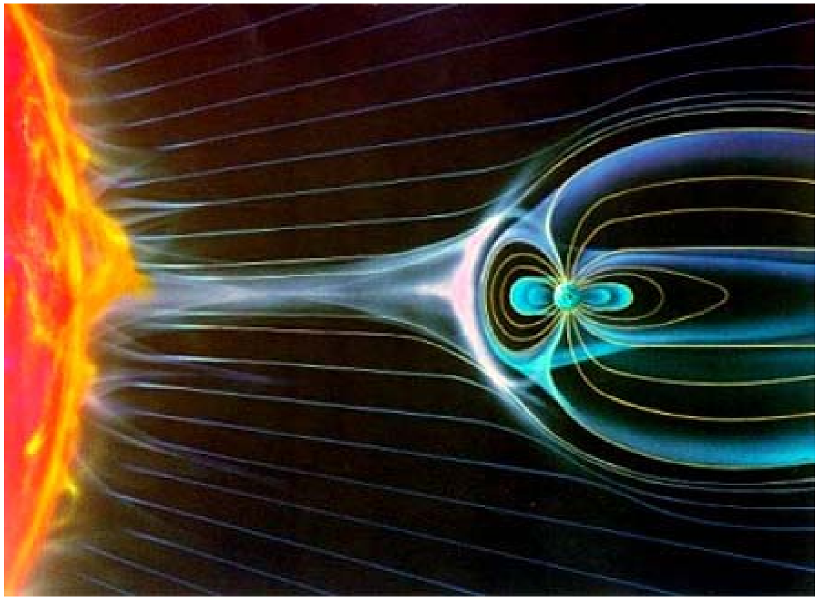
- Space weather originates from the Sun
- Solar flares are the sudden brightening on the surface of the Sun caused by large energy release (6 X 10^25 joules of energy, 500,000 times the annual energy consumption of US in 2010)
- Solar flares occur in active regions around sunspots, powered by the sudden (minutes) release of magnetic energy stored in the corona
- Solar flares often accompanied by CME (corona mass ejection)





Solar Wind

- Plasma consisting primarily of electrons and protons traveling at high speed
- When directed towards the Earth, it is called interplanetary CME (ICME)
- CMEs typically reach Earth in one to five days
- Solar wind interact with The Earth's magnetic field, resulting in Geomagnetic Disturbance (GMD)



Potential Impact on Earth by CME

- Disruption and damage to communication systems and GPS satellites, spacecrafts
- Damages to electrical transmission facilities and affect power system stability
- Pipelines

The Earliest Solar Storm on record
- The Carrington event of 1859

- The largest recorded geomagnetic storm (September 1–2, 1859)
- Named after British astronomer Richard Carrington
- Aurorae were seen around the world, most notably over the Caribbean
- People in the northeastern US could read a newspaper by the aurora's light
- Telegraph systems failures in Europe and North America; Some telegraph systems continued to work without power supply

How likely is extreme space weather (another Carrington event)?

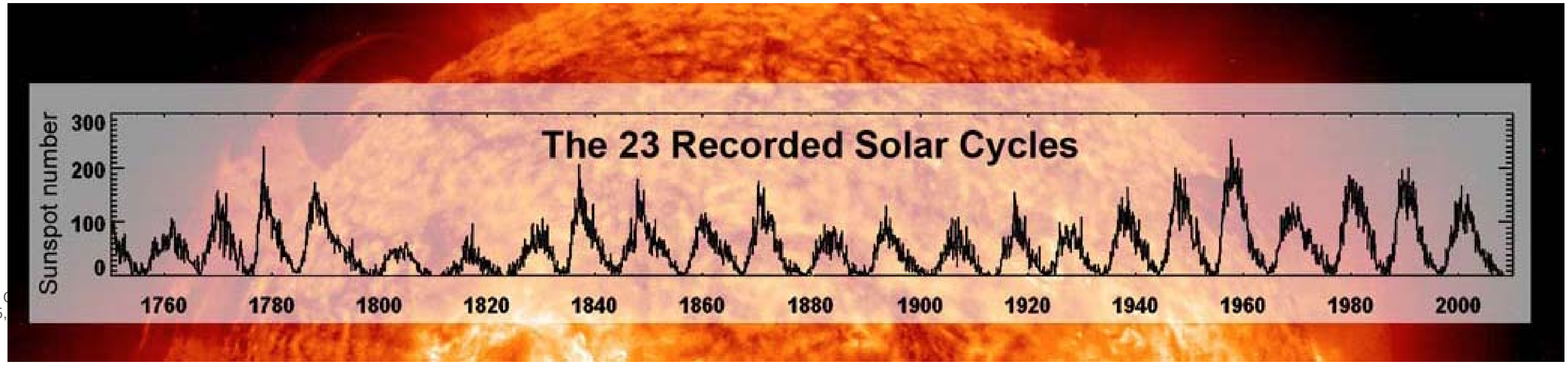
- Pete Riley, “On the probability of occurrence of extreme space weather events”, SPACE WEATHER: THE INTERNATIONAL JOURNAL OF RESEARCH AND APPLICATIONS, VOL. 10, S02012, 12 PP., 2012

- By virtue of their rarity, extreme space weather events, such as the Carrington event of 1859, are difficult to study, their rates of occurrence are difficult to estimate, and prediction of a specific future event is virtually impossible.
- Space physics datasets often display a power-law distribution
- Power-law distribution can be exploited to predict extreme events
- Probability of a Carrington event occurring over next decade is ~12%

- If this prediction is reliable should we expect to see more intermediate events?

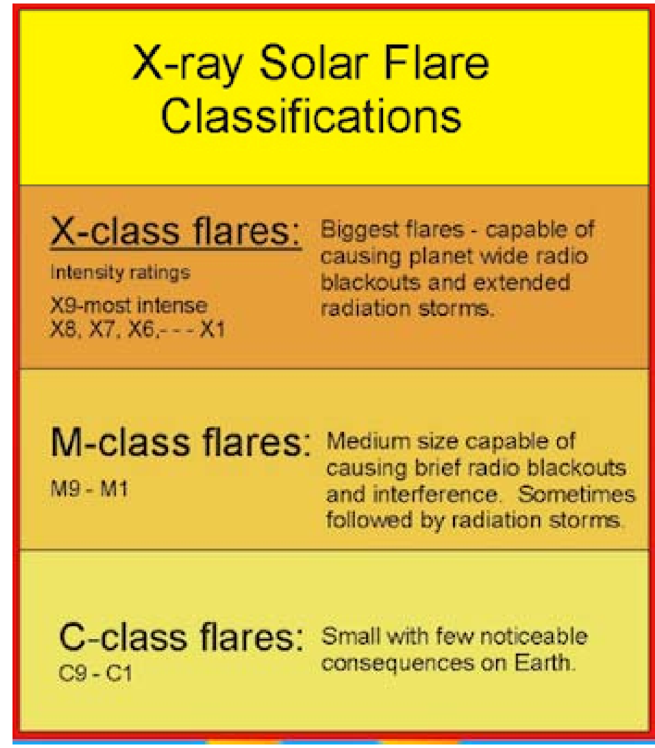
Solar Activity Cycle

- Sun's magnetic polarity reverses every 11 years, solar activities follow 11 year cycle
- The last solar maximum was in 2000
- Predictions of maximum's timing and strength very difficult.
- In 2006 NASA initially expected a solar maximum in 2010 or 2011, the strongest since 1958
- More recent projections is February 2013 and one of the weakest since 1928



Solar Flare Classifications

- Solar flares intensity is measured on log scale
- Each letter represents a 10 times energy output over the previous letter
- Each category is divided 1-9 subscales
  - A, B - background level
  - C - weakest
  - M - moderate
  - X - most powerful
- X28 event was observed in 2003 (not directed at Earth ☺)



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Recent solar flare activity

- August 9, 2011
  - X6.9 flare directed at Earth
- Jan 2012
  - M9 class on Jan 23, arriving at Earth on Jan 24-25
  - Delta rerouted 8 polar flights as precaution
  - United diverted one flight
- April 2012
  - M1.7-class on April 16, arriving at Earth on April 17

The effect on man made conductive structures - GIC

- GMD can cause GIC in man made conductive structures
- GIC – geomagnetically induced current
- Six steps from CME to GIC

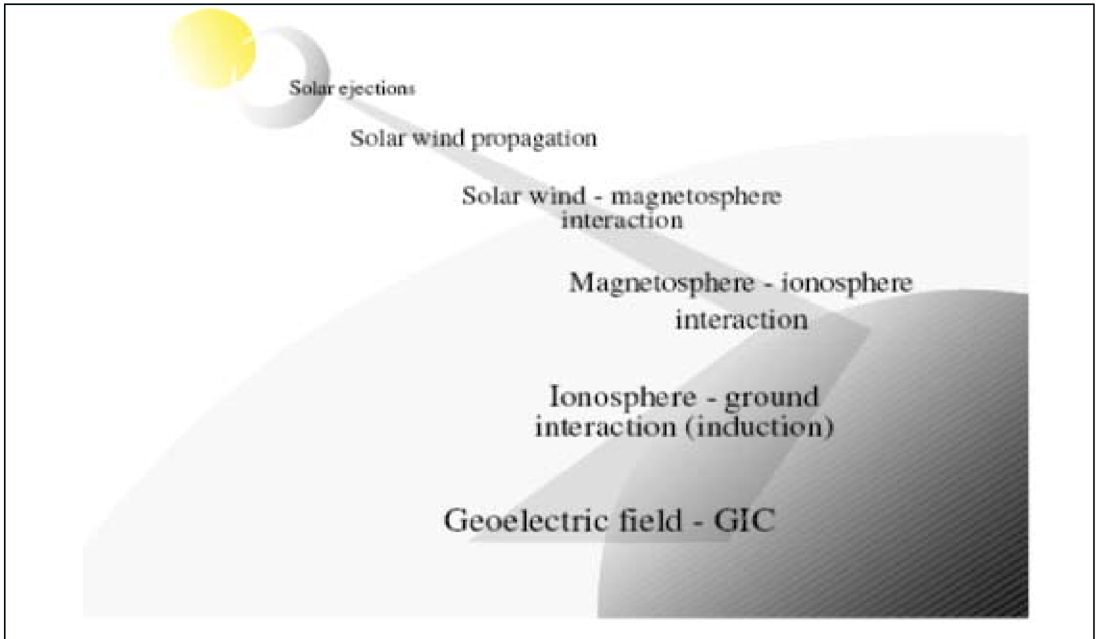


Figure 1.2: Six steps of space weather chain from the Sun to the ground.

Variations in the magnetic field induce an electric field according to Faraday's law

$\nabla \times E = -\frac{dB}{dt}$, which drives an electric current inside the Earth according to Ohm's law

$J = \sigma E$.

Properties of Earth Surface Potential (ESP)

- Magnitude ESP is relatively small, with maximum observed values in the order of 10 V/km.
- Only geographically extended systems, such as power systems, natural gas pipelines, are affected.
- Typical frequency range of ESP is 0.001-1 Hz, DC like
- ESP is a function of the rate of change of the magnetic field

Geomagnetic Storm Scale (magnitude of magnetic field fluctuation)

NOAA Space Weather Scale for Geomagnetic Storms

Category		Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects		
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	**Power systems:** : widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage.	Kp = 9	4 per cycle
G 4	Severe	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid.	Kp = 8, including a 9-	100 per cycle
G 3	Strong	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices.	Kp = 7	200 per cycle
G 2	Moderate	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage.	Kp = 6	600 per cycle
G 1	Minor	**Power systems:** weak power grid fluctuations can occur.	Kp = 5	1700 per cycle

K-index	a	Boulder, CO observatory measurement (nT)	NOAA G-scale
0	0	0 - 5	G0
1	3	5 - 10	G0
2	7	10 - 20	G0
3	15	20 - 40	G0
4	27	40 - 70	G0
5	48	70 - 120	G1
6	80	120 - 200	G2
7	140	200 - 330	G3
8	240	330 - 500	G4
9	400	>500	G5

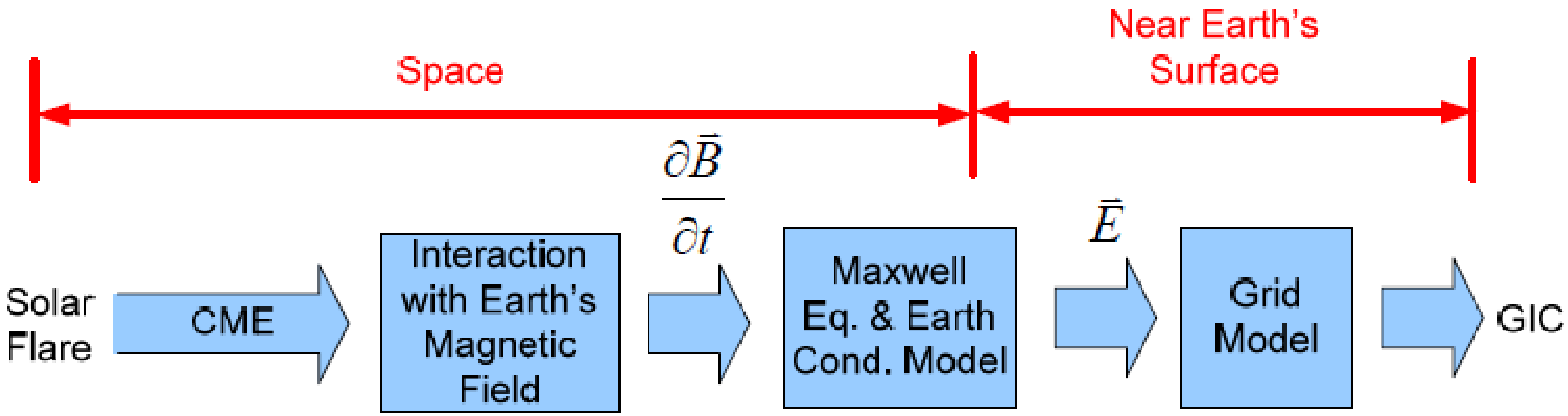
- K-index is derived from the maximum fluctuations of horizontal components observed on a magnetometer during a three-hour interval

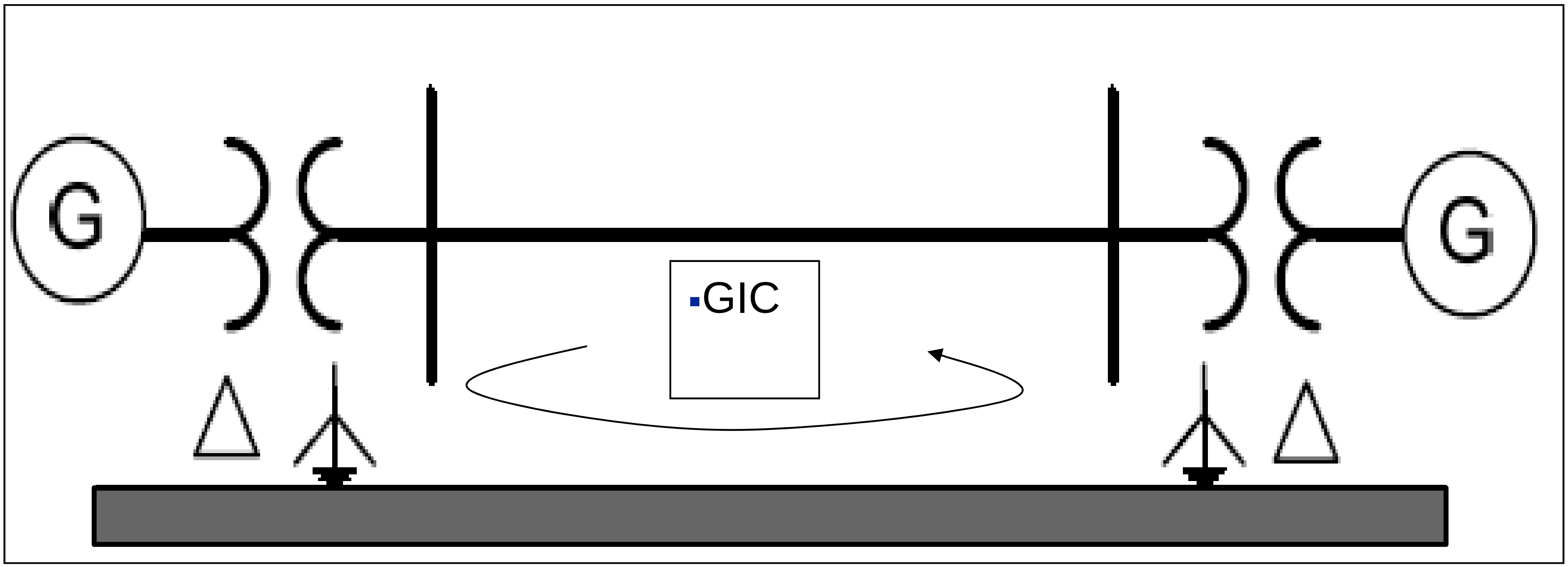
Forecast and Early Warning of GMD – NOAA SWPC

- Did a CME occur?
- Is it Earth-directed?
- How fast is it moving towards Earth?
- When it impacts Earth, how strong will the impact be?
- How long will the storm last?

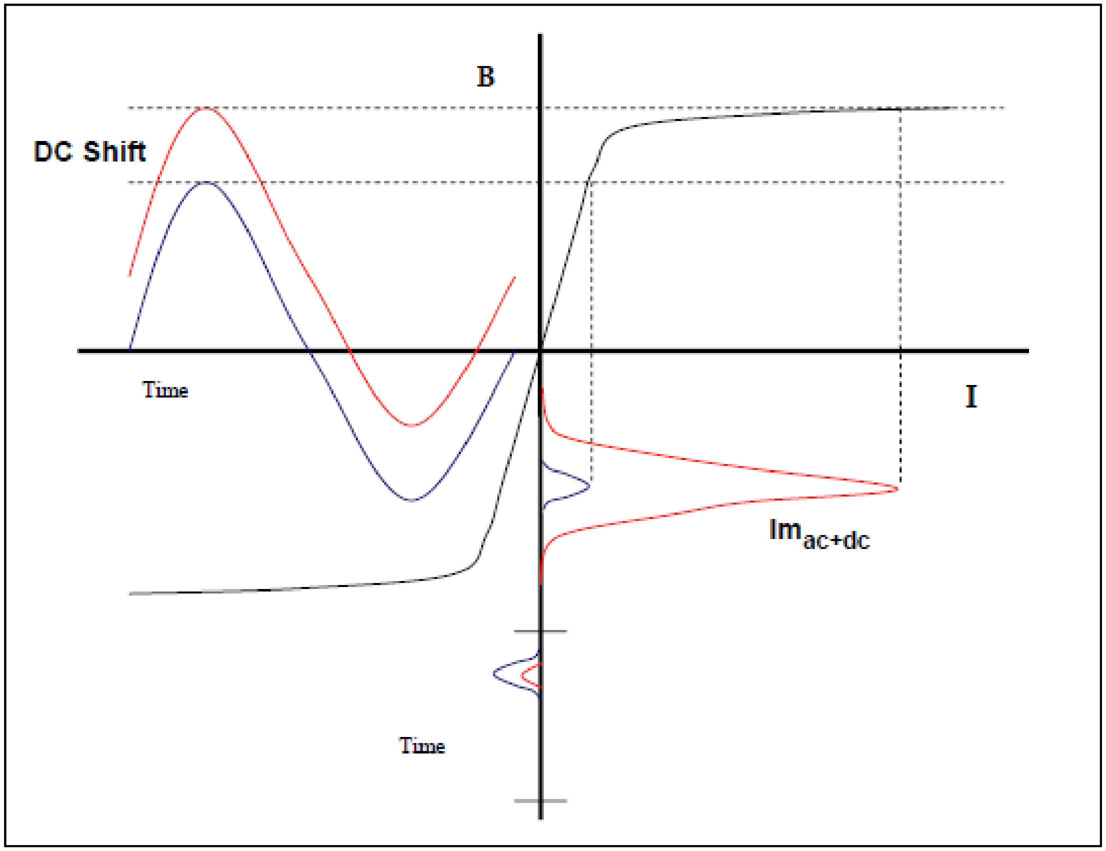
- CME can be spotted eight minutes after occurrence by STEREO (Solar Terrestrial Relations Observatory) satellite
- 40-60 minutes before reaching the earth, the CME reaches the L1 satellite, one million miles from Earth, Solar wind speed, temperature, density, and magnetic field are all measured at L1.

Induced current in power grid





GIC effect on power transformer – half cycle saturation



- High magnetizing current
- High harmonic content
- Increased loss and overheating
- Increased var consumption

GIC (indirect) Effect on Relay Protection

- Relays for SVC, lines, transformer, capacitors, generators can misoperate due to the harmonic currents caused leading the relay to perceive a fault or overload condition.
- Output of differential relay can become distorted and the relay will fail to trip under a fault condition.
- The remnant flux in the CT reduces the time to saturation for the CT and cause the CT to behave erratically, even days after the GMD

Other reported GIC Effect

- HVDC converter operation
  - Cause – harmonic content
  - 4th and 6th harmonics in on the DC side affects inverter control that depends on the extinction angle
- Generator rotor heating
  - Cause – harmonic current
- Switching transient
  - Overvoltage during energization of long lines
  - Circuit breaker recovery voltage can be higher in the presence of GIC

The most cited GMD event – March1989 Solar Storm

- March 9,1989 – Solar flare and CME
- March 13, 1989 – geomagnetic storm
- Quebec blackout
  - Unintended tripping of line protection
  - Failure of major power transformer
  - Loss of 9500 MW generation (out of 21500 MW)
  - Outage lasted 9 hours
  - Affected 6 million people
  - Estimated 2 Billion CAD economic loss

Failed transformer – Evidence or coincidence?

- Source: John Kappenman, Electric Power Grid Vulnerability to Geomagnetic Storms An Overview

The NERC Report Conclusion

- NERC Special Report 2012

The most likely worst-case system impacts from a severe GMD event and corresponding GIC flow is voltage instability caused by a significant loss of reactive power support[11] simultaneous to a dramatic increase in reactive power demand. Loss of reactive power support can be caused by the unavailability of shunt compensation devices (*e.g.*, shunt capacitor banks, SVCs) due to harmonic distortions generated by transformer half-cycle saturation. Noteworthy is that the lack of sufficient reactive power support, and unexpected relay operation removing shunt compensation devices was a primary contributor to the 1989 Hydro-Québec GMD-induced blackout.

NERC recognizes that other studies have indicated a severe GMD event would result in the failure of a large number of EHV transformers. The work of the GMD Task Force documented in this report does not support this result for reasons detailed in Chapter 5 (*Power Transformers)*, and Chapter 8 (*Power System Analysis*). Instead, voltage instability is the far more likely result of a severe GMD storm, although older transformers of a certain design and transformers near the end of operational life could experience damage, which is also detailed in Chapter 5 *(Power Transformers)*.

Dissenting views

- On April 30, 2012 FERC held a technical conference to discuss the impact of geomagnetic disturbances (GMD) on the bulk power system.
- Everyone agreed that GMD will continue to impact the grid and that precautions must be taken to prepare for them.
- However, experts disagree on the severity of the impact of GMD on the grid. The key disagreement seemed to be whether the more likely effect on the grid of a major GMD was a blackout due to voltage instability or severe damage or failure of power transformers and other power equipment (circuit breakers, surge arresters, insulators, and capacitors were specifically mentioned at various points during the conference).
- In short, NERC, utilities and grid operators aligned against the US Department of Homeland Security, researchers and academics, arguing that the threat of GMD can be met with fewer federal mandates than those unsatisfied with the report's conclusions recommend.

From theory to engineering

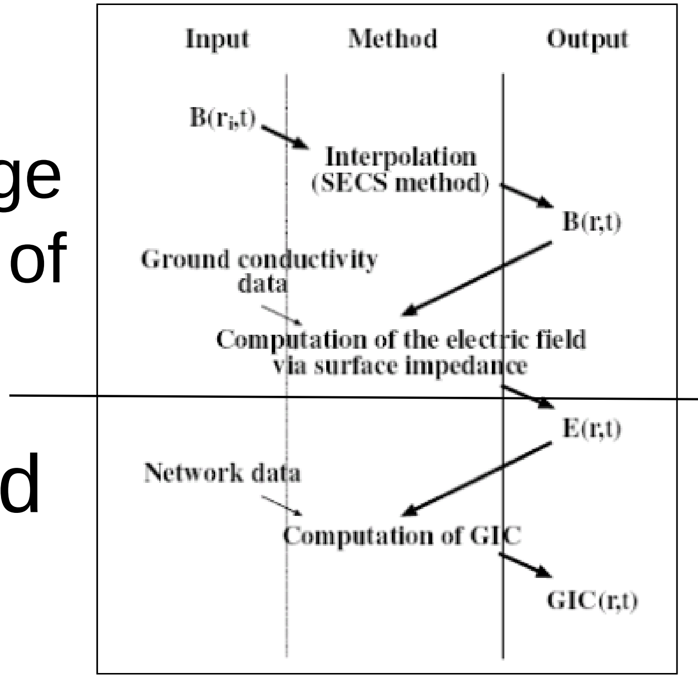
- Analysis
- Mitigation

Key factors determining GIC magnitude

- The distribution and intensity of the ESP.
- The topology and electrical characteristics of the man made systems.

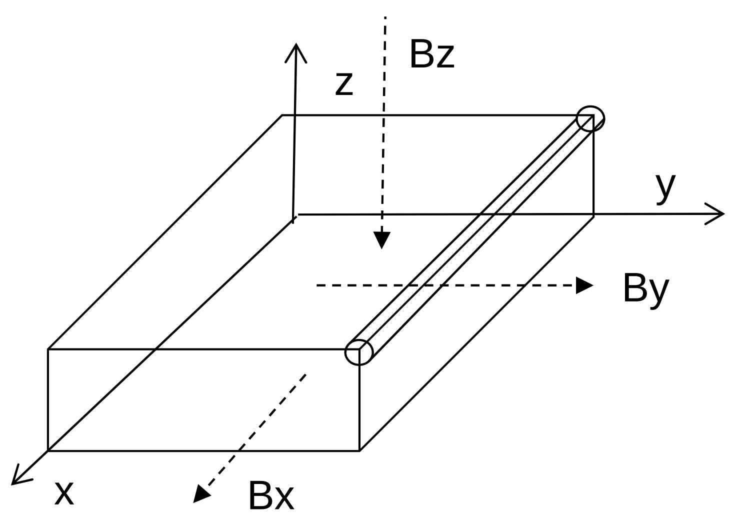
Calculating GIC – Two step process

- The geophysical step – the difficult and uncertain
  - Calculation of the surface horizontal geoelectric field based on the knowledge of the ionospheric source currents and of the ground conductivity structure.
- The engineering step – the easy and deterministic
  - Calculation of GIC based on the knowledge of the surface geoelectric field and of the topology and electrical parameters of the man made system



Calculating GIC – Simplifying assumptions

- No mutual coupling between Earth and the man mad system (Quasi-DC nature of GIC)
- Flat Earth
- Additional simplifications
  - Electric field inside Earth has horizontal components only
  - Vertical components of magnetic field variations ignored

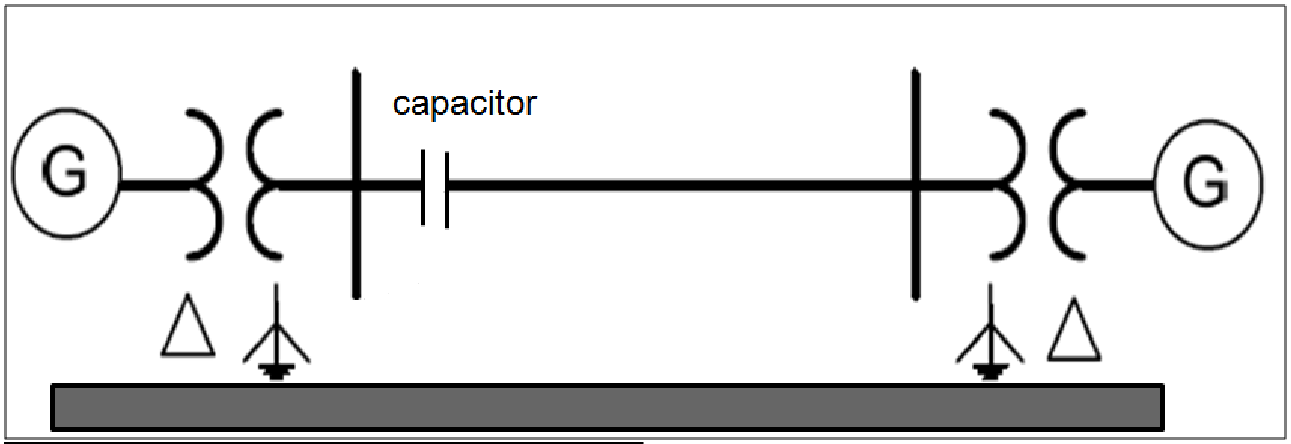


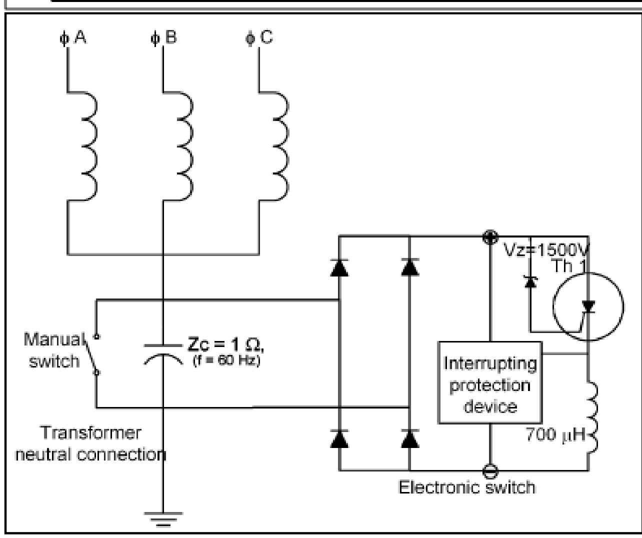
Mitigation Strategies

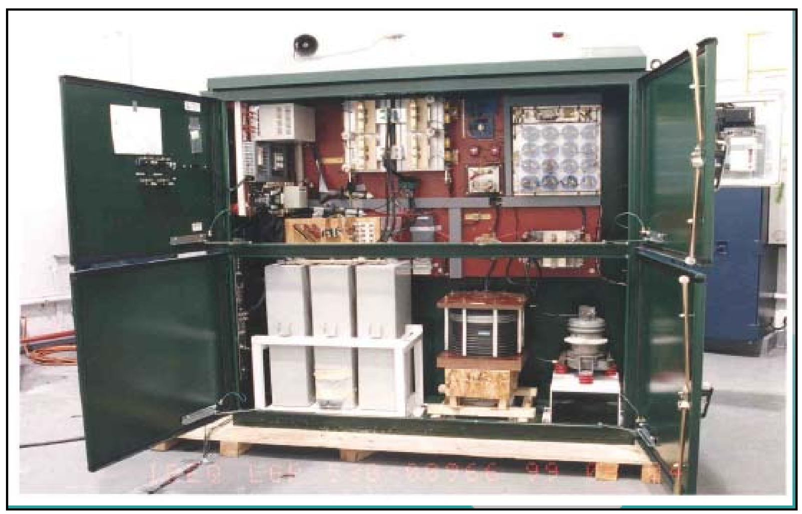
- Block, reduce or compensate the GIC entering the power system;
- Use transformer designs that are less likely to saturate in the presence of GIC.
- Adopt operation practices to reduce the probability of cascading failure by increased reserve;
- Improve the relay protection to handle harmonic current;

Blocking Solutions

- Series capacitor
- Neutral current blocking device (NCBD)





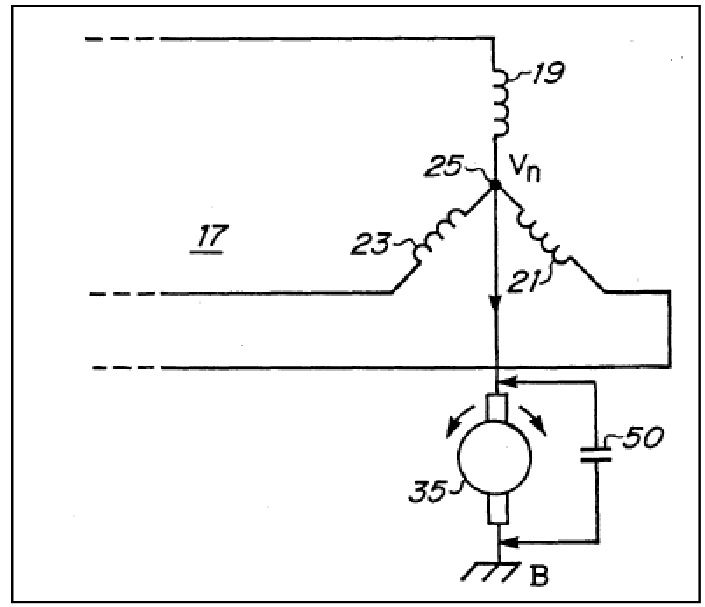


BOLDUC *et al.*: DEVELOPMENT OF A DC CURRENT-BLOCKING DEVICE FOR TRANSFORMER NEUTRALS

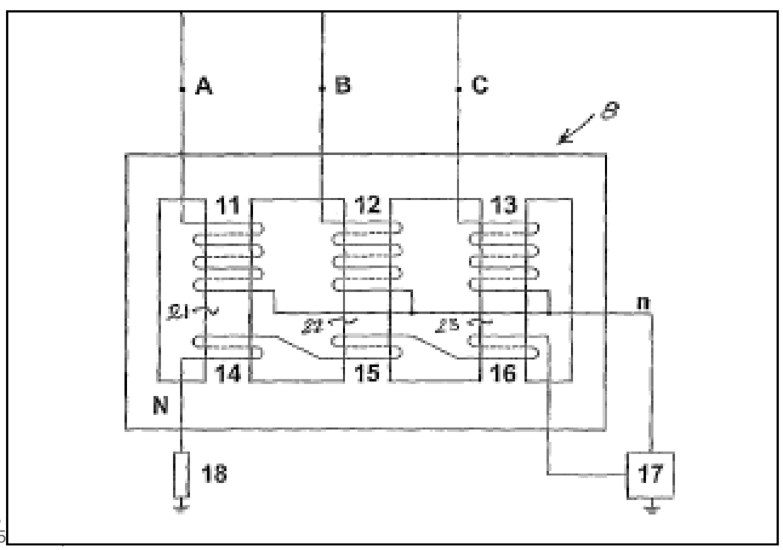
Compensation solutions

- Compensation
  - Additional winding,
  - Active compensation

United States Patent [19] Oliver
[11] Patent Number: 5,179,489
[45] Date of Patent: Jan. 12, 1993



United States Patent A F Klercker Alakula et al.
(10) Patent No.: US 7,489,485 B2
(45) Date of Patent: Feb. 10, 2009



Utility Practices

- Recognize the risk
- Rely on improved planning and operation practice to manage the risk

NERC's Reliability Standard, IRO-005-2, Requirement R6,[4] states:

> *"Each Reliability Coordinator shall ensure its Transmission Operators and Balancing Authorities are aware of Geo-Magnetic Disturbance (GMD) forecast information and assist as needed in the development of any required response plans."*

Typical Planning Practice \NERC advisory

- Review operating practices especially for areas where voltages are approaching operating range limits and HVDC schemes are operating in excess of nominal full load ratings.
- Adjust negative-sequence-current relay settings on transformers.
- Review harmonic unbalance relay settings.
- Verify and consider adjusting CT ratio or settings of ground backup and transformer differential relays including harmonic restraint.
- •Install monitoring devices to measure transformer neutral currents and provide better data on GIC activity.
- Simulate the effects of GICs on the power system to identify locations susceptible to transformer and/or reactor heating in the future.
- Perform more frequent inspections of transformers to check for abnormal noise, tank discoloration due to heating, and gas accumulator readings.

P.R. Barnes et al, "Electric Utility Industry Experience With Geomagnetic Disturbances," Oak Ridge National Lab, ORNL-6665, 1991

Typical Operation Practice \\NERC advisory

- Discontinue maintenance work and restore out-of-service transmission lines.
- Avoid taking long transmission lines out of service.
- Maintain system voltage within an acceptable operating range to protect against voltage swings.
- Reduce generator loading to provide reserve power and reactive capacity.
- Consider the impact of shunt capacitor banks and static VAR compensators that trip out on high-voltage transmission lines.
- Dispatch reserve generation to maintain system voltage and tie- line loading and to distribute operating reserves.
- Bring synchronous condenser equipment on line to provide reactive power reserves.
- Notify adjacent control areas about geomagnetic disturbance problems.
- Reduce power output at susceptible generator stations if erratic reactive power output from generators or excess reactive power consumption by generator step-up transformers is detected.
- •Reduce power transfers to 95% of the transfer limits

P.R. Barnes et al, “Electric Utility Industry Experience With Geomagnetic Disturbances,” Oak Ridge National Lab, ORNL-6665, 1991

Summary

- GMD induces ESP, which drives GIC to follow in power grid through neutrally grounded transformers
- Half cycle saturation of transformer results in high magnetizing current and harmonic distortions, increases risk of mis-operation and system collapse
- Power industry recognize the risk of GMD, disagree on the level of risk and damages to power transformers, due to lack of conclusive evidence

Summary

- GMD risk quantification is extremely difficult
- Mitigation technology is easy in principle, cost effective solution is not
- System operators currently rely on defensive (higher reserve) planning and operation practice to manage the risk
- The strategy appears to be effective, due to effect of GMD takes time to build, giving operator time for remedial actions

- Thank you
- Questions?

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