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Effect of GIC and GIC Capability of EHV Power Transformers – A Case Study on an AEP 765 kV Power Transformer Design

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The Federal Energy Regulatory Commission (FERC) issued a final ruling to direct NERC to develop reliability standards that address the impact of geomagnetic disturbances (GMD) to ensure continued reliable operation of the nation's Bulk-Power System. Those standards will require owners and operators to conduct initial and continuing assessments of the potential effects of specified "benchmark GMD events" on equipment, especially EHV transformers, as well as the Bulk-Power System as a whole. The work presented here is an important part of AEP's GMD impact assessment efforts to address the potential to negatively impact the reliable operation of AEP transmission systems. The paper presents results of calculations performed to quantify the impact of different levels of GIC on a large EHV power transformer design in the AEP Transmission Grid – a 750 MVA, 765/345/35.5 KV, 1-phase, auto-transformer. The evaluation included:

(a) Impact of GIC on additional VAR demand and magnitudes of current harmonics injected into the transmission system as a result of part-cycle core semi-saturation. These evaluations provide needed information to perform further system simulations and voltage stability analyses. The results of these studies help develop/refine GMD operating procedures with predetermined triggers for initiating mitigation actions.

(b) Impact of GIC on performance parameters of the transformer and the resulting hot spot temperatures of the windings and structural parts.

(c) Determining the GIC capability of the transformer design

The paper demonstrates that the effect of GIC on transformers is associated with:

- Significant increases in core loss, core noise, and load loss.
- High-peak, short duration pulse of magnetizing current, one per cycle, could potentially inject high current harmonics into the power system, to which the transformer is connected, and generate a significant VAR demand during a severe GMD storm.

The GIC capability curves confirm that transformers of this design can be subjected to GIC levels of as much as 155 A/phase for a duration of 30-minutes without the need for reducing their load while limiting the rate of loss of life of insulation to less than 1% and at the same time reducing the risk of forming gas bubbles in the oil.

Finally, it is recommended that this type of comprehensive evaluations is performed for individual designs of transformers determined to be critical to the Transmission system and located in areas of high susceptibility for high levels of GIC.

KEYWORDS
Geomagnetic Disturbance (GMD), Geomagnetically Induced Currents (GIC), GMD Impact Assessment, GIC Effect, GIC Capability, Transformer Hot Spots, Harmonics, Relays, Reactive Power

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Introduction

The Federal Energy Regulatory Commission (FERC) issued a final ruling [1] to direct NERC to develop reliability standards that address the impact of geomagnetic disturbances (GMD) to ensure continued reliable operation of the nation's Bulk-Power System. Those standards will require owners and operators to conduct initial and continuing assessments of the potential effects [2] of specified "benchmark GMD events" on equipment, especially EHV transformers, and the Bulk-Power System as a whole.

In order to mitigate the risks of severe solar storms and operate its grid through such events, AEP is implementing a GMD monitoring system [3] to detect and evaluate GMD impacts on its system and critical transformers as well as to provide assistance to Transmission Operators to protect transformers and to prevent system blackout. AEP is also collaborating with NERC, EPRI, power system analysis software vendors and transformer vendors to develop a GIC simulation model [4] and to conduct equipment vulnerability assessment. AEP has been working with transformer vendors to evaluate both the GIC impact and the GIC capability of AEP EHV transformers. These studies are an important part of AEP's 3-M (Monitoring, Modeling and Mitigating) GMD risk-mitigation plan [5]. The understanding developed in the assessment and simulations should improve bulk-power system reliability by shortening customer interruptions as well as minimizing the risks of equipment damage.

The effect of GIC on a transformer depends on the transformer design, including core type, as well as the magnitude and duration of the GIC pulse. This effect includes a unidirectional core flux density shift, a short duration high peak magnetizing current pulse one per cycle, increased core and load losses, higher core noise, and higher temperatures of windings and structural parts [6]. The evaluation of the GIC effect on a transformer design is to calculate the following performance parameters for a range of GIC levels to which the transformers of that design would be subjected:

1. Magnitude and wave-shape of the resulting magnetizing current pulse, and the associated additional VAR demand and harmonics
2. The increase in core losses, load losses, and core noise level
3. The increase in the hot spot temperatures of windings and structural parts

AEP has been working with transformer vendors to evaluate the GIC impacts on selected in-service and new EHV transformers. These studies provide necessary technical support in developing/refining GMD operating procedures and GMD mitigation plans. The results of these studies, such as reactive power demands, and current harmonics, due to GIC flow will be incorporated into AEP's GIC system impact studies such as voltage stability and protection & control impact studies. The GIC capability study will estimate the combinations of load current and magnitude of GIC that the transformer would operate at without exceeding loss of life of the transformer insulation beyond what is allowed by Industry Standards. This corresponds to what winding and structural parts hot spot temperatures would be allowed for the different durations of the GIC pulses [7]. AEP's objective of requesting transformer manufacturers to determine the GIC capability of representative EHV transformers is to identify potential transformer vulnerabilities.

GIC Profile for the Evaluation of the GIC Capability of Power transformers

In the Specifications of the design and performance requirements of new EHV 765 kV single phase transformers, AEP requires transformer manufacturers to show, by calculations, that when the transformer is subjected to a GIC profile of six 5-minute on/5-minute off cycles of 120 A/phase DC in the common and series windings, the transformer would not exceed the dissolved gas values listed in the AEP Specification. These GIC levels correspond to geomagnetic electric field strength in the range of 4 ~ 5 V/km. For the GIC Capability evaluation of 765 kV transformers, AEP specifies that the magnitudes of GIC used are 50, 100, and 200 A/phase for a 5-minute duration.

Impact of GIC on a 750 MVA, 765/345/35.5 KV, 1-phase, Auto-transformer Design

Impact on Core Flux Density

GIC flow in a transformer will cause core flux density shift. As shown in Table 1, the transformer experiences higher unidirectional flux density shift initially when GIC starts to flow in the transformer; when the peak flux density gets into the pre-saturation region of the core material, the shift increases in much lower increments. The calculations on this in-service 765 kV bank shows that the peak flux densities for GIC levels ≤ 30 A/phase are below the saturation level of the highly grain oriented steel used in this core.

Table 1: Effect of GIC on core flux density for the 765 KV 1-phase transformer design

GIC Amps/Phase	ΔB_{dc} Tesla	$Bm_{(dc + ac)}$ Tesla
15	0.323	2.023
20	0.334	2.034
30	0.348	2.048
40	0.359	2.059
50	0.367	2.067
100	0.391	2.091
200	0.415	2.115

Resulting Harmonic Content of the Magnetizing Current

The nature of the magnetizing current pulse resulting from above high flux densities in the core; when subjected to high levels of GIC, corresponds to a significant content of a large number of even and odd order harmonic currents. The harmonic content of the magnetizing current in % of the rated current for this transformer design is presented in Figure 1 below. As shown in the figure, the higher the level of GIC, the greater the magnitude of these harmonics. This is, obviously, caused by the higher magnetizing current for higher GIC levels. For example, for the 50 amps GIC, the 2nd harmonic is about 5.2 % of the rated load current and is about twice of that for a 25 amps GIC.

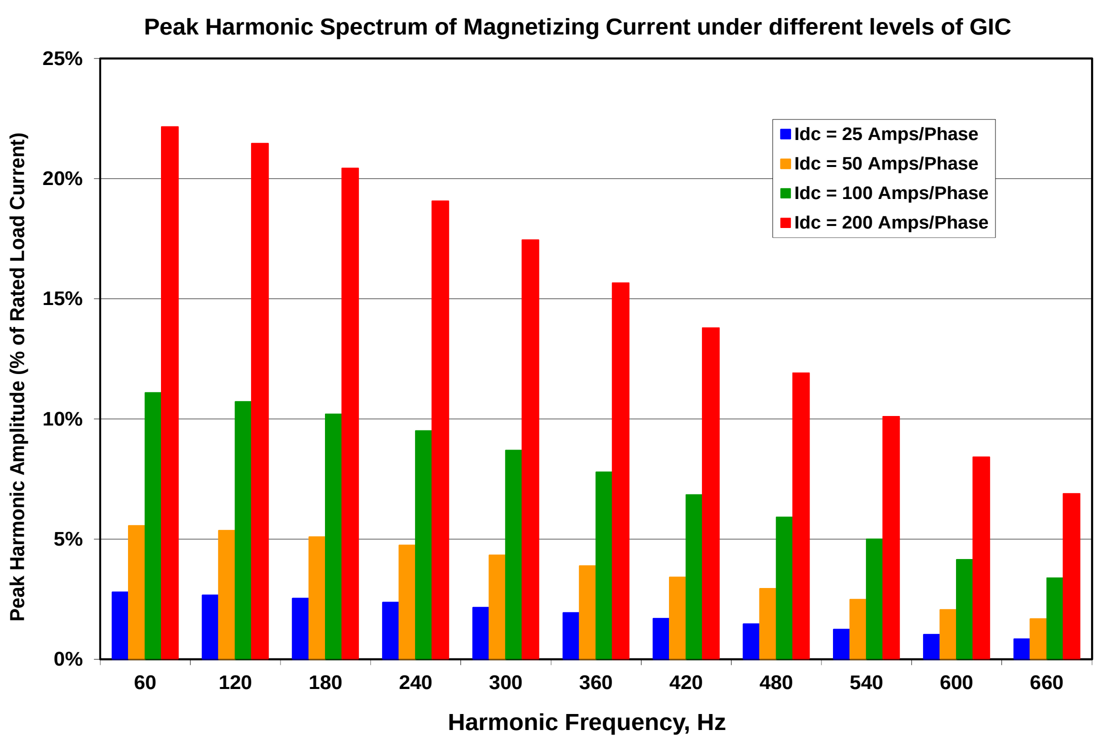


Figure 1: Peak of harmonics of magnetizing current when Transformer is subjected to GIC

Impact of GIC on Transformer Reactive Power Demand

Figure 2 below presents the RMS fundamental inductive VARs drawn by the transformer when subjected to different magnitudes of GIC. The VAR consumption is higher for higher levels of GIC. The additional reactive power consumption is calculated to be 4% of the rated MVA of the transformer for a 50 A/Phase GIC, which is equivalent to 30 MVar for a 750 MVA transformer**.** It is 4 times this value for a 4 times GIC of 200 amps/phase. The simultaneously increased reactive power demands in many transformers due to GIC flow may cause wide area voltage control problems, and may lead to system voltage collapse if a severe GMD event occurs and the additional VAR demand is not planned for or if VAR resources are exhausted.

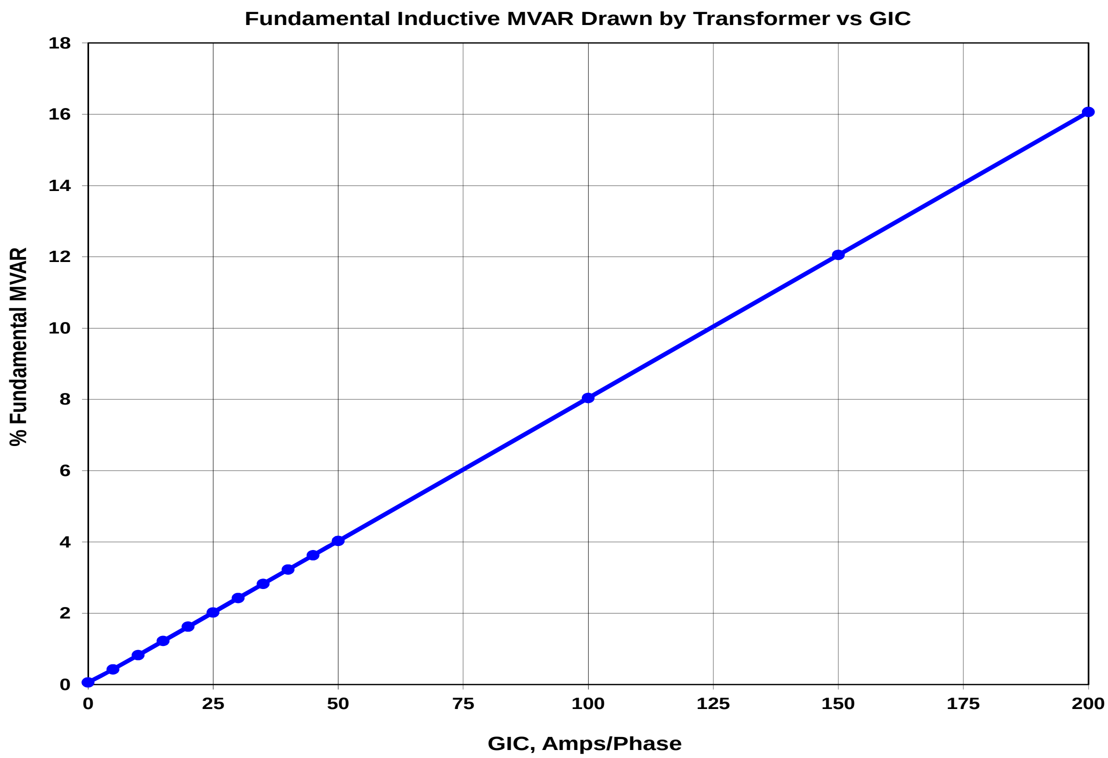


Figure 2: RMS of fundamental MVar drawn by Transformer, in % of Rated MVA

Increases of Core Loss and Core Noise

As a result of the unidirectional flux density shift in the core, both core losses and core noise experience significant increases in magnitude. In Table 2 below, calculated values of these increases are given for GIC levels from 15 – 200 A/Phase. The increase in the core noise level is typically very noticeable on site but is temporary and continues only through the GMD event. The small duration of the high peaks of GIC compared to the time-constant of the core material and to that of oil correspondingly produces small increases in the core temperatures.

Table 2: Calculated Increases of Core Loss & Core Noise

GIC (A/Phase)	Core Loss Increase	Core Noise level Increase (dB)
15	29.0%	29.6
20	31.5%	31.2
30	35.3%	33.7
40	38.1%	35.4
50	40.4%	36.9
100	48.2%	41.6
200	56.9%	46.7

Increases in Load losses

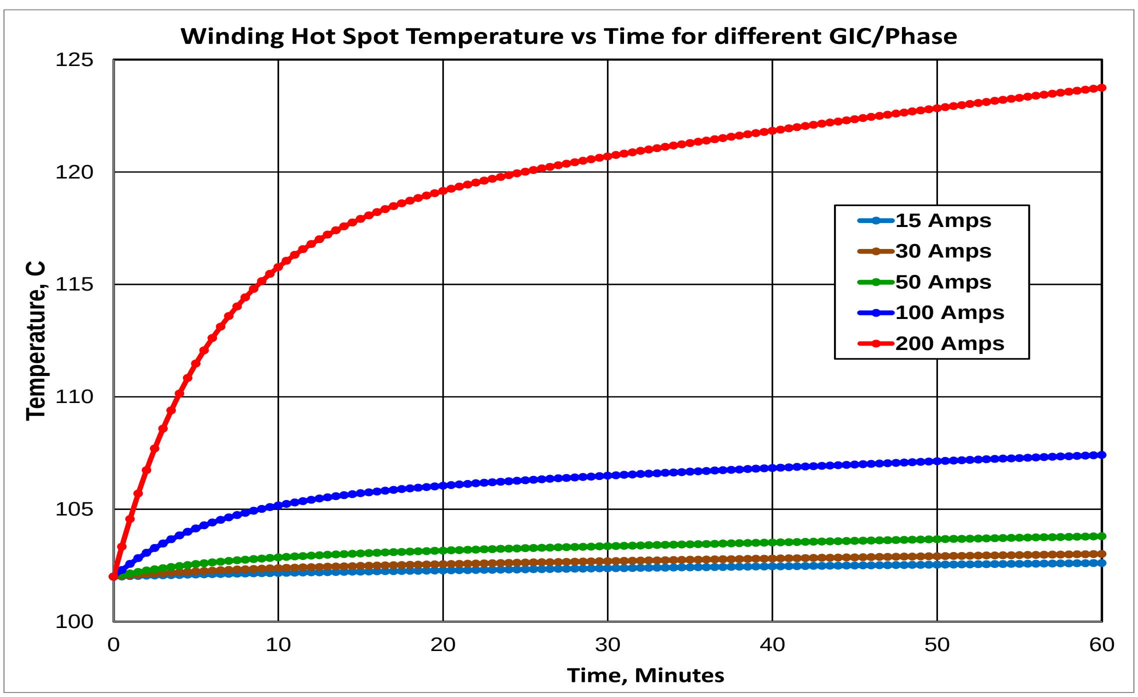
The much higher magnetization current, and the nature of its wave-shape, produce higher magnitudes of leakage flux that is also rich in harmonics. This results in higher eddy and circulating current losses in the windings as well as in the structural parts of the transformer causing an increase in load losses and hot spot temperatures. Table 3 below shows the calculated increases in the values of load loss components and total load losses for a wide range of GIC levels. The higher increases in the eddy losses in the windings results in a small increase in the total load losses as the magnitude of the winding eddy losses at rated power is a small fraction of its total load loss (about 10%).

Table 3: Calculated Increases of Load Loss Components for different levels of GIC

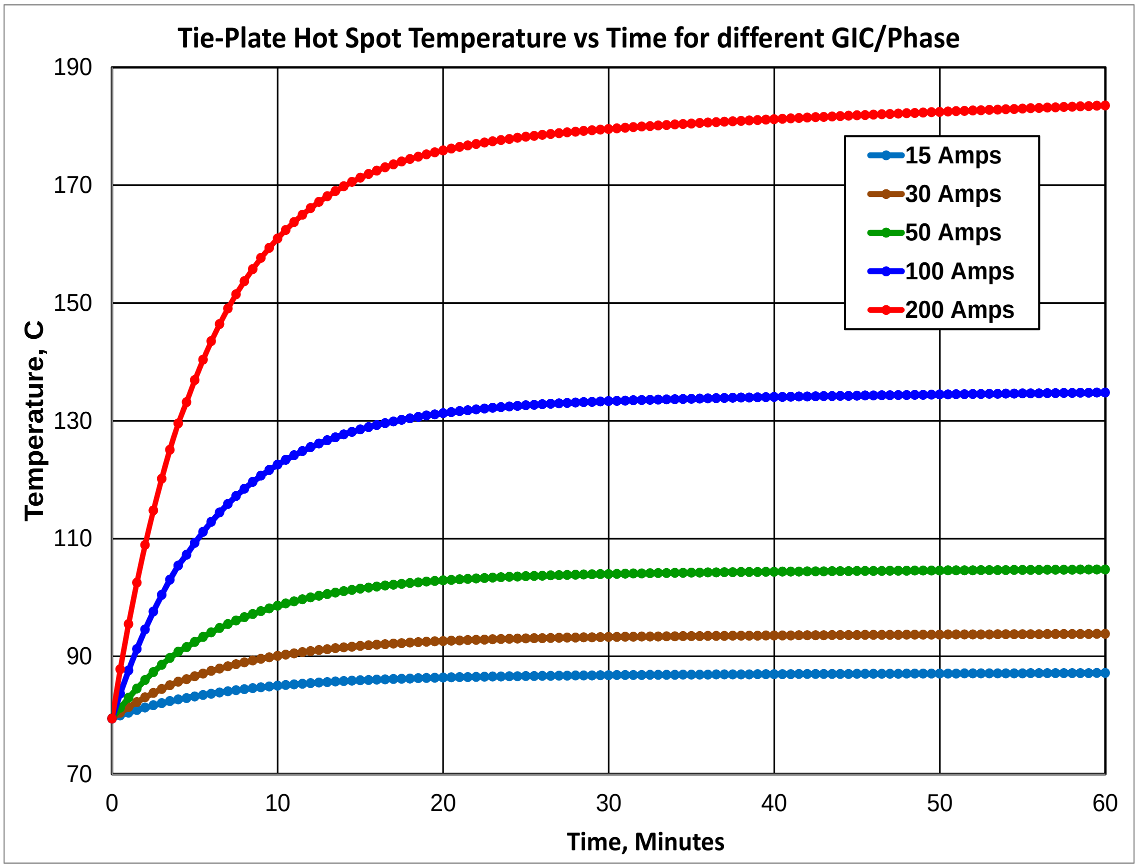
GIC (A/Ph)	Loss Increase In Windings			Loss Increase in Structural Parts	Increase in Total Load Losses
	Ohmic	Eddy Current	Windings		
15	0.05%	0.9 %	0.2%	0.1%	0.2%
20	0.1%	1.6%	0.4%	0.2%	0.33%
30	0.2%	3.7%	0.8%	0.5%	0.76%
40	0.3%	6.6%	1.4%	0.8%	1.35%
50	0.5%	10.3%	2.2%	1.4%	2.13%
100	2.1%	41.7%	9.1%	5.3%	8.55%
200	8.4%	169.5%	36.7%	21.4%	34.7%

Effect on Windings and structural parts Hot Spot Temperatures

In Figure 3 below, calculated temperatures of the windings and structural parts hot spots of this transformer design are presented vs. time when the transformer is fully loaded and subjected to 5 different levels of GIC currents for a 60-minute period. As the figure shows, the winding hot spot temperature of this transformer is 102°C at full load in the absence of GIC. The increase in the winding hot spot temperature, even for a 200 A/phase GIC, is only about 22°K. However, for the tie plates, after 5 minutes GIC duration, the hot spot temperature increase 12°K for the 50 amps GIC, 30 °K for the 100 amps, and 60 °K for the 200 A/Phase GIC. The final temperatures, even for the 200 A/Phase GIC, after 5 minutes, are far below (137°C) the 180°C recommended by industry standards for short period (15 ~ 30 minutes) emergency overload.



(a) Windings



(b) Tie-plate

Figure 3: Calculated Hot Spot Temperatures for Different Magnitudes of GIC

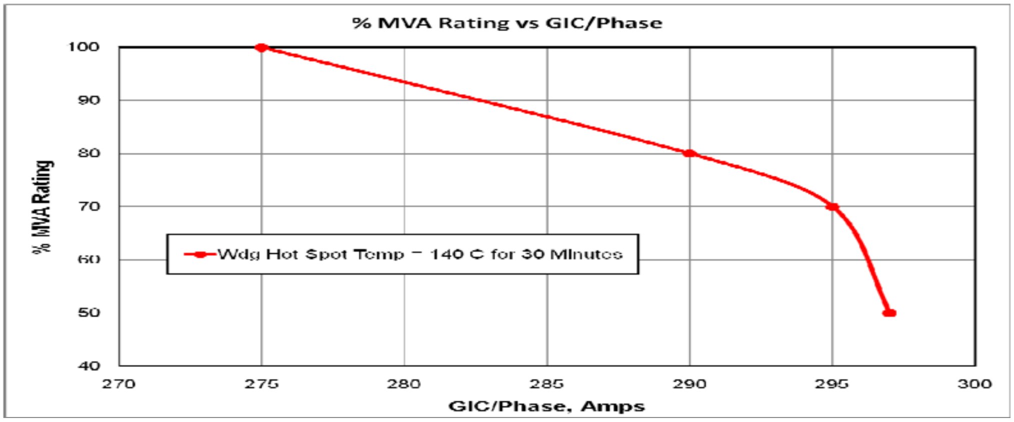
GIC Capability of the 765 KV, 1-Phase Transformer Design

The GIC capability of a transformer design is defined as the % of rated MVA of the transformer that would be allowed when the transformer is subjected to different levels of GIC current. The temperature limits recommended by the Industry Standards for long term overloading of transformers are 140ºC for cellulose insulation and 160 ºC for metallic parts not in contact with cellulose insulation. Correspondingly, the temperature limits recommended by the same Standards for emergency short-term overloading are used for the high peak short-duration GIC pulses. These are 180ºC and 200ºC, respectively. The purpose of these temperature limits is to:

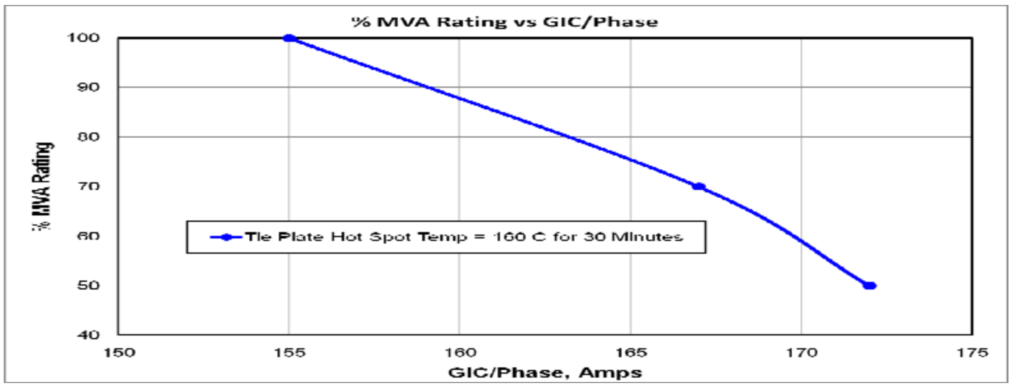
1. Limit the rate of loss of life of the solid insulation to a minimum of about 1%,
2. Preventing gas bubbles in the oil

Much higher temperature limits could be used if the attempt is to calculate the GIC capability of the transformer to prevent failure under GIC conditions.

Figures 4(a) & (b) below present the GIC capability of this transformer design based on the IEEE standard limits on temperatures of the windings and tie-plate hot spot for longer duration GIC. The figures show that, for this AEP transformer design, no reduction of load would be needed for a GIC level of up to 275 A/Phase for 30 minutes continuous when considering windings hot spot limit and 155 A/Phase considering the structural parts hot spot temperatures. Because of the low levels of temperature increases in the windings of this design, the load capability of the transformer would not be limited by overheating of the windings. Figure 4 (a) shows that, beyond a certain level of GIC, the losses in the windings are the dominant component and hence the load applied to the transformer does not affect the temperature of the windings much.



(a) Windings



(b) Tie-plate

Figure 4: Calculated GIC Capability of 765 KV Transformer for 30-minute Continuous GIC

Conclusion and Future Studies

The paper demonstrates that the effect of GIC on transformers is associated with:

- Significant increases in core loss, core noise, and load loss.
- High-peak, short duration pulse of magnetizing current, one per cycle, could potentially inject high current harmonics into the power system and generate a significant VAR demand during a severe GMD storm.

The GIC capability curves confirm that transformers of this design can be subjected up to 155 amps/phase of GIC for a duration of 30-minute without the need for reducing their load while limiting the rate of insulation loss of life to less than 1% and at the same time reducing the risk of forming gas bubbles in the oil.

In addition to the GIC effect and GIC capability studies on the 765kV transformer, it is recommended that this type of comprehensive evaluations is performed for individual designs of transformers determined to be critical to the transmission system and located in areas of high risk for high levels of GIC. Another area of interest for further studies and collaborations is to validate the calculations based on the measurements from fiber temperature probes at the winding and tie-plate hot spots, as well as the reactive power loss measurements during a storm.

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