INVESTIGATION OF GIC RELATED EFFECTS ON POWER TRANSFORMERS USING MODERN DIAGNOSTIC METHODS

M. Heindl[1*], M. Beltle[1], M. Reuter[1], D. Schneider[1], S. Tenbohlen[1]
D.T. Oyedokun[2] and C.T. Gaunt[2]
[1]University of Stuttgart, Pfaffenwaldring 47, 70569 Stuttgart, Germany
[2]University of Cape Town, Private Bag X3, Rondebosch 7701, South Africa
*Email: maximilian.heindl@ieh.uni-stuttgart.de

Abstract: Geomagnetically Induced Currents (GIC) are supposed to be a threat to power transformers worldwide. Recent surveys show correlation between solar storm activities, the cause of GIC, and transformers failing within a relatively short time period. The scope of this contribution is to create and investigate a laboratory setup emulating GIC effects by injecting DC currents into a three phase power transformer. Transformer under test is a 30 kVA oil immersed transformer energized by a 400 V variable ratio transformer. The load consists of a symmetric, star connected three phase resistance. A DC source situated between the secondary neutral terminal and the neutral point of the load injects a current emulating GIC. The effects of the DC offset on core hysteresis curve, partial discharge (PD) appearance and the transformers vibration behaviour are presented. The investigation shows half wave saturation of the core due to the DC offset contrary to nominal operating conditions. Hence a shift of the hysteresis loop can be monitored. Measured PD levels increase, which is potentially the reason of transformer failures after a GIC event. The measured vibration patterns of core and tank show a DC dependency. This change in the vibration pattern can be used as an easy to apply GIC indicator.

Index Terms - GIC, Power Transformer, Partial Discharges, Core Vibration Pattern

1 INTRODUCTION

Geomagnetically Induced Currents (GIC) are a phenomenon which is in causal connection with space weather. It is affecting long distance electrical conductor lines on Earth like high voltage overhead lines, pipelines or railways [1,2].

Solar flares are large eruptions originated on the surface of the sun, releasing large portions of energy (up several 10^{25} Joule) into free space. The ejected energy is transported by plasma streams radiating across the electromagnetic spectrum in a very broad band up to gamma ray frequencies. When a shock wave of particles, having high energy with almost speed of light, hits the Earth's magnetosphere, complex interactions result in a weakened geomagnetic field, enabling increased streams of charged particles through the atmosphere [3]. Periodic variations of the resulting geomagnetic field and the ionospheric currents lead, according to Faraday's law of induction, to variation of the electric field intensity penetrating the Earth's surface [1]. High voltage overhead lines of several hundreds of kilometres form a conductor loop together with the Earth ground, which is terminated by power transformers at the end of these transmission lines. The entire configuration enables induction of currents within the conductor loop area, the so-called GIC. Due to the fact that the variations of the electrical field are in the range of minutes, the currents can be regarded as quasi stationary direct currents (DC). Fig. 1 shows a

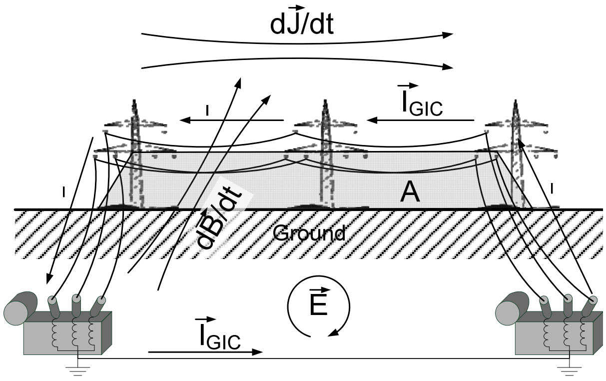

Figure 1: A varying ionospheric current density *dJ/dt* produces a variable electrical field *dE/dt* leading to quasi stationary currents I_{GIC} in a large conductor loop *A* formed by a long high voltage overhead line terminated by two transformers with grounded neutral.

simplified illustration of the underlying circumstances.

Stationary current flowing through a transformer's winding severely disturbs the coordination of its magnetic circuit, i.e. saturation of the core [4,5]. In the past, several transformer failures worldwide raised suspicion to be caused by GIC [6,7]. This paper investigates basic effects of GIC on power transformers using modern diagnostic methods on a small three phase distribution transformer, called transformer under test (TUT). Findings can be scaled up to large power transformers for further investigations and analysis in order to illuminate the GIC effect on power transformers.

2 EXPERIMENTAL SETUP

As TUT a 30 kVA YNyn6 distribution transformer with a maximum output voltage of 7.5 kV is used. The unusual secondary side voltage emerges from modifications of the primary side cabling. Before recabling the TUT has been wired Yzn5 with 10 kV secondary side voltage. For injection of DC into the star point this Yzn active part was rewired to YNyn with accessible star points on primary and secondary voltage side. A variable ratio transformer is used for supplying the primary side of the TUT with three phase AC voltage in a range of 0 – 400 V. The transformer was loaded with a star circuited three phase load having 40 kΩ in each phase, see Fig. 3.

For simulation of a GIC event DC is injected into the load side star point, raising its potential to 1.5 kV_{DC}. The AC voltage of the transformer is not raised significantly as the winding resistance is way lower than the load resistance. The voltage divider given by load and winding resistance leads to a DC voltage offset of 1.875 V_{DC} at the secondary side of the transformer according to $R_{Winding} / R_{Load} * V_{DC} = 1.25*10^{-3} * V_{DC}$. The DC source injects a current directly dependant to the single phase load resistance value, here 10 kΩ. As the maximum voltage is 1.5 kV_{DC} a maximum DC of 150 mA can be injected into the star point, hence 50 mA per phase. As the secondary side magnetization current of the TUT is about 100 mA the DC source is able to deliver a current that is half of the magnetization current. This leads to saturation effects within the transformer core

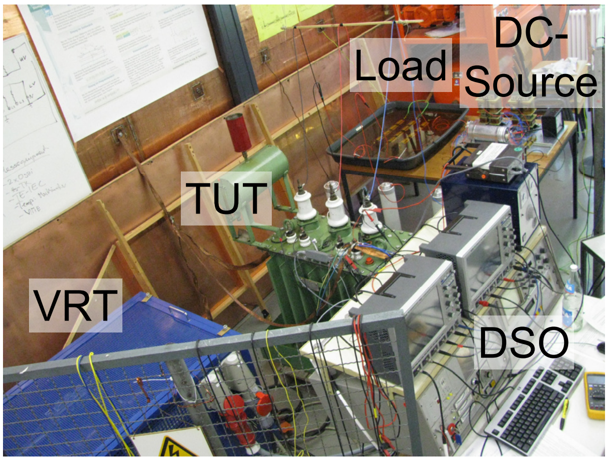

Figure 2: Photo of the experimental setup, showing TUT and measurement equipment

material, comparable to situations occurring at GIC events. The DC source itself is not affected by AC because superimposition of AC phases at load star point is null for symmetrical load cases.

For monitoring of the secondary side voltage to ground a 1:200 resistive voltage divider and a digital storage oscilloscope (DSO) is used (see Fig. 2). The primary side current is metered with a current clamp. To determine core magnetization a voltage integrator is used, consisting of a series resistor and a capacitor to ground. Given the case, that the used series resistor $R_S >> 1/\omega C$ and $R_S >> \omega L_{Sec.Side}$ the output voltage U_{out} of this RC-filter is proportional to $U_{out} \sim \int i(t) \sim B_{Core}(t)$. As the primary side current is measured directly the hysteresis curve $B(H)$ can be calculated.

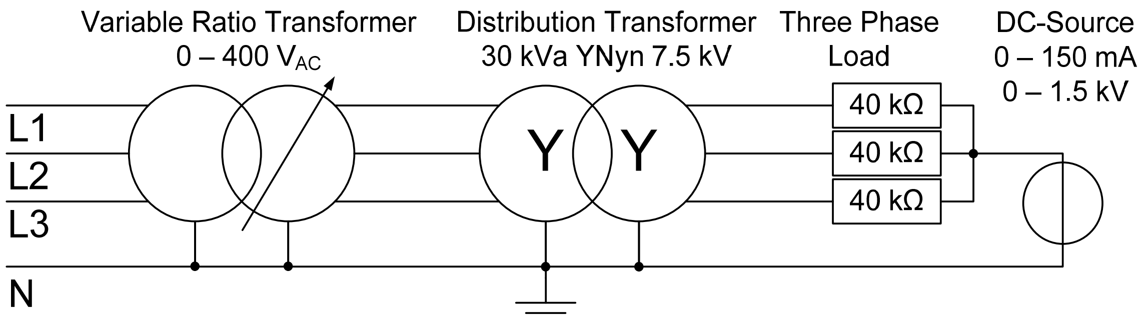

Figure 3: Three-Phase Test Setup, consisting of Variable Ratio Transformer, 30 kVA Distribution Transformer, three-phase Load and DC-Source for simulation of a GIC Event.

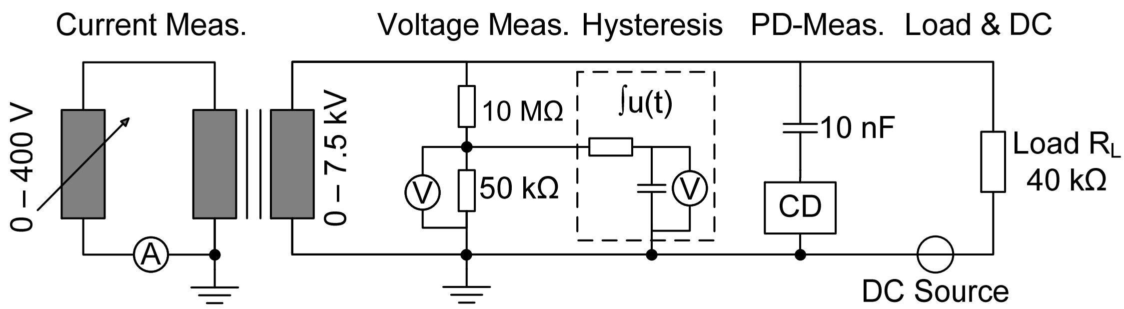

Figure 4: Measurement equipment at Phase 1 for monitoring of Voltage, Current, Core Magnetization and Partial Discharges (Only one of three phases sketched).

A system for 3-phase PD measurements according IEC 60270 (Omicron MPD540) is installed and also acceleration sensors for core vibrations are used.

3 INFLUENCE OF DC OFFSET ON TRANSFORMER CORE

3.1 Calculation of core losses with hysteresis curve

Ferromagnetic materials show a time variant, non-linear behaviour in terms of magnetic field strength and flux density which is caused by the Weiss Domains that align themselves along an external magnetic field. This effect can be observed by measuring the hysteresis loop of a transformer.

A primary (low voltage) winding coil of a transformer with number of turns n_1 and geometric length l_1 carrying current $I_1(t)$ generates the magnetic field $H(t)$:

$$H(t) = \frac{n_1}{l} \cdot I_1(t) \tag{1}$$

In the secondary (high voltage) winding with cross section area A and number of turns n_2, arranged concentrically around the primary winding, the voltage

$$U_{ind}(t) = -n_2 A \frac{\mathrm{dB(t)}}{dt} \tag{2}$$

is induced. Hence the magnetic flux density $B(t)$ can be obtained by integration of the induced voltage. This is done by an RC circuit where $R >> 1/\omega C$, see Fig. 4. As a good approximation, the voltage across the capacitor C is

$$U_C(t) = \frac{n_2 A}{RC} \mathrm{B(t)} \tag{3}$$

The signals of $I_1(t)$ and $U_C(t)$ are recorded with an oscilloscope and give the B-H-curve (hysteresis loop). The core losses $W_{Fe,0}$ of one transformer limb in open circuit condition (unloaded) can be calculated as

$$W_{Fe,0} = l \cdot A \cdot \oint HdB \tag{4}$$

Using (1), (3) gives

$$W_{Fe,0} = -RC \frac{n_1}{n_2} \cdot \oint I_1 dU_C. \tag{5}$$

In open circuit condition, the core losses per cycle are proportional to the area of the hysteresis curve. Under load condition, this area is proportional to the load energy plus the core losses per cycle.

3.2 Effect of DC injection on hysteresis curve

In order to verify correctness of the laboratory setup, the effect of DC on the transformer B-H curve was investigated with the above described techniques (40 kOhm star connected load). Fig. 5 shows the recorded low voltage current vs. the integrated high voltage. The injection of DC causes a vertical shift of the loop which means a direct component of the magnetic field $B(t)$.

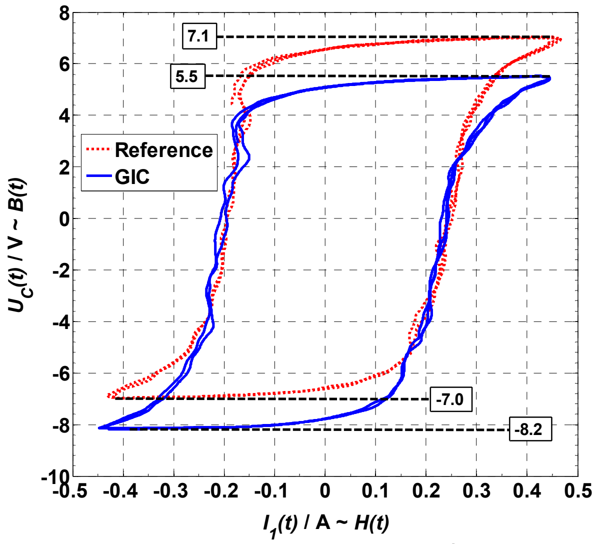

Figure 5: B-H hysteresis curve of TUT with resistive load, 3 cycles shown. Injection of DC leads to shift of the hysteresis loop.

This effect can be amplified by increasing of the DC. For the shown case the transformer does not reach full half wave saturation due to limitations of the DC supply. Saturation of the core leads to increased stray flux outside of the core which causes additional losses. Finally, this heats up the whole transformer. Thus, DC leads to an increased stress level of the entire insulation. Depending on the flux distribution the impact of local incidents e.g. hot spots could be intensified. In this experiment DC up to 150 mA was injected. Real GIC are assumed to be in the range of 50-200 A with significantly higher thermal energy.

4 DIAGNOSTIC MEASUREMENT RESULTS

4.1 Partial Discharges

According to IEC 60270 [8] a partial discharge (PD) is a localized electrical discharge that bridges the insulation between conductors. Thus it indicates an insulation weakness. PD can occur at construction faults or damaged electrical insulation of the transformer. PD activity is measured in apparent charge, as it is not possible to determine the actual discharge amount [9].

PDs are decoupled with a high voltage capacitor, as shown in Fig. 4 [8]. A coupling device (CD) is used to integrate the flowing pulse current as PD activity is measured in apparent charge. A parallel voltage measurement allows a phase resolved discharge partial discharge (PRPD) pattern correlating apparent charge with applied test voltage phase angle.

According to IEC 60270 the PD source activity is measured in a frequency range of 1 MHz and a bandwidth of 40 kHz. Measurements show a small PD source with a PD initiation voltage of 2 kV. Fig. 6 shows the PRPD of the PD source at a test voltage of 2.3 kV and active DC source.

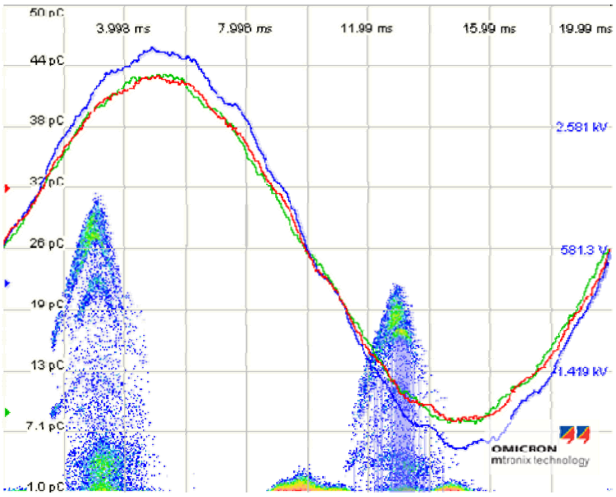

Figure 6: Phase resolved Partial Discharge Pattern of Phase 2 at a test voltage of 2.3 kV and active DC source. Phase stable clusters of ~30 pC in first and ~20 pC in third voltage quadrant are visible.

Lowering the test voltage below 2 kV the noise floor of this lab test setup is around 2 pC, depending on disturbances of ambient electronics.

Fig. 7 shows the PD source apparent charge over time. Within the first minute the PD source activity is around Q_{App} = *15 pC*. After one minute the DC source was activated injecting a DC of 50 mA per phase. Fig. 7 shows that having a DC offset, the PD source activity raises significantly to a level of about 27 pC, hence by factor 1.8. Switching the DC source off after 2 min the PD level lowers for 30 seconds. After reactivating the DC source also the PD source also is reactivated.

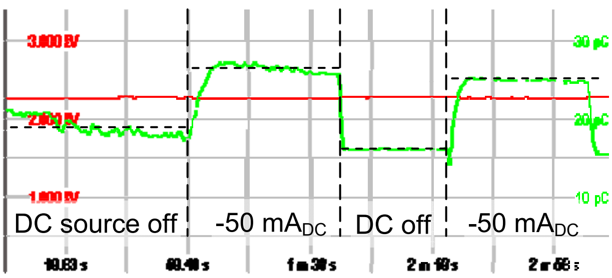

Figure 7: Apparent charge of PD source (green) within Phase 2 over time at constant excitation voltage (red). A clear correlation between PD activity and DC offset is visible.

The detected PD levels do not originate from the DC source: On the one hand, DC related PD would not result in phase synchronous PD patterns, and on the other hand, if there would be an active PD source inside the DC generator the discharge pulses would be attenuated by the load resistances, see Fig. 4. A PD calibrator, having an output of Q_{App} = *10 nC*, attached to the DC source output port did not show a noise level raise at the PD measurement system (~ 2 pC). Hence, PD sources inside the DC generator would need to have a way higher apparent charge than 10 nC to corrupt presented PD levels, which is unlikely due to the low applied DC voltage of $V_{DC,max}$ = *1.5 kV*.

In this setup it is possible to activate a PD source by injecting direct current. There is no theoretical explanation of this effect yet, because recent theory explains PD as voltage based phenomenon. But the PD activity enhancing effect of injected DC is reproducible. Because of voltage division of load and winding resistances the observed effect is current related and not DC offset voltage dependant.

Thus a transformer, having insulation weaknesses but no PD activity at normal service might show PD within a GIC event. That could lead to further insulation degradation. The activated PD source caused by GIC could remain active within the transformer even after the inducing GIC event has subsided, because of the meanwhile degradation. Therefore short pending GIC could lead to long term insulation weakening and even to a complete insulation failure.

4.2 GIC dependent vibrations

GIC on power transformer can be observed by vibration measurements. Vibrations are caused by voltage-dependent and load-dependent effects, which lead to oscillations in mechanical structures of power transformers.

The voltage-dependent vibration is originated by magnetostriction leading to oscillations of the core (e.g. lamination sheets). The Weiss Domains in metal align themselves along the time-varying magnetic main flux induced by applied voltage. For Weiss Domains claim a certain area in the material, their movement result in a changing length of the whole material. Expanding and tightening lamination sheets causes mechanical vibration at doubled electrical frequency [10].

At load condition, current-related effects superimpose magnetostriction. Forces of the alternating magnetic field affect current-carrying windings leading to an oscillation also with doubled electrical frequency.

4.3 Measurement of Vibrations

Vibrations are recorded using acceleration sensors. For the GIC setup, 2 sensors are used, see Fig. 8. For lamination sheets are considered to be a major source of vibrations sensors 1 and 2 are positioned directly on the yoke of the core. Sensor 1 is positioned over the middle limb, sensor 2 over one outside limb to detect unbalances. After amplification signals are recorded using a DSO.

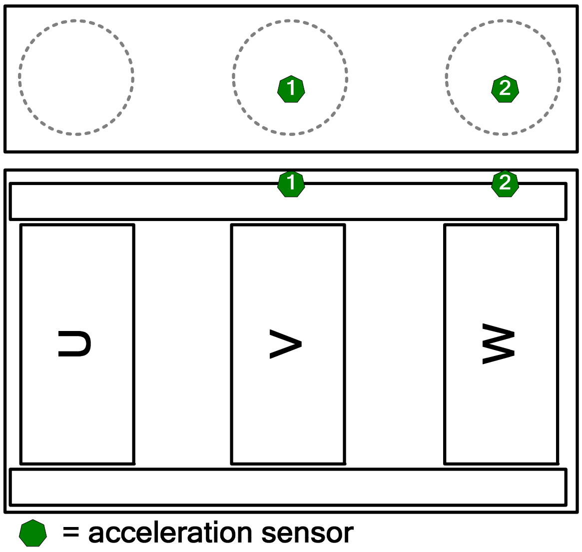

Figure 8: Transformer's top and side view with sensor positions

4.4 Vibrations of Direct Current

GIC related direct currents change the magnetic flux of the core leading to changes of correlated vibrations. Fig. 9 shows the vibrations recorded with sensor 1 in time domain. The dotted signal is recorded at an applied test voltage of $U_{Test} = 2\ kV_{AC}$, applied 3-phase load and no DC injection. With DC (straight line) the 100 Hz oscillation is superimposed by 50 Hz, as shown in the corresponding frequency spectrum in Figure 10.

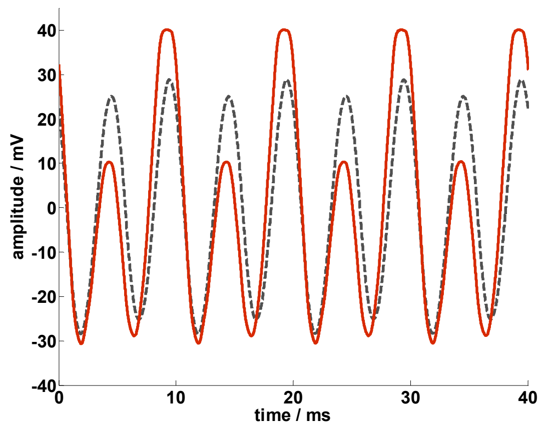

Figure 9: Vibration signal of Sensor 1 without (dotted) and with DC (straight line).

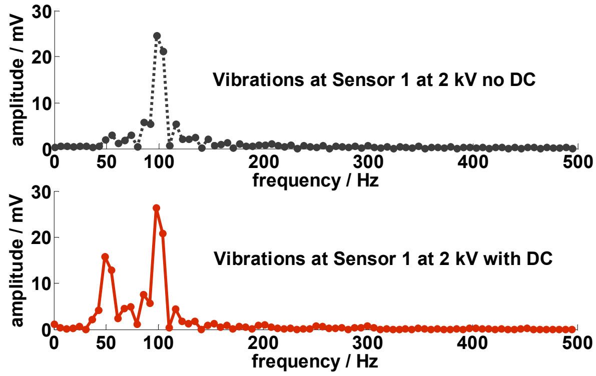

Figure 10: Frequency spectrum of sensor 1, vibration signal without (dotted) and with DC (straight line)

Considering sensor 2 the spectrum without DC differs from sensor 1 due to the complex mechanical structure of the core. Nevertheless the impact of direct current on the resulting core vibration can also be observed, see Figure. 11.

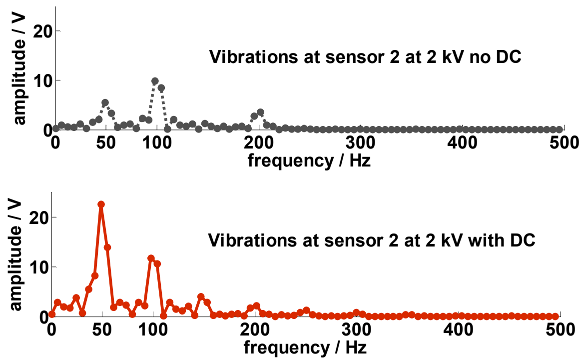

Figure 11: Frequency spectrum of sensor 2, vibration signal without (dotted) and with DC (straight line)

The effect can also be recorded using acceleration sensors on the tank surface. But tank surface sensors deliver a more complex frequency spectrum as only a superimposition of vibrations of all limbs can be measured.

Transformer's vibrations depend on direct currents. Therefore acceleration sensors could be used as easy to apply indicators for the occurrence of GIC. Thus duration and severity of GIC events can be recorded using power transformer monitoring with acoustic sensors.

5 CONCLUSION AND OUTLOOK

The focus of this contribution is to demonstrate the influence of geomagnetically induced currents on transformers. Therefore a lab setup is built, consisting of a 30 kVa 3-phase transformer and a 40 kΩ 3-phase load. Direct currents up to 150 mA can be induced into the system, simulating GIC on the high voltage side of the transformer.

Using this setup the influences on the transformer are determined. The transformer's magnetisation is measured by its hysteresis curve. A 3-phase electric measurement system is used to detect PD according to IEC 60270. Vibrations originated by the core are directly measured on the core yoke and on outside tank wall using acceleration sensors.

The investigation reveals a dependency of all mentioned variables and GIC. Direct currents lead to changes of the hysteresis curve. It is shifted and deformed. The resulting enlarged area within the curve indicates an increased loss of energy in the core and therefore additional heating and insulation stress.

The detected PD activity also shows DC dependent behaviour. On this setup it is possible to excite a phase correlated PD source by injecting direct current.

The change in the core magnetisation leads to modifications in its vibration behaviour. Vibration frequency pattern is superimposed with 50 Hz oscillations and harmonics when DC is applied.

The correlation of all variables concludes in the following. The observed effects of GIC on transformers considering PD are evident. GIC occurrence can be detected in a change of transformer's vibration spectrum. Vibration measurement is easy to apply by using sensors at the outside of its tank wall enabling onsite, online monitoring.

Although the considered laboratory setup is small with low excitation voltages, measurement results of hysteresis curve correspond to effects expected on power transformers. Therefore it is possible to emulate GIC by injecting DC in the small laboratory setup. The observed effects could also happen in bigger scaled power transformers leading to damages of the insulation or even to failures occurring after GIC events.

Further investigations about these phenomena on large scaled setups shall be followed and the scalability of the setup investigated. A PD measurement system, investigating the radiation of the PD source in the ultra high frequency (UHF) range should be attached to the UHF sensor inside the transformer tank. Also long term effects as core heating, dissolved gases in the insulation oil and electrical losses should be measured.

6 ACKNOWLEDGEMENTS

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