Comprehensive Study on Magnetization Current Harmonics of Power Transformers due to GICs

S. A. Mousavi, C. Carrander, G. Engdahl

***Abstract*-- This paper studies the effect of DC magnetization of power transformers on injected harmonics to power systems. DC magnetization due to geomagnetically induced currents can saturate the core of a power transformer during a half cycle. It causes a very asymmetric, high value magnetization current that contains large harmonic components.**

In this work, by using a three-dimensional finite element model, the effect of core type and DC current level on generated harmonics is investigated.

The results could help power system engineers to choose the proper types of power transformers and improve the protection aspects of the network.

***Keywords*: Geomagnetically induced currents, GIC, Power transformers, saturation, magnetization current, harmonic, FEM.**

I. Introduction

DC currents in the form of geomagnetically induced currents (GIC) can be injected in three-phase transformers or banks of single-phase transformers with grounded star-connected windings [1-5]. The frequencies of these currents are very low and they are quasi-DC. GIC current causes the transformer core to be saturated during one of the half cycles of each supply voltage period [1]. This phenomenon can lead to several ill effects in both power transformers and the power system. One of these effects is the problems of harmonics that are created due to magnetization currents of transformers. Both even and odd harmonics could exist during a GIC event. These harmonics cause increased stray losses inside transformers and also wrong relay tripping in power generators and capacitance filter bank [1-5].

The study on the effects of GICs on power transformers and harmonics of magnetization current has been performed in previous works such as [6-7]. However, most of them were based on the lumped parameter model of transformers or case study investigation. Therefore, there is a lack of comprehensive study using an accurate model of a power transformer.

In this paper, a three dimensional finite element model of a power transformer coupled with the external circuit is presented. The analysis type is the time-step transient. A script for 3D modeling of two, three and four-limb single-phase and three and five-limb three-phase power transformers have been written in the Vector Field 3D FEM package. The transformer model includes the core, windings and tank. Nonlinearity and anisotropy of the core material is considered and windings are coupled with external circuits. Then, the magnetization current is obtained by performing transient analysis. In the post processing stage, by applying FFT analysis on the waveform of the magnetization current, the harmonic components are acquired.

The role of core type and GIC level on the waveform and the harmonic components of the magnetization current are investigated. These results could help designers of power transformers when they want to take into account the probability of GIC. Also, they could be employed to distinguish GIC from other transient phenomena in power networks in order to avoid misoperation of protection and control systems.

II. FE Modeling and Circuit Coupling

A. Finite element modeling

The finite element method is a powerful tool in order to solve electromagnetic problems. It is widely used for modeling and calculations regarding power transformers [8-9].

Generally, transformers have a complex three-dimensional geometry and consist of linear and nonlinear magnetic and electric materials. However, according to the aim of the modeling, some simplification is required.

In this work a three-dimensional model is used for simulation of transformers with the aim of studying the effect of DC on the magnetization currents of power transformers. The different core types of core-form transformers: two-limb, three-limb, four-limb single-phase and three-limb and five-limb three-phase are modeled. This allows investigation of the impact of core type on the magnetization current when the transformer is under DC magnetization. Due to symmetry the

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computational load can be reduced to one eighth or one fourth of the geometry of single-phase and three-phase transformers respectively. Fig. 1 - Fig. 5 show the finite element model of the modeled transformers with symmetry.

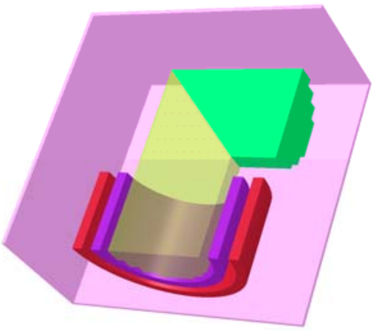

Fig. 1. Single-phase two-limb transformer model with 1/8 symmetry.

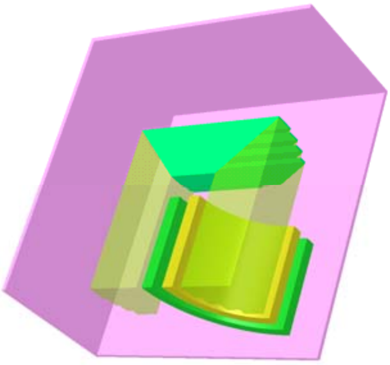

Fig. 2. Single-phase three-limb transformer model with 1/8 symmetry.

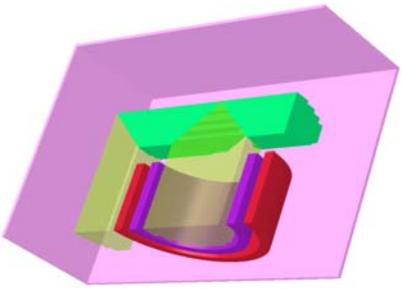

Fig. 3. Single-phase four-limb transformer model with 1/8 symmetry.

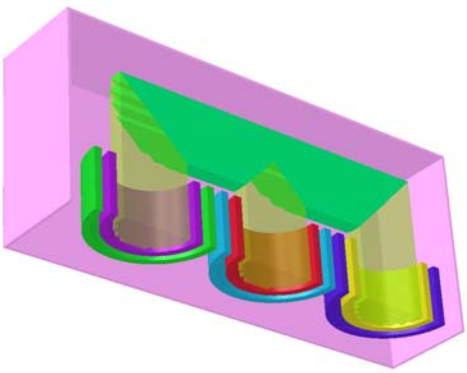

Fig. 4. Three-phase three-limb transformer model with 1/4 symmetry.

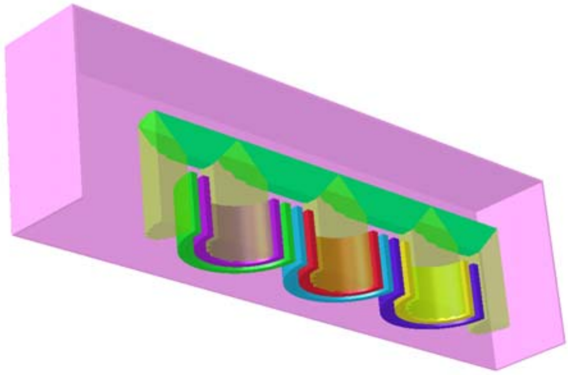

Fig. 5. Three-phase five-limb transformer model with 1/4 symmetry.

The core material in this model is considered nonlinear and anisotropic. The relative permeabilities of oil and windings are set to one. The tank material is linear with relative permeability of 1000. The conductivity of the tank is set to zero. The windings are modeled as stranded coils. This means that the current density distribution on cross section of the winding is assumed uniform. The program OPERA by Vector Fields [10] is employed for the modeling in this work, and all models are created by parametric scripts that allow changing the geometry and other parameters easily.

B. Circuit coupling

The connections of single-phase and three-phase transformers to external circuits are sketched in Fig. 6 and Fig. 7, respectively.

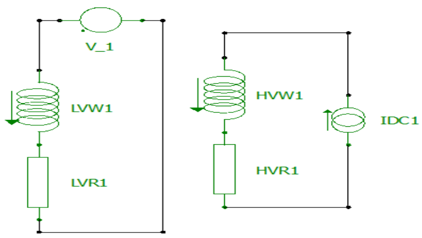

Fig. 6. External circuit coupled with a single-phase transformer

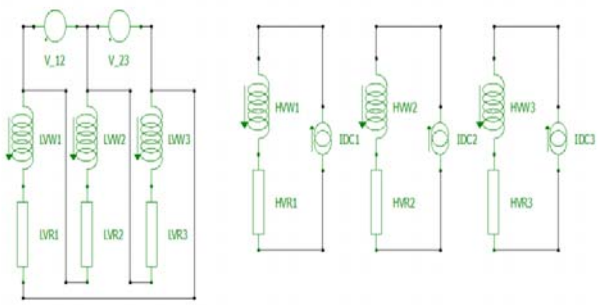

Fig. 7. External circuit coupled with a three-phase transformer

It is assumed that the injected DC is the same in each phase of a three-phase transformer or bank of single-phases. This is because the resistance determines the distribution of the DC current and we assume that the DC path is identical for each phase. Therefore, to study the effect of DC on no-load conditions of power transformers, the high voltage winding of each phase is connected to the DC current source and a resistor in series. The LV windings are connected to the voltage source. For three-phase transformers the connection type of the LV winding is a delta connection that is usual for step up transformers in power plants.

C. *Soft-start energization*

There is a transient phenomenon during the energization of RL circuits with an AC voltage [11]. This transient, which is damped through the resistance of the circuit, typically takes several cycles to decay. Therefore, in time-dependent finite element analyses it wastes a lot of time and computational effort to reach the steady state condition that is in the field of interest. In this work a soft-start energization is developed for omission of this transient. The soft-start process takes less than a quarter of a cycle and after that the real voltages are applied. The idea of soft-start process is to provide the linkage flux in each phase as the same as the steady state linkage flux corresponding to the applied phase voltage at the first moment, V_{start}.

The relation between the linkage flux and the induction voltage is determined by Faraday's law:

$$\psi(t)=\int V(t)dt+\psi_0 \qquad (1)$$

In power system under steady state condition the linkage flux of each limb crosses zero at the turning point (maximum or minimum) of the phase induction voltage and according to this reference point, the linkage flux corresponding with V_{start}, ψ_{start}, is calculated by using (1):

$$\psi_{start}=\frac{\beta V_{\max}}{2\pi f}\sqrt{1-(\frac{V_{start}}{V_{\max}})^2} \qquad (2)$$

, where V_{max} and f are the maximum and frequency of the sinusoidal induction voltage, respectively. β determines the sign of ψ_{start}. It can accept the value of +1 or -1 depends on the angle of the induction voltage at the first moment. If the induction voltage increases after V_{start}, it is -1. Otherwise it will be +1.

Therefore, the linear applied voltage to the windings during soft-start energization to reach the value of ψ_{start} could be:

$$V(t)=(\frac{\beta V_{\max}}{2\pi f}\sqrt{1-(\frac{V_{start}}{V_{\max}})^2}-0.5\,t_s\,V_{start})\frac{t}{T_{start}} \qquad (3)$$

, where T_{start} and t_s are the duration of the soft-start period, and time step of the simulation, respectively.

Fig. 7 and Fig. 8 show the magnetization currents of a three-phase transformer with the soft-start energization method and corresponding applied voltages, respectively.

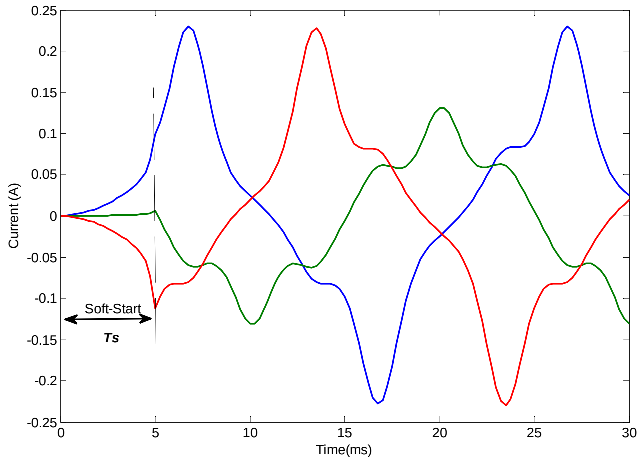

Fig. 8. Magnetization currents of a three-phase transformer with the soft-start energization.

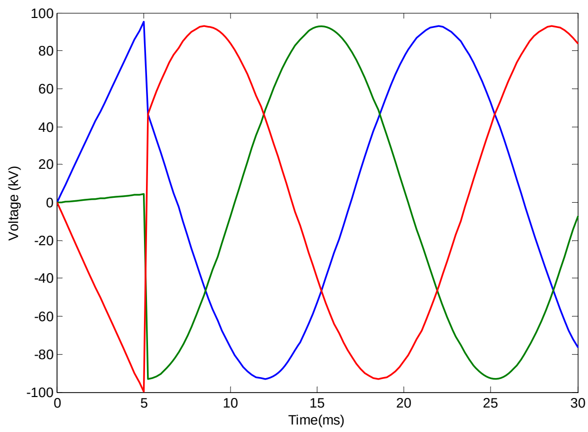

Fig. 9. Applied voltages with soft-start energization.

III. Results and Discussion

Saturation of a transformer core in one of the half cycles causes a very asymmetric magnetization current which contains both odd and even harmonics. These higher harmonics increase winding losses and stray losses in the metallic parts of the transformer. Furthermore, they can be important for the network and for protection relays. In this study the effect of core design on the created harmonics is investigated. The simulations have been performed for all mentioned types of power transformers. The generator step up transformer is studied in this work. The magnetization current has been obtained for several levels of GIC and applied voltage. The Fast Fourier Transform (FFT) has been employed for finding the frequency spectrum of the magnetization current waveforms.

The simulation results demonstrate that single-phase transformers are very sensitive to GICs. The various core types: two-limb, three-limb and four-limb, show similar behavior. The reason is that the DC current can easily saturate the core in single-phase transformers. In contrast, a three-phase three-limb transformer is very resistant against GICs. This is because of the structure of the core. The DC currents compensate each other in the main limbs and connecting yokes. As a result the core doesn't saturate easily and consequently it is not so affected by GICs. Nevertheless, three-phase five-limb transformers behave more similarly to single-phase transformers. Although DC currents compensate their effects of each other in the main limbs and their connecting yokes, they enhance each other to saturate the return limbs.

A. Single-phase transformers

The results of the simulations showed that single-phase power transformers have similar behavior regarding the magnetization current. For instance, the magnetization currents for a single-phase two-limb transformer without GIC, with GIC current near 50% and 100% of the maximum normal magnetization current are shown in Fig. 10 - Fig. 12, respectively. Also, Fig. 13 - Fig. 15 demonstrate the corresponding frequency spectrums. The amplitude of each harmonic is normalized to the peak value of the magnetization current waveform.

Analysis of the results shows that under normal AC magnetization, the first, third and fifth harmonics are dominant. However, in the presence of GIC, the second and fourth harmonics are enhanced. And, as was expected, the waveform contains a considerable DC component as well. The amplitude of the main harmonic can reach 30-40 % of the maximum magnetization current, which can reach nominal load current and even more, in turn. It means that the winding at least should endure 30-40% overload during the GIC.

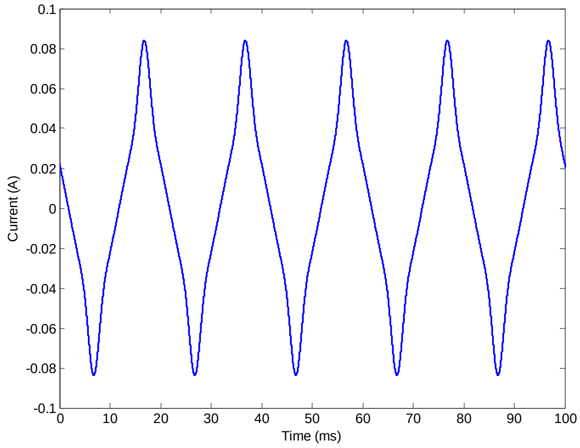

Fig. 10. Magnetization current of a single-phase two-limb transformer without GIC.

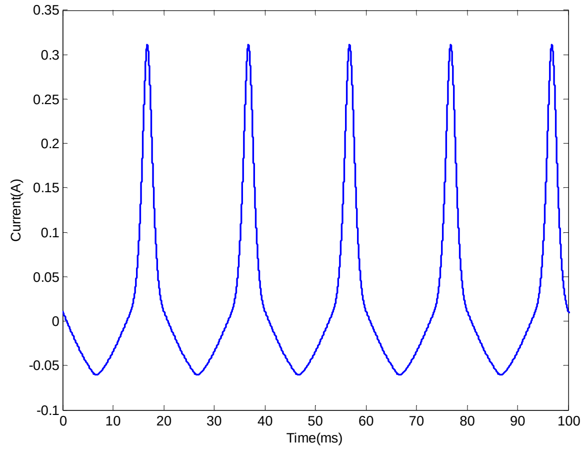

Fig. 11. Magnetization current of a single-phase two-limb transformer with GIC near 50% of maximum normal magnetization current.

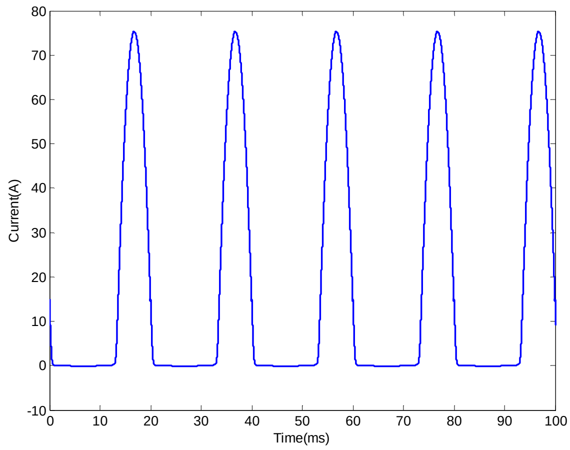

Fig. 12. Magnetization current of a single-phase two-limb transformer with GIC near 100% of maximum normal magnetization current.

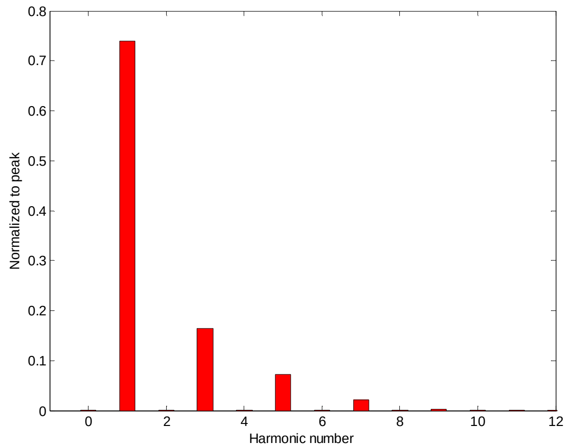

Fig. 13. Spectrum of a single-phase two-limb transformer without GIC.

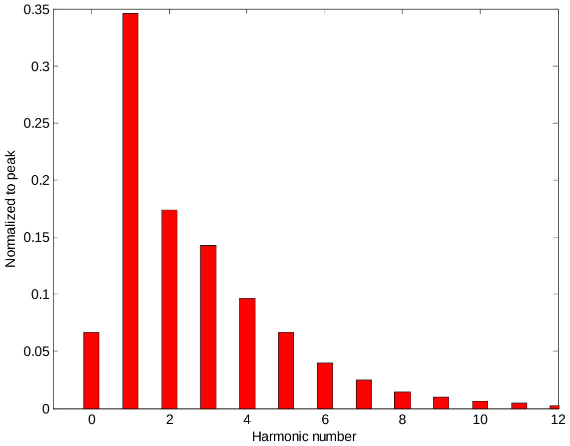

Fig. 14. Spectrum current of a single-phase two-limb transformer with GIC near 50% of maximum normal magnetization current.

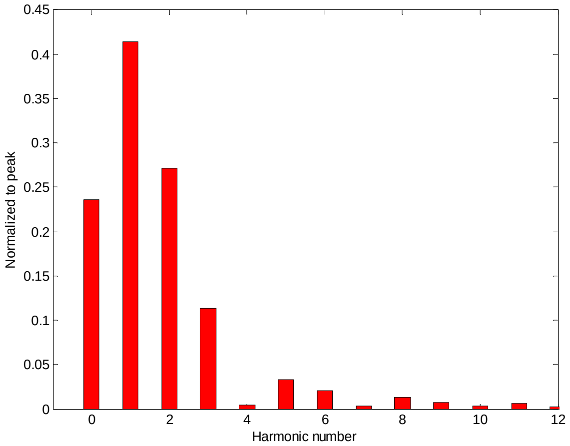

Fig. 15. Spectrum current of a single-phase two-limbs transformer with GIC near 100% of maximum normal magnetization current.

B. Three-phase transformers

As was expected, the behavior of three-phase three-limb transformers is different from three-phase five-limb transformers. Though five-limb transformers function similarly to single-phase transformers regarding GIC, the magnetization current shows a small difference.

The magnetization currents and the frequency spectrum of one of the phases under normal condition without GIC for a three-limb transformer are shown in Fig. 16 and Fig. 17, respectively. The magnetization current of this type of transformer does not show considerable change for low GIC levels. Fig. 18 and Fig. 19 show the magnetization currents and frequency spectrum, respectively, in the case of a high GIC level that is near 100 times the maximum of normal magnetization. It is obvious that GICs have no significant impact on the amplitude of the magnetization current. Although the even harmonics increase, they still are relatively small.

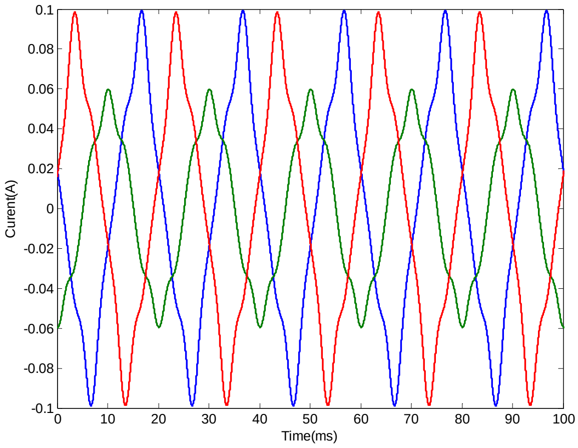

Fig. 16. Magnetization currents of three-phase three-limb transformer without GIC.

Although this type of transformer seems better for networks, due to higher leakage fluxes it could be more dangerous for transformer itself. Also, any unbalance in DC current distribution between phases could lead to saturation of the core.

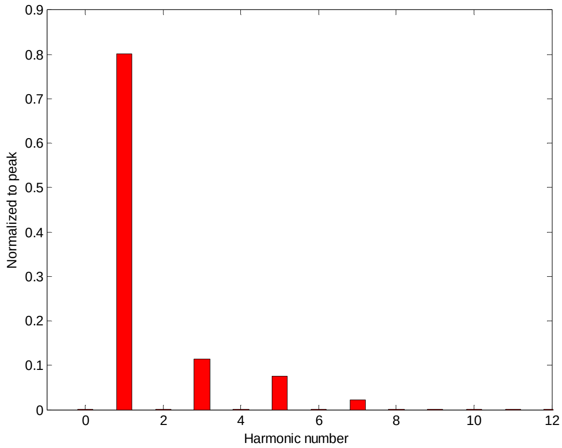

Fig. 17. Spectrum of a three-phase three-limb transformer without GIC.

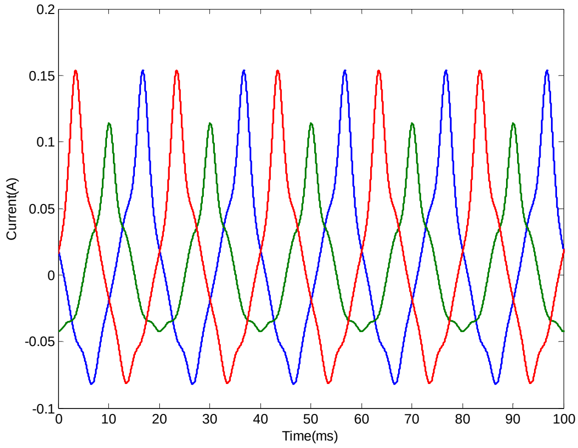

Fig. 18. Magnetization currents of a three-phase three-limbs transformer with a high GIC level.

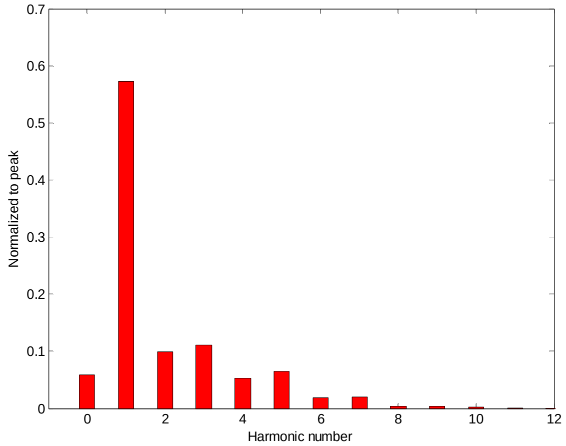

Fig. 19. Spectrum of a three-phase three-limb transformer with a high GIC level.

The magnetization currents of a five-limb transformer and the corresponding frequency spectrum are illustrated in Fig. 20 - Fig. 21 respectively. Comparison with Fig. 16 reveals that unlike the three-limb transformer the magnetization currents in each phase of the five-limb transformer have the same magnitude. Fig. 22 and Fig. 23 show the magnetization currents and frequency spectrum with GIC near half of the maximum normal magnetization current. It shows that the GIC can affect the magnetization current of a five-limb transformer the same way as a single-phase one, but more intensely. Also, the fifth and fourth harmonics are larger than the third one.

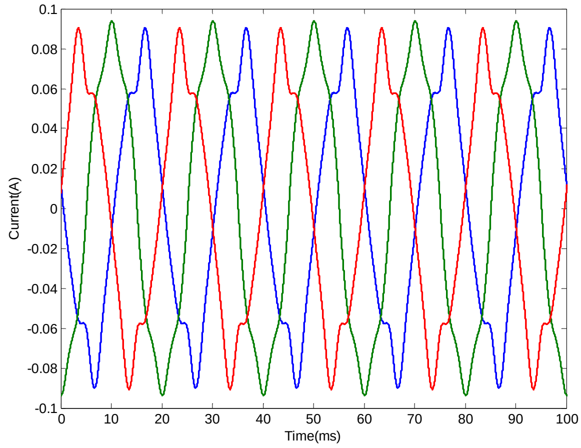

Fig. 20. Magnetization currents of a three-phase five-limb transformer without GIC.

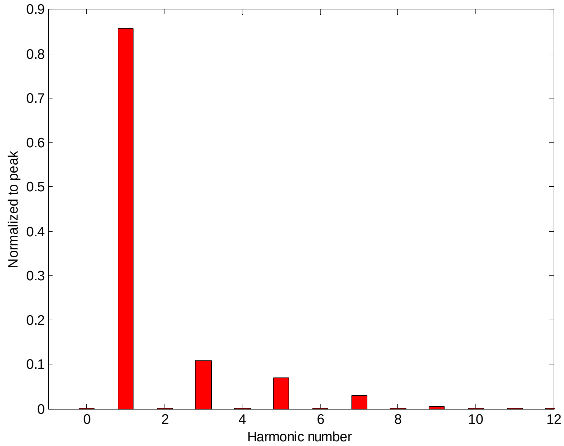

Fig. 21. Spectrum of a three-phase five-limb transformer without GIC.

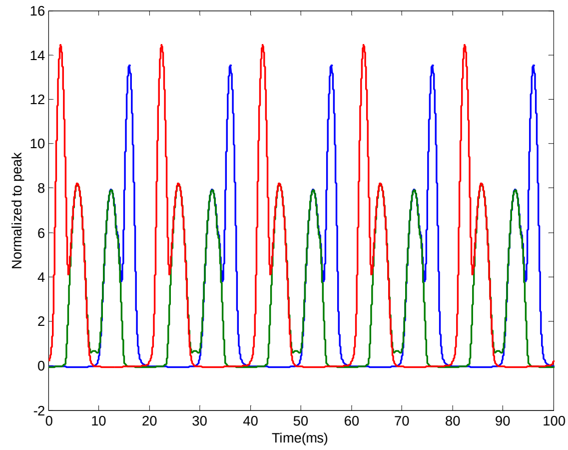

Fig. 22. Magnetization currents of a three-phase five-limb transformer with GIC near 50% of maximum normal magnetization current.

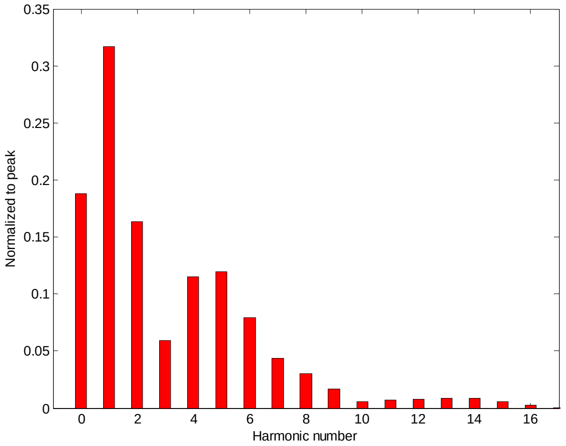

Fig. 23. Spectrum of a three-phase five-limb transformer with GIC near 50% of maximum normal magnetization current.

IV. CONCLUSION

The investigation of the effect of GIC on the magnetization current of power transformers has been done by using a three dimensional finite element model. This model can consider the geometry of transformers, saturation and leakage flux paths more realistically than transformer models that are used in power system analysis software. The aim of the study was the analysis of harmonic components that are generated by the asymmetric, high amplitude magnetization current caused by saturation of the transformer's core during a GIC event.

Also, different types of core-form transformers are modeled to have comparison between them.

The obtained results shows that in all types of single-phase transformers and also in five-limb three-phase transformers, even low level GICs can lead to half-cycle saturation of the core. This causes injection of both odd and even harmonics with considerable amplitude into the network, creating hot-spots inside transformers and misoperation of protective relays.

However, in three-phase three-limb transformers GIC hardly can saturate the core, since the injected DC currents in the limbs mostly compensate each other. As a result, even during high level GICs the magnetization currents of this type of transformers are not affected considerably. Although this type of transformer seems better for networks, due to higher leakage fluxes it could be more dangerous for transformer itself. Also, any unbalance in DC current distribution between phases could lead to saturation of the core.

This work can help to improve the protection system of power networks and transformers. Also, it can give a guide to choose of power transformers where is subjected to GIC.

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