LABORATORY TEST FOR GIC EFFECTS ON POWER TRANSFORMERS

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Abstract: Geomagnetic storms lead to large fluctuations of the earth magnetic fields which create the Earth Surface Potential (ESP) inducing quasi-DC currents in electric power systems through the grounded neutral of power transformers. These current are commonly referred to as Geomagnetically Induced Currents (GICs). History has proven that the effect of GIC's on power systems could be very disruptive, damaging and costly. When GIC is present in a transformer, the magnetic circuit is essentially distorted or skewed by the quasi-DC bias. Hence, the transformer operates more in its region of non linearity leading to half wave saturation. The laboratory test showed the following: a 22.5 mA impressed DC current on the neutral of the 4.5 KVA transformer distorted the High voltage on secondary side of the transformer and lead to half wave saturation of the core, local hot spots were detected on the transformer and the vibration on the transformer increased by a factor of two (2) during the zero crossing of the positive wave form. When the transformer was exposed to GIC for about 30 minutes, a very loud audible noise was heard, the transformer was destroyed and all the currents, voltages, noise and power waveforms were permanently distorted.

1 INTRODUCTION

Geomagnetically Induced Currents (GICs) are the result of changing geo-magnetic field which is a consequence of a geomagnetic disturbance.

Every eleven years, the sun is reported to undergo a solar maximum. This is a time when fierce solar storms erupt. During solar storms, enormous explosions of energy on the sun's surface hurl dense waves of charged particles - called Coronal Mass Ejections (CMEs) - and the flow of plasma-called solar wind - through space, which may take several days to reach earth. The interaction of these charges particle with the earth's magnetic field is known as a geomagnetic storm [1]. Other authors like [2] define geomagnetic storms as large transient fluctuations in the solar wind with sufficient severity as measured in nanoteslas. Geomagnetic storms lead to large fluctuations of the earth magnetic fields which creates the Earth Surface Potential (ESP) inducing quasi-DC currents in electric power systems through the grounded neutral of power transformers. Theses current are commonly referred to as Geomagnetically Induced Currents (GICs) [1].

2 EFFECT OF GIC ON POWER SYSTEMS

History has proven that the effect of GIC's on power systems could be very disruptive, damaging and costly. The first summary of GIC effect on the UC and Canadian power system was in the early 1940's [1]. GICs cause half wave saturation of transformers which leads to increased reactive power requirements and the generation of harmonic. In more severe cases, GICs has lead to the improper relay operations in protection systems, frequency shifts and high harmonic currents [1,2]

On the 10th of March, 1989, a gigantic solar flare erupted from a large sunspot area. Two days later, the earth's magnetic field captured protons and electrons hence producing northern auroras that lit the sky. On the 13th of March, virtually the entire Canadian province of Quebec was plunged into darkness. The blackout extended into the United States as many large power transformer failed. Voltage depressions and fluctuation in system frequency was experienced across the entire power system [3]. During solar cycles 21 and 22, the National Grid Company (NGC) experienced reactive power swings, voltage dips and negative sequence alarms and transformer failures [4].

3 EFFECT OF GIC ON POWER TRANSFORMERS

Over decades the design of power transformers has improved, leading to higher efficiency in their operation. Transformers operate over a relatively wide linear range, except at the voltage peaks which has a higher probability of non linearity. This region of high non linearity is also known as the region of saturation. When GIC is present in a transformer, the magnetic circuit is essentially distorted or skewed by the quassi-DC bias. Hence, the transformer operates more in its region of non linearity. Figure 3.1 shows the B-H curve of a transformer core. Half wave saturation is as a result of the transformer still operating in the high region of non linearity during one half of the ac cycle because of the continuous presence of the voltage variation.

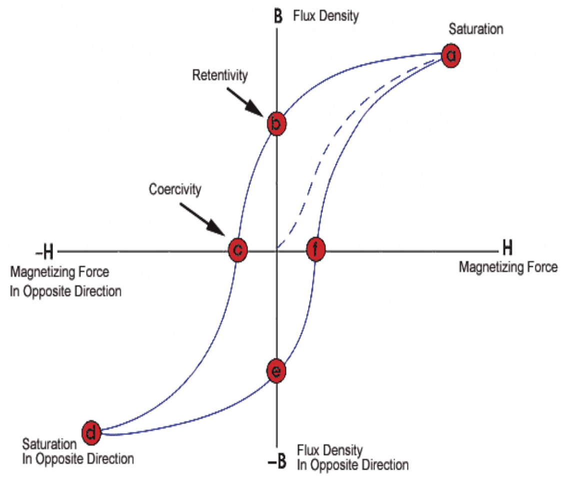

Figure 3.1 B-H Curve of a transformer [5]

Due to half saturation that occurs, the transformer draws a large unsymmetrical exciting current which lags the system voltage by 90 degrees. This gives rise to an increase in the reactive power lost in the transformer. In addition to the reactive power loss, collected data has shown that transformers undergo severe stress during exposure to GIC like local hot spots at high temperature. Stray flux during half wave saturation, finds other paths apart from the core to be the lowest reluctance path such as tank walls. Eddy currents are then induced in areas of the transformer that are not laminated which cause tank wall hot spots [5]. Intra winding increase in temperature is occurs which could inadvertently lead to degradation in transformer insulation. Another effect of GIC in transformers is the very loud audible noise and an increase in vibrations [3]. Some authors like [1] have described this noise as similar to that of a jet airliner taking off.

Research conducted by [7] showed that the most affected to the least affected transformer type to half-wave saturation is:

- Single phase shell or core form
- Three-phase shell form-seven leg core
- Three-phase shell form-conventional core
- Three-phase core form-five leg core
- Three-phase core form-three-leg core

According to [8] and [9], the average exciting ampere-turns is equal to the mean GIC dc ampere-turns. As a result, once saturation has occurred, there is a linear relationship between GIC and the excitation current. Their work also concluded that the magnetizing current as a result of GIC is highly dependent on the size of the cross section of the return limbs and yokes. Figure 3.2 shows the excitation current of a transformer as a result of a dc bias which in this work represents GIC.

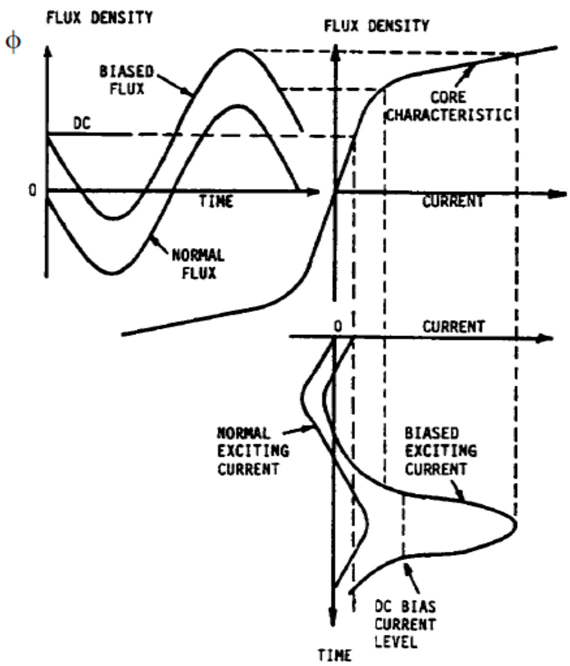

Figure 3.2 Excitation current of a transformer as a result of a dc bias [11]

According to [10], the mean flux obtained for allowing the dc current to flow depends on the nonlinear magnetizing inductance and the amplitude of the ac component. “*The greater the amplitude of the ac component, the smaller the mean magnetizing flux for the same dc current. The mean magnetizing current is equal to the dc current flowing in the transformer magnetizing inductance but it may be different from the mean current flowing through the transformer winding.”* [10].

The risk of transformer damage due to GIC is highly dependent on the design with the presence of core bolts been a very important feature. The presence of GICs in power transformer increases its audible noise. Increased transformer noise level is caused by magnetostriction. This is when the ferromagnetic material changes size slightly when magnetised causing increased vibration of the core. The noise level increases dramatically during half-wave saturation due to the presence of harmonics [1].

4 LABORATORY TEST AND RESULTS

From the reviewed literature, it became very necessary to verify some of the claims regarding the effects of GICs on power transformers. To achieve this, a laboratory set up was planned to test for the change in the magnetic properties of the transformer core, temperature rise, acoustics and possible damage to the transformer in the presence of GICs.

4.1 Base Case: Without Impressed DC

Two 230V/4.5 kV single phase transformers where used to step up and down the source voltage and transmission line voltage. The 25 ohm load was supplied for about 15 minutes without the imposed DC current in the transformer neutral. The voltage waveforms, hysteresis loop and the noise waveform are shown in figure 4.1 to figure 4.6.

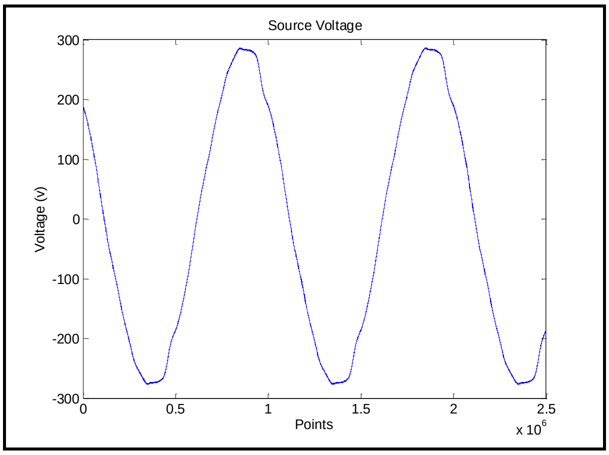

Figure 4.1 Voltage source waveform.

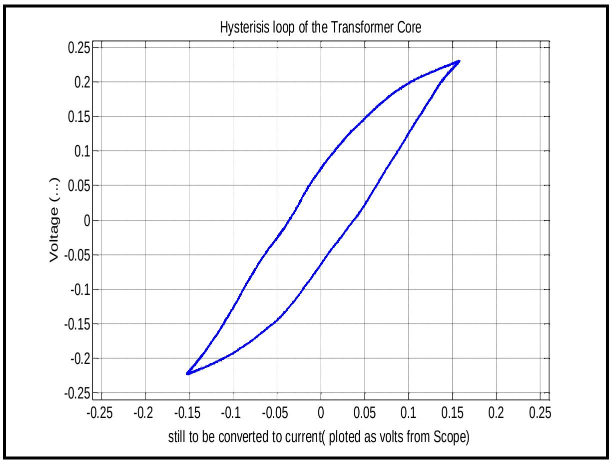

Figure 4.2 Core Hysteresis loop without GIC

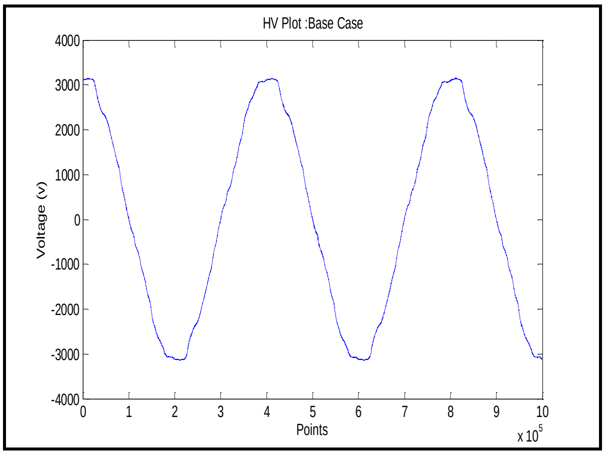

Figure 4.3 HV TX line Waveform plot without GIC

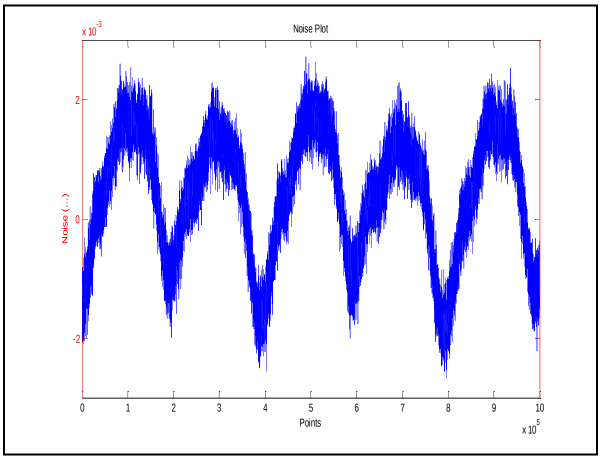

Figure 4.4 Noise on the TR lamination: Without GIC

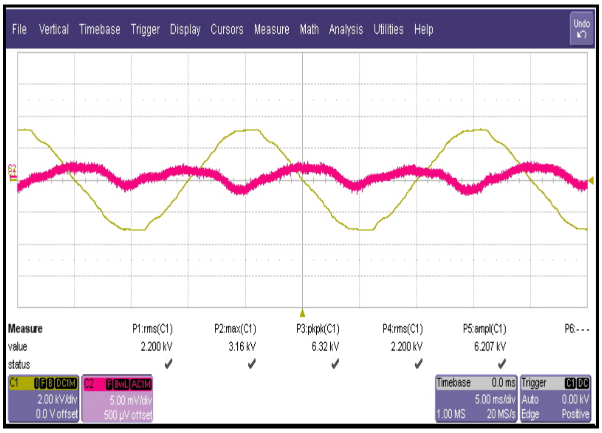

Figure 4.5 Scope snapshot of noise and HV TX waveforms

Table 4.1 shows the spots on the transformer where temperature was measured. TR1 refers to the step up transformer while TR2 refers to the step down transformer.

Table 4.2 and figure 4.6 show the temperature reading reference and the temperature location reference.

Table 4.1 Temperature reading

Base case no GIC As at 20mins				
TR1			TR2	
25.5	26		22.2	21.6
21	22.8		27.2	18.5
25	25		21.7	21

Table 4.2 Temperature reading Reference

TR	
A	B
C	B
E	F

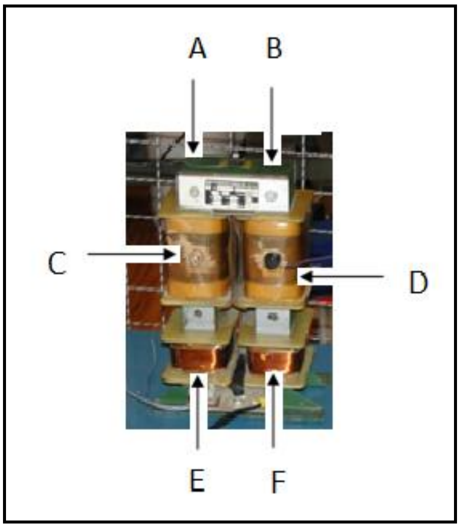

Figure 4.6 Temperature Location Reference

4.2 Case 2: Impressed DC (22.4 mA)

After establishing case 1 as the base operating condition, the setup was switched off for about one hour. This was done primarily to allow the transformer temperature drop. Following this, the 22.4 mA DC was induced in the transformer neutral to simulate the effect of a 22.4 mA GIC. The setup was allowed to run for about 15 minutes while supplying the load. The results obtained are shown in figure 4.7 to figure 4.10

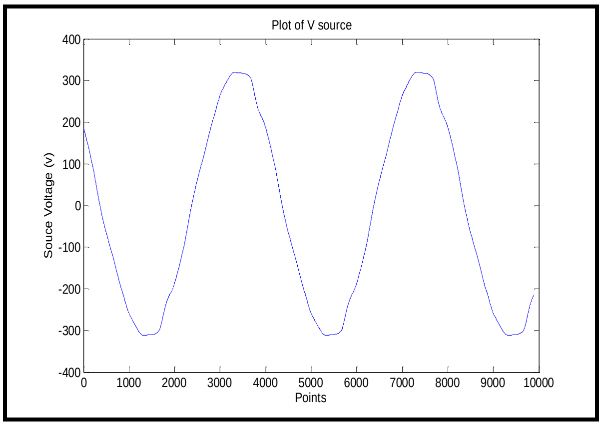

Figure 4.7 Voltage source waveform

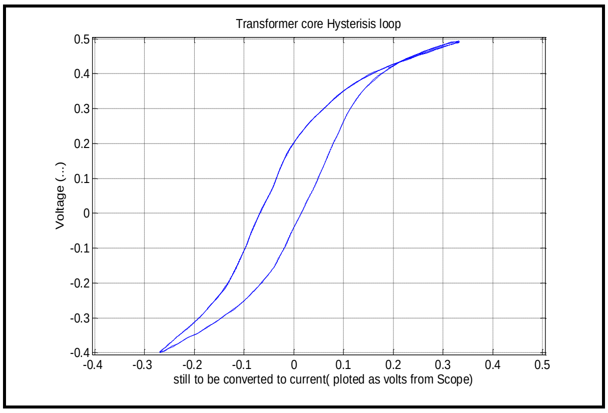

Figure 4.8 Core Hysteresis loop with GIC

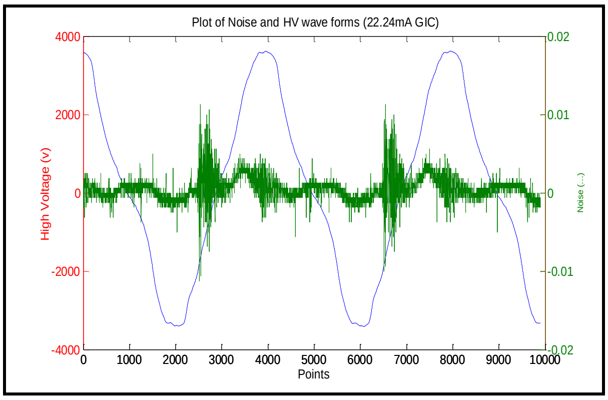

Figure 4.9 Noise and HV TX waveforms

Table 4.3 Temperature reading

After 15mins of 22.24mA GIC on				
TR1			TR2	
27.8	27.2		22.9	20.9
19.5	24.6		34.5	17.9
30	29.2		19.8	19.8

Table 4.4 Temperature reading Reference

TR	
A	B
C	B
E	F

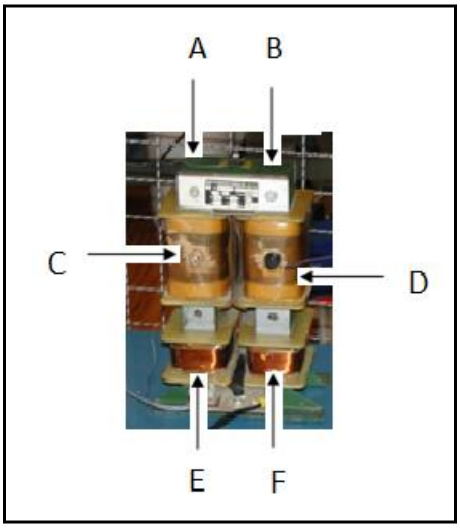

Figure 4.10 Temperature Location Reference

5 RESULT ANALYSIS

5.1 Recorded Results

5.1.1. Source voltage
The results presented in figure 4.1 and 4.7 shows that the voltage waveform before and after the DC bias are the same. Therefore, the transformer primary side voltage (LV) was not affected by the DC bias on the secondary side (HV).

5.1.2. High voltage transmission line
The High voltage (HV) transmission (TX) line voltage waveform for the pre and post DC bias are given in figure 4.3 and 4.9 respectively. These result shows that the superimposed DC bias distorted the HV TX line voltage waveform. This result supports what has been reported in literature about the incorrect tripping of relays.

5.1.3. Hysteresis loop
Figure 4.2 and 4.8 shows the hysteresis loop of the step up transformer (TR1) for both pre and post DC bias conditions respectively. By inspection using the gridline in figure 4.2, the area of both half waves are the same. However, after the DC bias in figure 4.8, the center of the hysteresis loop shifted to the right and down. Hence the area of the top half wave is larger than the area of the bottom half wave. Furthermore, the transformer operated more in its region of nonlinearity or saturation because of the DC bias.

5.1.4. Noise
The noise waveform from the step up transformer (TR1) is shown in figure 4.5 before the DC bias. The waveform is uniformly distorted with respect to time. However, after the DC bias as shown in figure 4.9, noise waveform was no more uniform. Rather, high peaks in the noise waveform are noticed at the zero crossing of the HV waveform when the slope of the HV waveform is positive.

5.1.5. Temperature
The temperature on each transformer was measured at six different locations as shown in figure 4.6 and figure 4.10. Table 4.2 shows the arrangement of the temperature reading in table 4.1 for the step up transformer (TR1) and the step down transformer (TR2) before the DC bias. Table 4.3 shows the temperature reading after the DC bias. Table 5.1 below shows the difference in temperature between pre and post DC bias across all six measurement locations for both transformers.

Table 5.1 Temperature difference between pre and post DC bias

TR1			TR2	
2.3	1.2		0.7	-0.7
-1.5	1.8		7.3	-0.6
5	4.2		-1.9	-1.2

The negative sign indicates that the temperature at that spot was lower after the DC bias, while the positive polarity indicated that the temperature at that spot was higher after the DC bias. From table the highest change in temperature was recorded at point “C” which is the High Voltage coil of the step down transformer (TR2). This could be as a result of the DC bias.

5.2 Non documented results

After about 30 minutes into the experiment with the DC bias, loud noises where heard from the DC source and both transformers. A quick look at the oscilloscopes showed that ALL measured waveforms and the hysteresis loop were heavily distorted. In fact, what was seen had no resemblance to the original signal. Unfortunately due to the fast precautionary measures taken, the experiment was quickly turned down before any reading could be taken. Based on what happed, it is suspected that the transformer/s and the DC source have been destroyed.

6 CONCLUSION

The laboratory test was successful. It was determined that the presence of GIC in a transformer will increase audible noise, core temperature and cause halfwave saturation. The high peaks in the noise waveform noticed at the zero crossing of the HV waveform when the slope of the HV waveform is positive needs to be investigated further. This could lead to ways through which the effect of GICs could be mitigated. The test also proved that transformer prolonged exposure to GICs could lead to its damage.

7 ACKNOWLEDGMENTS

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