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GIC Magnetic and Thermal Assessment of TVA's Fleet of 500 kV Transformers

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SUMMARY

This paper presents results of the Geomagnetically Induced Current (GIC) magnetic and thermal assessment performed on TVA's fleet of 500 kV transformers. The Magnetic assessment included calculating the additional VAR demand and 2nd, 3rd, and 4th order current harmonics for each of the 231 transformers in the fleet. The calculations were made for the highest magnitudes of GIC that each of these transformers was determined, by dc system modelling, that it would be exposed to under the TPL007 – 1 Benchmark GMD scenario.

The GIC Thermal Fleet Assessment was performed for transformers in the fleet (94 transformers out of the 231 total) that were determined, by GIC Susceptibility assessment to require it [3]. Thermal assessment included calculation of the hot spot temperatures of windings and structural parts of these transformers (Flitch-plates for Core Form Transformers and the Tank walls for Shell Form transformers) when subjected to the GIC signature calculated using the system modelling corresponding to the Benchmark time series specified by TPL 007 – 1. Again, all calculations were performed using ABB's Universal GIC Magnetic and Thermal models which require, in addition to the core type, only data available on Name Plates and Test reports of the transformer. Additionally, using the Universal models, rather than detailed modelling, makes performing assessments of fleets of transformers feasible as they require a small fraction of the effort it takes to perform detailed magnetic and thermal modelling of each transformer design.

Main findings of the magnetic and thermal assessment presented in this paper are:

1. Calculated magnitudes of the additional VAR Demand appear to be too low to cause voltage instabilities in the TVA power system.
2. Calculated magnitudes of the 2nd, 3rd, and 4th order current harmonics of transformers that are expected to be exposed to highest levels of GIC are sufficiently low but need to be examined for its impact on the power system and its components.
3. The thermal impact of GIC on Windings of the TVA transformers is very small.
4. No transformer structural parts hot spot temperature will exceed 140 °C for the TPL007 – 1 Benchmark GMD event.

KEYWORDS

Geomagnetic Disturbance (GMD), Geomagnetically Induced Currents (GIC), GIC fleet Assessment, Reactive Power, Current Harmonics, Winding and Structural parts heating

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INTRODUCTION

In its effort to perform a full GIC fleet assessment of their fleet of 500 kV transformers, and at the same time comply with the requirements of the TPL 007 – 01 Standard [1], TVA first performed GIC system modelling to calculate highest magnitudes and signatures of GIC to which each of the transformers in the fleet would be subjected to corresponding to the 1 – 100 years Benchmark GMD event specified by the TPL 007 – 01 Standard. This work and the results obtained were presented in Reference [2]. TVA then requested ABB to perform full GIC Assessment of TVA's transformer fleet. This involved three main assessment Tasks as follows:

<u>Task I</u>: Assessment of the Susceptibility of the transformers in the fleet to effects of the GIC Benchmark storm. The algorithm used to perform this assessment and the results obtained have been presented in Reference [3].

<u>Task II</u>: Magnetic Assessment of each of the transformers in the fleet to calculate VAR Demand and Current harmonics corresponding to highest GIC levels to which these transformers would be subjected. If high enough, these can cause system instabilities and eventual blackouts.

<u>Task III</u>: Thermal Assessment of the transformers in the fleet determined by Task – I to be susceptible to windings and / or structural parts overheating under that Benchmark GMD scenario. Thermal assessment refers to calculation of temperature rises of these transformer components corresponding to the Benchmark GMD scenario.

This paper presents the work performed as part of Tasks II and III above and the results obtained. First, the paper presents a summary of the system modelling performed to calculate highest magnitudes and signatures of GIC to which each of the transformers in the fleet would be subjected to corresponding to the 1 in a 100 years Benchmark GMD event specified by the TPL 007 – 01 Standard. This is followed by a description of the calculations performed as part of Tasks II and III along with presenting a sample of the results of the calculations performed and a summary of the observations and conclusions.

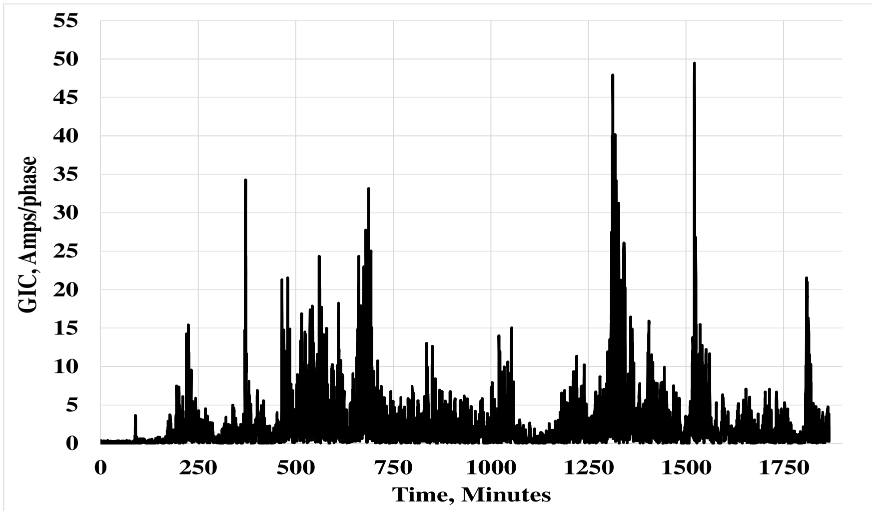
GIC SYSTEM MODELLING

The 500 kV system and underlying 161 kV network was modelled in PowerWorld Simulator. The model included DC element data for transformers, generators, capacitor banks, and substation ground resistance. The GIC currents and system voltages corresponding to the NERC benchmark GMD event were calculated [2]. The time series of GIC at each Substation and Generating Station resulting from this system modelling included GIC data recorded at ten seconds intervals for a duration of 1867 minutes (31 hrs).

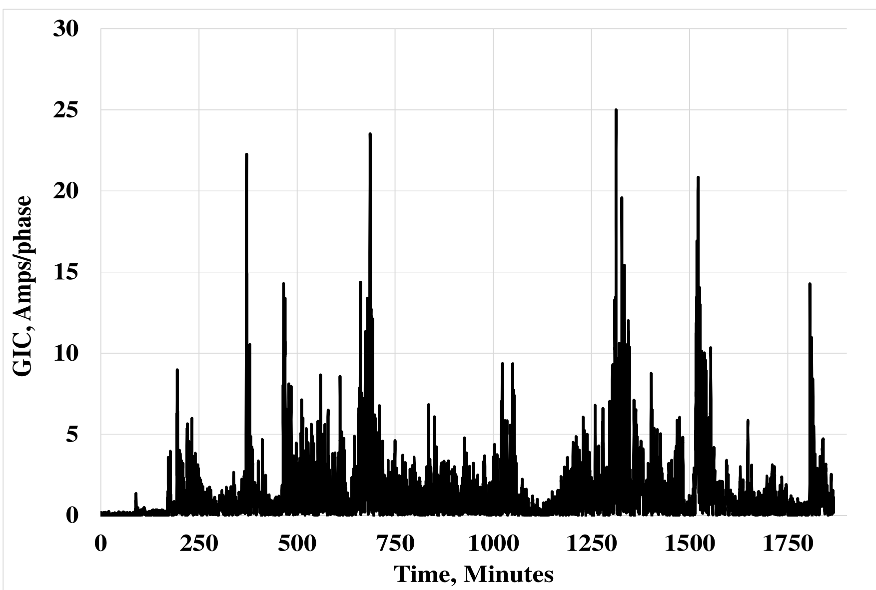
Two examples of this calculated detailed GIC Signature are shown in Figure 1 below for the "Paradise" Generating Station and the "Weakley" Substation. The figure shows that the general form of the GIC signatures; i.e. location of the peaks at corresponding times, to which different transformers are expected to be subjected, is the same but the magnitudes of the peaks are not related by a specific ratio. For example, the highest peak in the GIC signature at Paradise occurs at around the 1550 minute mark; while it occurs at around the 1350 minute mark at Weakley. Additionally, magnitudes of the highest peak and other peaks of the GIC time series vary from one transformer to another. For example, the GIC signature at Paradise (Figure 1 (a)) shows the highest four GIC magnitudes to be 33, 34, 48, and 49 Amps / phase. The corresponding peaks at Weakley (Figure 1 (b)) are 21, 23, 24, and 25 Amps / phase. However, these four peaks occur at the same times; corresponding to the peaks of the electric field time series of the Benchmark GMD event.

GIC MAGNETIC FLEET ASSESSMENT

The Magnetic assessment of the 500 kV transformers in TVA's fleet included calculating the additional VAR demand and the current harmonics when exposed to GIC. All calculations were performed using ABB's Universal GIC Magnetic models which: 1) Determine the additional VAR demand and 2) Provide magnitudes (rms) of the 2^{nd}, 3^{rd}, and 4^{th} order current harmonics that transformers inject into the power system as a result of exposure to GIC.



(a) "Paradise" Generating Station



(b) "Weakley" Substation

Figure 1: GIC Signature from DC system study corresponding to Benchmark GMD event

The Universal magnetic Models used for the calculations include 8 different sets of magnetic models for the 8 different core types of power Transformers (5 core types for Core Form transformers and 3 for Shell Form transformers). Each of these sets includes a model for calculating the additional VAR demand and 3 additional models for calculating the current harmonics associated with the level of GIC considered.

The data used for these calculations are the MVA & kV ratings of the transformer, whether the transformer design is single phase or three phase, Core Form or Shell Form, and Core type. This data was all available for transformers in the fleet that are ABB, or ABB Legacy transformers. Corresponding data of the rest of these transformers were provided by the TVA project team.

A sample of the detailed results of the GIC Magnetic Assessment of the whole fleet of the 500 kV TVA transformers is presented in Table – 1. It includes the following information:

- Transformer Identification and its corresponding location (Generating station / substation).
- Rated MVA and HV voltage
- Highest magnitudes of GIC to which each transformer is expected to be exposed.
- Calculated additional VAR demand corresponding to this magnitude of GIC
- Value of the K-factor corresponding to the calculated VAR demand
    - The definition of the K factor, as referred to in published literature, is the factor that is used for calculating the additional VAR demand by multiplying it by the magnitude of GIC and the rated voltage of the transformer.
- Calculated magnitudes (rms) of the 2^{nd}, 3^{rd}, and 4^{th} harmonic currents corresponding to the magnitude of GIC.

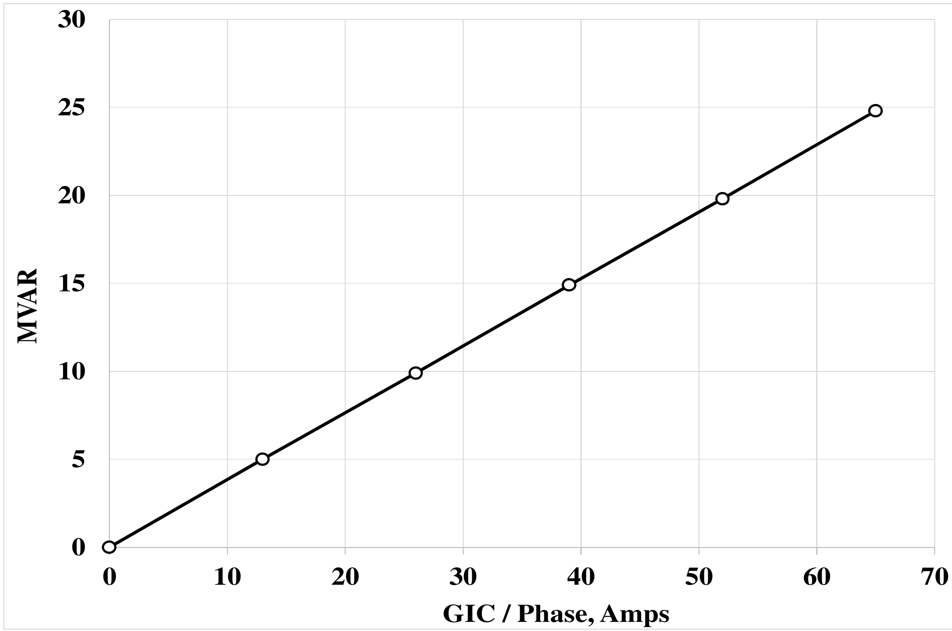
Table 1: Sample of Results of Magnetic Assessment of the TVA 500 kV fleet

Transformer	Location	MVA	HV Rated, kV	GIC, A / Ph	MVAR	K-factor	Harmonic Current, Amps		
							2^{nd}	3^{rd}	4^{th}
BM1	Benton Magnolia	360	500	24	0	0	0	0	0
BM2									
BM3									
BR1	Bradley	448	500	15	5.7	1.3	19.9	18.8	17.1
BR2									
BR3									
BUR1	Bull Run	448	500	41	15.6	1.3	53	48.7	42.2
BUR2		400	500	41	16.0	1.3	65.9	58.2	47.1
BUR3									

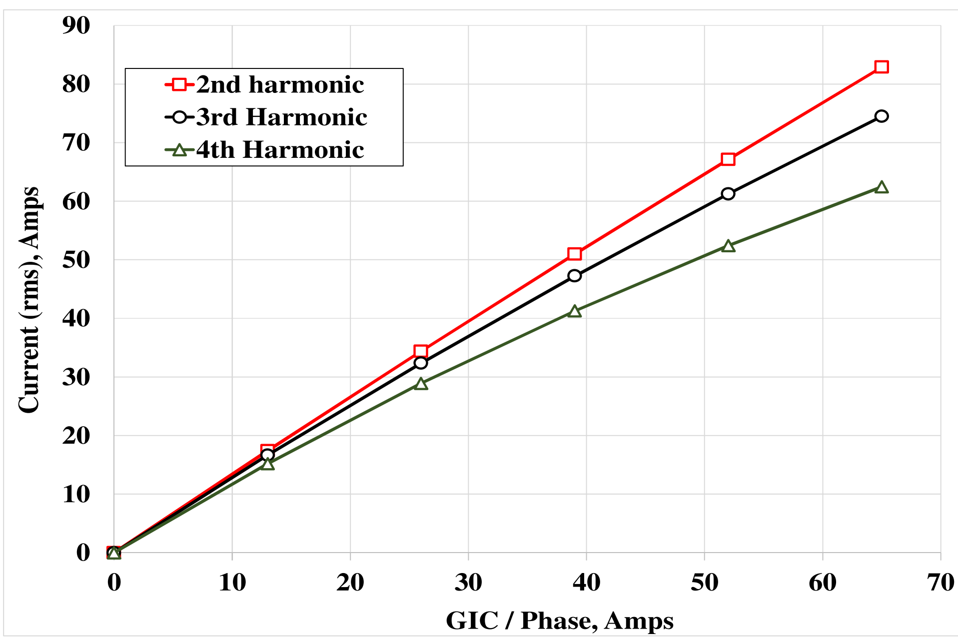
Figure 2 below presents detailed results of the magnetic assessment for the transformers that are expected to be exposed to the highest calculated levels of GIC; namely transformers at "Paradise" Generating station. The additional VAR Demand and current harmonics are given for the whole range of GIC up to the highest level of GIC expected.

From the figure below: The four transformers at Paradise would require 24.8 MVAR (5.3% of rated MVA) additional VAR demand when subjected to a GIC level of 65 Amps / Phase. The corresponding magnitudes of the 2^{nd}, 3^{rd}, and 4^{th} harmonics are calculated to be 82.9, 74.5, and 62.5 Amps, respectively. These correspond to 5.1 %, 4.6 %, and 3.8 % of the rated full load current of the transformer. These calculated magnitudes of the additional VAR Demand appear to be too low to cause voltage instabilities in the TVA power system. Calculated magnitudes of the 2^{nd}, 3^{rd}, and 4^{th} order current harmonics of the transformers that are expected to be exposed to highest levels of GIC seem to be high enough to need to be examined for its impact on the power system and its components. The magnitudes of the 2^{nd} order current harmonic are sufficiently low that they would not interfere with the operation of differential relays that uses the 2^{nd} harmonic current to identify Inrush current.

It is to be noted that values of the K-factor, and hence the VAR demand, calculated using the ABB Universal GIC Magnetic Models differ significantly from, and are more accurate than, the default values of the K-factor stated in the TPL 007 – 01 Standard.



(a) Var Demand vs. GIC



(b) Current Harmonics vs. GIC

Figure 2: Calculated VAR demand and Current harmonics for the transformers at "Paradise"

GIC THERMAL FLEET ASSESSMENT

The GIC Thermal Fleet Assessment was performed for the 94 transformers, out of the 231 total 500 kV transformers, that were determined by the GIC Susceptibility study [3] to require thermal assessment. This thermal assessment included calculation of the hot spot temperatures of windings and structural parts of these transformers (Flitch-plates for Core Form

Transformers and the Tank walls for Shell Form Transformers) when subjected to the GIC signature calculated using the system modelling corresponding to the time series specified by the TPL 007 – 01 Standard. Again, the GIC data was provided by the TVA team and the temperature calculations were performed using ABB's Universal GIC Thermal models.

The Universal Thermal Models used for these thermal calculations include 8 different sets of models for each of the 8 different core types of power Transformers (5 core types for Core form transformers and 3 for Shell form transformers). Each of these sets includes models for calculating the Steady state temperature gradient and corresponding Time Constant of windings and structural parts as a function of the magnitude of GIC. Windings and structural parts hot spot temperatures have been calculated using these parameters. The data used for these calculations included those used for the magnetic assessment as well as values of mass of the windings, and measured values of temperature rises of top oil, windings hot spot, and flitch-plates hot spot for core form transformers (if available). This data was all available for transformers in the fleet that are ABB, or ABB Legacy, transformers. Corresponding data of the rest of these transformers were provided by the TVA project team.

A sample of the detailed results of the GIC Thermal Assessment is presented in Table 2; which includes the following information:

- Transformer Identification with its location as well as its rated MVA and voltage
- Calculated Highest magnitudes of GIC exposure for each transformer
- Calculated highest values of hot spot temperatures of both windings and structural parts caused by GIC.

Table 2: Sample of Results of Magnetic Assessment of the TVA 500 kV fleet

Transformer	Location	MVA	HV Rated, kV	GIC, A / Ph	Maximum Hot Spot Temperature, °C	
					Windings	Structural Parts
BUR1	Bull Run	448	500	37.9	100.6	113.3
BUR2					100.0	106.0
EP1	East Point	250	500	22.9	106.2	130.1
EP2						
EP3						
EP4						
M1	Maury	448	500	32.5	97.0	124.9
M2						
M3						
M4						

Figures 3 and 4 below present example calculations of hot spot temperatures of the flitch plates of the GSU single phase core form transformers at "Paradise" Generating station and the tank walls of the single phase shell form Auto transformers at "Weakley" substation, respectively; corresponding to the GIC signatures presented in Figures 1 (a) and (b) above.

Thermal calculations performed in this study confirmed the following:

1. The thermal impact of GIC on Windings of the TVA transformers is very small
2. No structural parts hot spot temperature of any of the transformers in the TVA fleet of transformers (core form or shell form) will exceed 140 °C when subjected to the GIC signatures corresponding to the Benchmark GMD storm specified by TPL 007 – 01. The highest values are 138.1°C for the Tank of the shell form transformers at Weakley and 130.1 °C for the flitch plates of the core form transformers at East Point. Corresponding values for the rest of the fleet are lower or significantly lower than these temperatures.

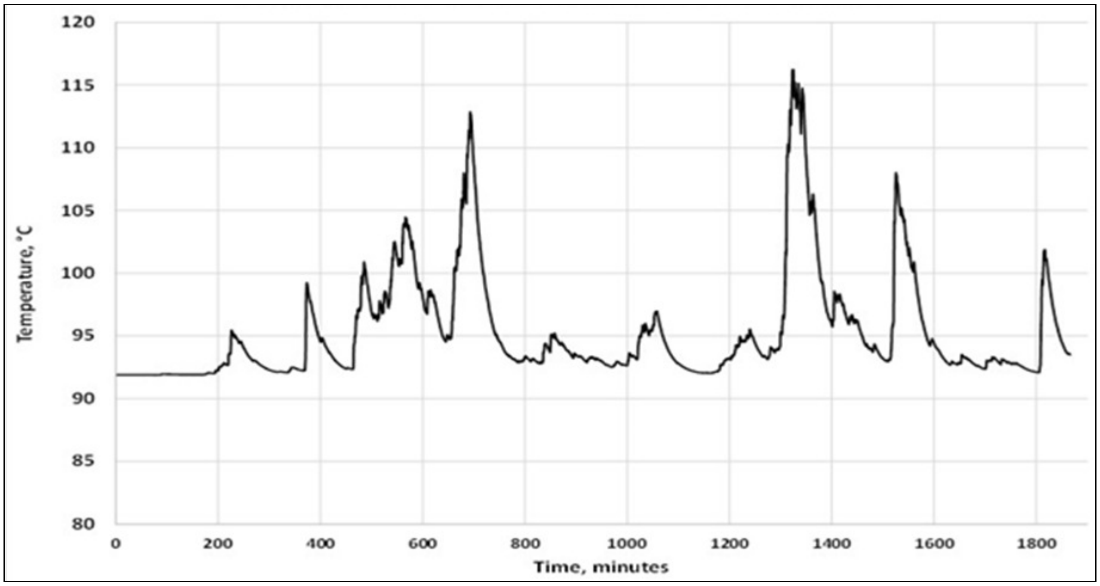


Figure 3: Calculated Flitch plate hot spot temperatures of transformers at "Paradise" Generating station corresponding to GIC Signature of Figure 1 (a)

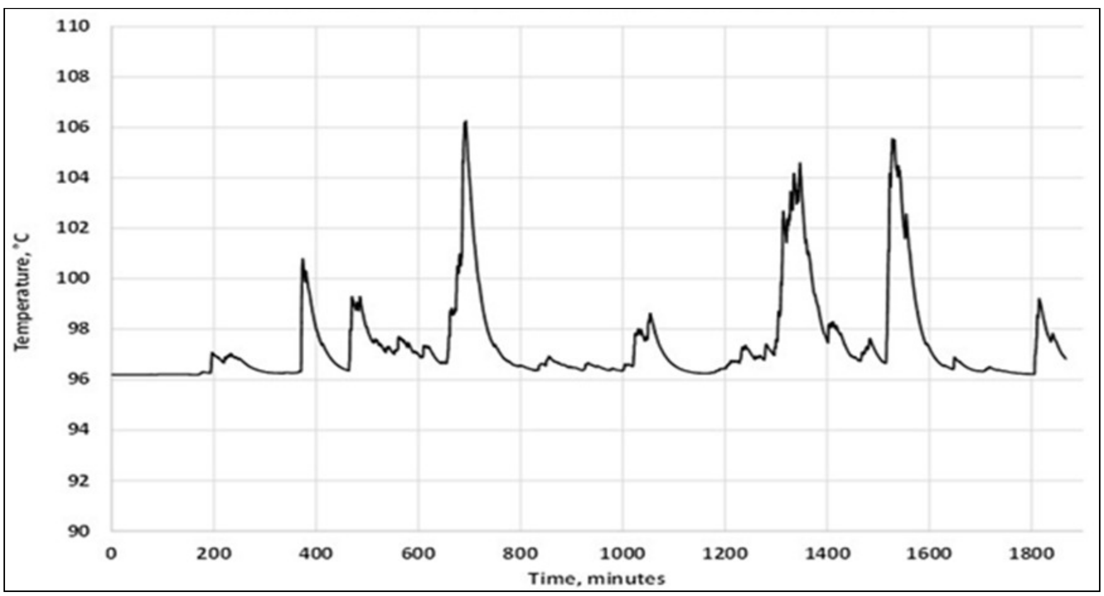


Figure 4: Calculated Tank wall hot spot temperatures of transformers at Weakley Substation corresponding to GIC Signature of Figure 1 (b)

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