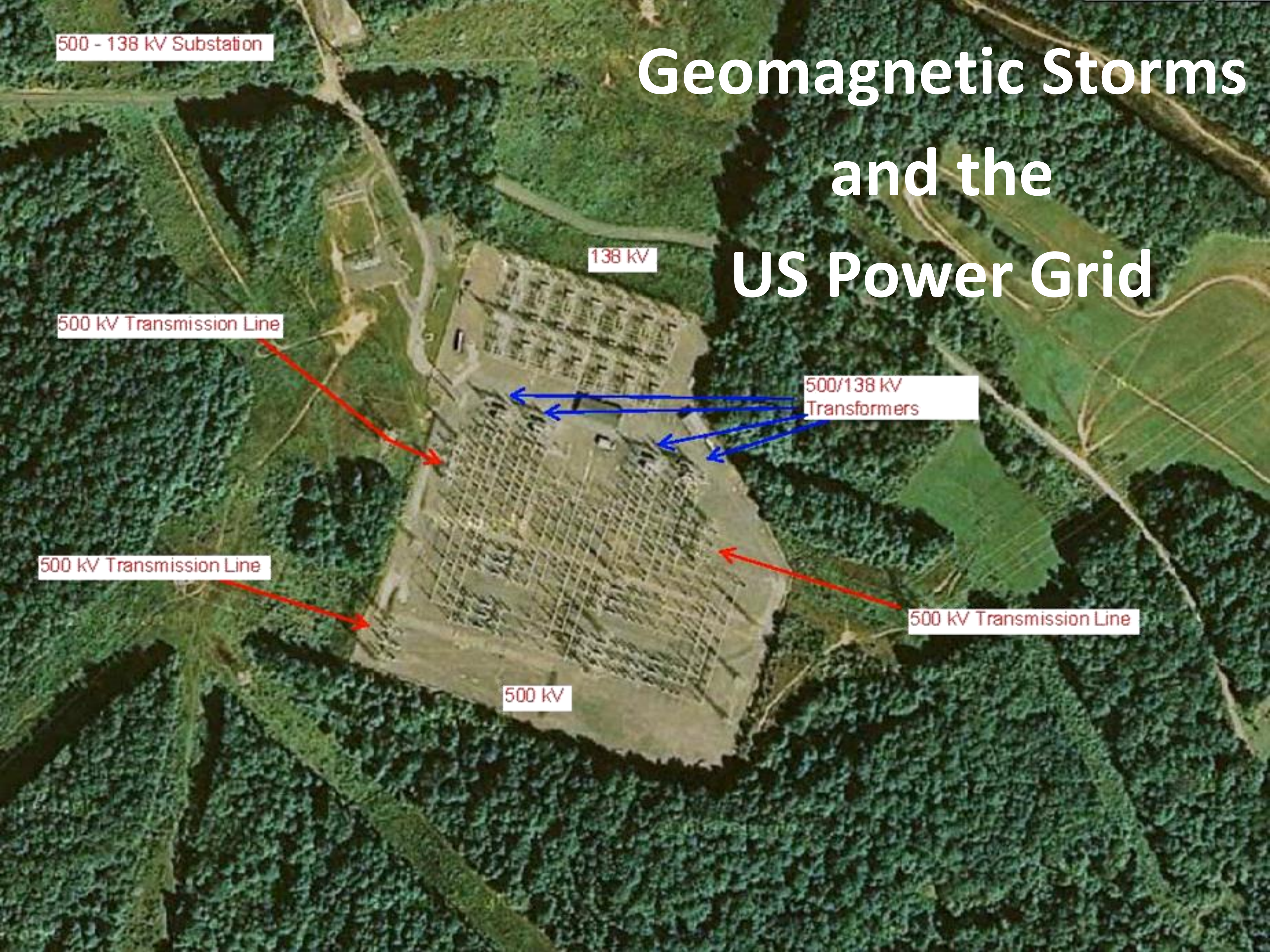
Geomagnetic Storms and the US Power Grid



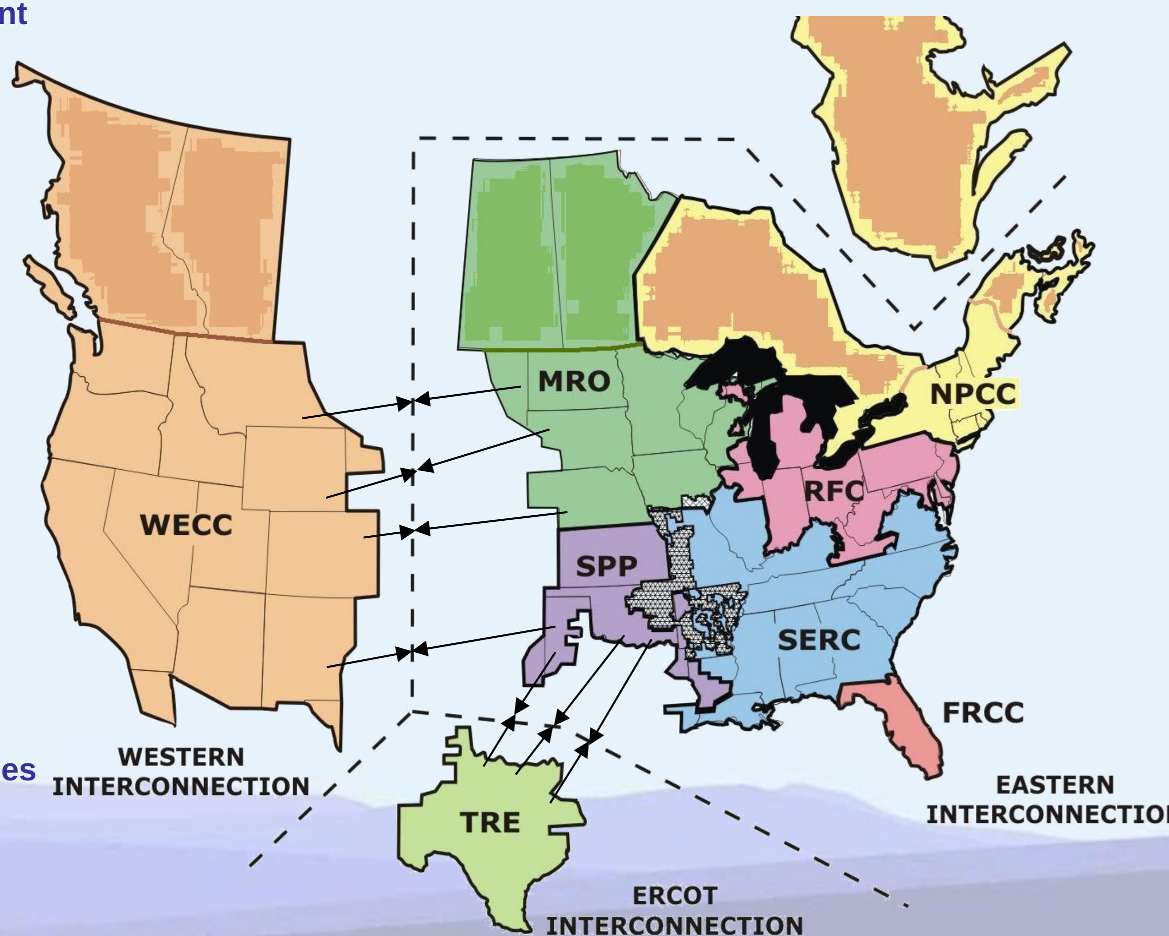
Effects of Space Weather on the US Power Grid

- **Look at how space weather can affect the electric power grid.**
- **Discuss how the Geomagnetically Induced Currents are introduced into the grid.**
- **Look at how these currents affect the grid**
  - **Particularly the effect on large power transformers**
- **Go over a few documented cases**
- **Briefly look at the grid structure and how its design contributes to the problem**
- **Review the results of the simulation a severe solar storm**

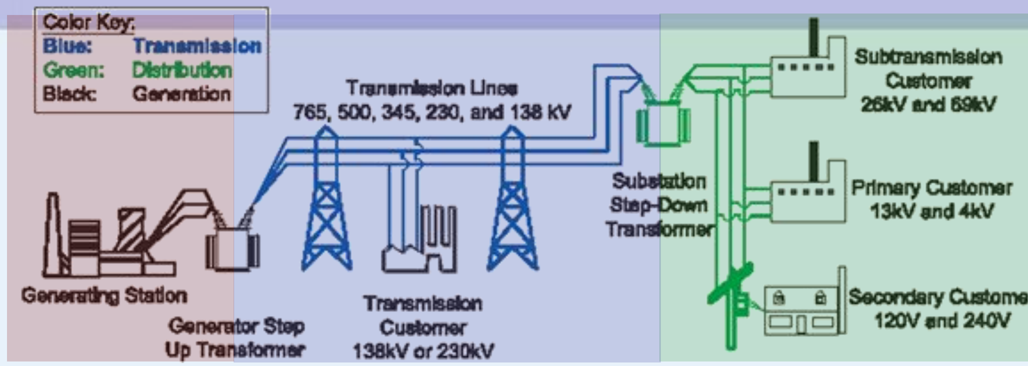
US Electric Grid Interconnections

(what is the Electric Grid)

- **The US Grid Consists of Three Independent AC Systems (Interconnects)**
  - **Eastern Interconnection**
  - **Western Interconnection**
  - **Texas Interconnection**
- **Linked by High Voltage DC Ties**
  - **Transmission Network**
  - **Distribution Systems**
  - **Generating Facilities**
- **T&D dividing line ~100 kV**
- **Distribution systems are regulated by the states**
- **Most Transmission and Generation facilities are fall under the Regulatory Authority of FERC**



United States Electric Grid

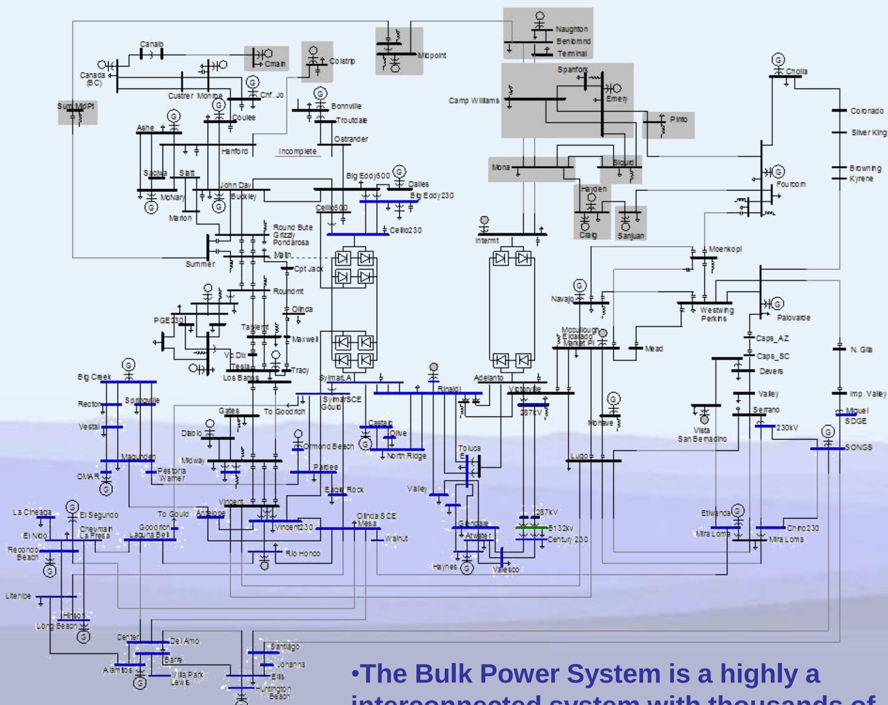


Makeup of the Grid

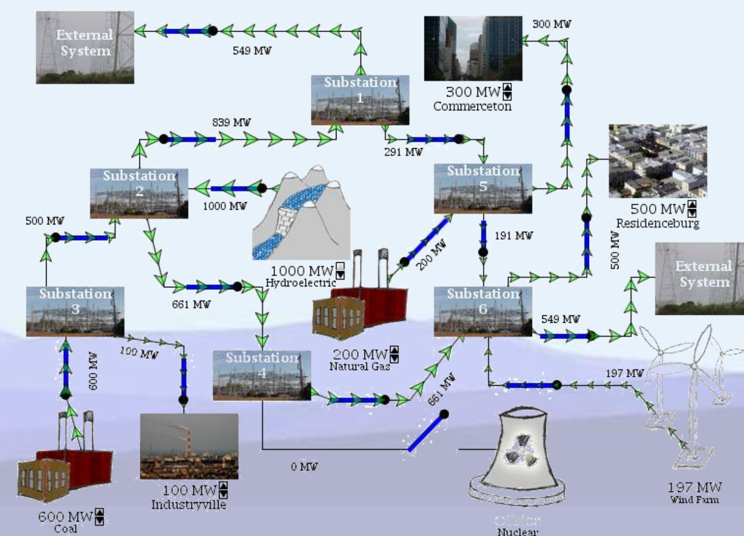
•The Distribution System (local utility) delivers the power.

•The Transmission system transports power in bulk quantities across the network.

•Generation system provides the facilities that make the power.



•The majority of Transmission and Generation facilities are part of Bulk Power System



•The Bulk Power System is a highly a interconnected system with thousands of pathways and interconnections

THE Power Grid Source: TCIPG Education University of Illinois url: tcipg.mste.illinois.edu/applet/pg

United States Transmission Grid

Transmission System consists of over:

180,000 miles of HV Transmission Lines
- **80,000 miles belong to the EHV system**

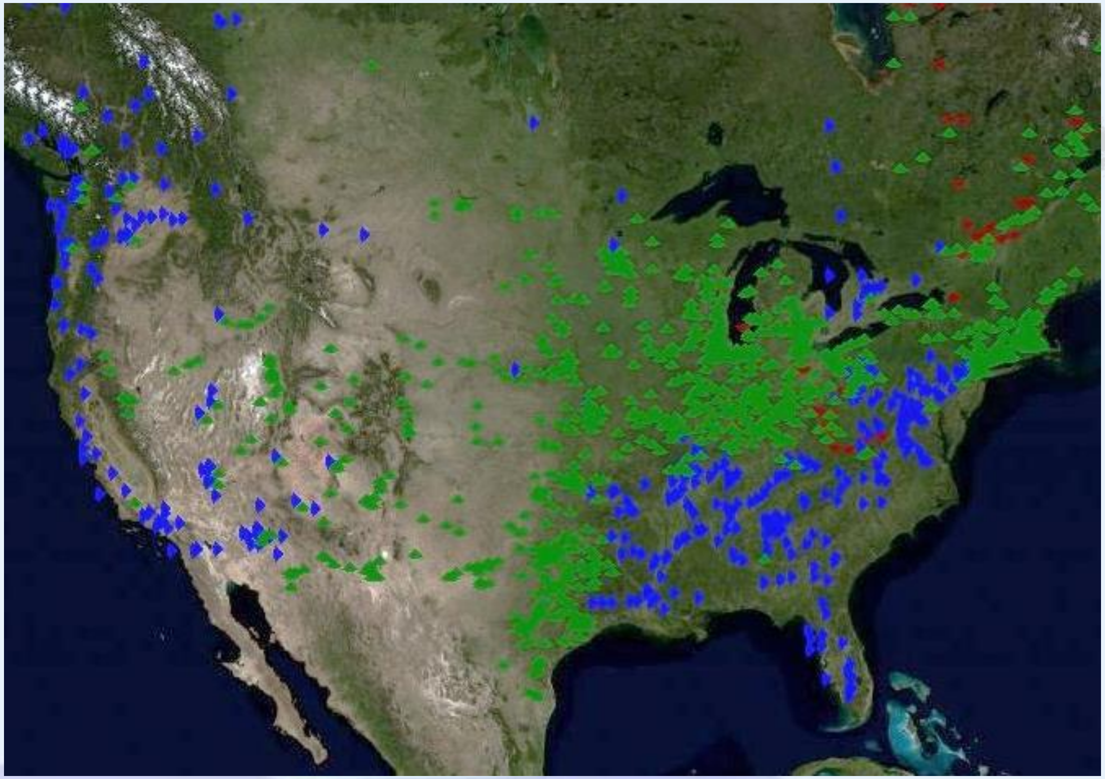
EHV System - facilities rated > 260 kV (345, 500 and 765 kV)

BPS is designed to handle minor upsets
- **must withstand a single contingency event (in an operating area)**
- **multiple contingency events more difficult to cope with (extreme solar event)**

~2000 interconnection points on the EHV network

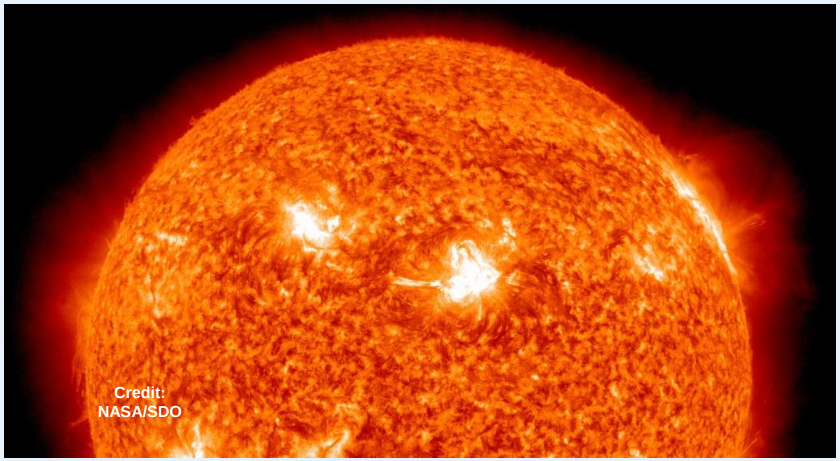
- **at each point is an EHV Transformer**
  - **Neutral Connection to Earth needed for normal AC operation**

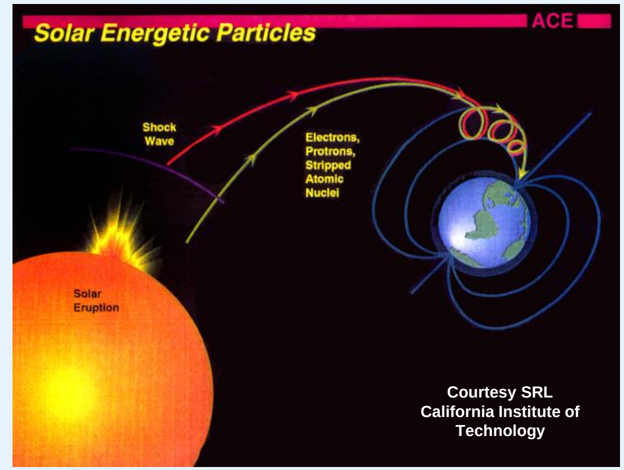
  - **Serve as entry and exit points for Geomagnetic Induced Currents (GIC)**

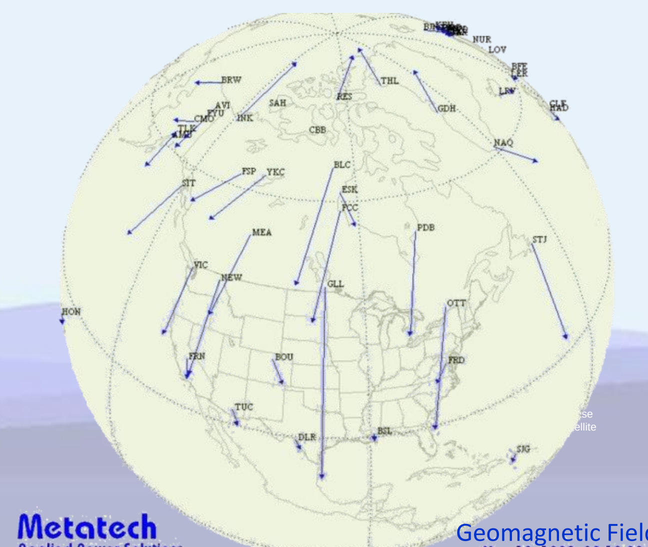


Where do GICs come from ?

(most GICs have beginnings with CMEs)

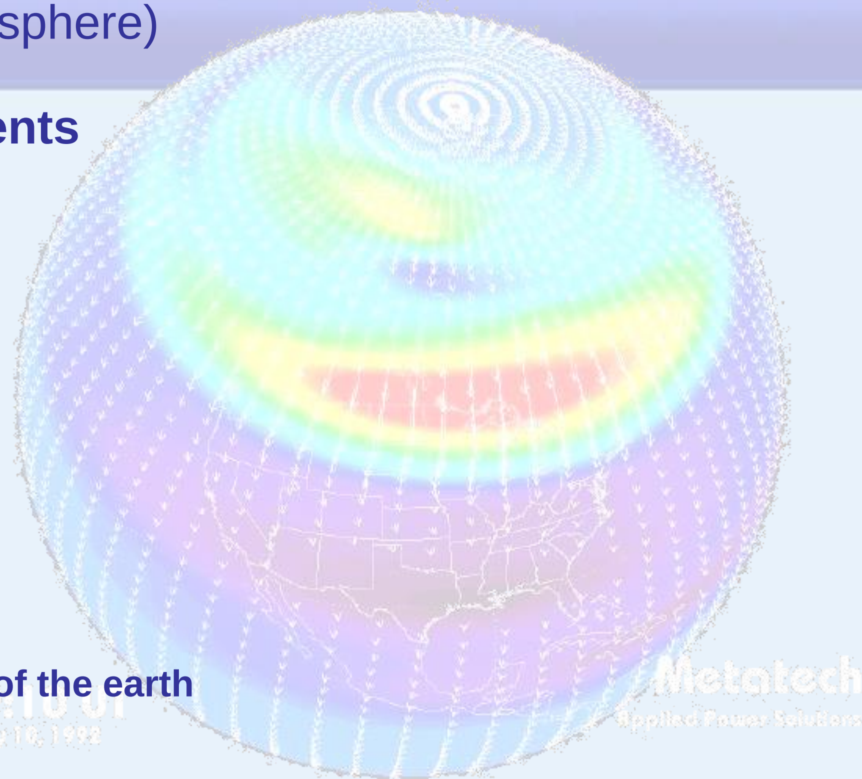






Solar CME to GIC

(northern hemisphere)



CMEs affect the Auroral Electrojet currents

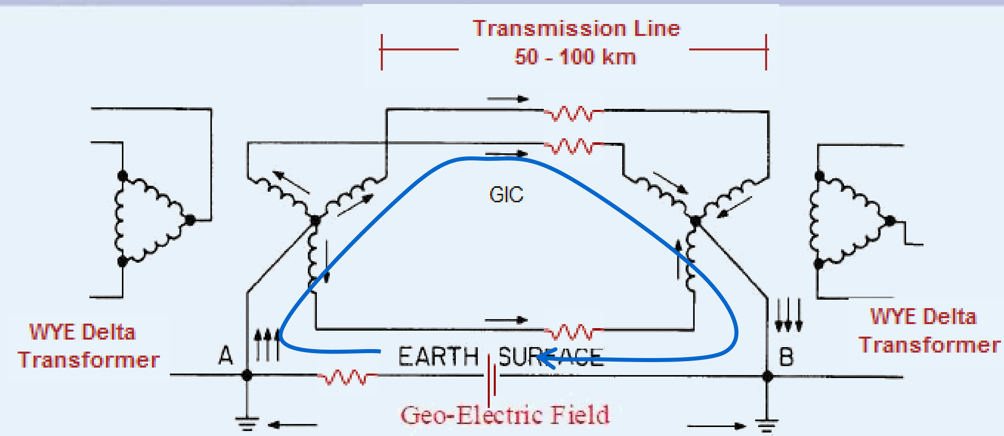
- **Normally confined to far north**
- **Expand southward as intensity of storm increases**

Currents

- **Reach millions of Amperes**
- **Affect Earth's Magnetic Field**
- **The induce electric fields along surface of the earth are the principle drivers of GIC**
  - Create Earth Surface Potentials
  - affected by earth resistivity
- **Variations in field is slow compared to system frequency**
  - GIC are Quasi DC currents
- **Moderate Storm - Electric Field at Earth's Surface 1-5 V/km**
  - Largest recorded 20 V/km

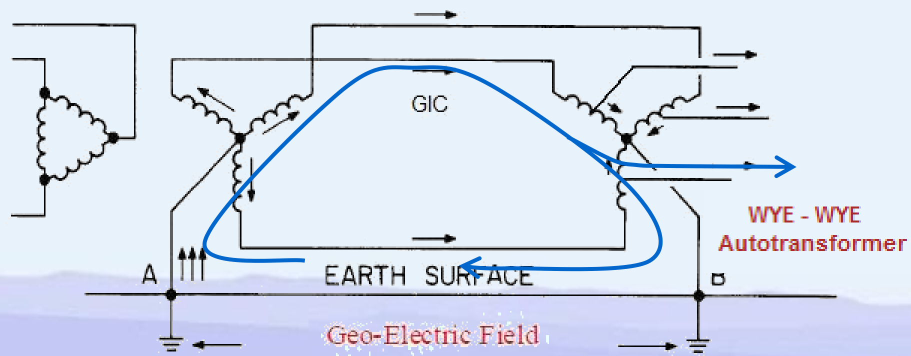
Earth Surface Potential and GIC

(How GIC enters the Grid)

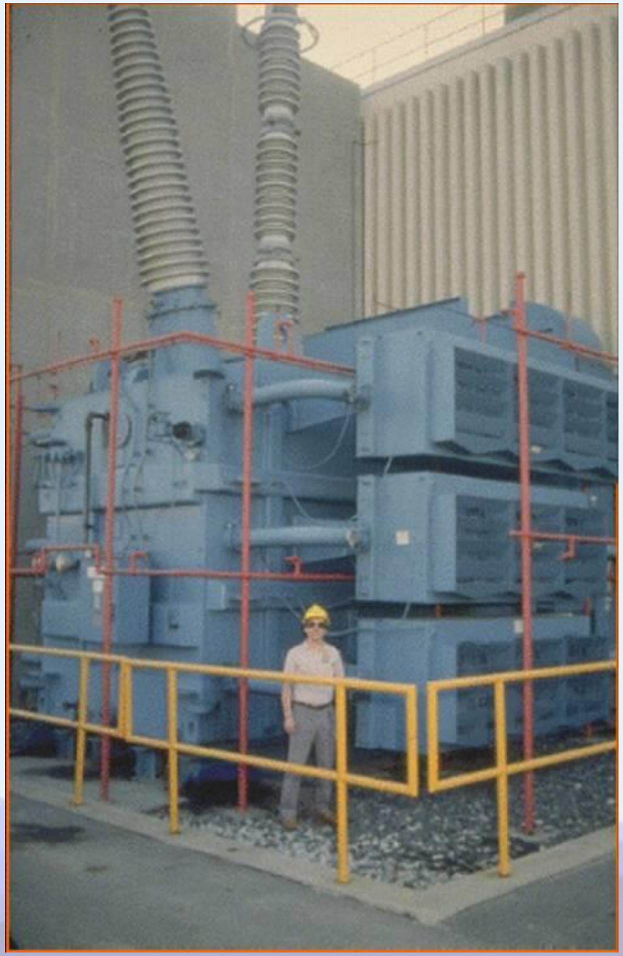


Grounded neutrals complete a low resistance DC circuit

GIC enters and exits through grounded transformer neutrals



Autotransformers have no isolation and GIC can flow onto other systems



Single Phase 500 kV GSU Transformer

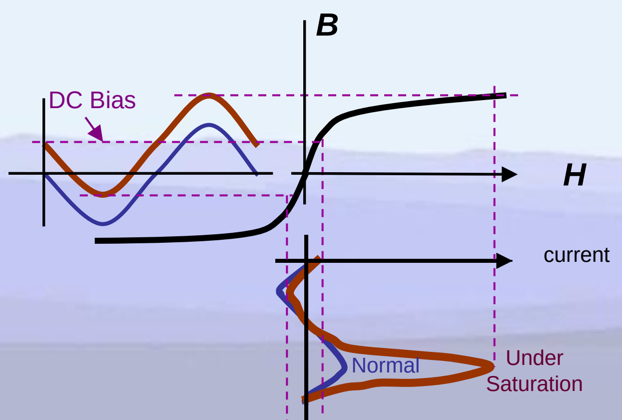
- **Surface potentials can be hundreds of volts drive high levels of GIC**
- **Transformer cores saturate at very low levels of DC current**

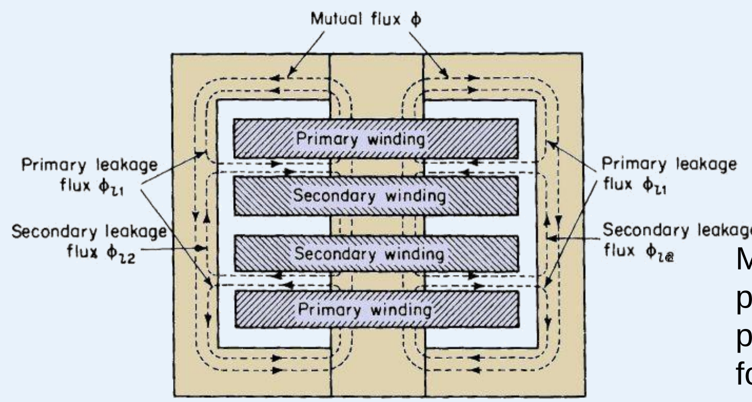
Magnetic flux paths through transformer cores normal conditions

Saturation is when the iron core can no longer effectively contain the magnetic flux

Leakage flux is forced into the surrounding space where it can flow through structural members including the tank wall

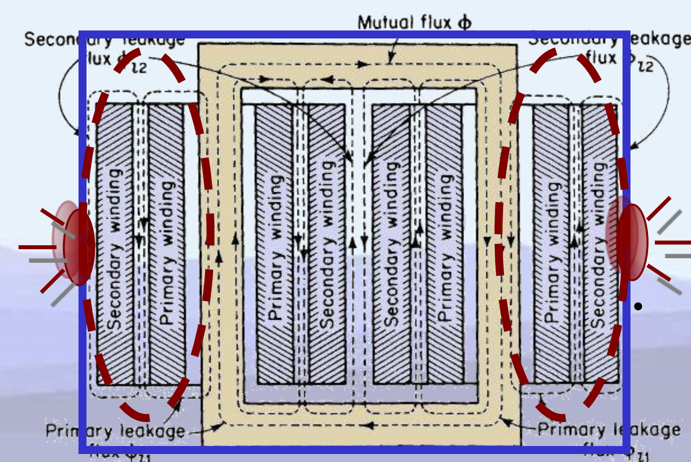
Eddy currents produced by the intense magnetic field can heat ferrous structural members of the transformer





Winding arrangement in shell-type transformer showing approximate paths taken by mutual flux and primary and secondary leakage fluxes.

Magnetic flux path single phase ***shell*** form transformer



Winding arrangement in core-type transformer showing approximate paths taken by mutual flux and primary and secondary leakage fluxes.

- Magnetic flux path single phase ***core*** form transformer

Localized transformer tank wall heating

Effects of stray flux and eddy current heating in transformer tank and structural members

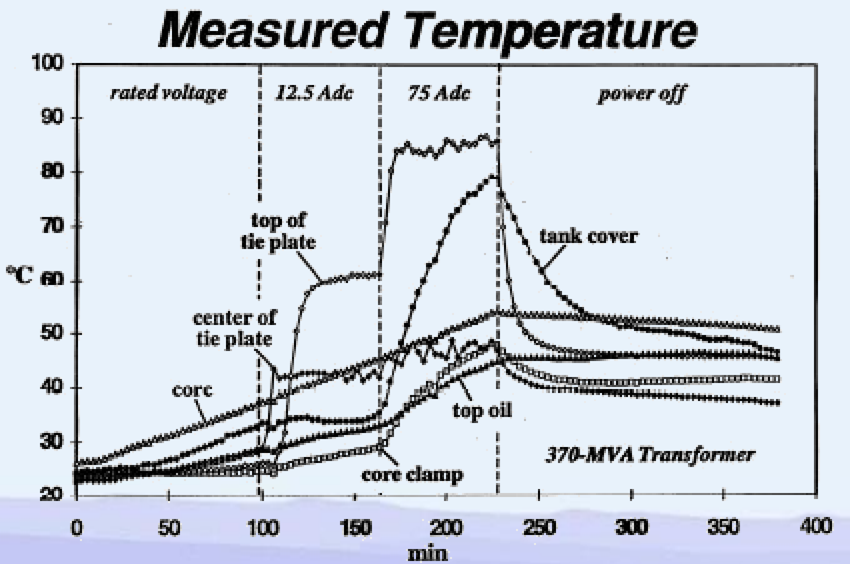
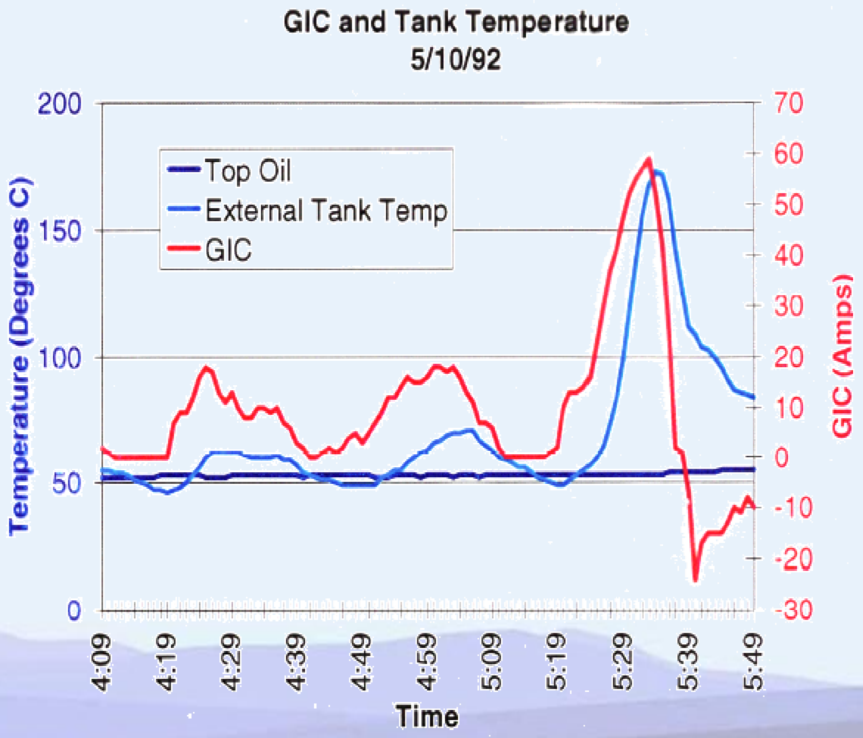


Figure 4-5. Observed temperature from Hydro Quebec tests showing response between two levels of neutral GIC (12.5 amps and 75 amps) and measured temperatures in the transformer in easy-to-access spots.

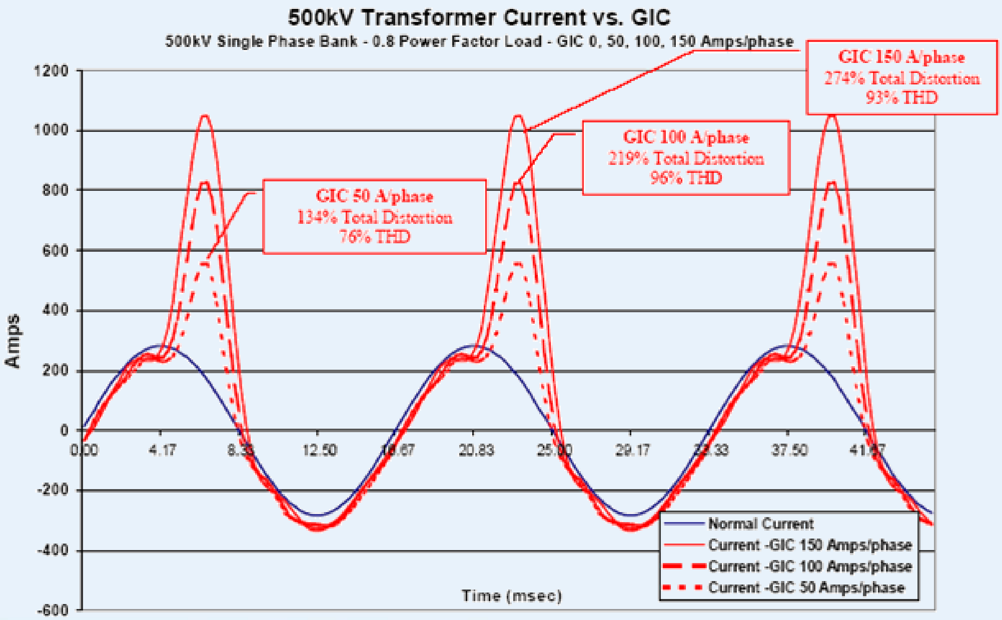


GIC and transformer tank temperature for May 10, 1992 geomagnetic storm.

Transformer load current during half cycle saturation

Primary effects

Winding Overheating : Insulation Damage

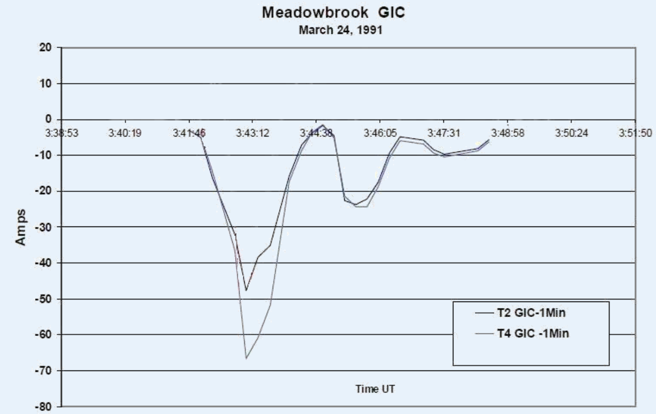


Transformer total load current – normal conditions and with 50, 100 and 150 amps/phase of GIC.

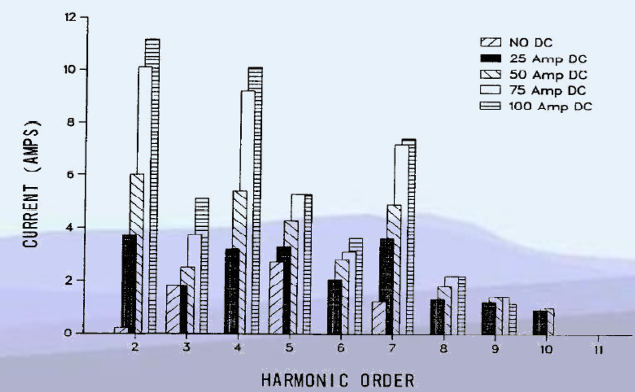
Transformer load current under core saturation

Secondary effects

Harmonics : VAR Consumption : Voltage Problems



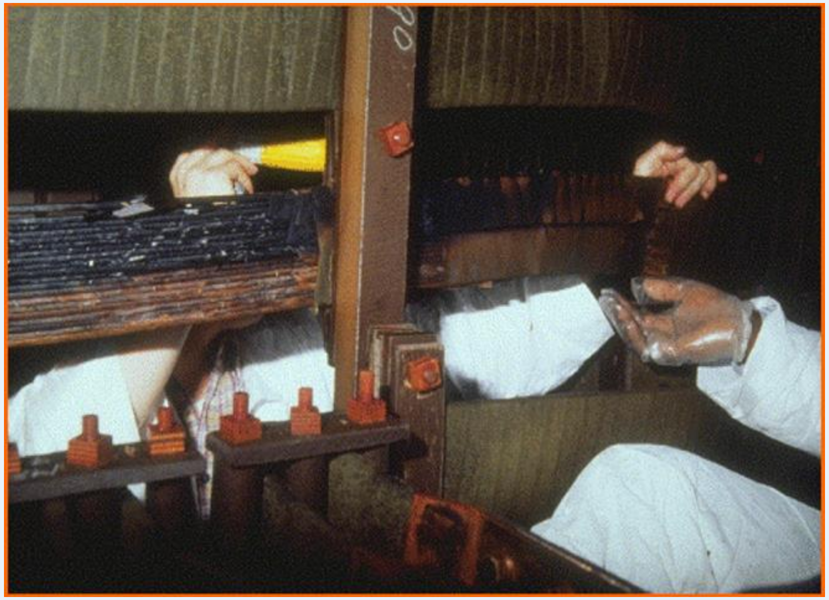
GIC flow measured in transformer neutral



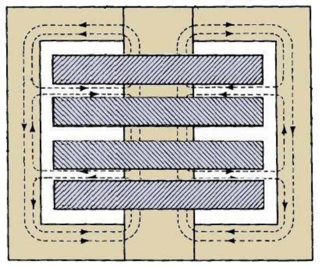
The test results (230/115 kV, 3-phase, shell form auto-transformer).

Harmonic current generation under saturation

Salem GSU Unit #1
(Winding Damage)

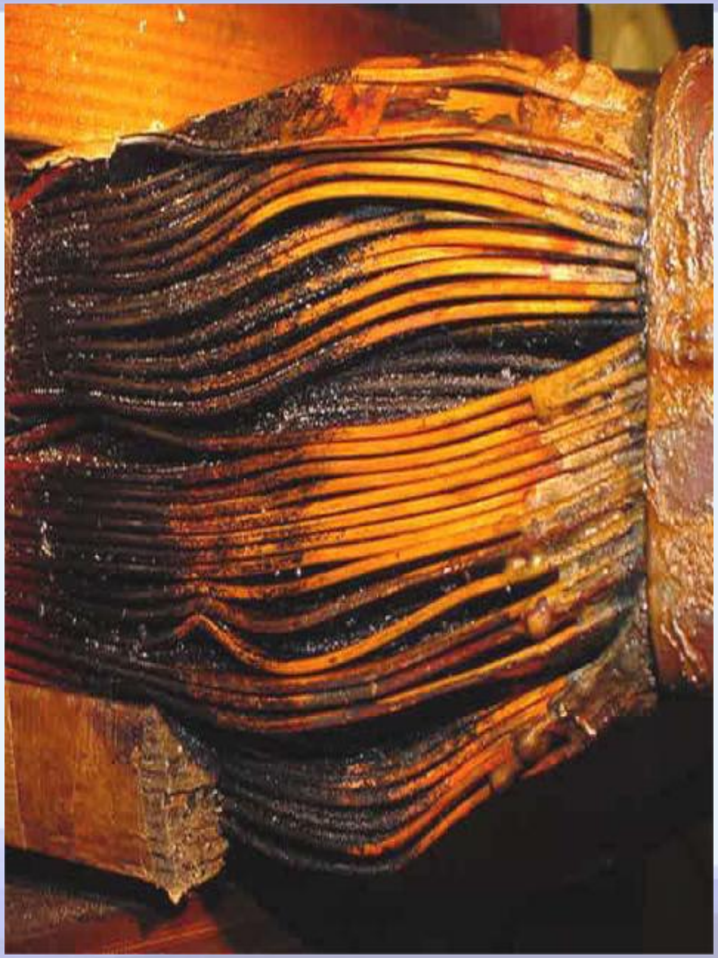


March 1989 Geomagnetic Storm
500/22 kV 1200 MVA transformer
low voltage winding thermal damage



ESKOM (South Africa)
400 kV EHV Transformer Failures

Transformer #4 HV Winding Damage



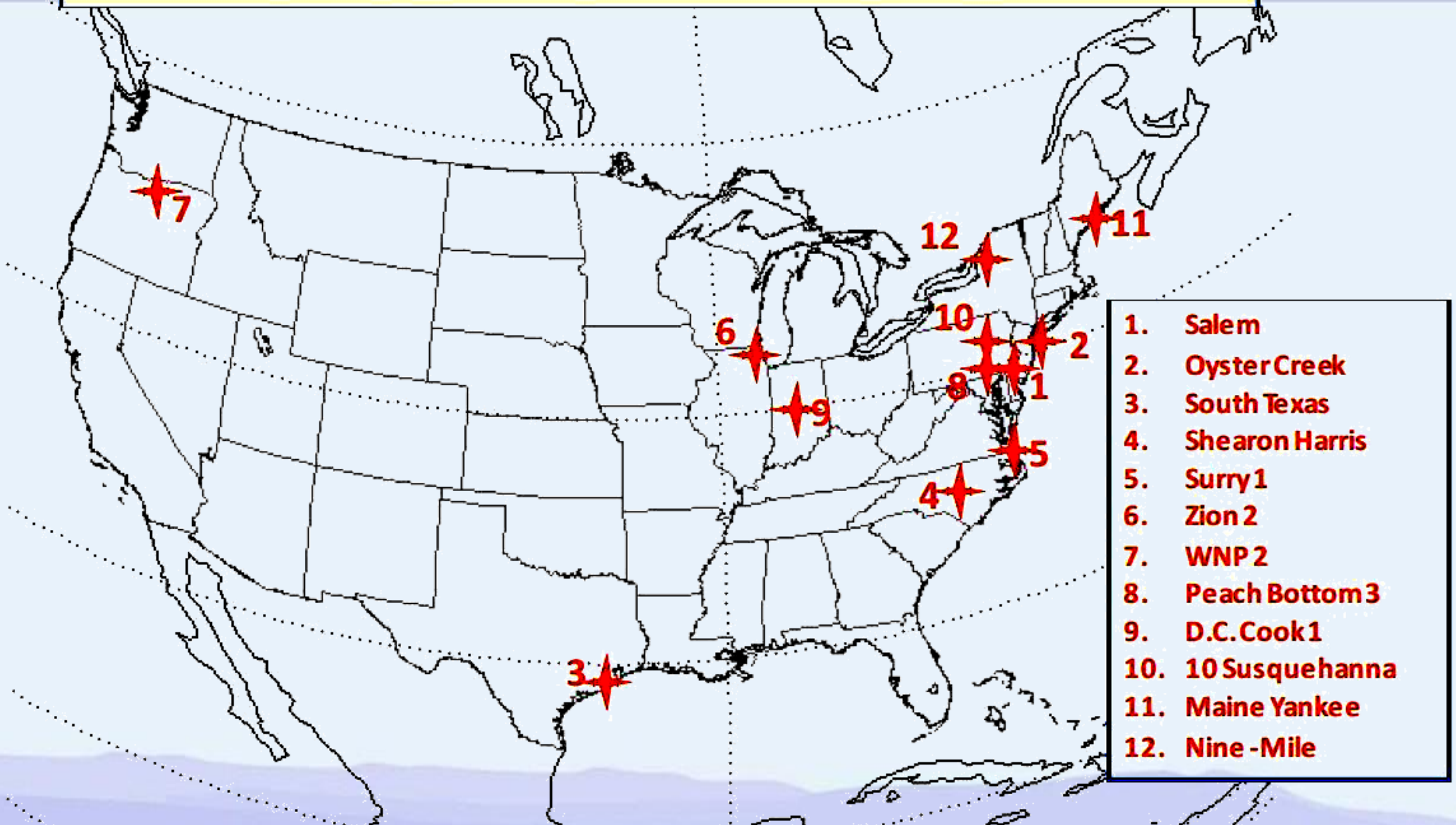
Transformer # 5 Lead Overheating

Transformer Damage   Oct-Nov 2003 Geomagnetic Storm

Courtesy Eskom, Makhosi, T., G. Coetzee

Nuclear Plant GSU Transformer Incidents

Within 25 months after the March 1989 Storm



Locations of nuclear plant GSU transformer failures reported in 25 month period of time after the March 1989 geomagnetic storm.

Take away points

1. **Immediate or long term damage to transformers from a geomagnetic event is a real concern**

    - **Salem and ESCOM transformers**

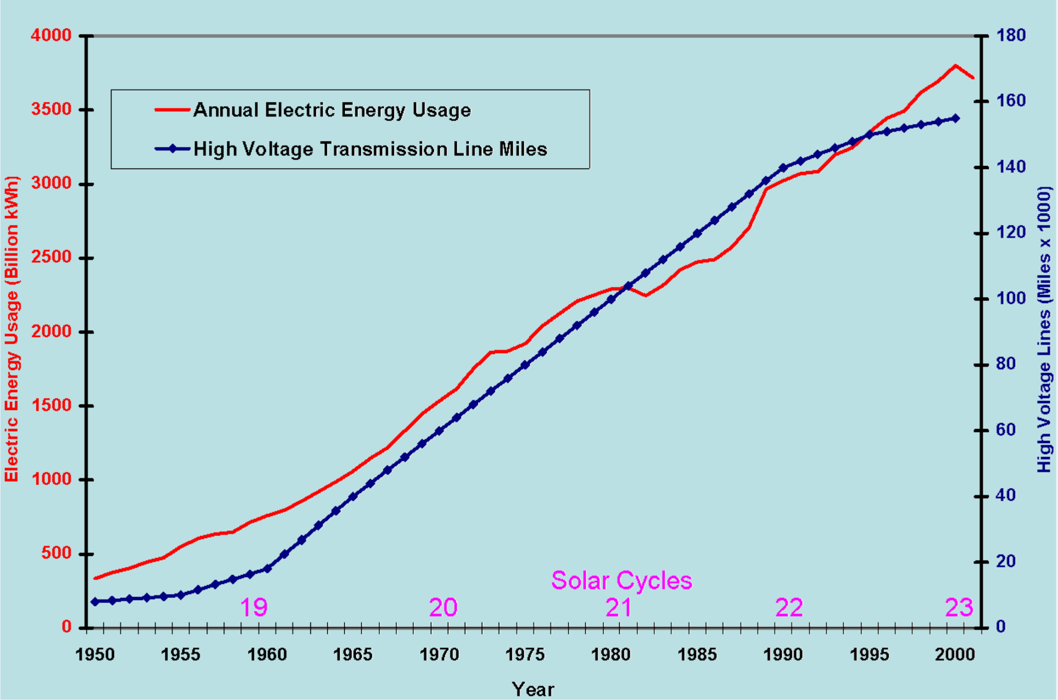
2. **Secondary effects from transformer saturation (harmonics, VAR absorption and voltage stability problems) can cause system problems**

    - **Hydro Québec system collapse 1989**

Growth of US Transmission Grid

(How grid design contributes to GIC flow)

- **Geomagnetic Storm effects on power systems first noted 1940**
- **HV system was not extensive and problems were not severe**
- **1950 HV expansion began**
- **Today 180,000 miles of HV lines**
  - **80000 miles of EHV lines**
  - **typical length 50-100 km**
- **Proposed expansion will add longer lines**



Concerns:

- **More lines spanning greater distances could introduce GIC to areas not previously considered as problems**
- **Higher GIC levels may be introduced into the system**

Severity of Geomagnetic Storms

(a case scenario)

- **March 1989 event is not the largest on record**
  - **How do we define large for GIC**
    - » **X-ray flux ?**
    - » **CME emission ?**
    - » **dB/dt ?**

- **Both 1859 Carrington event and the May 1921 events were of greater intensity than the 1989 event**
  - **10 times the intensity of the March 1989 event**
  - **Rate of change of the magnetic field estimated at ~5000 nT/min**
    - » **1921 Event electric field 20 V/km Sweden**

Concern:

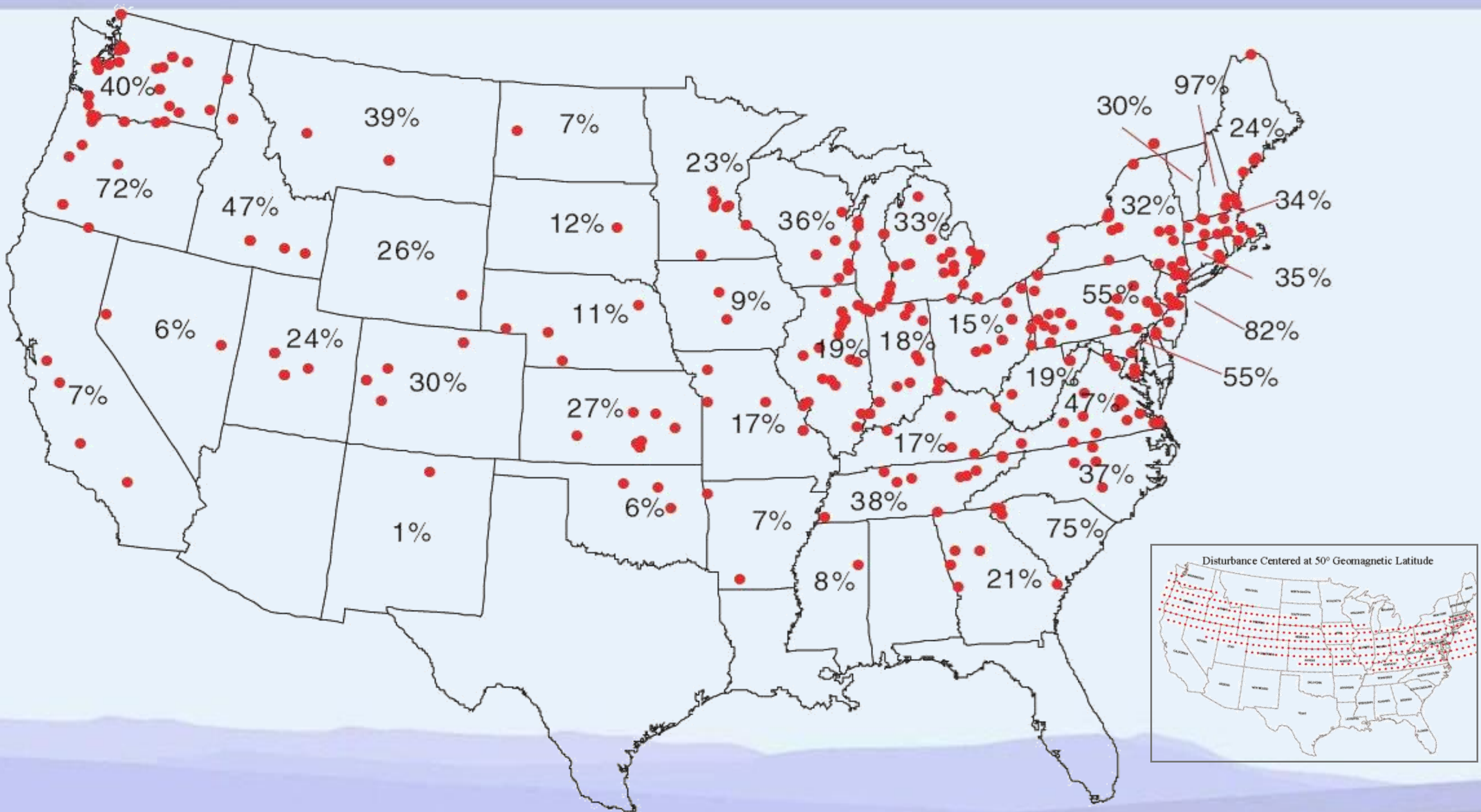
There is a likelihood that a severe solar event of much greater magnitude than previously experienced may occur.

The EMP Grid Effects Report included simulations of several events similar to the 1989 storm but at ten times the intensity.

The purpose was to estimate the number of transformers that were at risk of being damaged.

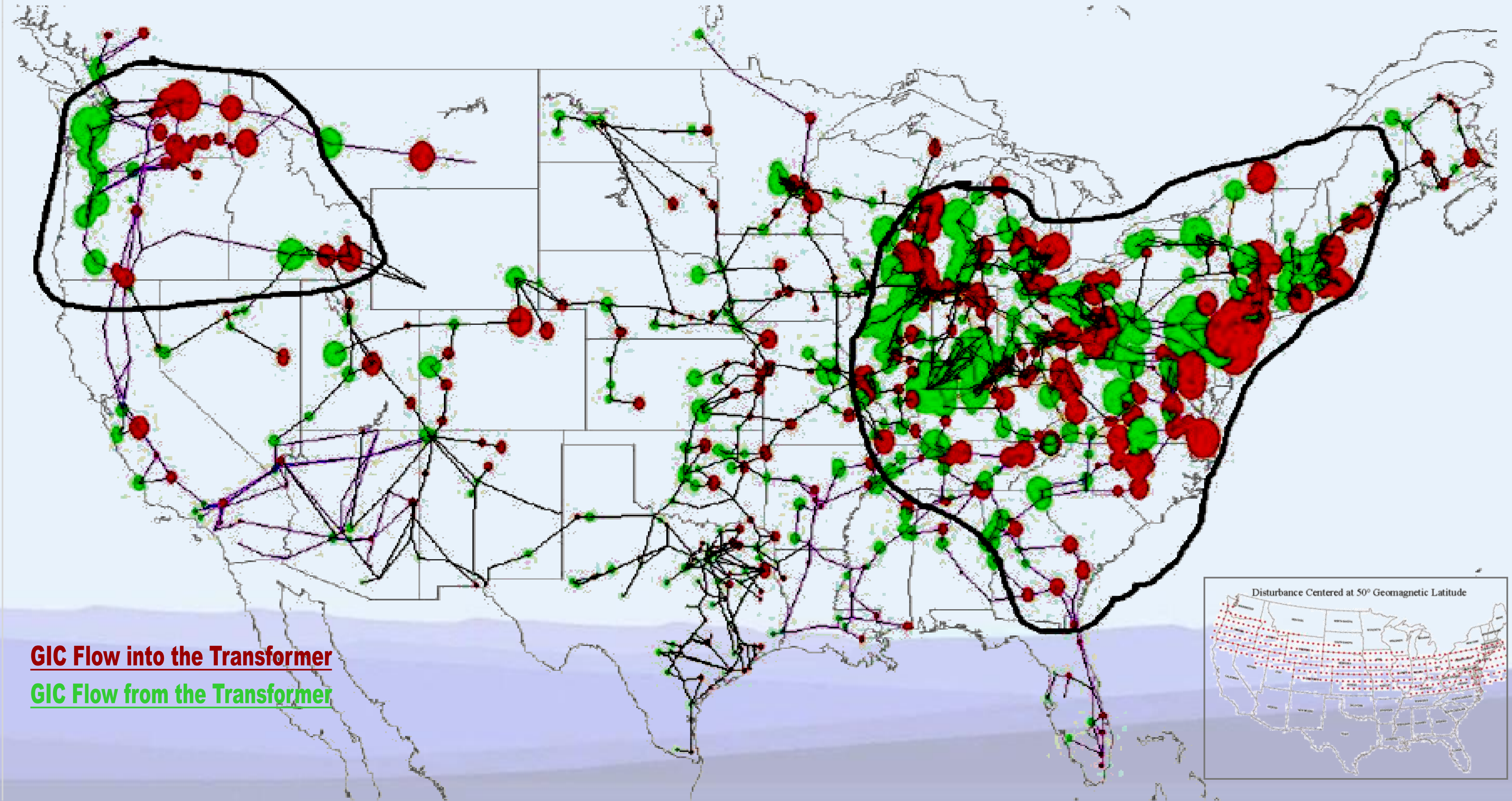
Simulation results showing at-risk EHV transformers for a 4800 nT/min geomagnetic field disturbance centered at 50º N Latitude

[At risk transformers are those with 90 amps per phase GIC]

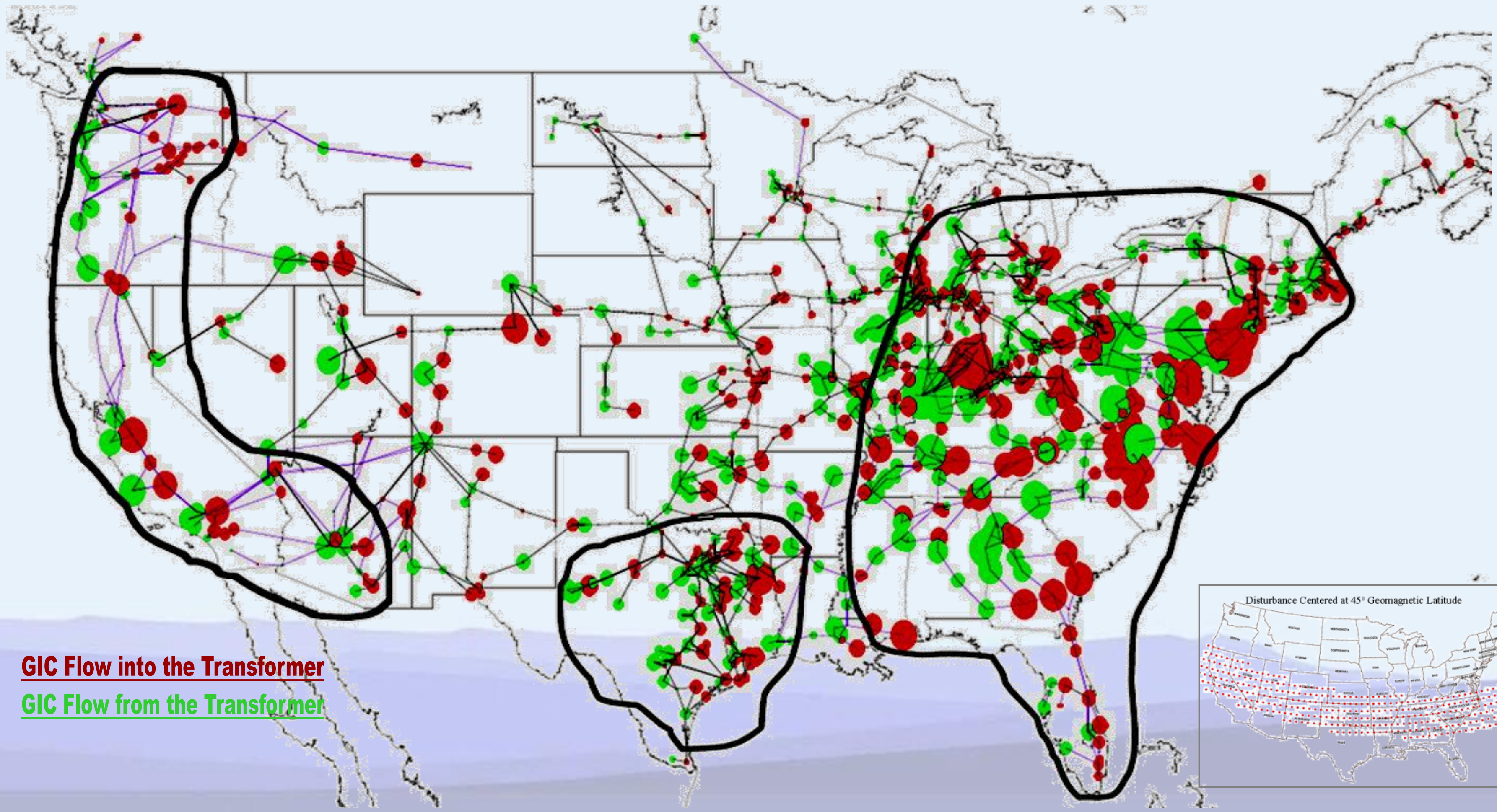


A map showing the at-risk EHV transformer capacity (estimated at ~365 large transformers) by state for a 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude. Regions with high percentages of at-risk capacity could experience long-duration outages that could extend multiple years. SOURCE: J. Kappenman, Metatech Corp., "The Future: Solutions or Vulnerabilities?," presentation to the space weather workshop, May 23, 2008.

Simulation results –using 4800 nT/min disturbance showing areas of possible grid collapse [Storm centered at 50º N Latitude]



Simulation results –using 4800 nT/min disturbance showing areas of possible grid collapse [Storm centered at 45º N Latitude]



Summary

What we know

- The threat of major equipment damage from GIC is real
- The grid is becoming more susceptible to GIC
- We may have yet to experience the most severe type of geomagnetic storm

What we need to do

- Determine what equipment is susceptible and at what levels of GIC
- Develop plausible scenarios for a Solar Event
- Determine what we can and are willing to protect against
- Develop effective mitigation

What would be helpful

- Accurate and meaningful forecasting
- Advanced and timely warnings

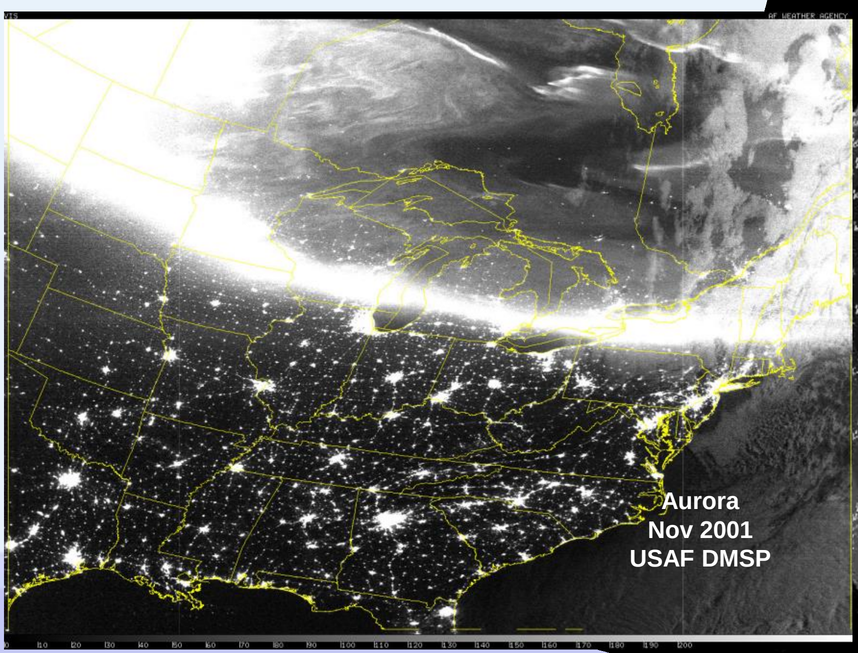
Referenced Report

Geomagnetic Storms and Their Impacts on the U.S. Power Grid (Meta-R-319), John Kappenman, Metatech Corporation, January 2010.

http://www.ornl.gov/sci/ees/etsd/pes/ferc_emp_gic.shtml

or Google ORNL Meta 319

Thank You


Aurora
Nov 2001
USAF DMSP


Electrojet Model
May 1992 Event
Metatech
Applied Power Solutions