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Assessment of the Impact of GMD on the TVA 500 kV Grid & Power Transformers
Part II: Magnetic & Thermal Capability of Paradise and Bull Run Transformers and Effects on System Performance

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SUMMARY

Part I of this paper described the development of a GIC model of the TVA 500 kV grid, which was used to show that for the TPL-007 benchmark electric field of 8V/km at the reference location TVA has no transformers which exceed the threshold of 75Adc/phase. However for higher fields up to 20V/km a small number of locations (four) would see GIC currents above the threshold. Therefore TVA decided to perform magnetic and thermal GIC assessments on three transformer designs. Those selected were the 500 kV GSU bank at Paradise and the 500 kV transformers at Bull Run (2 different designs).

Assessments found that the effect of GIC on these transformers is associated with significant increases in core loss and core noise but only a moderate increase in load losses. The GIC-caused high-peak short duration pulse of magnetizing current (3 per cycle for a 3 phase bank) causes VAR demands of 105 and 265 MVAR for the Paradise bank for field levels of 8V/ km and 20V/km respectively. Additionally, high current harmonics are injected into the power system.

The impact of the additional VAR demand on a TVA system wide basis is provided using the results of studies performed in Part I with the Paradise and Bull Run transformer evaluations. It was found that for the normal range of contingencies no instabilities for fields up to 20V/km should occur.

Studies indicate that these transformers can operate at full load even when exposed to a GMD event of 20V/km. The highest temperatures of the windings and tie plates of these designs are calculated to be 112 C and 155 C respectively, when subjected to a reference GIC waveform with pulses up to 200Adc/phase for a 4 minute duration.

KEYWORDS

Geomagnetic Disturbance (GMD), Geomagnetically Induced Currents (GIC), GMD Impact Assessment, GIC Capability, Harmonics, Reactive Power
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INTRODUCTION

The magnetic and thermal GIC assessments were performed by ABB using in-house models. The three transformer designs were all single phase core form. The units at Bull Run were a 1968 ASEA 400 MVA and a 2008 ABB 448 MVA, both 500/161/13.2 kV, while the GSU at Paradise was a 1969 GE 470 MVA 500/22.5 kV. Calculated performance for all 3 designs was found to be similar, so results presented in this paper are typical and differentiate only in Table 3 unless otherwise noted.

Calculations of performance were made for magnitudes of GIC of 20 and 100 Adc/phase in the HV winding. The values are selected to represent the levels of base GIC and short duration GIC pulses that transformers might be subjected to in a strong GMD storm.

The thermal response of windings and structural parts was calculated for a GIC profile of 100 & 200 Adc/phase for the GIC pulses and 20 & 40 Adc/phase for the base GIC respectively [1].

IMPACT OF GIC ON POWER TRANSFORMER PERFORMANCE PARAMETERS

Core Flux Density

Table 1 presents the calculated dc flux density shift in the core as well as the resulting peak core flux density for magnitudes of GIC of 20 and 100 Adc/phase. Because of the strong nonlinear characteristic of the core material, the flux density shift is only slightly higher for the 100 Adc/phase. The saturation level of the highly grain oriented steel used in this core is 2.05 Tesla.

GIC , Adc/phase	ΔB_{dc}, Tesla	$B_{m\,(dc+ac)}$, Tesla
20	0.363	2.025
100	0.437	2.091

Table 1: Calculated Core flux density shift & Peak for two different levels of GIC

Magnetizing Current

Figure 1 shows the calculated magnitude and wave shape of the magnetizing current pulse that results from GIC levels of 20 and 100 Adc/phase Since the duration of this pulse is only 1/10th to 1/12th of the cycle, these currents produce only low levels of increases in load losses and hot spot temperatures.

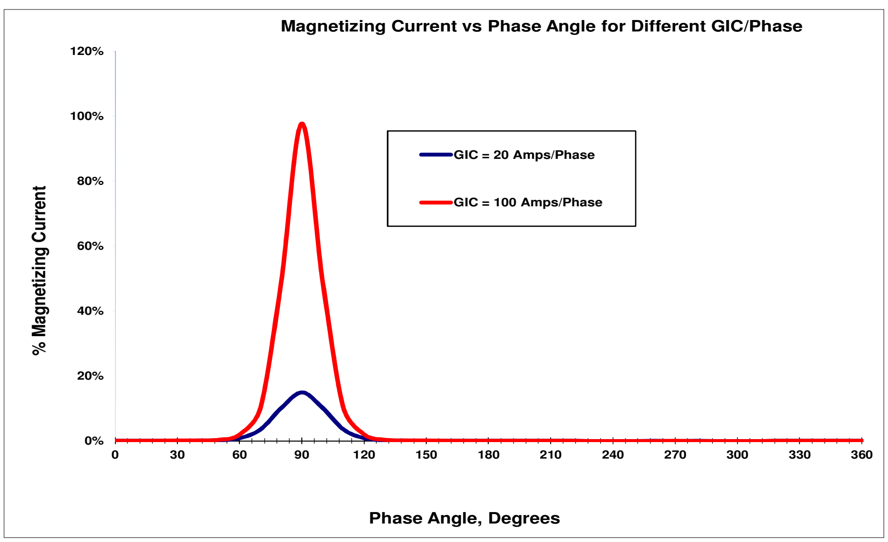

Figure 1: Magnetizing Current pulse in % of rated load current

Core losses and Core Noise Level

Core losses and core noise level both experience increases that are higher for higher magnitudes of GIC. However the increases in the core losses, although significant, would not increase the core hot spot temperature significantly. The increase in the noise level of the transformer would be observed only during the period when the GIC current is flowing through the neutral of the transformer and the accompanying increase in core vibrations is mainly higher frequency components so tank vibrations will not be as damaging.

Load Loss And Its Components

The higher magnetization current and its wave shape produce higher magnitudes of leakage flux that are rich in harmonics. This results in higher eddy and circulating current losses in the windings and the structural parts of the transformer. Table 2 shows calculated values of load loss increases.

GIC, Adc/phase	Winding Ohmic Losses	Winding Eddy Current Losses	Total Winding Losses	Structural Parts Losses	Total Load Losses
20	**0.1**	**0.7**	**0.2**	**0.1**	**0.2**
100	**2.1**	**36.3**	**7.8**	**4.9**	**7.1**

Table 2 – Calculated % increases of Total Load losses and Loss components

Windings and Structural Parts Hot Spot Temperatures

Temperatures of the tie plate hot spots are calculated when the transformer is fully loaded and subjected to 20 Adc/phase for 60 minutes (representing base GIC) and 100 Adc/phase GIC for 5 minutes (representing short duration pulses). Results show that the tie plates hot spot temperature at full load in the absence of GIC is 104.7 C. After 60 minutes of exposure to 20 Adc/phase, the temperature increase is only 4.9 K; correspondingly, after 5 minutes of 100 Adc/phase, the hot spot temperature increase is 14.4 K. Corresponding temperature increases for the windings are 1.0 K and 0.8 K; respectively. These temperatures are far below recommended temperatures for short and long periods of overload.

PEAK MAGNETIZING CURRENT, VAR DEMAND AND CURRENT HARMONICS ASSOCIATED WITH GIC

Peak Magnetizing current

Figure 2 demonstrates the magnetizing current pulse magnitude as a result of GIC. High magnitudes of this pulse current can have damaging effects on the capacitive components of the power system.

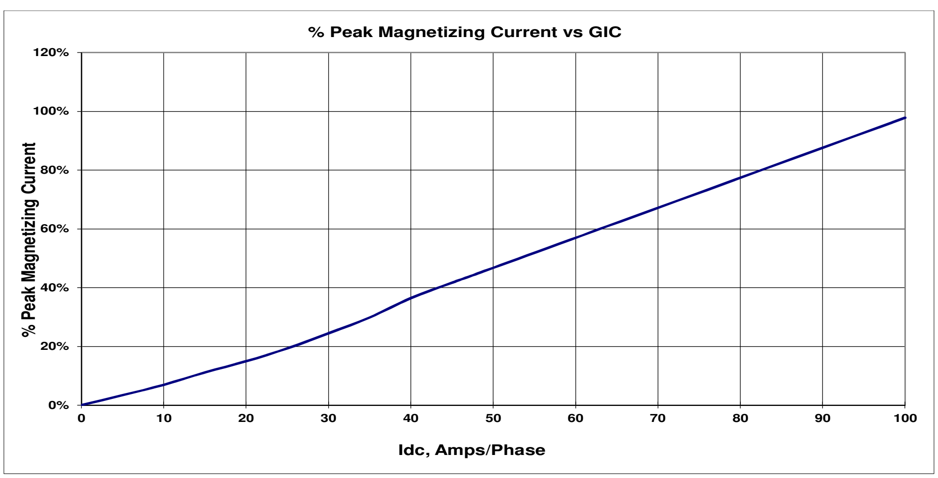

Figure 2: Peak of Magnetizing Current in % of rated current versus Level of GIC

Harmonic Content of the Magnetizing Current

The pulse wave-shape of the magnetizing current due to GIC events corresponds to a large content of higher order harmonic currents; both odd and even. These harmonics may cause electrical resonances in different parts of the Power System, leading to Power Quality problems, voltage dips, and voltage instability. Figure 3 shows calculated harmonic content of the magnetizing current for a range of GIC levels up to 100 Adc/phase.

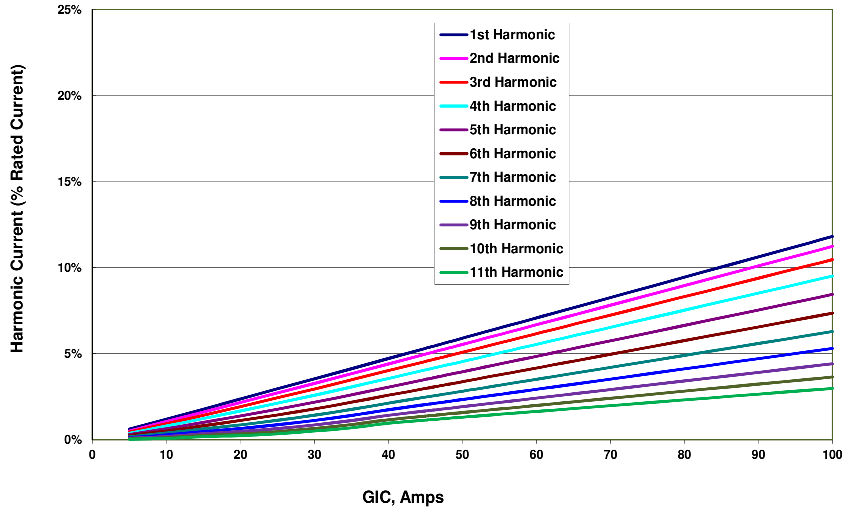

Figure 3: Amplitude of magnetizing current Harmonics versus level of GIC

The figure shows significant content of higher order harmonics, and also that magnitudes do not decrease significantly for higher order harmonics. This is due to the short duration of the magnetizing current pulse.

Additional VAR Demand

Figure 4 presents the calculated MVARs drawn by the transformer when subjected to different magnitudes of GIC. At 63.6 Adc/phase which is the calculated GIC level corresponding to the 8 V / km benchmark, the MVAR demand on the Unit 3 Bank at Paradise is calculated to be 106 MVAR for the 3 phase bank. This compares to a value of 72 MVAR calculated using PowerWorld which is based on a simplified generic calculation used for all single phase transformers irrespective of their core construction. The core construction of this transformer design is a 4 limb core type. At 20 V/km, the corresponding GIC level increases by a factor of 2.5 to 159 Adc/phase and a demand of 265 MVAR.

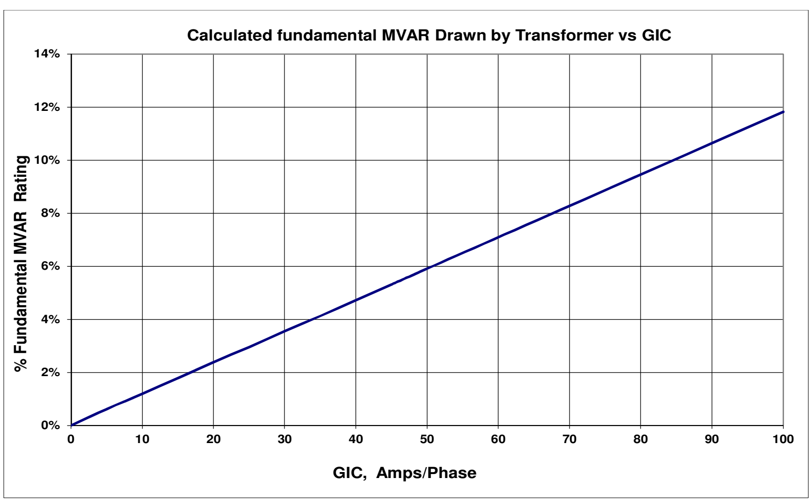

Figure 4: Additional MVAR demand by Transformer in % of Rated MVA

Evaluation of Effects of Additional VAR Demand

To evaluate the impact of the increased VAR demands on a system wide basis, the VAR results from the PowerWorld GIC analysis in Part I were adjusted to reflect the higher 4-limb core results in the Paradise and Bull Run transformers as the majority of TVA's 500-kV transformers utilize 4-limb core construction. Additional VAR demand totaled 1,004 MVARs for the benchmark event of 8 V/km and 2,541 MVARs for the extreme 20 V/km event.

PSS/E was used to perform a steady state analysis. The complete TVA system model was used and not just the > 200kV facilities. VAR demand in neighbouring utility transformers was not modelled. Increased reactive losses less than one MVAR were ignored. Studies were performed for near term normal peak and off-peak load cases as well as the same single contingency analysis that would be performed in typical planning studies. GIC currents were not recalculated for the contingency configurations.

Near term peak and off-peak load cases were used in accordance with the NERC guideline. Appropriate contingency conditions, such as loss of reactive support devices, were studied. In accordance with NERC's GMD Planning Guide [3], study outputs were reviewed for violation of TVA operational voltage limits, potential voltage collapse, and cascading outages during normal system configuration as well as various contingencies such as shunt capacitor bank or static VAR compensator (SVC) outages.

The load flow analysis did not identify any violations of TVA's planning criteria for either the benchmark 8 V/km geo-electric field or the increased field of 20 V/km. The TVA system proved sufficiently robust to handle the increased VAR demand, and no voltage or capacity issues resulted from the increased VARs.

GIC THERMAL CAPABILITY OF THIS TRANSFORMER DESIGN

Definition of GIC Capability

As presented in Reference 2, the GIC capability of a transformer design is the loading of the transformer that would be recommended when the transformer is subjected to different levels of GIC current. The limiting factor is the maximum allowed temperatures of the windings and tie-plates hot spots. For base GIC, the temperature limits, as recommended by the IEEE Loading Guide (C57.91) for long duration (>30minutes) overloading of transformers has been used. Correspondingly, the limits recommended by the same Standards for short duration emergency (< 30 minutes) overloading are used for the high peak GIC pulses.

Calculated GIC Thermal Capability

Figure 5 presents the corresponding Thermal Capability curves for this transformer design. The figure shows that no reduction of load would be needed up to a base GIC level of about 128 Adc/phase and a peak GIC level over 790 Adc/phase. Corresponding calculations for windings show that no reduction of load would be needed up to a base level of about 540 Adc/phase and a peak level over 1050 Adc/phase. The thermal capability of the transformer is higher for the GIC pulse than for the base GIC because of its shorter duration. These GIC capability curves correspond to limiting the rate of loss of life of the solid insulation used in the transformer as well as preventing gas bubbles in the oil. The corresponding ability of the transformer to resist thermal failure under GIC conditions would be much higher than presented in the figure.

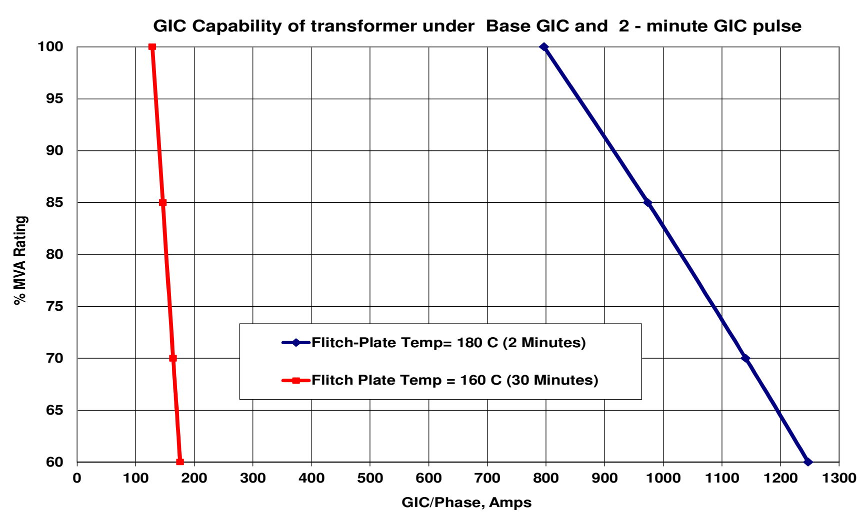

Figure 5: GIC Thermal Capability of Transformer Considering the Structural Parts

THERMAL RESPONSE OF THE TRANSFORMER DESIGN TO GIC SIGNATURE

Calculations were made of the thermal response of the windings and tie-plates of this transformer design to the GIC signature shown in Figure 6 (Per Ref 1).

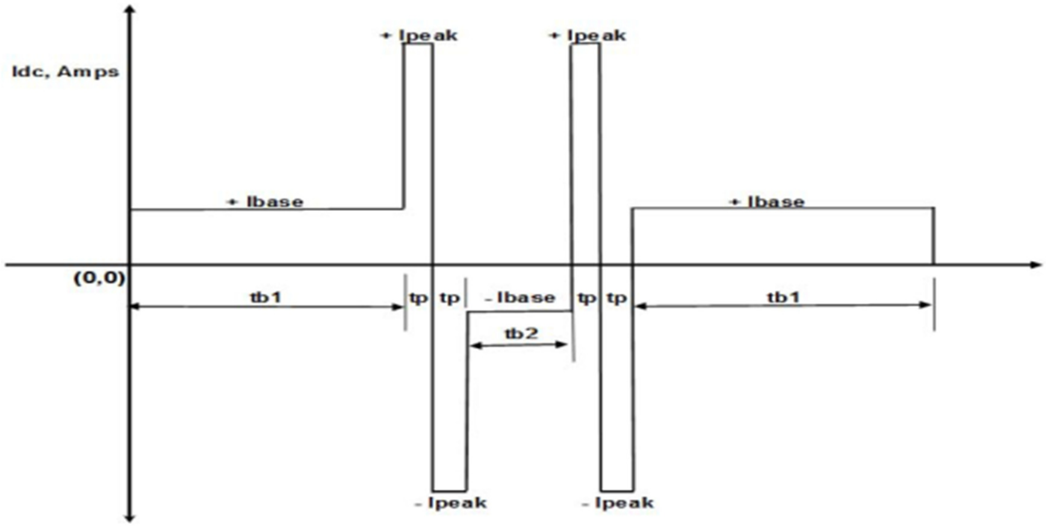

Figure 6: GIC Signature

The thermal calculations were performed for the following set of parameters of this signature:

I_{peak} = 200 Adc/phase, I b_{ase} = 40 Adc/phase

t_p = 2 minutes, t_{b1} = 60 minutes, and t_{b2} = 10 minutes

The calculated thermal response of the transformer windings and tie-plates for this GIC Signature is shown in Figure 7.

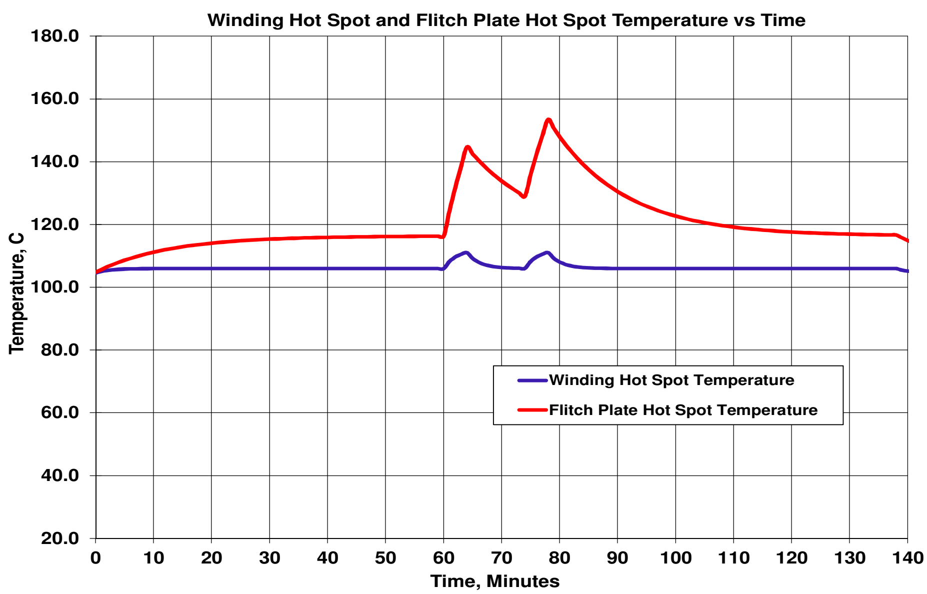

Figure 7: Thermal Response of Transformer Design to Proposed GIC Signature

The figures show that the maximum hot spot temperatures of this transformer design are 111 C for the windings and 154 C for the tie plates when subjected to two successive GIC Pulses of 200 Adc/phase and 4 minutes duration. These temperatures are experienced for a few minutes and are much lower than allowed by Industry Standards even for longer emergency overload.

SUMMARY

Table 3 below presents a summary of the different quantities calculated for the three different designs at Paradise and Bull Run as related to GIC.

<table>
<tr><th rowspan="2">GIC</th><th rowspan="2" colspan="2">Parameter</th><th colspan="2">Bull Run</th><th>Paradise</th></tr>
<tr><th>Design # 1
448 MVA</th><th>Design # 2
400 MVA</th><th>Design # 3
470.4 MVA</th></tr>
<tr><td rowspan="4">100 Adc/phase</td><td colspan="2">% VAR</td><td>12.3</td><td>13.9</td><td>11.8</td></tr>
<tr><td colspan="2">VAR Demand of Bank</td><td>165.3</td><td>166.8</td><td>166.8</td></tr>
<tr><td colspan="2">% 2nd Harmonic</td><td>12.0</td><td>13.4</td><td>11.5</td></tr>
<tr><td colspan="2">% 3rd Harmonic</td><td>11.0</td><td>12.6</td><td>10.7</td></tr>
<tr><td rowspan="2">20 Adc/phase</td><td rowspan="4">Increase in Temperature</td><td>Winding</td><td>1.2</td><td>0.8</td><td>1.0</td></tr>
<tr><td>Tie Plates</td><td>8.0</td><td>8.4</td><td>4.9</td></tr>
<tr><td rowspan="2">100 Adc/phase</td><td>Winding</td><td>0.9</td><td>1.0</td><td>0.8</td></tr>
<tr><td>Tie Plates</td><td>25.0</td><td>26.4</td><td>14.4</td></tr>
<tr><td rowspan="2">Limit GIC at Full Load, Adc/phase</td><td>Base GIC</td><td rowspan="2">Tie Plates</td><td>130</td><td>137</td><td>128</td></tr>
<tr><td>Pulse GIC</td><td>1150</td><td>1142</td><td>796</td></tr>
<tr><td rowspan="2">40 Adc/phase base GIC & 200 Adc/phase Pulse GIC</td><td rowspan="2">Final Hot Spot Temperature, C</td><td>Winding</td><td>112</td><td>107</td><td>111</td></tr>
<tr><td>Tie Plates</td><td>155</td><td>138</td><td>154</td></tr>
</table>

Table 3: Summary of Impact of GIC on TVA's 3 transformer designs

CONCLUSIONS

Detailed magnetic and thermal assessments of 3 designs of single phase large power transformers were performed and results of these assessments are presented in this Part – II of the paper. The magnetic modelling included calculations of the increase in core losses, load losses, core noise, the additional VAR, and resulting current harmonics. The thermal modelling included calculations of hot spot temperatures of windings and flitch plates corresponding to a GIC profile that has GIC pulses of 200 Amps / phase for a 2 minute duration and 40 Amps / phase for up to 60 minutes duration.

As a result of above calculations, it was confirmed that the increased VAR demand corresponding to a Geo-magnetic electric field of 20 V / km will not cause instability in the TVA. Also, temperature limits for windings and structural parts hot spot temperatures will not be exceeded when the transformers are operating at full load and subjected to GIC levels of as high as 200 Amps / phase for 2 minutes or 40 Amps / phase for 40 minutes. Yet to be performed are detailed studies of the impact of the resulting current harmonics on the grid.

BIBLIOGRAPHY

[1] "IEEE Guide for Establishing Power Transformer Capability while under Geomagnetic Disturbances", IEEE Std. C57.163™-2015.

[2] Ramsis Girgis and Kiran Vedante: "Methodology for Evaluating the Impact of GIC and GIC Capability of Power Transformer Designs", Presented at the IEEE PES Conference, July 2013, Vancouver, BC, Canada.

[3] NERC, "Application Guide--Computing Geomagnetically-Induced Current in the Bulk-Power System" December 2013