Effects of Geomagnetically Induced Currents on Power Transformers and Power Systems

R. GIRGIS*, K. VEDANTE
ABB Power Transformers
USA
K. GRAMM
ABB Power Transformers
SWEDEN

SUMMARY

The purpose of this paper is to present to the power industry the true effect of GIC on power transformers. First, the phenomenon of part - cycle, semi - saturation of transformer cores due to GIC is described briefly. The magnitude and wave - shape of the resulting magnetizing current pulse are given for of an example large power transformer when subjected to different levels of GIC. The corresponding harmonics associated with these magnetizing current pulses are also presented. Proper evaluation of this magnetizing current pulse and the associated high order harmonics are critical to the determination of the response of power systems to a GIC event.

In the discussion of the effects of GIC on the temperature rises in windings and structural parts of a power transformer, typical signatures of GIC associated with Solar Magnetic events are presented. Based on these measured signatures, calculations are presented in the paper for winding and structural parts hot spot temperature rises due to a representative GIC signature.

One of the most significant contributions of this paper is a detailed description of some of the cases in which power transformers were reported to have suffered damage, or over - heating, during past GIC events which was blamed solely on GIC. Also presented in this paper, are actual measurements, made by 3 major utilities on full size power transformers when subjected to high levels of DC. The paper demonstrates that, because of the nature of the GIC currents, the great majority of power transformers would not experience damaging overheating due to even high levels of GIC. Only transformers with certain design features could suffer some winding damage due to high winding circulating currents when exposed to high levels of GIC.

The paper also presents the real issue with GIC; namely, the narrow pulse of the magnetizing current which results from part - cycle, core semi - saturation when subjected to high levels of GIC currents. This one current pulse / cycle causes relays and capacitive components in power systems, such as SVC(s), to trip causing grid instability. Also, the current pulse is associated with higher order harmonics. As a result, resonance may occur, differential relays may operate, and stability of the grid may be compromised.

KEYWORDS
Power Transformers, Power Systems, Geo – Magnetically Induced currents, GIC, DC

*ramsis.girgis@us.abb.com
1. INTRODUCTION

Effects of Solar Geomagnetic Disturbances on power transformers and power systems have been observed for many decades and in many parts of the world. These events had created a certain level of concern in the electric power industry about the implications of GIC currents flowing into the neutrals of large power transformers. Now, with the approach of the upcoming solar cycle (Cycle 24) in the Years 2012 – 2013, the level of concern is as great as ever. Additionally, there is some misconception in the electric power industry today that Geo – magnetically induced currents have caused, and would cause significant damage to many of the large power transformers installed around the World, resulting in transformer failures of a large scale.

2. PHENOMENON OF PART – CYCLE, CORE SEMI – SATURATION UNDER EFFECT OF DC / GIC

When a power transformer is subjected to DC, it results in a unidirectional DC flux in the core. The magnitude of this flux depends mainly on the magnitude of the DC current, number of turns in the windings carrying the DC current, and reluctance of the path for this DC flux. The result is that the DC flux adds to the AC flux in one half – cycle and subtracts from the AC flux in the other half – cycle. When large enough, this leads to core peak flux densities in the magnetic core pre – saturation range in one half of the cycle. For higher magnitudes of DC, the core provides a very high reluctance to the DC Ampere – Turns; resulting in a smaller further increase in the flux density DC shift. Correspondingly, the magnetizing current becomes a short duration pulse with a high peak. The duration of this pulse is only in the range of 1/6th to 1/10th of the cycle, Figure 1.

![Figure 1: Part – Cycle, Semi – Saturation of Transformer cores when subjected to DC / GIC](image)

As mentioned earlier, the magnitude of the DC flux shift in the core depends on the magnetic reluctance of the DC flux path. It follows that the DC flux shift in a 3 – phase, 3 – limb core form transformers would be the lowest of all core types. This is because this core design offers orders of magnitude higher magnetic reluctance to the DC Ampere – Turns in the Core – Tank magnetic circuit. In this core type, the DC flux has to pass through the very high reluctance path from the core top yoke to the tank cover, through the tank walls, and return to the bottom yoke through again the high reluctance path from the tank bottom. All other core types offer much less reluctance to the DC Ampere – Turns because the return path to this DC flux is through the core which has orders of magnitudes higher permeability. Core material and core joint type have some influence. However this influence is small and depends on the core type and the operating flux density in the core.
3. MAGNITUDES AND HARMONIC CONTENT OF THE MAGNETIZING CURRENT PULSE

As explained above, magnitudes of the magnetizing current pulse resulting from core semi – saturation are typically an order of magnitude higher for transformers with core types other than the 3 – phase, 3 – limb core form. It follows that magnitudes of the harmonic content are also lowest for 3 – phase, 3 – limb cores. This is demonstrated in Figure 2 below. The Figure presents the % harmonic content of the magnetizing current of two transformers of two different core – types, relative to their corresponding full load current, when subjected to 30 Amps DC / phase. The figure shows that the short duration nature of the magnetizing current pulse results in an almost uniform magnitude of low and high order harmonics. Another observation from Figure 2 is that transformers have levels of the 2nd order harmonic that would give an erroneous message to the differential relay set at a low value of 2nd harmonic content to differentiate between Inrush current events and a fault condition. Additionally, as will be explained in section 8 of this paper, the 3rd order harmonics could cause relays to operate resulting in tripping of transmission lines during a GIC event; hence grid instability and system blackouts.

![Figure 2 Harmonic content of magnetizing current of 2 transformers subjected to DC / GIC](image)

4. INCREASES IN HOT SPOT TEMPERATURES OF WINDING AND STRUCTURAL PARTS WHEN SUBJECTED TO DC / GIC

The several orders of magnitude higher magnetizing current, and the nature of its wave – shape, produce correspondingly higher magnitudes of leakage flux that is also rich in harmonics. This results in appreciably higher eddy and circulating current losses in the windings and the structural parts of the transformer; increasing their temperatures, Figures 3 and 4. The figures show that the hot spot temperature reached close to a final value within 5 minutes for windings, and within 10 minutes for structural parts, from the application of the DC. This corresponds to the typical range of the time – constant of the windings and structural parts, respectively. Under actual GIC, however, this temperature rise will be much lower than shown below due to the very short duration nature of GIC (1 – 3 minutes). This is demonstrated in the following section of this paper.
Fig. 3 – Winding Hot spot temperatures for different values of DC.

Fig. 4: Tie – Plate hot spot temperature for different values of DC Current
5. **EFFECT OF GIC ON POWER TRANSFORMERS**

In order to accurately determine the capability of a transformer to GIC, one needs to consider the nature of the signature of the GIC current; namely its magnitudes and duration. GIC current is typically characterized by low levels of 10’s of minutes / a few hours duration interrupted by a few, much higher, peaks of pulses that have a very short time duration (typically 1 – 3 minutes).

Due to the short duration of these high peaks of GIC and the fact that the duration of the resulting magnetizing current pulse is only a small fraction of a cycle, the actual duration of the resulting core part – cycle, semi saturation and associated high peak pulses of the core magnetizing current is only a few seconds. Hence, temperature rises in the transformer windings and structural parts due to GIC would be expected to be much lower than that estimated based on continuous duration DC currents. In order to illustrate the above, a profile of GIC, per Figure 5 (a) below, was assumed and winding hot spot temperature was calculated for a fully loaded large 1 – phase power transformer for this assumed GIC current profile. The assumed GIC profile has a base level of 20 Amps / phase (60 Amps for a 3 phase bank) interrupted, every 30 minutes, by a 2 – minute duration very high level GIC pulse of 400 Amps / phase (1200 Amps for a 3 phase bank). The results are presented in Figure 5 (b).

It can be seen from the figure that:

1. The temperature rise of the winding hot – spot due to the base 20 amps is only 1º C.
2. The temperature rise of the winding hot – spot, due to the 2 – minute duration of 400 Amps / phase of GIC, increases by about 35 C; and a hot spot total temperature of about 146 C. The temperatures would be much lower when the transformer is not fully loaded and / or ambient temperature is lower than 30 C. Such winding hot spot temperatures for such a short duration would not cause any appreciable damage of the windings, structural parts, or loss of insulation life of the transformer. In fact, Industry Standards for overload (IEEE and IEC) allow much higher winding hot spot temperature levels for much longer times under emergency loading conditions (160 – 180 C).
3. After these 2 minutes, the hot spot temperature of the windings goes back down to the original temperature existing before that pulse of GIC.
4. The duration of that pulse of temperature rise of the windings is only a few minutes; which would not result in any damage to the windings.

The same is true for structural parts, except that the temperature rise will be even smaller for these structural parts as their time constant is higher than that of the windings.

![Simulated GIC Current](a)
6. TRANSFORMERS REPORTED AS HAVING FAILED / SUFFERED OVERHEATING DURING GIC EVENTS

Reference [1] reports several of those cases. One of these is a shell form transformer that experienced significant overheating of the LV leads of a GSU transformer at PSE&G in NJ, USA, during the March 13, 1989 K9 GIC event. The transformer was taken out of service a week later because of significant gassing. Same design transformers at the same general location experienced similar overheating, although to a lesser degree. These were old Shell form transformers that had an old winding lead design that made it susceptible to overheating caused by high circulating current when the core experienced part – cycle, semi – saturation; during which the leakage flux pattern changed and resulted in very high circulating currents in the LV windings of this transformer [2].

Another case reported in Reference [1] is a Shell – form Transformer that had tank wall heating during the same GIC event. In such transformers, wood slabs are placed between the core and tank walls. When the core goes through semi – saturation, part of the core and leakage flux travel to the tank wall causing localized eddy losses in the tank. Being blanketed by the wood slabs, these regions of the tank overheated. Additionally, it should be noted that this temperature increase had only resulted in discoloration of the tank paint at the tank regions opposite to the wood slabs. New designs allow improved cooling of tank walls in these regions.

It was also reported in Reference [1] that within 2 years of the 1989 GIC event, 11 nuclear plants experienced failures of several GSUs. During that period, a number of these failures were studied and found to be caused by back – feed mode operation. In this mode of operation, the generator step – up transformers are not sufficiently protected from switching and lightning surges and the electrical damping in the electric circuit is very low making it vulnerable to transient voltage magnification due to winding resonances.

Other cases were reported in Reference [3] of significant winding overheating in a few large core form power transformers in S. Africa during the period between 2003 and 2004. These incidents were found to coincide with winding overheating caused by the phenomenon of the conducting Copper Sulphide.
forming and causing winding failures of transformers worldwide. This was attributed to high sulphur content in some types of transformer oil during this period. It is plausible that increases in the winding temperature, caused by GIC, could have accelerated the formation of Copper Sulphide in the windings of these transformers. However, the magnitudes of GIC, reported to have been associated with these incidents, do not seem to be high enough to cause much winding overheating.

It was reported by HQ in reference [4] that two transformers were subjected to external faults during the GIC event and are believed to have been caused by over – voltages due to System instability. Also, one transformer in New Zealand, that was reported in the same reference as have failed one minute after a GIC event, is believed to have been caused by System instability associated with the GIC event. Also, Reference [5] reports on two transformer failures in National Grid in Britain after a GIC event but no details were given to ascertain that claim. Finally, in Reference [6], account is given of a number of 400 kV large power transformers in southern Sweden that were subjected to high levels of GIC in the October 2003 GIC event. No transformer damage was reported; including a 3 – Phase, core – form transformer with a 5 – limb core, which was subjected to an estimated peak of 330 Amps of GIC in the neutral. The authors of this paper reported that a 20 – 50 minute black – out occurred in the Malmo area which was caused by the tripping of a 130 kV line resulting from the operation of a relay that had a higher sensitivity to the 3rd harmonic than to the fundamental frequency.

It is to be noted here that, as in the case of the PSE&G shell form transformers, core and shell form transformers, with certain winding / lead arrangements, could experience high levels of circulating current and suffer some winding overheating when these transformers are subjected to levels of GIC that would cause core semi – saturation. These types of transformers will need to be investigated and identified on an individual basis.

7. ACTUAL MEASUREMENTS OF EFFECT OF DC / GIC

Two full size experiments were performed by Hydro Quebec [7] and FIN Power [8], where very large 1 – phase and 3 – phase power transformers were injected with high levels of DC (75 Amps for 20 minutes and up to 200 Amps for 30 minute intervals), respectively. Temperature rises were measured in windings and structural parts of the transformers. It was found that the temperature rises were in a reasonable range in spite of the high levels of DC applied continuously for long durations. As concluded by these studies, even high levels of GIC currents should not cause transformer damage. An earlier experimental study of the effect of DC on power transformers was conducted by Tokyo Electric Power Corporation, in collaboration with Toshiba, Hitachi, and Mitsubishi [9]. The study tested several small scale models of core form as well as shell form transformers with different core types. Based on the measurements performed on these models, measurements were made on two large – Scale models of 1 – phase, 3 – legged 1000 MVA / 550 KV core form and shell form transformers. These transformers were tested with up to a DC level of 66 Amps which corresponds to 400 – 600 Amps / phase for the corresponding full size transformers. The DC was applied for up to 20 – 30 minutes continuous. The leakage flux and temperatures were measured in windings and structural parts of these transformers. The maximum temperature rise measured after 30 minutes of applying such large magnitudes of DC continuously was approximately 110 C in both the Tie – plate for the core form transformer and the core support in the shell form transformer. The study again concluded that because of the short duration of these temperatures, the transformer life would not be appreciably affected. Also, the very short duration of GIC would not allow hot spot temperatures to rise to a fraction of these temperatures.

8. EFFECT OF GIC ON POWER SYSTEMS

As presented earlier in this paper, part – cycle, core semi – saturation is associated with a high magnitude narrow magnetizing current pulse; once per cycle. This represents high levels of VAR pulse requirement on the power system causing system voltage distortions. Also, the narrow current pulse causes capacitive components on the system, such as static VAR compensators, etc. to increase their currents and may become overloaded and trip causing grid instability. Moreover, the magnetizing current pulse is associated with high harmonics, and as a result, resonance may occur and stability of the grid may be compromised due to the creation of virtual zero at some point and opening of
transmission lines. Also, as observed from Figure 2 of this paper, transformers have levels of the 2nd order harmonic. This is significant as lower levels of 2nd order harmonics associated with the total primary current of the transformer would give an erroneous message to the differential relay set at a low value of 2nd harmonic content to differentiate between Inrush current events and a fault condition. Additionally, as reported in Reference [6], operation of relays that have higher sensitivity to the 3rd harmonic than to the fundamental frequency, would cause tripping of transmission lines during a GIC event; causing grid instability and system blackouts.

9. CONCLUSIONS

- High levels of GIC could cause part – cycle, semi – saturation of transformer cores. This results in a short duration, high peak pulse of magnetizing current.
- Because of its short duration, in the great majority of the cases, even high levels of GIC would not cause damaging overheating of neither windings nor structural parts of power transformers.
- Only transformers, core – or shell – form, where part – cycle, core semi – saturation would cause high winding circulating currents would be susceptible to winding overheating when the transformer is subjected to high levels of GIC.
- Cases of significant overheating and winding damage, reported in the published literature as have been solely caused by GIC, were found to have been caused totally, or partially, by other effects, or by system instability experienced during or after the GIC event.
- The main impact of GIC is on the system instability it causes due to high levels of VARS and significant current harmonics as a result of transformer part – cycle, core semi – saturation.

10. BIBLIOGRAPHY