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Experimental Application of Leakage Flux to the Detection of Insulation Faults on Disc-Type Winding Transformers

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Abstract. This paper presents an experimental study carried out on a disc-type winding transformer. Although several industrial methods exist for the on-line and off-line monitoring of power transformers, all of them are expensive and complex, and require the use of specific electronic instrumentation. In this paper, an on-line analysis of transformer leakage flux is tested as an efficient alternative procedure for detecting insulating failures during their earliest stages. A power transformer was specifically manufactured for the study. A finite element model of the machine was designed to obtain the transient distribution of leakage flux lines in the machine's transversal section under normal operating conditions and when shorted turns are intentionally produced. Very cheap, simple sensors, based on air core coils, were built in order to measure the leakage flux of the transformer, and non-destructive tests were also applied to the machine in order to analyse pre- and post-failure voltages induced in the coils. Results point to the ability to detect very early stages of failure. The asymmetry produced by the failure generates an indicator (induced EMF in the coils) that can be easily distinguished from the one obtained for the healthy machine. In fact, diagnosis can be perfectly achieved in spite of the variation of such an indicator with load.

Key words

Power transformers insulation, diagnosis, leakage flux analysis.

1. Introduction

Electrical rigidity of the interturn insulating systems in power transformers is much greater than the dielectric stress produced when the machine is operating in steady state under its rated voltage. However, when a Very Fast Transient Overvoltage (VFTO) appears, interturn insulation is exposed to a high electrical stress capable of deteriorating the system. VFTO's sources are usually two: switching operations of circuit breakers and atmospheric discharges affecting the electrical grid.
Atmospheric discharges produce VFTO's that may affect machines and facilities by means of different mechanisms: direct coupling through the conductors, magnetic induction in conductors located at the vicinity, capacitive coupling, generation of electric arcing to lower potential points, ground potential rise (GPR), etc, [1]. This type of transient overvoltage, become the windings of electrical machines a set of transmission lines. For this reason, voltage distribution of a surge is never linear and regions with high concentration of electrical potential appear at different turns of the windings. In the case of power transformers, the highest risk appears when the surge excites any resonance frequency of the windings [2,3]. In fact, resonant overvoltage can cause interturn electrical discharges or discharges between the windings and the magnetic core, [2]. Numerous studies have demonstrated that interturn insulation is especially affected by this type of high frequency oscillation, [2,4].

Switching operations of circuit breakers can also produce similar effects on the transformer windings. In [5] a non linear voltage distribution caused by VFTO's during switching operations is analysed. In this case, abnormally high voltage levels appear between turns number 1 and 2 and turns number 41 and 42 of an experimental transformer specially designed for the study of the propagation of voltage surges.

During switching operations, the circuit breaker may suffer pre-strikes and re-strikes, [6], than can lead to high frequency oscillations that are superimposed to the supply frequency. The repetition of this phenomenon may lead to long-term faults, especially if the oscillations match the natural frequency of the transformer and thus produce the partial resonance of its windings, [7].

Although transformers are always equipped with arresters in order to eliminate or reduce the effects of VFTO's, they are only able to diminish the overvoltage amplitude but not its rise time [8]. For this reason, its protection capacity is limited and even with a proper design of the protections interturn insulation may be subjected to high stresses.
The above results clearly demonstrate that interturn

insulation system in power transformer is subjected to stresses caused by both switching operations and atmospheric phenomena. The stress appeared at the turns of the windings during these phenomena may easily exceed the electric rigidity of the insulation. For this reason, interturn faults may be considered as one of the more likely root causes of breakdown in high voltage power transformers. Since transformers are essential components of the electrical power systems, their perfect operation determines the quality of power supply. Moreover, faults affecting these machines are usually serious for the electrical facility and the production process in which they are involved. These reasons make the prevention of insulation faults on transformers an important goal to improve the quality of electrical power systems. This paper will present experimental results about on-line analysis of transformer leakage flux: an efficient alternative procedure for assessing machine integrity and detecting the presence of insulating failures during their earliest stages.

2. Foundations of Leakage Flux Analysis Applied to the Diagnosis of Power Transformers

In power transformers, not all the flux produced by the primary winding passes through the secondary winding, nor vice versa. Instead, some of the flux lines exit the iron via the air. The portion of flux that goes through one of the transformer windings but not the other is called leakage flux. The amount of this flux mainly depends on the ratio between the reluctance of the magnetic circuit and the reluctance of the leakage path. Leakage flux lines in transformers are curved at the ends of the coils and flow through the air almost parallel to the winding axis, [9]. The degree of curvature of the lines is affected by the distance between the coils and the machine's shield and the latter's distribution in the air is influenced by the type of winding used in the machine's construction, [10].

Leakage flux has been previously proposed by the authors as a tool for fault detection in a different type of transformers [11-12]. The aim of this paper is to study more in deep the behaviour of this magnitude in different operating conditions in order to be applied to the early detection of interturn insulation failures in operating three-phase power transformers with disc-type windings. The foundations of the method, presented in [13], are extremely simple since they are based on the detection of changes caused in leakage flux linepaths by the presence of the insulation failure. Leakage flux can be analysed by measuring the voltage it induces in very simple air core coils located at the surface of transformer windings. As will be later shown, leakage flux lines in a healthy transformer have a horizontal axis of symmetry that passes through the middle of the magnetic core of the machine. When a short circuit, or even a strong deformation, of one or several turns occurs, this symmetry is lost and the fault can be detected by measuring voltage changes induced in the sensors. In the next sections, an experimental transformer specifically built for this study, and laboratory tests, will demonstrate the validity of leakage flux for the early detection and location of shorted turns in three-phase disc-type winding power transformers.

3. The Experimental Transformer

Power transformers generally present two different structures in their windings: concentric layer windings and disc-type windings. Fig. 1 shows these two types of winding.

The first stage of the study consisted of designing and constructing a power transformer with this type of winding to analyse the behaviour of leakage flux under different failure levels when operating at different loads. A 12 kVA 400/400V transformer was thus built with a series of leads connected to different turns in the three phases of the primary and secondary windings. The overall structure of the transformer is shown in Fig. 2, its technical specifications are presented in Table I and its appearance can be seen in Fig. 3.

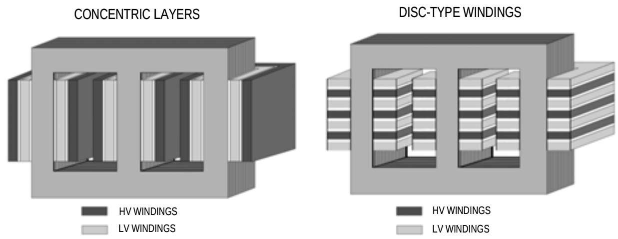

Fig 1. Types of windings in power transformers

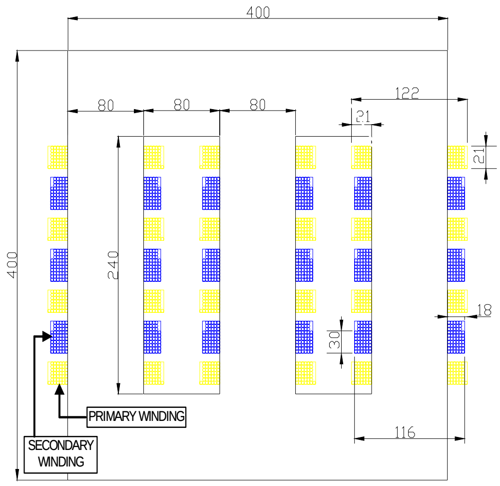

Fig. 2. Structure of the transformer

The windings of this transformer are built in several discs: 4 discs for the primary winding and 3 discs for the secondary windings. The windings were built with connection leads between different turns belonging to different layers of several discs. These leads were connected to a secondary terminal box fixed to the transformer structure. Different number of turns could thus be externally short-circuited by simply connecting a cable or a resistance. If limitation of the failure current is desired in order to prevent permanent winding damage during the tests, a set of air-cooled resistances can be connected to the transformer windings. In this way, the current circulating through the failure zone (I_S) is limited to a value that does not cause irreversible insulation failure: $I_S < I_{1R}$; I_{1R} being the primary rated current of the transformer. By this method, the ability of the diagnosis procedure to detect the failure is perfectly evaluated: if failure effects on a short circuit with a limited failure current can be analyzed, it ought to be much easier to achieve the same outcome in a real breakdown, when the current through the shorted turns is unlimited.

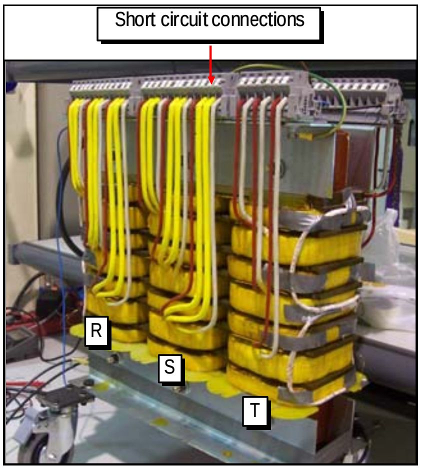

Fig. 3. External appearance of the transformer

The system also allows failure analysis under different load levels by connecting an 11 kW three-phase motor coupled to a magnetic powder computer-controlled brake to the secondary winding of the transformer. By varying the brake torque produced by the brake, the transformer can be operated at different load levels and with different power factors. Fig. 4 shows the overall test system with transformer windings, connections for applying the short circuits and current limiting resistances.

In order to evaluate the possibility of detecting insulating failures in different conditions, the short circuit leads were distributed in the following way. For every disc, the beginning and the end of the winding is externally available. Moreover, two leads have been connected to the outermost and innermost layers respectively. In this way, the screening effect that might be produced by the layers wound around the faulty region can be easily analyzed. Fig. 5 shows the way leads are connected to the discs.

4. Detection of changes in leakage flux

In order to analyze the path described by the leakage flux lines of the transformer when operating under normal conditions and with insulation failures, a series of finite element simulations were made with the transformer operating at rated load in different time.

The results demonstrated that leakage flux lines in a healthy machine have a horizontal symmetry axis that passes through the mid-height of the transformer core limbs even if the windings are composed by discs, and primary and secondary are alternatively wound in the same column. This symmetry in the leakage flux distribution exists at all times during the machine's supply cycle. Fig. 6 shows the flux lines in the same time instance for the transformer operating under normal conditions and with a shorted turn in the first disc of the R phase (left column).

Table I. – Technical Specifications of the Test Transformer

Voltage	400/400 Yy – 400/230 Yd
Apparent power	12 kVA
Winding Conductors	3 mm copper wire class H
Primary winding discs	4 Discs – Total turns=173. 7 Layers
Second. winding discs	3 Discs – Total turns=171. 6 Layers
Leads for short-circuit	Turns 1, 3, 7, 15, 31, 61
Connection	Yy6 (Yy–Yd–Dy –Dd possible)
Magnetic Core	Cold lam. steel 0.86W/kg-0.33 mm
Winding insulation	Tercott CF™ (Polyester paper)
Core dimensions	350 x 350 mm
Window dimensions	80 mm
Magnetic flux density	1.2 T (average)
Voltage per turn	2.3 V aprox.

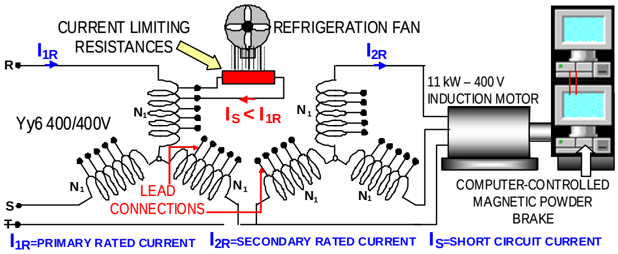

Fig. 4. Structure of the test bench

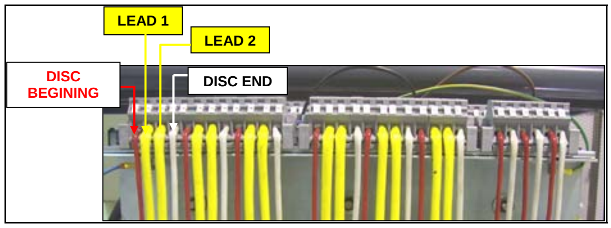

Fig. 5. Short circuit leads connections

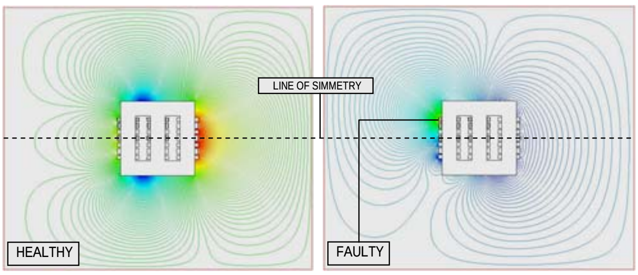

Fig. 6. Leakage flux lines at a time instance of a steady state operation cycle of the machine. Left: healthy machine. Right machine with a shorted turn.

In order to observe this phenomenon in greater detail, close up views of the flux lines in the winding region were also registered and the leakage flux line paths inside the machine's shield were analyzed. This deeper analysis demonstrated the influence of the shield on the curvature of the leakage flux lines. However, the symmetry of leakage flux inside the shield was perfectly maintained when no shorted turns were present. In order to obtain a clearer representation, leakage flux was represented along a line parallel to the windings surface. This line was called 0→200 line and it is represented in Fig. 7. As can be deduced from the location of the line, a symmetrical distribution of the flux will be obtained at any time instance for a healthy machine. However, symmetry will be lost as soon as the fault is present in the windings.

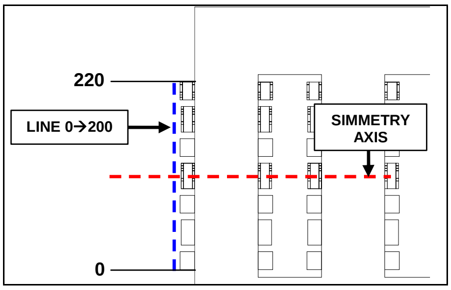

Fig. 7. Location of the line used as a reference to analyze symmetry in leakage flux distribution.

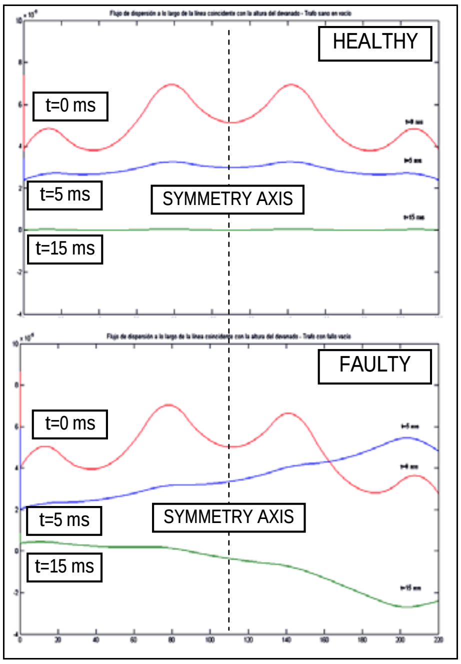

Fig. 8. Flux across the 0→200 line during an electrical cycle.

Figure 8 shows a detail of the flux across the 0→200 line during a complete electrical cycle for the healthy machine and the machine operating with a shorted turn. Perfect symmetry can be clearly observed for the case of a healthy transformer. However, an asymmetrical distribution, with strong leakage flux concentration in the region of the faulty turn, [14, 15], is exhibited in the case where the interturn insulation fault has been intentionally applied.

The following step was to check that failure could be detected by measuring induced voltage in coils attached to the transformer windings. Coils were introduced into the model in the same way than in [11, 12]. Simulations were carried out to obtain the induced EMF and the results were experimentally verified.

5. Experimental measurements by means of search coils

Experimental measurement of leakage flux variations were done by means of two 300-turn air core coils. These coils were made by simply wrapping 0.19 mm insulated copper wire around a square piece of foam and covering the resulting coil with fibre glass tape. Then the coils were attached to the surface of the R and T phases of the winding, series connected and magnetically coupled as indicated in Fig. 9. In the central limb, where the S phase is wound, the installation of the coils was not possible because of the small gap between the windings. The terminals of every equivalent coil were placed outside the machine shield and V_{OUT} was registered with a 60 MHz bandwidth digital oscilloscope; V_{OUT} being the EMF resultant of both coils.

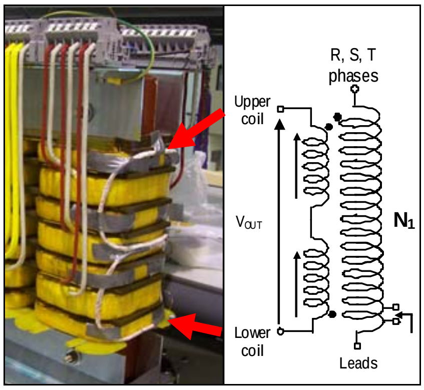

Fig. 9. Air core coils attached to the surface of the transformer windings

As coils were manually manufactured, completely identical devices cannot possibly be obtained. Moreover, installation of the coil at the transformer surface also implies certain unavoidable positioning error. The transformer windings present unavoidable deformations in their structure caused by the leads connections. This unavoidable asymmetry of all the system components leads to the production of leakage flux by the phase currents that is not perfectly symmetrical and therefore exerts a certain influence on the final value of the induced electromotive force V_{OUT}. Fig. 10 shows this effect in the oscillograms of the EMF induced in each coil.

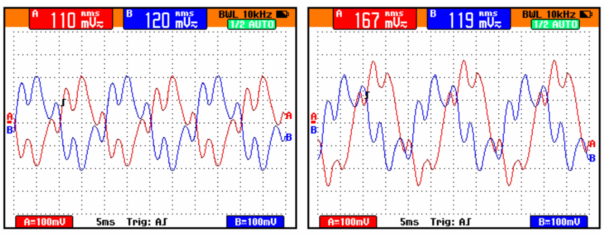

Fig. 10. EMF induced in each coil (transformer operating at no load). On the left side healthy transformer, on the right side transformer with a shorted turn

This influence cannot be predicted, as it is impossible to predict the effect of the structural asymmetries in the leakage flux. Therefore, the values of V_{OUT} are not nil when the machine is healthy. This is not a problem for diagnosis, since a tuning procedure must be done before the measurement in order to compensate this natural offset.

6. Influence of load on the diagnosis procedure

In order to study the influence of the transformer load on the efficiency of the diagnosis method, an 11 kW motor was used. V_{OUT} was measured for different load levels, with all the experimental results demonstrating the consistency of the new method for the detection of minor insulation faults under extremely adverse conditions. To verify the ability of the method to give accurate results even in the most adverse cases, all the studied failures had their fault current limited to a value lower than rated current, and the tests were carried out for load levels varying between 0 and the transformer rated load.

The motor, coupled to a magnetic powder brake, was supplied from the transformer (Fig. 4). In this way, the voltage V_{OUT} was measured in 4 different load conditions (0%, 33%, 66% and 100% of the rated load) for the transformer operating in normal conditions and after producing an interturn short circuit. Fig. 11 and Fig. 12 show the oscillograms obtained for V_{OUT} in both cases. The RMS value of the voltage is presented in the graphs. The results show how easy it is to detect such a minor fault, since V_{OUT} values considerably increased when there was a failure in all the tests that were run.

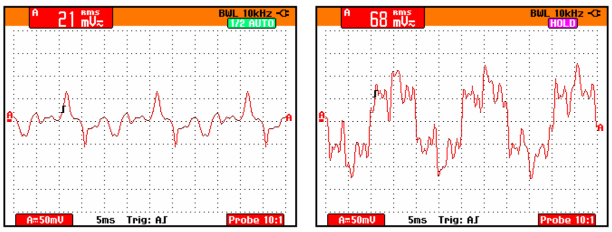

Fig. 11. V_{OUT} for a healthy transformer. On the left side transformer operating at no load, on the right side transformer operating at the rated load

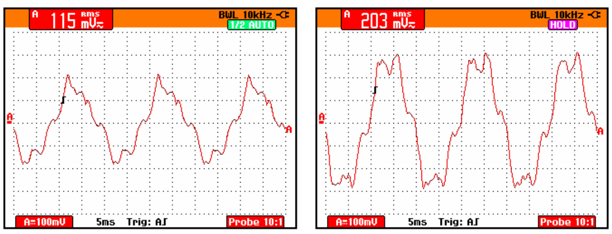

Fig. 12. V_{OUT} for a transformer with a shorted turn. On the left side transformer operating at no load, on the right side transformer operating at the rated load

Fig. 13 shows the evolution of V_{OUT} vs. the transformer load when it is operating in normal conditions and after producing an interturn short circuit. Both graphs show that V_{OUT} increases with the machine load, although the slope is higher for the faulty machine. When the transformer is healthy, an increase in the load and thus in the current flowing through the windings produces a higher level of leakage flux. Manufacturing asymmetries of both machine windings and flux coils produce different levels of induced EMF in every single coil for the different load levels. For this reason, a higher value of the V_{OUT} indicator is obtained when the machine is loaded.

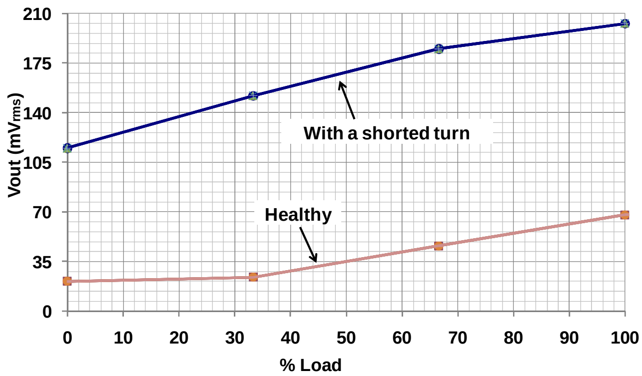

Fig. 13. V_{OUT} rms value vs. load level in the cases of the healthy transformer and with an interturn short circuit

When the transformer presents an interturn short circuit the same process occurs. However, under fault conditions the higher asymmetry produced by the failure generates a higher level of V_{OUT} that can be easily distinguished from the one obtained for the healthy machine. In fact, diagnosis can be perfectly achieved in spite of the variation of V_{OUT} with load. Fig. 13 demonstrates that the difference between the maximum V_{OUT} produced by the healthy transformer and the minimum V_{OUT} generated by the faulty machine is large enough to discriminate both status under any load regime.

4. Conclusions

The experimental results of this study show that leakage flux distribution in three-phase, three-limb core transformers has a horizontal symmetry axis which passes through the middle-height of the magnetic core even if the winding are disc-type and primary and secondary windings are alternating located.

This symmetrical distribution is maintained at all times during the supply cycle of the machine independently of load value. It has been demonstrated that leakage flux symmetry is automatically lost when an interturn short circuit exists in the transformer windings.

When the transformer presents an interturn short circuit the asymmetry produced by the failure generates a high level of V_{OUT} that can be easily distinguished from the one obtained for the healthy machine. In fact, diagnosis can be perfectly achieved in spite of the variation of V_{OUT} with load. Therefore, leakage flux can be easily applied for the early detection of this type of failure in any kind of transformer.

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