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Journal of Applied Research and Technology

Journal of Applied Research and Technology 14 (2016) 87–92

www.jart.ccadet.unam.mx

Original

Core saturation effects of geomagnetic induced currents in power transformers

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Received 20 January 2015; accepted 1 March 2016
Available online 5 May 2016

Abstract

Saturation of the magnetic core of transformers in a power system is an important effect that can be attributed to solar Geomagnetic Induced Currents (GICs). This saturation can conduce to voltage-control problems, generating harmonic currents, and heating of the transformer internal components, leading to gas relay alarm/operation and possible damage. This paper presents an analog physical reduced scale model of GICs in power transformers. The instrumentation employed to carry out this study consists of a single-phase reduced scale transformer, a controllable current source, a resistive load and a data acquisition system. The work establishes not only that it is possible to model the behavior of magnetic variables and to extrapolate the results to large full size power transformers, but also provides insight into GICs generation and their effects on power transformers. Obtained results are related to the non-linear behavior of GICs due to asymmetric saturation of the magnetic core in the power transformer, where computational model simulation is not able to give acceptable outcomes. Results are discussed for several GICs magnitudes, which include voltage, current, harmonics waveforms, magnetic core point of operation, the behavior of the stray flow, instantaneous power and core temperature.

Keywords: Geomagnetic currents; Scale model; Asymmetric non-linear behavior

1. Introduction

Geomagnetic Induced Currents (GICs) are currents related to current flow in the ionosphere that interact with power systems. These currents are associated with solar storm activity and produce currents in the power grid that flow through transmission lines. These currents have a very low-frequency of 0.01–0.001 Hz (quasi DC) with average magnitudes of 10–15 A and peaks of up to 100 A for 1–2 min (Heindl et al., 2011).

Transformers with star connections and grounded neutrals that are linked by long transmission lines, as depicted in Figure 1, are susceptible to GICs problems due to the induced currents that flow through the transmission line and the neutrals that are grounded to close the circuit.

Several undesirable effects, produced by GICs in electrical power grids and transformers, have been reported. Moreover, when the DC magnetic flux is superimposed on the AC flux, the magnetic cores in the transformers are asymmetrically saturated (Lahtinen & Elovaara, 2002; Takasu, Oshi, Miyawaki, Saito, & Fujiwara,1994). The reported failures in transformers due to GICs are mainly dielectric and not a result of overheating. The effects of GICs on the grid and the transformers are summarized as follow: effects on the electric grid; on the one side when the reactive loads in the system are changed, the protections are misaligned and the internal resonant frequencies of the transformer change.

This process generates voltage surges that eventually degrade the insulation. On the other side, the magnetization impedance decreases, and the magnetizing current and the losses without loading increase. Reactive load absorption can cause instability in the electric grid (Berge, Varma, & Marti, 2011). Moreover, harmonics are contributed to the system, and even harmonics are generated.

Effects on the transformers are related to the relative permittivity of the magnetic core and the magnetization impedance decrease significantly (Bolduc, Gaudreau, & Dutil, 2000; Price, 2001). The magnetic core losses increase due to hysteresis, and

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Peer Review under the responsibility of Universidad Nacional Autónoma de México.

http://dx.doi.org/10.1016/j.jart.2016.04.003

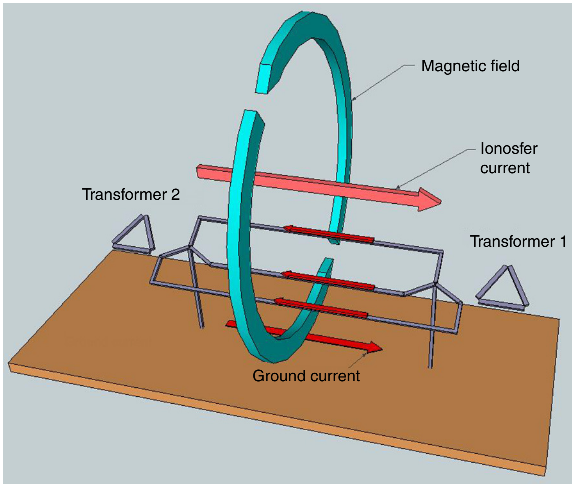

Fig. 1. Schematic diagram of the GICs flow in the electrical power grid transmission line.

eddy currents and the losses in the windings due to the Joule effect increase. Furthermore, the skin effect that is associated with harmonics in the current and in the magnetic flux increases. Heat increases in the fittings and tank due to the effects of eddy currents that are associated with increasing stray flux and with the appearance of even harmonics (Picher, Bolduc, Dutil, & Pham, 1997; Walling & Khan, 1991; Zhigang et al., 2010). The first harmonic vibration component in the transformer arises due to magnetostriction. Residual magnetism occurs in the core even when GICs are no longer present and the Inrush phenomenon occurs until the transient has died away.

These effects make it difficult to determine transformer design parameters that consider the effects of the GICs and adequately support them. The simulation of these operating conditions with a reduced-scale functional model provides useful information regarding the non-linear behavior of the transformer. In a real power transformer, these tests are very difficult to carry out, due to the big magnitudes of the currents and powers involved. This problem was resolved by using approximate numerical solutions. However, only real measurements are capable of validating these results. Currently, digital simulation tools do not account for time-dependent asymmetric saturation, which requires the development of specific models for each type of transformer (Egorov, 2007). The approach proposed in this work considers a fabricated small reduced-scale transformer, an experimental setup that permits the simulation of GICs and the use of instrumentation for measuring key variables.

2. Reduced-scale model and GICs simulator

The transformer model is specified and scaled in order to simulate GICs effects over real transformers. The focus in this work is to simulate only the core losses, losses in the windings produced by GICs, which are the dominant sources of heat associated with the currents and magnetic fluxes harmonic content.

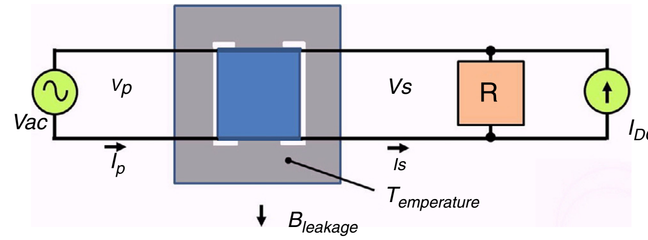

Fig. 2. Monophasic transformer GIC simulator block diagram.

2.1. Reduced-scale transformer

To manufacture transformer scaled must consider several design parameters so that their behavior is as close as possible to real transformers. For example, the operating point of the magnetic core is desired to be equal to the real transformers. The sectional area of the magnetic core and windings must be scaled based on the transformer's power. High voltage windings were not considered since only the effects of the currents in the transformer are intended to be analyzed. A single phase of a three phase transformer bank scaled manufactured to simulate in the GICs was selected.

2.2. Structure of the GICs simulator

The simulator consists of a transformer with single-phase reduced scale with three legs, a controllable current source, a resistive load and the electronic instrumentation data acquisition system for measuring the primary and secondary voltages and currents, DC current in order to simulate GICs, the density stray magnetic flux outside the magnetic core and the temperature of the transformer core for different operating points. Figure 2 shows a simplified schematic diagram of the simulator.

The scaled single-phase transformer was designed to be feed with a voltage of 120 V in the primary and the secondary 6.0 V and a load current in the secondary of 100 mA and shell-type construction. A resistive load of 50 Ω, which is the rated transformer load, was considered. The objective of this simulator is to evaluate the effect of GICs with the transformer operating at its rated load.

The reduced-scale transformer is feed by a variac that allows changing the supply voltage from 0 to 120 VAC. The source of DC current "IDC" that simulates the GICs, allows the current supplied to the secondary of the transformer to be adjusted from 0 to 250 mA DC, from 0 to 250% of the value RMS of nominal current. The IDC current mainly flows through the secondary winding of the transformer because its resistance is 1/50 of the load resistance. The currents in the primary and secondary transformer are measured by resistive shunts, and the voltage measurement points have voltage dividers that are appropriate for not exceeding the voltage limits of the data acquisition system.

The stray magnetic-flux density is measured with a Hall-effect sensor that is located in the external portion of the core, at the central leg and parallel to the magnetic flux that is produced by the transformer winding. This localization was chosen