What we’ve been doing:

- February F2F in Charlotte
- April 19-20, 2011 NERC GMD Workshop
  - Broad participation outside of TF, broader range
- May 10, 2011 NERC Advisory re: GMD
  - Summarized current advice
- April 25-26 – Workshop to define GMD Products in Support of the Electric Utilities – Utilities/NOAA
  - Focus on forecasts and modeling responsibilities
- June _____Agreement with EPRI for support
The Geomagnetic Disturbance Task Force (GMDTF) will investigate bulk power system reliability implications of [GMD] risks and develop solutions to help mitigate this risk.

Our Task Force has nearly 80 people on its roster including equipment experts, utility engineers, Scientists, and government representatives.
# Deliverables per Scope

<table>
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<th>2011</th>
<th>Deliverables</th>
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| **1st Quarter** | Whitepaper outlining the current industry experience and capability and identifies opportunities, options and alternatives to enhanced how the industry manages GMD risks.  
[Activity: Assimilated regional plans, NERC GMD advisory] |
| **2nd Quarter** | Whitepaper on current warning limitations, the ability of operators to take mitigating action, and areas for improvement. |
| **3rd Quarter** | Whitepaper on restoration abilities and areas for improvement. |
| **4th Quarter** (Dependencies) | 1. Whitepaper that reviews industry prevention approaches to GMD events.  
2. Final report incorporating the findings of the whitepapers and simulations with suggested recommendations and follow-on actions. |
Where we are: Products – (all Draft)

- NERC GMD Advisory
- GMDTF-1 Compilation of Current GMD Reliability Coordinator Operating Procedures – March 2011 (internal)
- Draft Subgroup 1 Whitepaper – Procedures & Equipment - May 2011
- Draft Subgroup 2 Whitepaper – Modeling - May 2011
1. Acknowledge the NERC GMD advisory as meeting the industry need to have a clear and effective document that captures the:

- understanding,
- potential vulnerabilities, and
- prudent actions (equipment and procedures)

for the interim as the GMDTF develops a final product

And……..
Proposed Plan for Deliverables

2. Focus our efforts on all the elements of our final product including:

- Identifying the “chapters”

- Develop the scientific and engineering approaches to each chapter.

- Actively and formally vet all technical findings to the degree necessary.

- Produce the a final product that is also publically vetted
Proposed Plan for Deliverables

Some thoughts on assuring reliable content

- We *will* develop the content necessary to address our scope of responsibilities and products

- All assertions that are important to understanding, assessing, mitigating impacts, and responding to a GMD will be verified appropriately.

- Any assertions that are not verified whether by lack of acceptable scrutiny or not being able to be verified reliable will be included in the products of the task force nor endorsed in any way by the GMDTF
Critical Priorities (We must get this right!)

- **Transformer Vulnerability**
  - ID vulnerability, prioritize, establish characteristics (GIC vs T)
  - This is the primary reason for concern with GMD
  - What is your “Live to fight the next day.” plan in an extreme storm?

- **“Reference Event”** – given a locational 1:100y:
  How should we establish performance requirements? :
  - Each system should be able to withstand the reference storm, or
  - Should each do what is prudent in their own estimation
  - Should it be a reference worse credible case with each entity deciding how to protect their system? (This is where we are headed)

(Did I mention that we have to get this right?)
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<td>Bill Murtagh + Chris. Get 6h forecast – satellite issues</td>
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<td><strong>Chapter 3 – Assessment of existing response capability</strong></td>
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<td>Eric Rollison – attach alert + regional RC. (get the WECC RC</td>
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<td><strong>Chapter 4 – System Design Considerations</strong></td>
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<td>- Performance “standard” for various levels of storm</td>
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<td><strong>Chapter 5 – System Modeling</strong></td>
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<td><strong>Chapter 6a - Transformers</strong></td>
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<td>Design, vulnerabilities, impacts, Ramses, et al</td>
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**GMDTF Deliverables – Final Report**

<table>
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<th>All other equipment Luise, protection.</th>
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<td><strong>Path forward – how do we apply this</strong>**</td>
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<td>Chapter 11 – <strong>Equipment Improvements</strong></td>
<td>Mike Bockovich, Transformer relays to avoid, etc</td>
</tr>
</tbody>
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**NERC**

**NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION**
What is missing? Changes? (e.g.):
- “Reference Storm
- Guidelines or performance requirements

Will this serve our “customers”? 

Specific issues we will need to address beyond the Science and engineering?
GMDTF Deliverables – Final Report

Proposed Time line

- Topic/Issue related workshops? Methodology?
- US and Canadian Govmt Workshops?
- **August 30th** ?? for External review (2 wk before Committees)
- Further refinement
- **December 29th** – Submittal for Approval by NERC Technical Committees
Generation of 100-year geomagnetically induced current scenarios

Pulkkinen, A.¹, J. Eichner² and others to by included to the author list

¹ CUA and NASA/GSFC Community Coordinated Modeling Center, Greenbelt, USA.
² Munich-Re, Munich, Germany.
Contents

• Goals of the exercise.
• Key geophysical factors and the proposed approach.
• Generation of the backbone statistics and the effect of the ground structure.
• Effects of the geomagnetic latitude.
• Generation of temporal and spatial scales of the scenario.
• Summary of the generated geoelectric field scenarios.
• Mapping of the geoelectric field scenarios into GIC.
• Summary.
Goals

- Generate (quickly) regional extreme geoelectric field and GIC scenarios that can be used in further engineering analyses.
- Proposed definition for the extreme event: 100-year 10-second maximum geoelectric field amplitude.
- Notes:
  - “10 times March 1989” does not necessarily work: for example, minimum $Dst$ index of the 1859 Carrington event was only about 70% larger than that of the March 1989 event.
  - It is straightforward to map the geoelectric field into GIC.
Four key geophysical factors that need to be addressed

- The effect of the ground conductivity structure on the extreme geoelectric field amplitudes.
- The effect of the geomagnetic latitude on the extreme geoelectric field amplitudes.
- Temporal scales of the extreme events.
- Spatial scales of the extreme events.
Four key geophysical factors that need to be addressed

- The effect of the ground conductivity structure on the extreme geoelectric field amplitudes - two ground conductivity models representing realistic extreme ends of conducting and resistive grounds are applied.
- The effect of the geomagnetic latitude on the extreme geoelectric field amplitudes - we will identify a threshold geomagnetic latitude across which the maximum geoelectric field amplitudes experience approximately an order of magnitude decrease.
- Temporal scales of the extreme events - representative time series from selected magnetometer stations for a major event storm event are used to provide realistic temporal profiles.
- Spatial scales of the extreme events - we will assume uniform geoelectric field structure in regional scales. Generating a global scenario will be significantly more complicated due to poorly known spatiotemporal geoelectric field correlations at global scales.
Selected approach

1) Assume regionally (100-1000 km) spatially uniform geoelectric field. Assumption may not always hold especially at high-latitude locations.

2) Select a storm event and super- and sub-threshold geomagnetic observatories to obtain representative temporal storm profiles. Compute the geoelectric field and normalize the amplitudes.

3) Scale the normalized geoelectric field amplitudes obtained via 2) to obtain 100-year 10-second maximum amplitude event. Use previously computed statistics to determine the maximum amplitudes (Pulkkinen et al., 2008).

4) Compute GIC. Direct linear mapping or quasi-dc power grid model can be utilized.
Generation of the statistics and the effect of the ground conductivity

Statistical occurrence of modeled geoelectric field in Quebec and British Columbia (Pulkkinen et al., 2008)

Visual extrapolation to 100-year amplitudes
The effect of the geomagnetic latitude

Max. values over March 1989 storm

Max. values over October 2003 storm

Order of magnitude drop in max. amplitudes

50 deg. of geomag. latitude
The effect of the geomagnetic latitude
Temporal scales

- Need to capture great variety of geospace processes and temporal scales associated with extreme storms. Chose to use observational data for a major event to capture the variability.
- We use two representative stations. One from sub-threshold latitudes (Memanbetsu, Japan, 37 deg. of geomagnetic latitude) and another one from super-threshold latitudes (Nurmijärvi, Finland, 57 deg. of geomagnetic latitude).
- 10-s geomagnetic field observations from the two stations for 29-31, October 2003 provide representation of the temporal profiles.
- Geomagnetic field mapped into geoelectric field using the plane wave method and the Quebec ground model. Amplitudes normalized for scaling.
Temporal scales (normalized fields)
Spatial scales

- Two-fold nature of major and extreme events: a) large geoelectric field magnitudes can be experienced across the globe in the region covered by the auroral current system, b) spatial correlation lengths associated with the field fluctuations can be short.
- Spatial GIC and geoelectric field correlations on global scale not well-known.
- We will assume spatially uniform geoelectric field on regional (100-1000 km) scales.
Summary of the scenarios

Resistive ground

Above threshold geomagnetic latitude

Conducting ground

Below threshold geomagnetic latitude
Mapping to GIC

- Apply extreme geoelectric field scenarios to quasi-dc models of the regional grid → obtain GIC through each node of the system.
- Or apply simply (shown to hold to a good approximation):
  \[ GIC(t) = aE_x(t) + bE_y(t) \]

System parameters

Geoelectric field scenario
Summary

- Extreme regional geoelectric field scenarios generated as a function of ground conductivity structure and geomagnetic latitude.
- Numerical data for scenarios publicly available for mapping to GIC and further engineering analyses. Note: further refinements to the scenarios likely.
- For details, see Pulkkinen et al., 2011 (draft of the manuscript prepared).
EPRI / NERC Statement of Work

Geomagnetic Disturbance
Education

Research Question

• State of the knowledge on GMDs
• How to effectively convey to decision makers
• What magnitudes of currents occur

EPRI Strategy:

• Interest Group
• Summarize Past Work
• Measure Induced Currents (Sunburst)

Status:

• White paper completed
• Interest Group being formed
• Sunburst Network being expanded
Vulnerability Assessment

Research Question
- Impacts to grid
- Determine influencing factors

EPRI Strategy:
- Measure induced currents (Sunburst)
- Assessing vulnerability of Transformers
- System wide modeling

Status:
- Sunburst Network Being Expanded
- 6 Transformer Assessments ongoing
- Scoping System Models
Mitigation

Research Questions

- Warnings & procedures for operators
- Effectively blocking of GICs
- Relay trip transformers

EPRI Strategy:

- Laboratory testing of blockers
- R&D on relay parameters
- Collaborate with NASA on Solar Shield utilizing Sunburst

Status:

- Launch Supplemental on Testing & Relay parameters
- Support NASA
Deep Dive on Today’s Discussion – Task 2 Vulnerability Assessment

• Detailed system modeling will be performed in three regions (TBD) of the EHV grid to assess its vulnerability to GMD.

• Particular emphasis will be placed on:
  – Possible effects of GIC on large power transformers
  – Increased var consumption → voltage stability
  – Harmonic generation and related effects on equipment such as capacitor banks, harmonic filters, etc.
  – GIC effects on protection and control (P&C) systems
Modeling and Analysis Approach

- **Task 2A** - Determine GIC flows in network using available data and assumptions.
- **Task 2B** - Perform AC load flow with additional var demand caused by $\frac{1}{2}$ cycle saturation.
- **Task 2C** - Perform time-domain analysis to determine possible harmonic generation due to $\frac{1}{2}$ cycle saturation, and potential impacts on power quality and equipment such as capacitor banks, harmonic filters and transformers.
- **Task 2D** - Using information from time-domain analysis in Task 2C, determine potential impacts on system protection and control (P&C).
- **Task 2E** - Screen vulnerable transformers to more manageable list.
Task 2A - GIC Flow Analysis

• An open source software program will be developed to determine GIC flows in the transmission grid.
  – Capable of performing multiple cases (contingency analysis)
Task 2B – AC Load Flow Analysis

- When a transformer begins to saturate due to GIC, its reactive power demand increases dramatically.
- This effect must be taken into account in an AC load flow analysis to ensure that system voltage is not depressed beyond limits.

\[ Q \approx kI_{dc} \]

Additional var demand due to half cycle saturation
Task 2C – Time-Domain Analysis

- Time-domain simulations will be performed using EMTP-RV to analyze impacts of GIC in more detail.
  - Requires more sophisticated system model than GIC flow or AC load flow analysis

```
System Data
  PSS/E  PSLF  CAPE  ASPEN
GIC Flows
  EMTP-RV
FFT
  Harmonics
  Waveforms
Sat. Curves
  COMTRADE
```

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Task 2D – P&C Analysis

- COMTRADE files will be created from time-domain simulations and used as inputs to protective relays to analyze impacts of GIC.
Task 2E - Transformer Analysis

- Develop screening methodology
- Simulations will be performed to analyze impacts of GIC on transformers.
  - Requires testing of select transformers to validate model and close coordination with OEMs
Together…Shaping the Future of Electricity
AN ANALYSIS OF THE THREAT POTENTIAL TO THE US ELECTRIC POWER GRID FROM SEVERE GEOMAGNETIC STORMS

Storm-R-111

Storm Analysis Consultants

John G. Kappenman, P.E.
Principal Consultant

Voice: (218) 727-2666
Fax: (218) 727-2728
E-Mail: jkappenma@aol.com
Threat Potential Report on Power Grid Vulnerability to Geomagnetic Storms

- Report on Severe Geomagnetic Storm Threats has been provided to NERC
  - Provides Overview and Summary of GIC Flow for various 2400 nT/min and 4800 nT/min Disturbance Scenarios
  - Model includes EHV Assets Only - ~2180 Transformers modeled
  - GIC Levels and Resulting Reactive Power Demands provided for each scenario
  - Uses First Principle Methods for Simulation of Space Environment, Ground & Network

- Alternative Methods were also Examined to Provide Added Validation of Results
  - Method 2 – Paired Observations of GIC & Disturbance Environments – using Linear Extrapolation of GIC to Higher Disturbance Levels
  - Method 3 – Static Geo-Electric Field & Network Model – Since there is greater degree of certainty on location and “R” of assets in power grid, this provides a simpler short-cut to examine for potential Peak GIC levels across the network

- Comparison of Independent Methods to Estimate Peak GIC Levels
  - The Three Methods using different approaches all indicated Peak GIC Levels in US Grid that could reach GIC levels approaching ~1000 Amps/phase in most heavily exposed Transformers
  - This agreement would suggest that GIC levels are being accurately determined at least at this stage of model development
  - More detailed models which include contributions from 115-230kV systems not modeled should also be encouraged.
Modeling Space Weather to Power Grid Performance

Space Environment Model Complex
Temporal & Spatial Dynamics

- Process Requires development and linkage of four dynamic and complex modeling domains
- The greatest uncertainty arises in the Ground Model and AC Behavior Models
- Many steps taken to benchmark each model separately and in unison
- Performance of model generally produces conservative threat estimates

Layered-Earth Ground Model
Geospatial Complexity & Frequency Response

Grid AC Performance Model – estimates grid stress

Power Grid GIC Model – Complex topology & circuit apparatus for GIC Flows
Benchmarking the US Grid Model – Feb 21, 1994 Storm

Storm is relatively weak – lack of coherent magnetic field disturbance presents challenging environment to model
AEP Reported some Surprising GIC Observations in 1994 from a System Monitoring Campaign

Observed activity in this region adds new insights on scope of GIC influence in North America

Reported GIC Observation in Indiana & Ohio for Feb 21, 1994 Storm Demonstrates significant GIC Influence in this Mid-Latitude Region
Observed dB/dt during Storm

OTT RGI - Feb 21, 1994

FRD RGI - Feb 21, 1994
GIC Observations/Simulations in the Lower Mid-West

Observed GIC

Simulated GIC
GIC Observations/Simulations in the Lower Mid-West

Marysville SMD Data
February 21, 1994

Marysville Simulated Neutral GIC - Feb 21, 1994

Observed GIC

Simulated GIC
GIC Observations/Simulations in the Upper Mid-West

Forbes Minnesota Measured & Calculated Neutral GIC

Feb 21, 1994 Storm Event

Forbes - Measured
Forbes - Calculated

Neutral GIC (Amps)

Time UT

Storm Analysis Consultants
Comparison of Observed and Calculated Peak GIC
Feb 21-22, 1994 Storm Event

GIC Observations/Simulations Across the US

Location
Bell, Chester, CPS, Hope Ck, Marysvl, Monroe, Moss Ld, PLV, Rockpt, SPA

Neutral GIC (Amps)

Observed Peak GIC
Calculated Peak GIC
Based upon observations and expected storm dynamics a number of simulation scenarios have been developed to review potential threat extremes to the US Power Grid

- 2400 nT/min and 4800 nT/min Disturbances across the US (the 2400nT/min is likely a 1 in ~30 Year Scenario)
- The most severe parts of the disturbances confined to a 5° wide Latitude Band (conservative estimate)
- Various Equatorward Expansion Locations for these intense disturbances Centered on 55°, 50°, and 45° Geo-Magnetic Latitude across North America
Distribution of Transformer GIC Flows for 4800 nT/min Disturbance

45, 50 and 55 Degrees Geomagnetic Latitudes

GIC (Amps/phase)

CONUS Model Transformers

45 Degrees
50 Degrees
55 Degrees

Storm Analysis Consultants
Comparison of Peak GIC in Top 500 US Transformers for 4800 nT/min Disturbance at 45°, 50°, and 55° Geomagnetic Latitudes

Transformer GIC in Amps/phase

US Transformers 345kV, 500kV & 765kV

Legend:
- 45 Deg 4800
- 50 Deg 4800
- 55 Deg 4800
Location of At-Risk Transformers
4800 nT/min at 55° (GIC > 90 Amps/phase)
Location of At-Risk Transformers

4800 nT/min at 50° (GIC > 90 Amps/phase)
Location of At-Risk Transformers
4800 nT/min at 45° (GIC > 90 Amps/phase)
US Transformers At-Risk due to High GIC Levels

2400 & 4800 nT/min Disturbance Centered at Various Geomagnetic Latitude

- **45 deg**: # At-Risk 4800 = 249, # At-Risk 2400 = 79
- **50 deg**: # At-Risk 4800 = 351, # At-Risk 2400 = 114
- **55 deg**: # At-Risk 4800 = 270, # At-Risk 2400 = 92
Increased CONUS Region Reactive Power Demand for 2400 & 4800 nT/min Threats Scenarios

- 2400 nT/min
- 4800 nT/min

45 Degrees: 60,000
50 Degrees: 120,000
55 Degrees: 80,000

Increased MVARs
Method 2 – Empirical Estimates of Peak GIC

- Paired Observations of GIC and Nearby Geomagnetic Observatory
  - Establish through observations at GIC and dB/dt that was driver of GIC at Network Location
  - Higher Storm dB/dt will also result in higher GIC (assuming all other factors are unchanged)
  - Valid to Assume Deep Earth Conductivity will not change or be influenced by saturation
  - Assume that Frequency Spectrum of Disturbance Environment is same
  - Assume Network Topology has no-change
  - For Auto-transformers we assume GIC in Neutral reflects 1/3 GIC per phase
  - Orientation of threat environment unchanged
  - Linear Extrapolation to Estimate GIC

\[
\frac{\text{GIC observed}}{\text{dB/dt observed}} = \frac{\text{GIC Estimated}}{\text{dB/dt @ 4800 nT/min}}
\]

- Approach is very simple & straight forward
- Takes into consideration all the important In-Situ factors that created Observed GIC
- Limitation in that Only a Few Locations available for evaluation
Defining Regions to Classify Region Specific Geomagnetic Storm Climatology

RGI for Mid-Atlantic Region – based on OTT Magnetic Observatory

RGI for Mid-Atlantic Region – based on FRD Magnetic Observatory

RGI for Mid-Atlantic Region – based on BSL Magnetic Observatory

NY/NE/Can

Mid-Atlantic

South East
Meadow Brook Transformer GIC & Hot-Spot Observations

At 5000 nT/min Levels – GIC in 3 Transformers would produce ~600 Amps/phase of GIC

Storm Analysis Consultants
Nov 6, 2001 Storm and GIC Measurements at Hurley Ave (NY)

60 Amps at 2:13 EST Nov 24 (7:13 UT Nov 24)

At 5000 nT/min Levels – would produce ~530 Amps/phase of GIC
At 5000 nT/min Levels – would produce
~1400 Amps/phase of GIC
At 5000 nT/min Levels – would produce ~250 Amps/phase of GIC
Feb 21, 1994 Storm and GIC Measurements at Rockport (IN)

At 5000 nT/min Levels – would produce ~333 Amps/phase of GIC
At 5000 nT/min Levels – would produce ~1000 Amps/phase of GIC (Now a Series Compensated Line)
Observed GIC in 500/161kV Transformer Neutral in TVA System
October 29-31, 2003

At 5000 nT/min Levels – would produce ~400 Amps/phase of GIC
Oct 29-31, 2003 Storm and GIC Measurements at Bell BPA (WA)

At 5000 nT/min Levels – would produce ~333 Amps/phase of GIC
Method 3 – Static Geo-Electric Field

• Limited Observations of Geo-Electric Field have been captured from Several Storms
  
  • Using this Geo-Electric Field Data Directly, GIC Flow can be calculated
  • No Need for Storm Environment Model or Deep-Earth Conductivity Model
  • Model of Power Grid is all that is needed – have good confidence on Asset Locations and “R” of Lines and Transformers
  • Model Problem simplifies to Ohm’s Law and Geometry Calculations
  • Uncertainty Remains on How High can Peak Geo-Electric Field Reach
Uniform Geo-Electric Field – 0° (North)
Uniform Geo-Electric Field – 30°
Historically Observed Geo-Electric Fields

Note – 20 V/km has been measured in Europe during May 1921 Storm
Maximum GIC in US Transformers
for Uniform 7 Volt/km Rotated Geo-Electric Field

Transformer GIC in Amps/phase

US Transformers 345kV, 500kV & 765kV

Storm Analysis Consultants
Maximum GIC in US Transformers
for Uniform 11 Volt/km Rotated Geo-Electric Field

US Transformers 345kV, 500kV & 765kV

Transformer GIC in Amps/phase

0 100 200 300 400 500 600 700 800

1 201 401 601 801 1001 1201 1401 1601 1801 2001
Maximum GIC in US Transformers for Uniform 20 Volt/km Rotated Geo-Electric Field

Transformer GIC in Amps/phase vs US Transformers 345kV, 500kV & 765kV
Other Geomagnetic Storm Events can cause Large Geo-Electric Fields at Low Latitude Locations
Large Geo-Electric Fields & GICs at Low Latitude Locations

Comparison of Electrojet-Driven and SSC Bx Disturbances


Electrojet Disturbance is Large but Slower than SSC

SSC Disturbance is Small but Fast and has Big Footprint

Storm Analysis Consultants
Large Geo-Electric Fields & GICs at Low Latitude Locations

Comparison of Electrojet-Driven and SSC-Caused Geo-Electric Fields

Small but Fast Geomagnetic Disturbance Produces Equivalently Large GIC compared to Slower/Larger Disturbances
Electrojet Intensification and SSC

Spectral Response of Layered-Earth Ground Models

- SSC Content yields large Geo-Electric Field
- Than Larger EJ Field of Low Frequency Content

SSC Bandwidth

EJ Bandwidth
GIC and Transformer Failure in New Zealand due to SSC

- Sudden Onset of Impulsive Geomagnetic Field Disturbance on Nov 6, 2001
- Transformer Located Hydro Station on South Island
- Failed within One Minute of Onset (1:52UT), Sudden Impulse Relay due to major internal flashover

This GIC Event is Identical in Timeframe to E3, but much smaller in magnitude
The Shock Onset of November 6, 2001 – Solar Wind Driven Event

Just after SSC Onset, all Australian Observatories are first to observe delta B changes.
Several Seconds later the delta B changes are clearly evident in northern Hemisphere Asia.
Delta B changes are now beginning to appear in night time regions of North America and Western Europe/South Africa.
Observed & Calculated GIC – Nov 6, 2001
Southern/Central Japan

GIC flows out of Network

GIC flows into Network

Geo-Electric Field

Meso-Scale Models Validation Across the System
WORKSHOP TO DEFINE GEOMAGNETIC STORM PRODUCTS IN SUPPORT OF THE ELECTRIC UTILITIES – THE WAY AHEAD
• SWPC will work with partners for development continent-wide products depicting estimated electric field strength and direction. This will require a partnership with USGS, CCMC, NRCan, academia, private sector, and others.
  • Validation and Verification is critical
  • Product must translate into “actionable” response

• SWPC and partners will investigate (currently working) ways to add more real-time ground magnetometer stations and to model ground conductivity.

It is likely that forecasts of dB/dt and the electric field will be very difficult.

• Therefore, forecasts of Kp, K, or alternate summary measures will be necessary for the near-term. It is possible to provide climatology for dB/dt, range, standard deviation, local electric field, for a given activity level. SWPC will work with partners to carry out this analysis and make such climatology tables available.
• SWPC will coordinate with the NERC and GMDTF personnel on an option for a teleconference with the NERC Reliability Coordinators in the event of an exceptional space weather situation (e.g., Oct 28-29 2003). Thresholds, quantitative measures, and response procedures need to be addressed.

When this would have happened – Oct 2003

When it may not have happened – Mar 1989
SWPC will explore partnering with international partners, particularly NRCanada and the British Geological Survey (BGS), on the development and improvement of geomagnetic storm products and services.

- UK – US Agreement
- Ongoing NR Canada efforts (International Space Environment Service)

Implement process for information sharing during and after geomagnetic disturbances. Feedback on system effects and impacts due to geomagnetic disturbances would be very valuable to space weather community for warning validation, and validation and verification of models.
• SWPC and partners will investigate alternate measures to local K-indices. The goal will be to have summary measures that extend the disturbance scale up to larger values to avoid saturation, and to have summary measures that can be compared in a meaningful way. Examples include, range, standard deviation, delta-B, and so on, all which are quantities that would be expressed in standard units (nT).

• SWPC and partners will also investigate a ‘storm catalog’ and will study better ways to characterize the envelope of these disturbances. This effort will address the requirement to characterize the intensity and duration of the disturbances.
• **Solar wind measurements at L1 orbit are critical for space weather services**
  
  Currently provided by ACE spacecraft - launched in 1997.

• **Coronagraph vital for long-range (20-90 hrs)**
  
  Currently provided by SOHO spacecraft - launched in 1996. STEREO spacecraft of some value now but not for long!

• Critical model input

• Drives more accurate warnings

Efforts to ensure follow-on, operationally dedicated missions need help.

• **Recommend GMDTF and community support**
WATCH: Geomagnetic A-index of 50 or greater predicted
Issue Time: 2001 Sep 24 1732 UTC
Valid for UTC Day: 2001 Sep 26
NOAA Scale: Periods reaching the G3 (Strong) Level Likely
CME impacts ACE spacecraft

WARNING: Geomagnetic K-index of 7 or greater expected
Valid From: 2001 Sep 06 1630 UTC
Valid To: 2001 Sep 07 2300 UTC
Warning Condition: Onset
NOAA Scale: G3 or greater - Strong to Extreme
Industry Paper on the Effect of GIC on Power Transformers and Power Systems
NERC GMDTF Toronto June 9-10, 2011
Effect of GIC on Power Transformers and Power Systems

Outline of Presentation

- Effect of DC on power Transformers
- Effect of GIC on Power Transformers
- Cases of transformer failures / damage / over – heating reported in the published literature as caused by GIC
- Consequences of core part – cycle, core semi – saturation on power systems
- Factors that determine the magnitude of GIC
- Available Means of Mitigating the effect of GIC
- Conclusions & Summary
Effect of DC on Power Transformers
DC Flux Density Shift in Transformer Cores
DC causes Part – Cycle, Semi – Saturation of the core

- Non-linearity of the core material limits core from fully saturating
Magnetizing current of a Transformer under effect of DC / GIC

- Duration of the core semi-saturation depends on core type, transformer design, and magnitude of DC

Typically $\frac{1}{10^{th}}$ to $\frac{1}{6^{th}}$ of a Cycle
% $I_{mag}$ of 1-phase Transformer under effect of DC

- Duration of core semi–saturation = $F_n$ (core – type, transformer design, and magnitude of DC / GIC)
  
  **Typically 1/10th to 1/6th of a Cycle**
Main Factors affecting how much GIC would cause core semi-saturation

- Core Type
  - 3 phase, 3 limb core vs. all other core types
- Number of turns in windings carrying the GIC
- In 3 phase, 3 limb cores
  - Core operating Flux density
  - Distances between tank & core
3 phase, 3 limb cores require much higher magnitudes of DC to saturate compared to all other core – types

All other core – types are basically equivalent
Effect of GIC on Magnetizing Current

P.U. Magnetizing Current v/s magnitude of GIC

- 3 - Phase, 3 - Limb Trafo
- 1 - Phase, 2 - Limb Trafo

P.U. Excitation current

GIC Amps / Phase

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Harmonic Content of magnetizing current associated with Core part-cycle, semi-saturation

Harmonics Spectrum of Excitation current under DC Conditions

- **3 - Phase, 3 - Limb Transformer**
- **1 - Phase Transformer**

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Impact of core part-cycle, semi-saturation

- Higher temperatures in windings, leads, structural parts, and tank
  - A high magnitude pulse of magnetizing current
    - High magnitude of leakage flux, rich in harmonics
    - Higher eddy & circulating current losses
  - Some of the main core flux flows outside the core
- Tank wall heating
  - In shell form and in Core form transformers with 3 – limb cores
    - Leakage flux => Tank walls
- High winding circulating currents
  - As a result of significant change in the leakage flux pattern
  - In some old shell form designs
  - In some other transformers with particular design features
Effect of GIC on Power Transformers
Characteristics of GIC

- Moderate magnitudes of current pulses over a few hours
- Much higher short – duration current peaks
- Duration of highest magnitudes in an event is 1 – 2 minutes

Fig 4.8 in Meta-R-319 Report by J. Kappenman
Effect of GIC on Winding Hot Spot in a 1 – phase Transformer

- Actual temperature rise is much lower due to short duration of highest peak of GIC
- For a 2 – minute duration: Rise is 3, 4, and 6 C for GIC of 20, 30, and 50 Amps
Heating of Core Tie – plates due to GIC

- Again, for a 2 – minute duration: Rise is 3, 7, and 11 C for GIC of 20, 30, and 50 Amps
Per phase GIC Wave – Form used for Thermal Calculations

Idc

(0,0)

<table>
<thead>
<tr>
<th>Time, Minutes</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
</tr>
</tbody>
</table>

400 Amps

20 Amps

About 5 times the levels experienced at PSE&G Salem Generating Power station in March, 1989
Winding Hot Spot rise due to GIC in a 1 – phase Transformer

Winding Hot Spot Temperature vs Time
Winding Hot Spot rise due to GIC in a 1 – phase Transformer

- 1° C rise due to 20 Amps
- 35° C rise in the 2 – minute duration of the GIC pulse
- Drops back to original temperature in 4 minutes
- Duration of Temperature pulse is too short to cause any winding damage
- Temperatures & durations << allowed by IEEE for emergency overload
- Same is true for structural parts of the transformer
## Winding Temp. rise caused by a 2 – minute duration GIC

<table>
<thead>
<tr>
<th>GIC Level</th>
<th>Temperature Rise, C</th>
<th>Total Temperature, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per Phase</td>
<td>Per 3 phase</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>300</td>
<td>5</td>
</tr>
<tr>
<td>200</td>
<td>600</td>
<td>9</td>
</tr>
<tr>
<td>300</td>
<td>900</td>
<td>20</td>
</tr>
<tr>
<td>400</td>
<td>1200</td>
<td>35</td>
</tr>
</tbody>
</table>
Measured Temp. rises in Windings / structural parts due to DC

- 1 – phase at HQ, 75 Amps DC for 20 minutes
- 3 – phase, 5 limb at FINGRID using 50, 100, 150, 200 Amps DC for intervals of 30 minutes each
- Tokyo Elec., Toshiba, Hitachi, and Mitsubishi, tested large models of core form and Shell form transformers with DC equivalent to 400 – 600 Amps / phase for full size transformers for 30 – 120 minutes
- Measured from 30° – 110° C temp rises in mainly structural parts
- No damage observed in windings or major insulation
- Again, because of its short duration, GIC would cause much lower temperature rises and no insulation damage / loss of life
Cases of Transformer failures / damage / over – heating reported in the published literature as caused by GIC
PSE&G Salem’s GSU Winding overheating during the 1989 GIC event

- An old Shell form transformer with an old design of LV windings
- Overheating: Caused by high $I_{circ}$ as a result of core semi – saturation
Reported lead – overheating in S. Africa after a GIC Event

- Reported cases were a number of same design transformers where the leads were heavily insulated with poor oil – flow in leads
- Overheating caused charring of the inside wraps of insulation
- Caused gassing but no failures
- Overheating was found later during planned maintenance
- Higher temperatures of leads due to high GIC is expected
- Part of the overheating is believed to have been there before the GIC event
Reported tank overheating in APS transformers after GIC Event

These were shell-form transformers

- Wood slabs exist between core & tank walls
- No oil cooling of these tank areas; not needed for normal operating conditions
- Temperature increase due to localized heating caused by stray flux during a GIC event is expected (140° – 160° C, not 400° C)
  - Had no consequences
Consequences of Core part – cycle semi – saturation on power systems
Consequences of Core part - cycle, semi - saturation on power systems

- Causes a high magnitude of 1 – 2 msec. – duration current pulse / reactive power (One / cycle) to flow in the system

- This pulse causes the capacitive components on the system, such as static compensators, etc. to increase their currents and may become overloaded and trip, causing grid instability

- The current pulse is associated with high harmonics:
  - Resonance may occur and stability of the grid may be compromised due to the creation of virtual zero at some point and opening of lines.
  - Low % of 2nd order harmonic could send the wrong message of fault current to the differential relays

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Factors that determine the magnitude of GIC

- Affected location on Earth is dependent on location of the activity on the sun
- A significant Sun – spot activity may, or may not, mean high GIC in a particular location on Earth
- Magnitude of GIC is a function of location on earth, resistance of the soil, and direction, height, and length of the transmission lines
- Therefore, 500 kV and 765 kV transmission lines travelling long distances North – South are the most susceptible to the high levels of GIC
- Based on above, only specific power grids, or parts of a power grid, would be susceptible to high levels of GIC
Available Means of Mitigating the effect of GIC

- Alerting
- Monitoring / Measurements
- Simulations and evaluation of risk
- Increasing robustness of network
- Providing network protection
- Installation of appropriate DC blocking devices
- Proper operating procedures during a storm
  - Line load – sharing, desensitization of susceptible equipment, and minimizing voltage regulations
- Taking advice of utilities who have experience
Effect of GIC on Power Transformers and Power Systems

Conclusions / Summary

- Because of its short duration, even high levels of GIC would not cause damaging overheating of neither windings nor structural parts of the large majority of power transformers.

- The failure of only one old shell form transformer of a very old winding design is confirmed to have been a consequence of GIC. All other failures, reported in the published literature to have been caused by GIC, were not caused by GIC.

- Cases of lead and tank overheating, reported in the published literature to have been caused by GIC, were either minor heating of minimal consequences or were only partially caused by GIC.

- The main impact of GIC is on the system instability it causes due to high levels of VARS and significant current harmonics as a result of transformer core part – cycle, semi – saturation.
Effect of GIC on Power Transformers and Power Systems

Conclusions / Summary

- There are a number of means available for mitigating the effect of GIC both on transformers and power systems
- Manufacturers have different levels of competence in modeling technology and the know-how to evaluate transformer designs for the impact of GIC
- It is possible to design transformers to be less vulnerable to part-cycle, semi-saturation during a GIC event
  - Specifications of transformers to be subjected to high GIC levels should include information on what level of GIC is expected at the transformer location
- The issue should not be concern over “GIC causing transformer failures”, rather: Transformers can be “susceptible to core saturation” and not to “failure”
NASA Perspective: Solar Shield – Forecasting Solar Effects on Power Transmissions Systems
(cemc.gsfc.nasa.gov/Solar_Shield)

Pulkkinen, A., M. Hesse, S. Habib, F. Policelli, B. Damsky, R. Lordan, L. Van der Zel, D. Fugate, W. Jacobs, E. Creamer
Contents

• Some (general NASA Space Weather Laboratory) background.
• Solar Shield overview.
• Solar Shield forecasting system.
  – Level 1 approach. The first tailored physics-based 2-3 day lead-time forecasts.
  – Level 2 approach. The first tailored physics-based 30-60 min lead-time GIC forecasts.
• Coupling of the system to the SUNBURST research support tool.
• Summary.
Background

- NASA Space Weather Laboratory (GSFC) provides numerous state-of-the-art real-time space weather products for a wide variety of customers and collaborators.
- Space Weather Laboratory leverages NASA’s observational and modeling capacity to push the space weather forecasting envelope.
Background

• For a quick overview of the available space weather products, check iswa.gsfc.nasa.gov.
GIC forecasting challenge
Solar Shield overview

• In Solar Shield, we developed a system to forecast space weather effects on the North American power grid; initial development funded by NASA’s Applied Sciences Program.
• NASA/GSFC/CCMC and Electric Power Research Institute (EPRI) the key players.
• System has been running in real-time since February 2008.
• DHS proposal was selected for contract award March 21, 2011.
System requirements (summary)

- **Two-level GIC forecasts:**
  - Level 1 providing 1-2 day lead-time.
  - Level 2 providing 30-60 min. lead-time.

- **Coupling to EPRI’s SUNBURST research support tool.**

  Used by the SUNBURST member utilities to monitor GIC.
Level 1 forecasts
Solar observations of eruptive events are used to compute “cone model” parameters. SOHO and STEREO data used.

MHD output at the Earth used in a statistical model providing probabilistic estimate for GIC at individual nodes of the power grid. GIC forecast file is generated.

Plasma “cone” introduced to the inner boundary of a heliospheric MHD model. Model propagates the disturbance to the Earth. Computations carried out at the Community Coordinated Modeling Center.
Level 2 forecasts
Lagrange 1 observations used as boundary conditions for magnetospheric MHD. NASA’s ACE data used.

Magnetospheric MHD model used to model the magnetospheric-ionospheric dynamics. Computations carried out at the Community Coordinated Modeling Center.

Magnetospheric MHD output used to drive geomagnetic induction and GIC code providing GIC at individual nodes of the power grid. GIC forecast file is generated.

Pulkkinen et al. (Annales Geophysicae, 2007)
Level 2 forecast example

Modeled GIC at lat: 53.2, long: -99.3

Measured GIC at lat: 53.2, long: -99.3

Oct 24, 2003
Coupling to the SUNBURST research support tool

% Level 1 GIC forecast produced by REALTIMEGIC_LEVEL1
% The format of the data is as follows:
% 0 0 0 0 0 lat1 lon1 lat2 lon2 ...
% yy mm dd hh mi GIC1low GIC1high GIC2low GIC2high ...
% 0 0 0 0 53.16 -99.29 45.39 -68.53
2006 12 14 14 6 76 15 153

% Level 2 GIC forecast produced by REALTIMEGIC_LEVEL2
% The format of the data is as follows:
% 0 0 0 0 0 0 lat1 lon1 lat2 lon2 ...
% yy mm dd hh mi GIC1low GIC1high GIC2low GIC2high ...
% 0 0 0 0 0 53.16 -99.29 45.39 -68.53
2008 03 19 11 02 31 -0.11 0.00 0.13 0.00
2008 03 19 11 04 31 0.02 0.00 0.03 0.00
2008 03 19 11 06 31 -0.02 0.00 0.04 0.00
2008 03 19 11 08 31 0.00 0.00 0.01 0.00
Summary

- Solar Shield system leverages NASA’s unique space weather modeling capabilities.
- Tailored two-level GIC forecasts generated for selected nodes of the North American high-voltage power transmission system.
- System is coupled to EPRI’s SUNBURST tool.
- System has been running in real-time since February 2008.
- Further development with DHS support underway.
- Much of the new forecasting capacity based on NASA’s science missions. Need better guarantee for data availability and continuity.