Assessment of the Impact of GMD on the TVA 500 kV Grid & Power Transformers
Part I: GIC Modelling and Initial Studies

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October 31, 2016

Summary/Overview

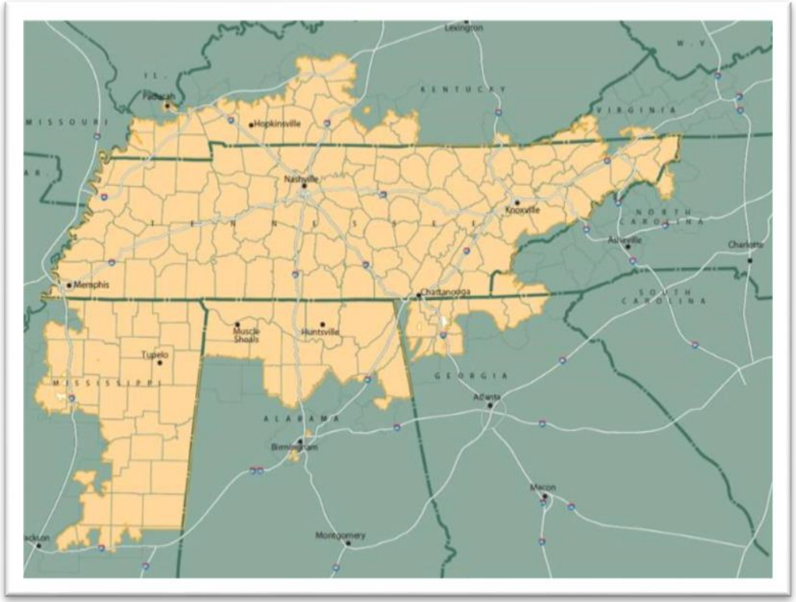
In response to/preparation for NERC TPL-007, TVA conducted GIC studies and evaluation of 500kV transformers

- Introduction
- Description of analysis software
- Building the model
- Studies and results
- Mitigation alternatives
- Conclusions

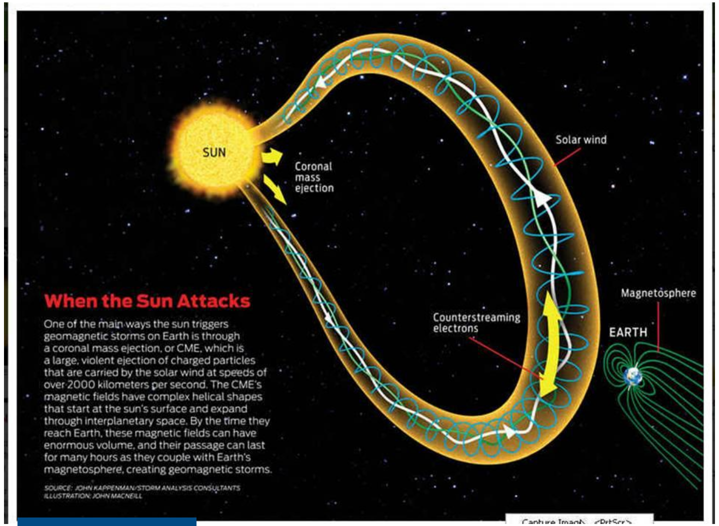
GMD
GIC

Tennessee Valley Authority

- A federally-owned, self-financed corporation
- Mission: Provide navigation, flood control, & electric power in the Tennessee Valley region
- Largest public power system
- Service Area:
    - Parts of 7 states
    - 80,000 square miles
    - 9 million people
- Primarily a wholesaler of power serving distributors
- TVA also sells power to direct served customers



Introduction



GIC phenomenon

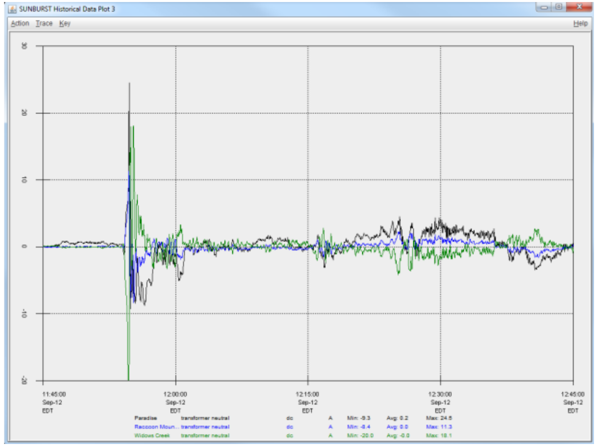
- Solar flares emit charged particles
- Earth's magnetic field affected → Geomagnetically induced current (GIC)
    - Quasi-dc
    - Flows according to Kirchoff's/Ohm's Laws
    - Paths include EHV lines, grounded EHV transformer neutrals
    - Power transformer part-cycle saturation → Increased VAR demand, harmonics, heating

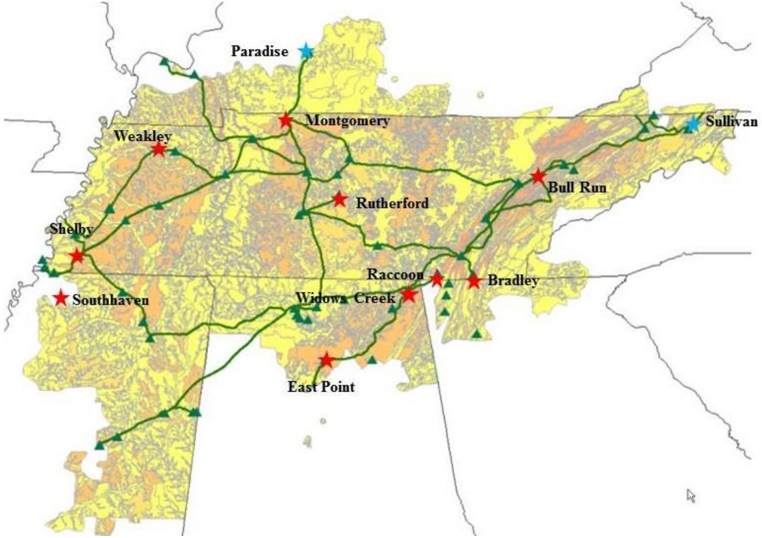
To-date TVA has not been significantly affected by or detected any power transformer concerns due to GIC

July 15, 2000 → Several 161kV capacitor banks tripped

TVA – SUNBURST network

- EPRI project dating back to 1990
- Installed in 12 TVA EHV transformers
- EPRI via contractor provides post GMD event reports on GIC data for all monitors in network
- Magnetometer at Paradise





NERC & GIC Studies

TPL-007-1 — Transmission System Planned Performance for Geomagnetic Disturbance Events

A. Introduction

1. **Title:** **Transmission System Planned Performance for Geomagnetic Disturbance Events**
2. **Number:** TPL-007-1
3. **Purpose:** Establish requirements for Transmission system planned performance during geomagnetic disturbance (GMD) events.
4. **Applicability:**
   4.1. Functional Entities:
   4.1.1 Planning Coordinator with a planning area that includes a Facility or Facilities specified in 4.2;
   4.1.2 Transmission Planner with a planning area that includes a Facility or Facilities specified in 4.2;
   4.1.3 Transmission Owner who owns a Facility or Facilities specified in 4.2;
   4.1.4 Generator Owner who owns a Facility or Facilities specified in 4.2.
   4.2. Facilities:
   4.2.1 Facilities that include power transformer(s) with a high side, wye-grounded winding with terminal voltage greater than 200 kV.
5. **Background:**
   During a GMD event, geomagnetically-induced currents (GIC) may cause transformer hot-spot heating or damage, loss of Reactive Power sources, increased Reactive Power demand, and Misoperation(s), the combination of which may result in voltage collapse and blackout.
6. **Effective Date:**
   See Implementation Plan for TPL-007-1

B. Requirements and Measures

R1. Each Planning Coordinator, in conjunction with its Transmission Planner(s), shall identify the individual and joint responsibilities of the Planning Coordinator and Transmission Planner(s) in the Planning Coordinator's planning area for maintaining models and performing the study or studies needed to complete GMD Vulnerability Assessment(s). *[Violation Risk Factor: Lower] [Time Horizon: Long-term Planning]*

M1. Each Planning Coordinator, in conjunction with its Transmission Planners, shall provide documentation on roles and responsibilities, such as meeting minutes, agreements, copies of procedures or protocols in effect between entities or between departments of a vertically integrated system, or email correspondence that identifies an agreement has been reached on individual and joint responsibilities for maintaining models and performing the study or studies needed to complete GMD Vulnerability Assessment(s),

Page 1 of 26

TPL-007 Requirements

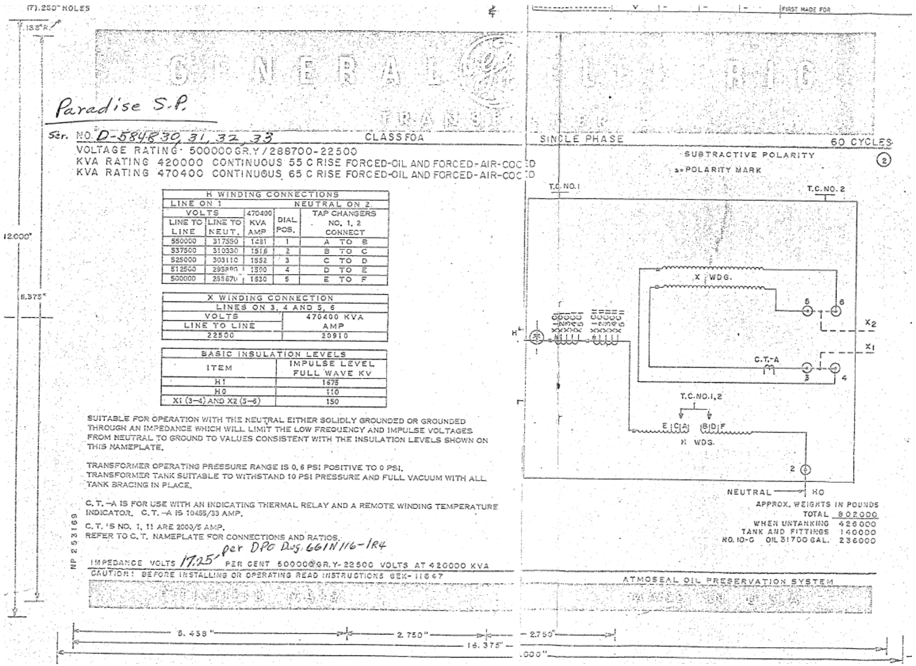
- Maintain models
- Complete GIC vulnerability assessment every 5 years
  - Peak/off peak load
  - Maximum E-field 8V/km, scaled for geomagnetic latitude & earth resistivity
    - TVA maximum 0.38 to 1.9V/km
- Calculate GIC

For transformers where GIC > 75A/phase → thermal impact assessment

Potential mitigation: Reconfigure transmission, series capacitors, neutral blocking impedance

GIC Modeling

- TVA has ~2500 miles of 500kV transmission line, 85 EHV transformer banks (most with three single-phase units)
- Modeled 500kV and underlying 161kV network using PowerWorld
- Transformer DC winding resistance (bridge)
- Substation ground resistance by test



GROUND IMPEDANCE VALUES

Technical Support Branch ← Jerry Cooke
Compiled October 1, 1985

Substations, Generating Plants, Switching Stations, and Line Metering Points

Location	Station Ground Ohms 1	2	3	Fence Ground Ohms	Fence Tied to Station	Ground Condition	Test Date	Date Verified or Remarks
Paradise S.P.	0.08			0.16	Yes	Dry	11-5-81	Largo

Resistances

Voltage	1-2 @ 24.7°C	1-2 @ 75°C
317550	.1631	.1950
310330	.1593	.1908
303110	.1554	.1856
295890	.1520	.1814
288670	.1483	.1722

LV	3-5 @ 24.7°C	3-5 @ 75°C	4-6 @ 24.7°C	4-6 @ 75°C
22500	.001568	.0009055	.001534	.0009055

PowerWorld

Simulator GIC option

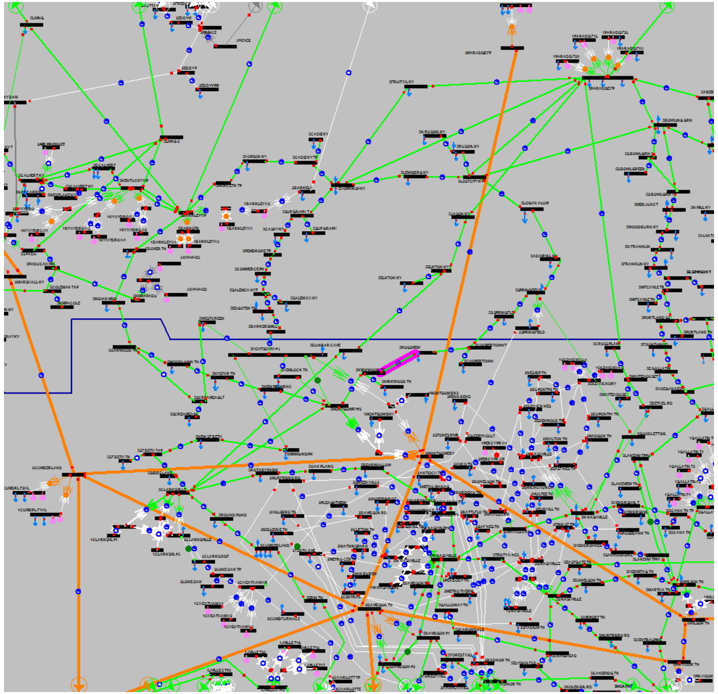
DC circuit model of the power grid for quasi-DC GIC calculation

GMD surface electric fields modeled as DC sources in series with transmission lines

Incorporates earth resistivity models, geomagnetic latitude scalars

Identify worst-case field orientation

Export transformer GIC time-series for thermal evaluation



Additional capability

GIC → Xfmr MVAR losses → AC loadflow

Vary E-field strength, calculate QV curves to point of collapse

Identify locations for mitigation

Building the Model

3.0 Resistance

HV Winding		Resistance at 75 °C
Voltage (kV)	Position	(Ω)
550.00	17	0.201953
543.75	16	0.200626
537.50	15	0.199180
531.25	14	0.197612
525.00	13	0.196286
518.75	12	0.194839
512.50	11	0.193513
506.25	10	0.191945
500.00	9	0.190137
493.75	8	0.191945
487.50	7	0.193513
481.25	6	0.194598
475.00	5	0.196165
468.75	4	0.197492
462.50	3	0.199300
456.25	2	0.200626
450.00	1	0.202073

LV Winding		Resistance at 75°C
Voltage (kV)	Position	(Ω)
165.025/√3	-	0.020002

TV Winding		Resistance at 75°C
Voltage (kV)	Position	(Ω)
13.2	-	0.002157

Data gathering

- Transformers:
  - DC bridge test data from test reports
  - Core construction for three-phase banks
- Substation grounding resistances (dated 1960s-1980s)
- Transmission line DC resistance assumed equal to AC

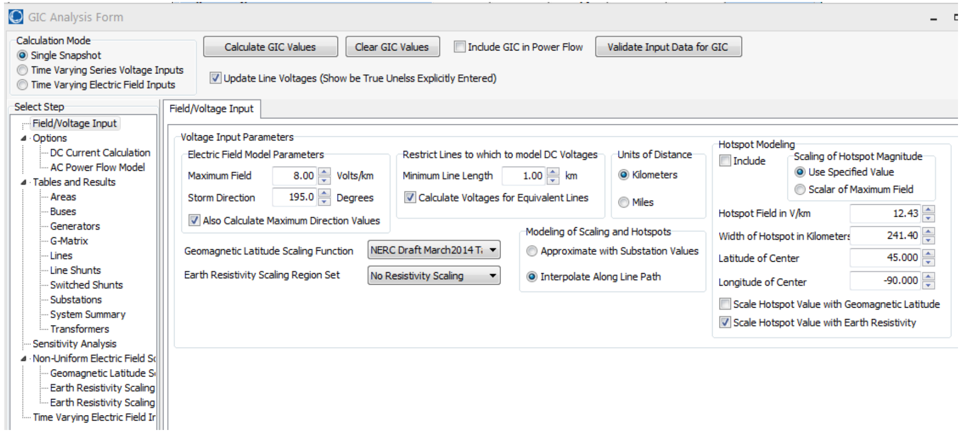
Took about 12 months

Sources included Transmission Planners, Field Offices, Equipment Vendors

Studies

- Winter 2016 base case
- Solve AC power flow
- Input substation/transformer/earth resistivity scaling region data
- Calculate GIC Values:
  - Constant electric field strength (8V/km), varying storm direction 0-360 degrees in 5 degree steps
  - Constant storm direction (15 degrees), increasing field strength up to 20V/km in 1V steps
    - 15 degrees was determined from step 1 to be worst case with all-ties-closed

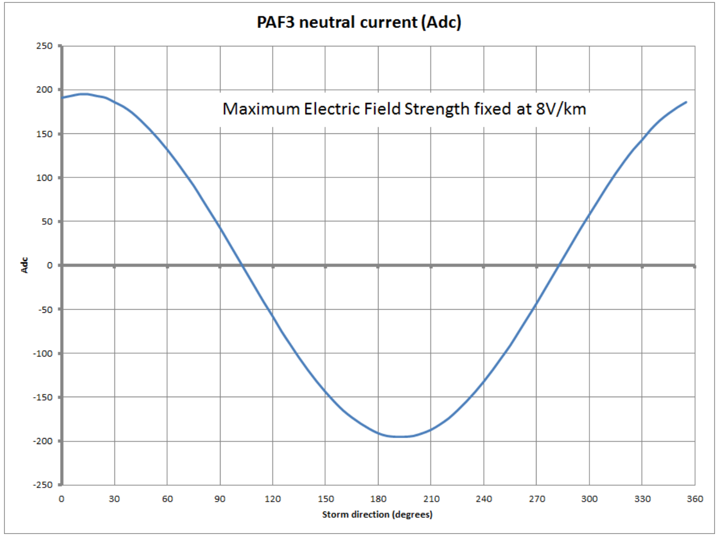
Substation Records						
Sub Name	Sub Num	Nominal kV(max)	Grounding Resistance (Ohms)	Latitude	Longitude	Bus Num
8BENTON MS	26512	500	0.47	34.829361	-89.20015	360612
8BR FERRY NP	26094	500	0.15	34.704365	-87.11862	360052
8BRADLEY TN	26547	500	1.31	35.04253	-84.95871	360662
8BULL RUN FP	26117	500	0.09	36.018799	-84.15793	360093
8ACKERMAN CC	26522	500	0.219	33.385777	-89.21067	360627



GIC Transformers													
Sub Name High	Nom kV High	Nom kV Med	Nom kV Ter	Manually Enter Coil Resistance	Coil Resistance (Ohms) for High winding	Coil Resistance (Ohms) for Medium winding	XF Config High	XF Config Med	XF Config Ter	Is Autotransformer	Core Type	GIC Model Type	GIC Model Param
Paradise Fossil Plant	500	24		Yes, User Set	0.1769	0.0018	Gwye	Delta		NO	Single Phase	Default	0
Montgomery TN 500kV Substation	500	161	13	Yes, User Set	0.2092	0.0216	Gwye	Gwye	Delta	NO	Single Phase	Default	0
Montgomery TN 500kV Substation	500	161	13	Yes, User Set	0.179936	0.015631	Gwye	Gwye	Delta	NO	Single Phase	Default	0
Browns Ferry Nuclear Plant	500	20		Yes, User Set	0.164575	0.00068258	Gwye	Delta		NO	Single Phase	Default	0
Browns Ferry Nuclear Plant	500	20		Yes, User Set	0.160235	0.0006717	Gwye	Delta		NO	Single Phase	Default	0

TVA

Results



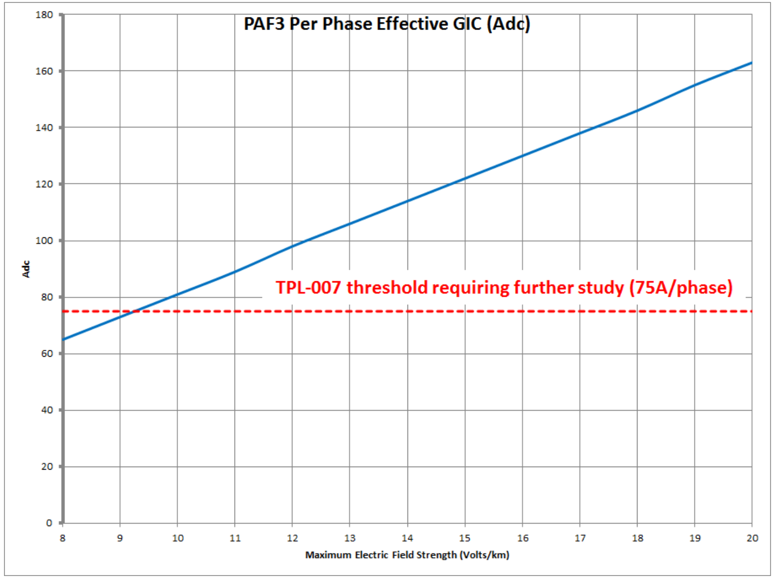
Fixed E-field, varying orientiation

Most sensitive site is Paradise GSU #3

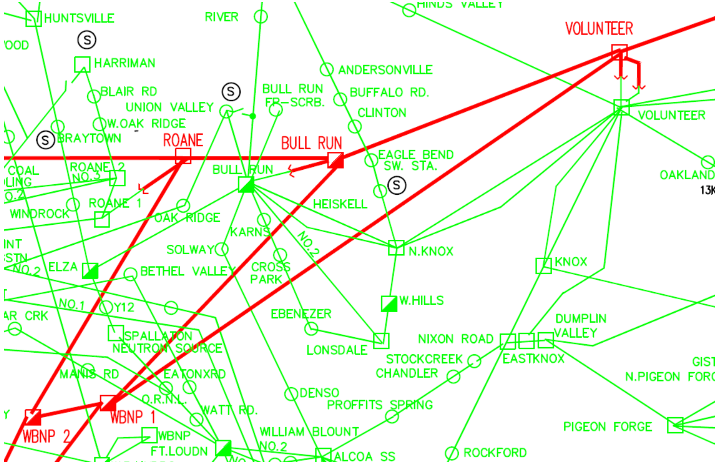
Worst case is storm direction 15 (195) degrees: 195Adc neutral current at 8V/km electric field strength

Results

- Present draft of TPL-007 requires further study only if per-phase effective GIC exceeds 75A/phase
- Study indicates PAF3 exceeds that threshold for electric field strength at 10V/km (TPL-007 requires only up to 8V/km right now)
    - At 19V/km two additional banks exceed 75A/phase: Bull Run, Weakley
    - At 20V/km one additional bank exceeds 75A/phase: Union Bk1
- A neutral blocking device (NBD) at PAF3 introduces no additional problems with all-ties-closed



Mitigation



Three areas

1. Replace capacitor bank protection
2. Neutral blocking device (Paradise GSU)
3. Transmission reconfiguration
    - 500kV elements around Bull Run

Capacitor bank relays replaced by end of 2016

Paradise NBD did not result in GIC > 75A/phase in other xfmrs

Transmission reconfiguration evaluated for other factors (n-1)

Conclusions

- Most effort in development of DC models
- No locations >75A/phase for scaled 8V/km E-field
- For 20V/km, four locations exceeded 75A/phase
- Transmission reconfiguration, NBD possible mitigations

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