Mitigation of flux produced by geomagnetically induced currents (GIC) on power transformers with delta windings

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***Abstract*—Geomagnetically induced currents (GIC) arise in our power system due to fluctuations in the Earth's magnetic field, which commonly is caused by space weather events. These currents may result in core saturation of transformers that get exposed. The purpose of this project is to clarify the possibility of reconnecting the delta connected tertiary windings in order to mitigate the saturation that is caused by GIC. Laboratory studies were performed on different types of transformers, which later were simulated and compared to the experimental results, in order to verify the credibility of the simulations. The study concludes that partial DC flux mitigation can be very effective in order to prevent core saturation as a result of GIC.**

***Keywords*—GIC, DC flux mitigation, power transformers.**

I. Introduction

The cause of GIC are solar storms and space weather events. These events start at the surface of the Sun when the Sun's magnetic fields collide and large clouds of plasma is thrown out in space. These clouds of plasma do sometime travel in the direction of Earth. Depending on the direction of the magnetic field inside the cloud of plasma it has different impact on our magnetosphere. This can generate electric fields which drive an electric current between the magnetosphere and the ionosphere. Due to the orientation of the Earth's magnetic field the currents are most common in the auroral ovals. Since this magnetic field is alternating, an electric filed is induced in conducting structures such as the power system, [1].

Due to the induced GIC, which has a low frequency compared to the power system, the power transformers behave like they are subjected to a quasi-DC offset. The consequence of a DC offset in a power transformer is half-cycle saturation of the core. The partial saturation occurs when the combined AC and DC flux exceeds the maximum amount of flux the core can conduct without saturating. This can occur when the current and core flux no longer oscillate around zero but instead around the DC offset, see Fig 1.

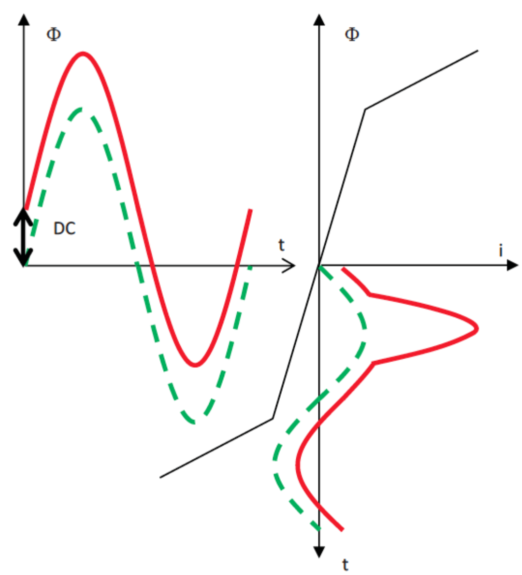

Fig. 1. Mapping from magnetic flux in the transformer core to primary current. Dashed corresponds to without GIC and solid corresponds to with GIC.

This periodic core saturation results in a distorted current waveform causing harmonics, heating and reactive power losses.

II. Principal idea

Wye-wye connected transformers usually have delta connected tertiary windings in order to compensate for zero sequence currents. This study has evaluated the impact of reconnecting these tertiary windings, see Fig 2, into flux compensation windings, that mitigate the flux offset. This is done by leading the DC current through the compensation windings to counteract the DC flux produced by GIC.

The turns ratio between the compensation windings and the windings which the GIC enters the systems through sets the amount of compensation. A turns ratio of 1/3 between the entering and compensation windings will completely eliminate the DC flux, resulting in perfect compensation. However, as this ratio is lower for the commonly implemented tertiary windings (i.e 1/10), re-configuring the tertiary winding to a compensation winding will only reduce the DC flux and not completely eliminate it.

This study has evaluated the impact partial DC flux compensation makes for the steady state behaviour as well as the transient behaviour of the transformer.

Laboratory studies have primarily been preformed on three 800 VA single phase transformers, but also evaluated the behaviour of 2.4 kVA five and three legged 3-phase transformers. These are small shelf sized laboratory transformers.

Simulations have been preformed on three 800 VA single phase transformers in order to evaluate the credibility of the simulation model. This model was later reconfigured to 400 MVA which simulates large transformers that are used in the power grid.

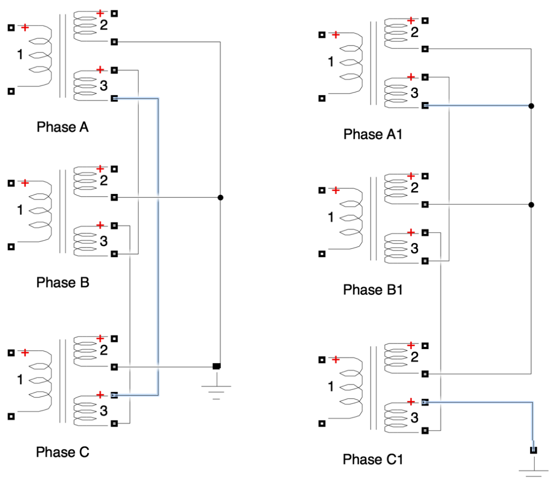

Fig. 2. Reconnection from delta to compensation winding

III. Results

A. Mitigation efficiency

The following results are from the laboratory study of three single phase 800 VA E-core transformers. These have shown that partial mitigation can in fact completely eliminate the core saturation. This is due to the fact that the core will not saturate until the DC flux combined with the AC flux is equal or larger than the maximum flux capacity of the core. Hence the core is able to operate properly with a small enough DC offset.

B. Steady state

The study has shown that the partial compensation windings mitigate the DC flux in the transformer. This results in smaller amplitude of the current spikes in the primary windings, as well as smaller amplitude of the third harmonics.

The primary current waveform for a transformer that is not exposed to GIC is almost perfectly sinusoidal, as shown in Fig 3. The small error is due to the fact that the transformer and supplying grid are not perfectly ideal.

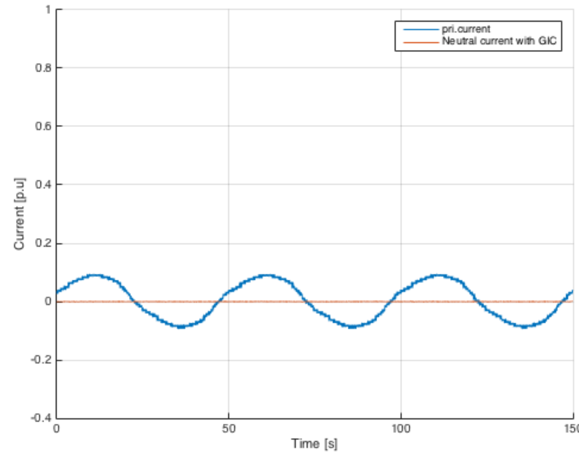

Fig. 3. No GIC and DC flux compensation windings. Primary voltage 230V

When the GIC enters the transformer, large current spikes occur on the primary side, as a result of partial periodic saturation. This correlates to the behaviour shown in Fig 1. It also results in large third harmonics in the current of the tertiary windings, see Fig 4.

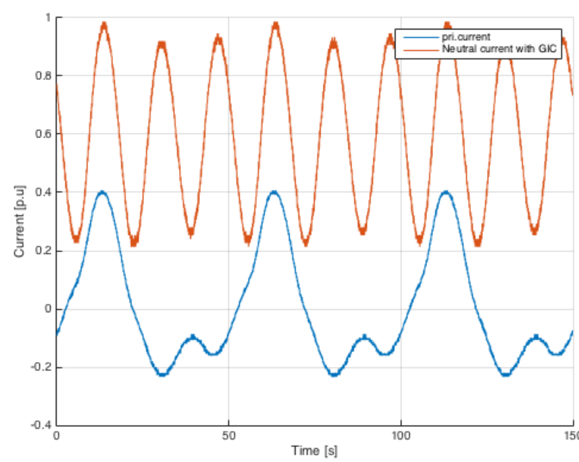

Fig. 4. GIC and no DC flux compensation windings. Primary voltage 230V

The implementation of compensation windings heavily reduces the amplitude of the primary current spikes as well as the amplitude of the third harmonic in the tertiary windings, see Fig 5.

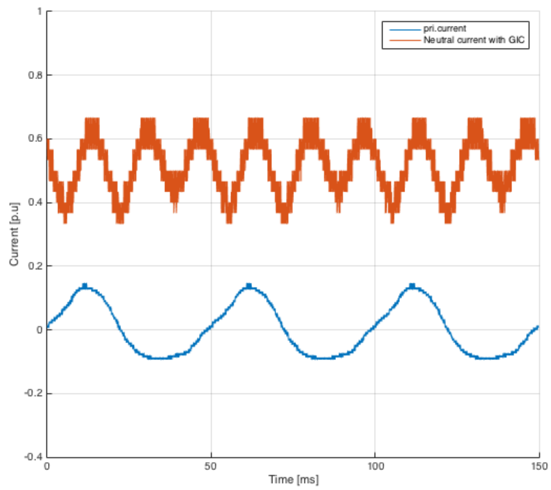

Fig. 5. GIC and DC flux compensation windings with turns ratio 3/4. Primary voltage 230V

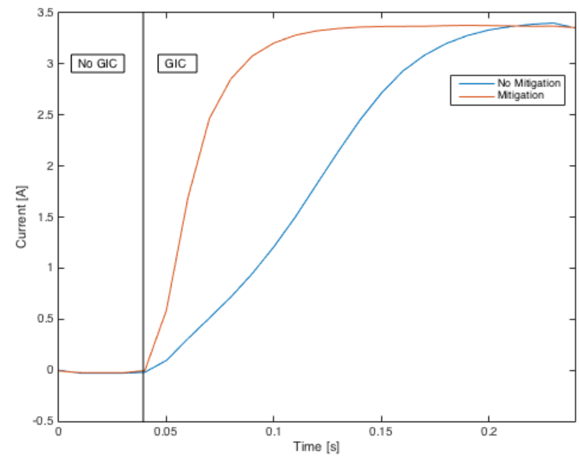

Fig. 6. Step response with and without DC flux mitigation windings. Primary voltage 50V

The study has also shown that a decreased grid inductance will decrease the amplitude of the third harmonic in the compensation windings, as well as increase the amplitude of the current spikes on the primary side.

C. Transient behaviour

The time constant of the DC current response to a DC voltage step decreases as the flux compensation windings are implemented. This is due to the fact that the inductance of the transformer seen from the GIC is decreased as a result of the DC flux counteraction. The decrease of the time constant is inversely proportional to the amplitude of the steady state DC flux. This implies that the overall rate of change for the flux is not affected by the amount of compensation. However, as the duration of the change is in proportion to the amount of compensation, the decrease of the steady state DC flux is proportional to the amount of compensation as well, see Fig 6.

The current step response for the uncompensated transformer is very similar to the corresponding step response simulated by Boteler and Bradley [2].

IV. Conclusions

The reconfiguration of the delta connected tertiary windings to compensation windings mitigates the steady state flux, which results in less half cycle saturation. The turns ratio of the compensation windings compared to the main windings decides the amount of compensation, where 1/3 results in perfect DC flux compensation. Partial DC flux mitigation could be enough to completely eliminate core saturation, as this can result in enough mitigation of the DC flux to make the sum of the DC and AC flux smaller than the maximum amount of flux that the core is able to handle. However, third harmonics become problematic when the delta connected tertiary windings are opened and reconnected to compensation windings. The time constant of the DC current response of the DC voltage step decreases as the flux compensation windings are implemented. However, the overall rate of change for the DC flux is not affected by the amount of compensation, resulting in i a lower steady state DC flux as the duration of change is proportional to the amount of compensation. Larger transformers usually have a larger $\frac{X}{R}$ ratio, which makes it more vulnerable to saturation, since a larger quota of the total impedance is removed when the inductance is heavily lowered as a result of core saturation.

References

[1] D. H. Boteler "Geomagnetic Hazards to Conducting Networks" Geomagnetic Laboratory, geological Survey of Canada 7 Observation Crescent, Ottawa, Ontario.

[2] D. H. Boteler and E. Bradley "On the Interaction of Power Transformers and Geomagnetically Induced Currents" IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 31, NO. 5, OCTOBER 2016