Effects of GIC on Power Transformers and Power Systems

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Background

There has been some misconception in the electric power industry that Geo–magnetically Induced Currents (GIC) have caused, and would cause, significant overheating damage to the majority of power transformers installed around the World and consequent system blackouts of a large scale [1]. The purpose of this paper is to present to the power industry the true effect of GIC on power transformers and the power system and its components.

Phenomenon of Part – Cycle, Core semi – saturation under effect of DC

When a power transformer is subjected to DC, unidirectional DC flux results in the core. The magnitude of this flux depends mainly on magnitude of the DC current, number of turns in the windings carrying the current, and reluctance of the DC flux path. The result is that the DC flux adds to the AC flux in one half – cycle. When large enough, this leads to core peak flux densities in the range of core pre – saturation. For higher magnitudes of DC, the core provides a much higher reluctance to the DC Ampere – Turns; resulting in a smaller further increase in the DC flux density shift. Correspondingly, the magnetizing current becomes a high peak of short duration pulse, Figure 1. The duration of this pulse is in the range of only 1/6th to 1/10th of the cycle. Because of the nature of its magnetic circuit, the DC flux density shift in a 3 – phase, 3 – limb core form transformers would be the lowest of all core types.

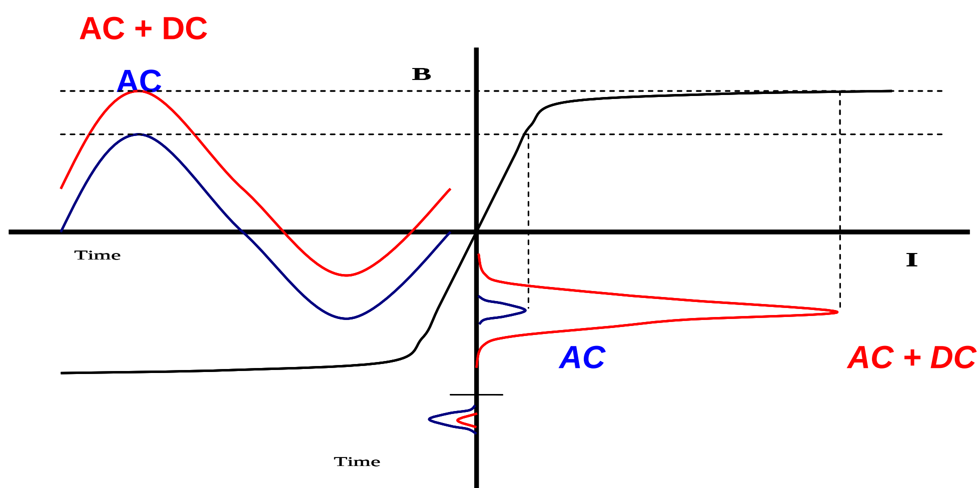

Figure 1: Part – Cycle, Semi – Saturation of Transformer cores when subjected to DC

Magnitudes and harmonic content of the magnetizing current pulse

The high peak magnetizing current pulse, seen in red above, increases the reactive power absorbed by the transformer. Hence, the power network sees a large increase in VAR demand for the duration of the GIC. Figure 2 depicts the relationship between the Transformer VAR demand and the GIC for a large power transformer. This increase in VAR demand is one of the major concerns during Geo – magnetic disturbances (GMD). If VAR resources are exhausted during a GMD event, voltage collapse can occur. Therefore, accurate estimation of the VAR consumption of the transformer during a GMD event is critical for proper mitigation of effects of GIC on power system stability.

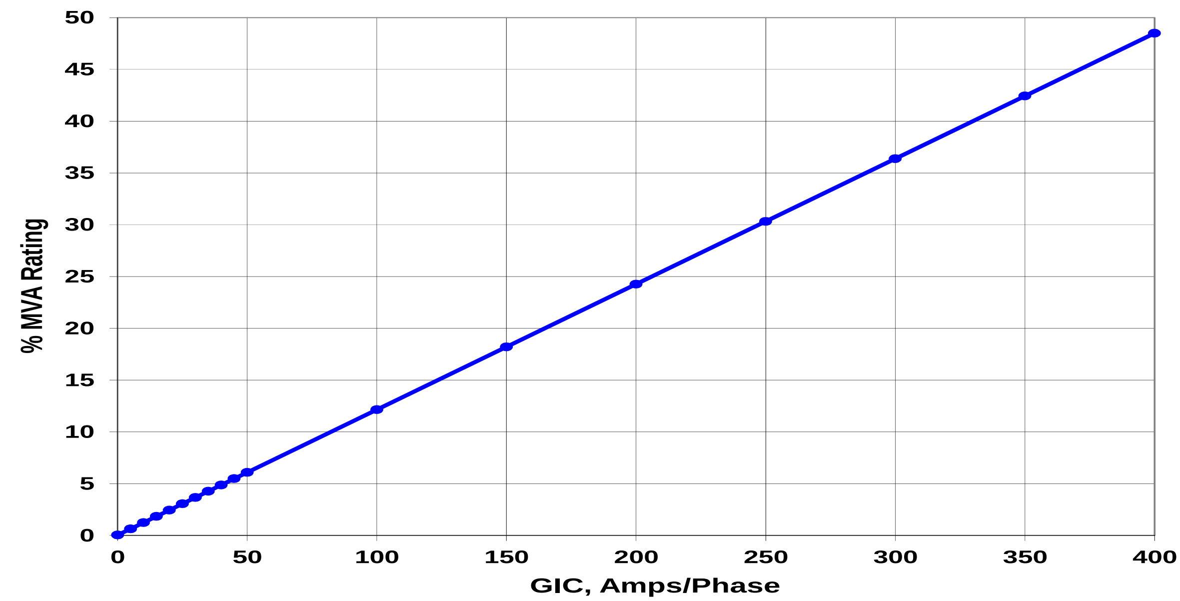

Figure 2: Calculated reactive power drawn by a large Transformer subjected to GIC

The magnetizing current pulse additionally injects significant even and odd harmonics into the power system as presented in figure 3 below. 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. These harmonics can have a significant impact on the power system. Shunt capacitor banks used for VAR support become low impedance paths for harmonic currents, and can lead to tripping of the bank by relay protection schemes. Harmonic filters for SVCs banks create parallel resonances which can exacerbate voltage distortion issues and result in tripping of the protection devices. Harmonics can also cause the unintended operation of relays.

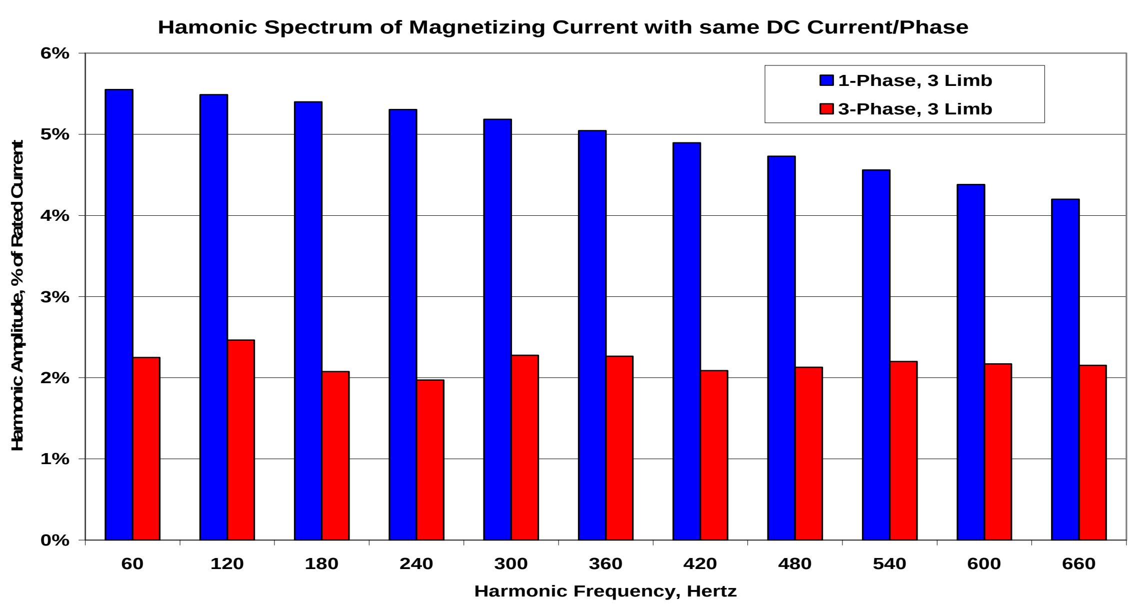

Figure 3: Harmonics of magnetizing current of transformers subjected to 30A/phase GIC

Increase of hot spot temperatures in transformers when subjected to GIC

The high peak magnetizing current pulse produces correspondingly higher magnitudes of leakage flux that is also rich in harmonics; resulting in much higher eddy and circulating current losses in the transformer windings and the structural parts; increasing their temperatures. Figure 4, below, presents calculated hot spot temperature of flitch – plates of a 1 – phase large power transformer subjected to different levels of DC current. As the figure shows, the hot spot temperature reached close to its final value within 10 minutes from the application of the DC as determined by the time – constant of the structural parts.

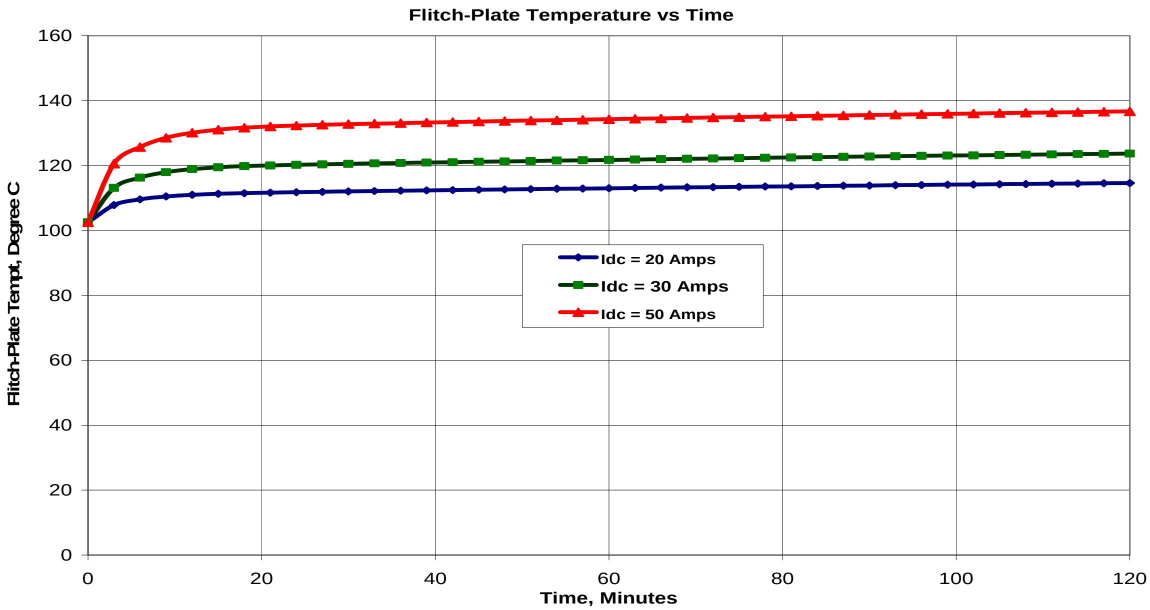

Figure 4: Calculated Flitch – Plate hot spot temperature for three values of DC

However, in order to determine the true thermal effects of GIC on transformers, one needs to consider the nature of the GIC profile; namely its magnitudes and duration. Figure 5, below, presents measured GIC at the neutral of a 3 – phase transformer in a generating station during a recent GMD event. As demonstrated in figure 5, below, GIC current is characterized by a large number of consecutive narrow pulses of low – medium levels over a period of hours and occasional high peaks of short duration pulses.

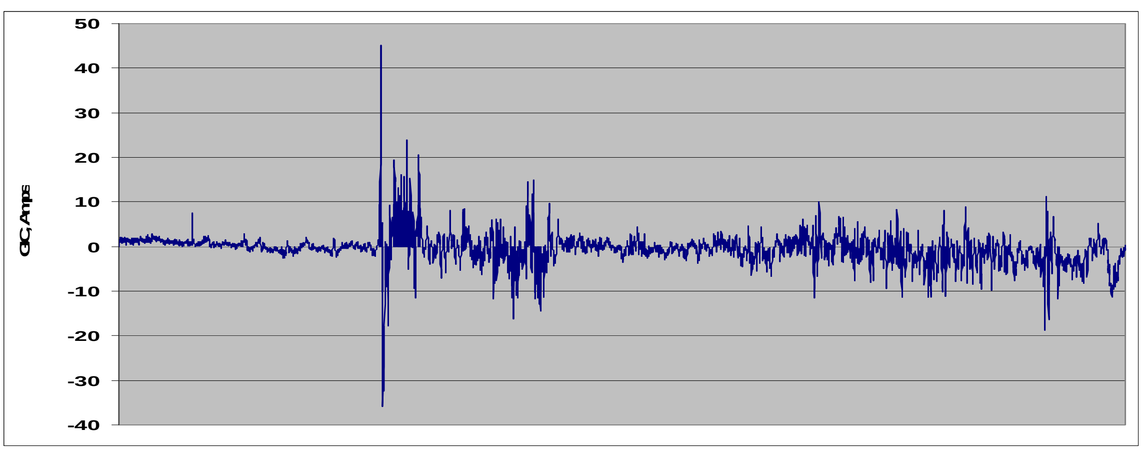

Figure 5: Measured GIC at a GSU transformer; during a 7 hours period

Due to the short duration of these high peaks of GIC pulses 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. In order to illustrate the above, the winding hot spot temperature was calculated for a fully loaded large 1 – phase power transformer when subjected to an assumed GIC current profile that has a base level of 20 Amps / phase; and two 2 – minute duration high peak pulses of 400 Amps / phase. The resulting calculated winding hot spot temperatures are shown in Figure 6 below.

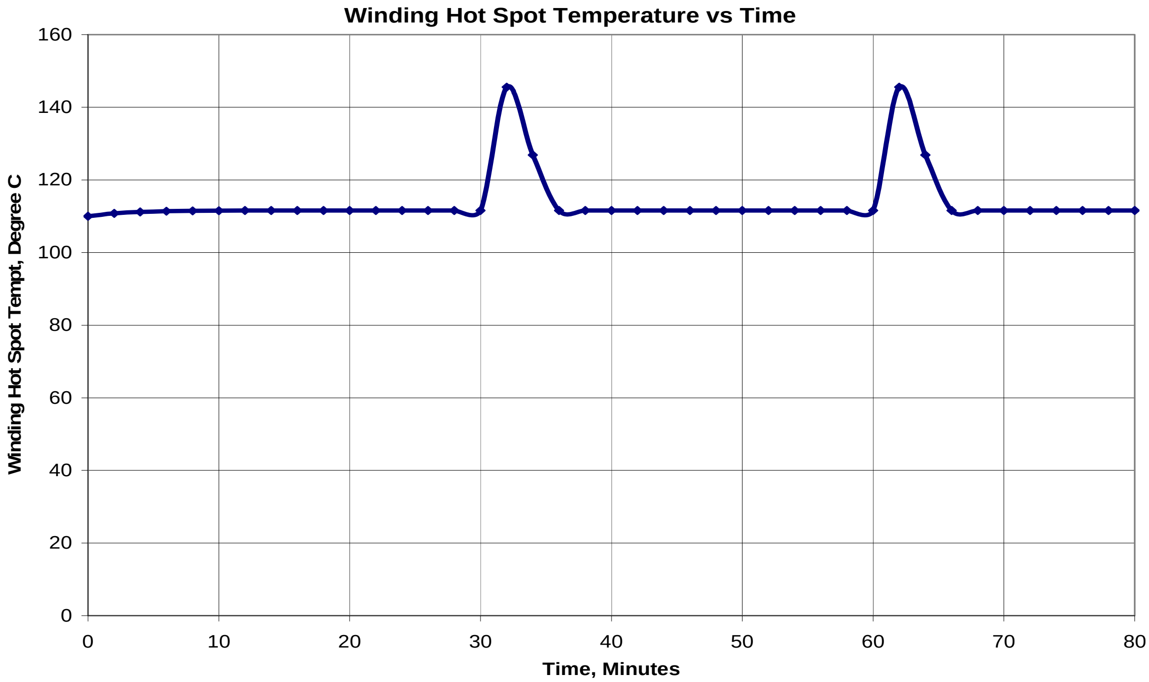

Figure 6: Calculated Winding Hot Spot Temperature due to GIC profile described above

The figure demonstrates that the increase in the hot spot temperature is limited by the duration of the GIC pulse, and drops to the original temperature after the pulse is over. The winding temperature reached (146ºC) in this case of an extremely high peak of GIC would be much lower when the transformer is not fully loaded and ambient temperature is lower than 30 C. The same is true for structural parts, except that the temperature rise will be governed by the higher time constant of the structural parts. Also, such 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. Industry Standards for overload (IEEE and IEC) allow much higher hot spot temperature levels for much longer times under emergency loading conditions (160 – 200 C).

Actual measurements of thermal effects of GIC on power Transformers

Two experiments were performed by Hydro Quebec and Fingrid [2, 3]; where large in-service single–phase and three–phase power transformers were injected at no load with high levels of DC. Temperature rises were measured in the windings and structural parts of the transformers. When compared to limits established by Industry Standards, winding temperature rises were low and temperature rises in the structural parts were moderate. Both reports concluded that at GIC levels injected no transformer damage would occur.

Transformers reported as having failed or suffered overheating damage due to GIC

Reference [1] reports several of those cases. One of these is a Shell form transformer that experienced significant overheating of the LV leads during the March 13, 1989 K9 GIC event. Same design transformers at the same general location experienced similar but less overheating. These were old transformers that had an old winding lead design that made it susceptible to high circulating currents when the leakage flux pattern changed as the core experienced saturation [4]. Another case reported in Reference [1] is a Shell form Transformer that had tank wall heating during the same GMD event. The construction of these transformers is such that wood slabs are placed between the core and tank walls. With core saturation, part of the core and leakage flux travels to the tank wall causing localized eddy losses in the tank. Being blanketed by the wood slabs, these regions of the tank overheated.

It was also reported in Reference [1] that within 2 years of the 1989 GMD 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. Significant winding overheating was also reported to have occurred in a few large core form power transformers in S. Africa between 2003 and 2004 [5]**.** 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 World – wide. It is believed that the increase in the winding temperature, caused by GIC, could have accelerated the formation of Copper Sulphide in the windings of these transformers [5, 6]. It was also reported by HQ in reference [7] 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. Finally, 400 kV large power transformers in southern Sweden were reported to have been subjected to as much as 330 Amps in the October 2003 GMD event. No transformer damage was reported. Instead, a black–out occurred; caused by tripping of a 130 kV line resulting from operation of a relay that reacted to a 3rd harmonic current [8].

Conclusions

The paper demonstrates that, because of the short duration nature of the high GIC current peaks, 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. Also, the paper presents the real issue with GIC; namely, its effects on the power system and its components. The large peak magnetizing current pulses caused by core semi – saturation represents a large increase in VAR demand and can, if not planned for, result in voltage collapse. Additionally, the magnetizing current pulse injects significant harmonics into the power system; which can have a significant impact on shunt capacitor banks, SVCs, and relays, and could compromise the stability of the grid.

References

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