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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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SUMMARY

Geomagnetic Induced Current (GIC) is a quasi-dc current that flows in grounded power systems due to variations of the earth surface potential caused by geomagnetic storms. GIC may cause part-cycle saturation in power transformers resulting in an increase in their reactive power consumption and current harmonics resulting in transformer heating and potential misoperation of protective relays and system voltage collapse.

TVA's transmission grid consists of 2500 miles of 500 kV overlaying 11,500 miles of 161 kV supplying almost all the State of Tennessee and portions of 6 surrounding states. The service area covers 80,000 square miles, approximately 450 miles east-west by 180 miles north-south. The grid is relatively densely interconnected so line lengths average 35 miles. There are eighty five 500/161 kV transformer banks from various manufacturers with a range of designs dating from the earliest units in 1965. TVA has not specified GIC performance requirements for any existing transformers.

Although the TVA service area is relatively southerly, GMD storms in 2000 and 2003 caused harmonics leading to nuisance trips of 161 kV capacitor banks. GIC from the mild storms experienced since installation of twelve EPRI Sunburst detectors have several times exceeded 5A trigger levels.

This paper describes TVA's GIC system modelling, studies, initial evaluation of 500 kV transformers, and initial conclusions following the recommendations of the NERC Guideline [1]. In an accompanying Part II paper magnetic and thermal modelling of transformers at two of the most affected sites are presented together with an analysis of grid stability.

KEYWORDS

Geomagnetic Induced current, GIC, Geomagnetic Disturbance, GMD, Power Transformers, Power systems, VAR demand

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INTRODUCTION

TVA grid

TVA is a federally-owned, self-financed corporation with the mission to provide navigation, flood control, and electric power in the Tennessee Valley Region. TVA operates the nation's largest public power system with a service area covering parts of seven states and 80,000 square miles serving 9 million people. It is primarily a wholesaler of power to distributors, but also sells power directly to larger industrial customers.

GIC phenomenon

Geomagnetic disturbance (GMD) solar flares emit charged particles that can affect the earth's magnetic field and induce currents known as geomagnetically-induced currents (GIC). These currents are quasi-dc (10μHz to 1Hz), flowing through all available paths according to Kirchoff's and Ohm's Law. Available paths include EHV transmission lines and transformers, and when flowing through power transformer windings the currents cause part-cycle saturation which can lead to increased VAR demand, generation of harmonics, and heating.

TVA experiences with GIC events

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

Following a National Oceanic and Atmospheric Administration (NOAA) solar storm alert for a Planetary Kp index K-9 storm, over the course of July 15, 2000 TVA experienced tripping of several 161kV capacitor banks (820MVAR total) separated by hundreds of miles, with each trip due to residual overcurrent or overvoltage relay misoperation due to harmonics. No system problems were caused by these trips. Subsequent changes included replacing capacitor bank protection relays that were sensitive to harmonics. Although full replacement of all relays will not be completed until late 2016, TVA has experienced no further capacitor bank trips.

TVA's SUNBURST network

In late 1990 the Electric Power Research Power Institute (EPRI) started the SUNBURST project which provides GIC detectors to participating utility partners for installation in EHV bank neutrals.

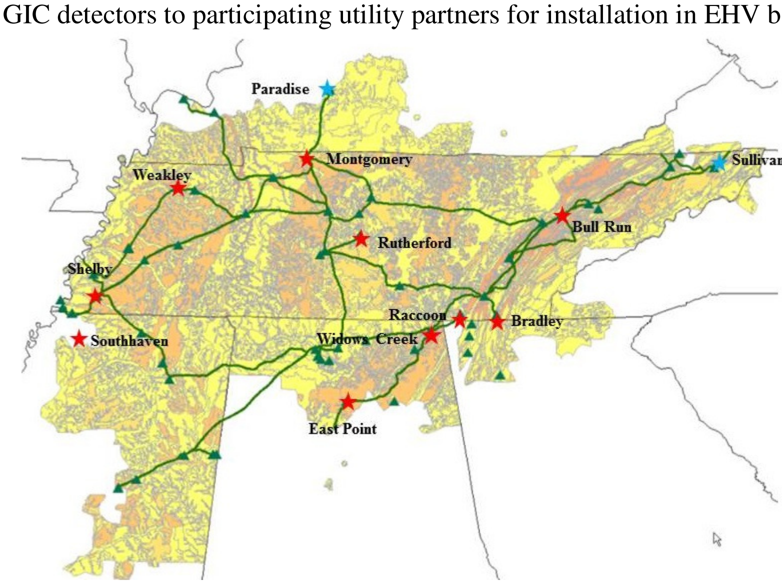

Figure 1: TVA Network of Sunburst Detectors

Figure 1 shows the locations of the 12 detectors in TVA's 500 kV system. Locations were determined from an early study with the assistance of EPRI, using an approximate network model. The detectors communicate data via cell phone links to the contracted support company, which provides quasi-real-time reports on GIC data during significant events. In the summer of 2015 a magnetometer was installed at the Paradise Fossil Plant site which is TVA's location most sensitive to GIC.

Detector Experience

With the exception of a few moisture seal failures in early detectors the equipment has been reliable. The main problem has been inadvertent interruptions of the 110 volt supply to the detectors. It is planned that the detector network will be transitioned to real-time data flow direct to TVA with real-time operator displays.

NERC TPL-007 guidelines/requirements for GIC studies

NERC's draft TPL-007 transmission planning standard, expected to be approved for implementation in 2016, would require utilities to maintain models and complete a GMD vulnerability assessment every five years. The studies would include peak and off-peak load conditions and be based on a benchmark GMD event, characterized by a maximum surface electric field of 8 V/km at a reference location. The field magnitude varies geospatially with geomagnetic latitude and earth resistivity. Using currently accepted coefficients for geomagnetic latitude and earth resistivity, the maximum surface electric fields in the TVA footprint vary from 0.38 to 1.9 V/km for the benchmark GMD event. Calculated GIC currents are then used for transformer magnetic and thermal impact assessments. Calculations assume worst case Geo-electric field orientation as well as the benchmark GIC time series.

For transformers where maximum GIC exceeds 75A per phase a thermal impact assessment is required. Measures to mitigate the effects of GIC could include operational schemes such as reconfiguring transmission line connections, installation of line series capacitors, or transformer neutral capacitive or resistive blocking.

Overview of GIC modelling

TVA operates an extensive 500kV network with 2500 miles of transmission line and eighty-five 500kV transformer banks. Most banks have three single-phase transformers.

The 500kV system and underlying 161kV network has been modelled in PowerWorld Simulator. The model includes DC element data for transformers, generators, capacitor banks, and substation ground resistance. The DC winding resistance for each transformer was obtained from transformer test reports (bridge tests).

DESCRIPTION OF ANALYSIS SOFTWARE

The PowerWorld Simulator GIC option is a DC loadflow software for the studies required by the pending NERC TPL-007-1 standard. Requirements are to:

- assess the impact of transformer reactive power losses due to part-cycle saturation on system voltages; and
- assess thermal stress on transformers due to GIC.

The Simulator will simulate GIC currents and system voltages for the NERC benchmark GMD event or other user-defined surface electric field patterns. It can incorporate geospatially varying one-dimensional earth resistivity models and geomagnetic latitude scalars and can identify worst-case geomagnetic electric field orientation with respect to an entire area or individual system elements.

Transformer GIC time-series can be exported to thermal models to calculate winding and structural part temperatures.

PowerWorld Corporation has completed several studies of the impact of GMD on various regions of the North American interconnected power grids. These studies have shown that GMD can cause wide-area effects, but voltage collapse due to transformer reactive power losses are often localized in areas with weak reactive power support. The Simulator can be used to vary the surface electric field strength to trace reactive power loss-voltage (QV) curves up to the point of system collapse. This helps the power system planner identify good locations for mitigation measures. More details on this study methodology can be found in [2].

BUILDING THE MODEL

Developing the DC load flow model of the TVA service territory was a significant task. The process took approximately 12 months and involved transmission planners, equipment owners, field offices, and equipment vendors. While AC load flow data is maintained in a central planning data base, DC data is not frequently used and was found to be filed in multiple locations.

Substation grounding resistance is a critical element in performing GIC studies [2]. TVA had records of grounding resistance from all stations dated from the 1960s to the 1980s which included specific test conditions such as whether static and line neutral wires and fence ground were connected to the station ground mat, and the ground condition (wet/dry/damp). It is expected that data from stations constructed in the past 15-20 years will be more accurate since older stations may have experienced some ground mat degradation. At this time TVA does not retest 500kV stations for changes in station ground resistance.

Transformer test data included winding resistance from dc bridge tests, which involved reviewing transformer test reports for all banks. For the three-phase banks the type of core construction was also determined (i.e. core form or shell form, number of legs). This test data is considered reasonably accurate.

The DC resistance of the transmission lines was assumed to be equal to the AC value already available in the AC load flow model [1].

STUDIES and RESULTS

Simulator Version 18 was used with an MMWG winter 2016 base case. The substation and transformer data was entered into a template spreadsheet (see http://www.powerworld.com/knowledge-base/gic-modelling-data-requirements) and read in as an auxiliary file, as illustrated in Figure 2.

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

Figure 2: Illustration of Study Input Data

The earth resistivity scaling region data was also read in as an auxiliary file (see http://www.powerworld. com/knowledge-base/earth-resistivity-model-for-gic-calculations). This data is from the United States Geological Survey (USGS) and is included in the NERC TPL-007 document. After solving the AC power flow, GIC values were calculated under the following conditions:

1. Constant electric field strength (8V/km at the reference location), varying storm direction 0-360 degrees in 5 degree steps (version 19 of the Simulator does this automatically)
2. 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)

Results indicated the most sensitive transformer location is at the generator step-up (GSU) for Unit 3 at the Paradise Fossil Plant. Worst case storm direction was determined to be 15 degrees (195 degrees), with neutral current of 195Adc and an electric field strength of 8V/km (as prescribed by TPL-007). See Figure 3 & 4.

As stated previously the draft of TPL-007 requires further study only if effective GIC exceeds 75Adc per phase (assuming a 3:1 ratio of 3-phase neutral current to per-phase effective current applies when only one winding is grounded as in a Delta-Wye GSU) for the benchmark case of 8V/km. TVA results indicated the Paradise #3 GSU current would not reach that threshold until the electric field strength reached 10V/km at the reference location. Two other banks reached 75Adc per phase if the electric field strength was 19V/km (Bull Run, Weakley), while at 20V/km, Bull Run, Weakley, and Union bank 1 exceeded 75Adc per phase. Results also predict that at 20V/km, Paradise #3 GSU neutral current would be 488Adc, which for this two-winding delta-wye transformer results in an effective per phase current of 163Adc)

Now that the study model is complete and all Sunburst detectors and the magnetometer are in place, it is planned that for the next GMD of significance a full comparison will be made between the measured and modelled GIC at each detector site.

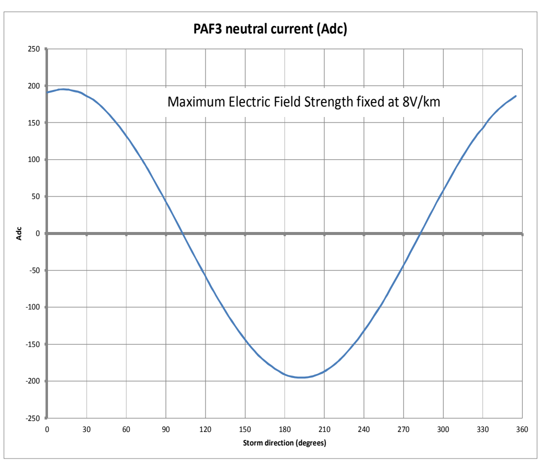

Figure 3. GIC in Paradise GSU #3 vs storm direction

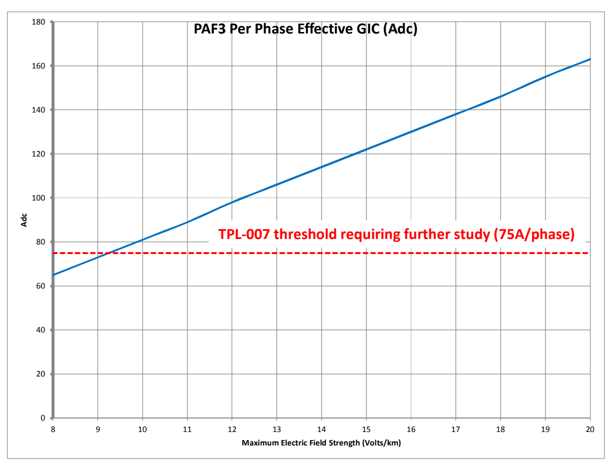

Figure 4. GIC in Paradise GSU #3 at 15 degree storm direction vs electric field strength

MITIGATION ALTERNATIVES

Existing TVA operating procedures include anticipating the simultaneous loss of 161kV capacitor banks due to harmonics. However, TVA has largely eliminated this risk by replacing relays.

Consideration of Blocking Device

A typical neutral blocking device (NBD) was modelled in the Paradise #3 GSU neutral. Although GIC in the transformers at the Montgomery TN 500kV Substation increased with the NBD at Paradise (bank #1 increased from 31Adc to 73Adc per phase, bank #2 from 23Adc to 55Adc per phase) no transformers exceeded 75Adc/phase at 8V/km. Even at 20V/km, transformers at Bull Run, Weakley, and Union did not significantly increase (<1Adc/phase) with the addition of the NBD at Paradise.

T*ransmission Reconfiguration*

With Paradise GSU #3 connected to the system via a single 500kV line, other mitigation options (short of opening the line which would remove the unit from service) are few, so a NBD would be a reasonable option for this site.

Considering the next most sensitive site, Bull Run, there are three 500kV transmission lines (shown red in Fig. 5) terminating at that station. Opening the Bull Run-Roane line results in GIC in the Roane bank exceeding 75Adc per phase, while opening the Bull Run-Volunteer line results in GIC in the Bull Run bank increasing to 136Adc per phase. Switching out the Bull Run-Watts Bar line or opening the Bull Run bank would likely be good candidates, since GIC in the Bull Run bank decreased with no other banks exceeding 75Adc per phase.

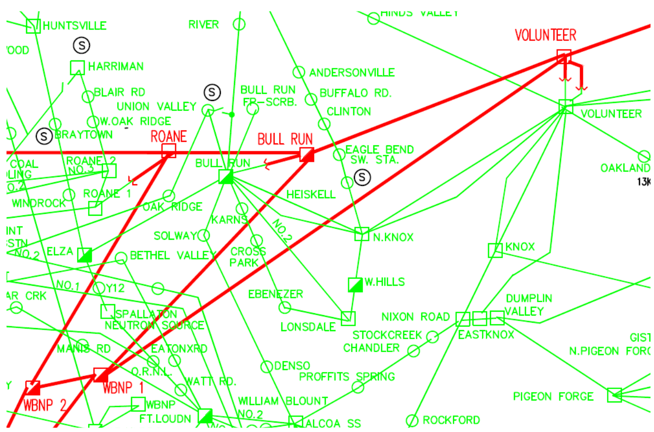

Figure 5. TVA system around Bull Run

CONCLUSIONS.

Development of the DC models required for a GIC study proved to be a lengthy and onerous procedure, but once completed the studies and identification of the most sensitive sites were straightforward. It was found that for the NERC benchmark event TVA has no locations that exceed the proposed 75Adc per phase benchmark. For the extreme case of 20V/km four locations exceeded the thermal screening criterion, with a maximum effective current of 163Adc.

Operational reconfiguration can reduce GIC at 3 of the 4 locations. The 4th location is limited by being on a radial line, but a blocking device could be used to reduce GIC without causing significant negative effects elsewhere.

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[1] NERC, “Application Guide--Computing Geomagnetically-Induced Current in the Bulk-Power System” December 2013
[2] Thomas J. Overbye, Trevor R. Hutchins, Komal Shetye, Jamie Weber, Scott Dahman, “Integration of Geomagnetic Disturbance Modeling into the Power Flow: A Methodology for Large-Scale System Studies”. North American Power Symposium 2012, September 9-11