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A Novel Flux-Based Protection Scheme for Power Transformers

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ABSTRACT

Internal Turn-Turn faults (TTF) are the most common failures in power transformers, which could seriously reduce their life expectancy. Although common protection schemes such as current-based differential protection are able to detect some of the internal faults, some other minor ones (such as TTFs and short circuit near the neutral point) cannot be detected by such schemes. Likewise, these relays may have false trip due to energizing inrush currents, transformer over excitation, and occurrence of CT saturation at one side. In this paper, a novel Linkage Flux Based (LFB) scheme is proposed to detect TTF in power transformers, which uses some Search Coils (SC) located on the transformer legs to sense the related linkage flux. Any difference in induced voltage in the corresponding SCs (located on any leg) suggests passing unsymmetrical linkage fluxes through them (unlike the normal conditions), which stands for the occurrence of a fault inside the transformer. The proposed technique not only can be used to protect power transformers, but also can be employed to find the fault location during repair activities, as well.

KEYWORDS

Power Transformer, Internal Fault, Search Coil, Linkage Flux, Finite Element Method (FEM).

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1- INTRODUCTION

Power transformers are one of the most important and expensive apparatus in power systems. The design of relays for power transformer protection was a challenging issue for many years [1].

Short circuit can be occurred in the power transformers due to insulation breakdown. TTFs are the most common faults in the transformer windings. A brief review on the records of the modern transformer breakdowns shows that about 70-80% of the failures are caused by TTFs [2].

A TTF can be started by [3- 5]:

1- A metallic contact resulting from the mechanical forces due to the external short circuit,
2- Sever insulation deterioration as a result of excessive over-loading,
3- Insulating oil degradation due to the contamination by moisture,
4- Applying a huge impulse voltage due to a switching/lightening overvoltage, and etc.

Although differential relays are the most common protection devices to protect power transformer, issues indicated below can reduce their sensitivity:

1- Magnetization current;
2- CTs turn ratio error;
3- Operation of tap-changer;
4- CT saturation in heavy following current and/or DC decaying component.

On the basis of these issues, an Operate-Restraint characteristic can be considered for any differential relay activity. This characteristic determines the sensitivity and security of the protection, and the relay performance is limited by it during the internal faults.

Moreover, a short circuit happening on a few turns of the transformer windings will result in a sever short circuit current in the related turns. Because of the high ratio transformation between the whole winding and the short circuited turns, this high short circuit current will not appear in transformer terminals. As a result, transformer differential relay will not have sufficient sensitivity to detect such TTFs. Therefore, fast and reliable detection of TTFs is a crucial task in power transformers protection [5].

In recent years, various methods have been presented to improve the power transformers protection facing TTFs ([3],[6],[7],[8]) on the basis of various current sequences. A method on the basis of zero current sequence investigation, which appears in a delta winding during faulty condition, is described in [3]. Another scheme based on negative sequence current to detect minor TTFs is presented in [6- 7].

As an alternative to the mentioned algorithms, which are based on the output voltage/current components, an online leakage flux based detector method to diagnose internal faults has been proposed in [8]. The obtained results on the basis of a finite element model of the transformer suggests that the model is able to detect internal faults in early phases of occurrence [8].

The leakage flux based method excels the general voltage/current based alternatives, from the viewpoint of the casual relationship. Indeed, when a fault occurs, flux lines change their path as the first reaction, based on Lenz's law. This phenomenon results in a reduction in the linkage flux (at the fault location and its vicinity), and accordingly, a proportional reduction will happen in the magnitude of the induced voltage on the faulty side. As a result, this event will eventually cause a change in the transformer turns ratio, which may (or may not) be sensed by differential relay. Therefore, differential current based algorithms use the third priority outcome (minor product) of the fault in the transformer; while the flux based methods use exactly the major fault product. However, the presented method can be criticized from the viewpoint of some practical limits, as discussed below:

Leakage flux sensors are located around the high voltage winding. This assumption can be impractical from the viewpoint of the allowable clearance, and then some modifications (such as increase tank dimensions) may be needed to do. Transient over voltages can also cause failure in the connected monitoring/protective devices.

Fault detection process by such sensors requires the passage of leakage flux through them, while the leakage flux cannot traverse in locations far from the core due to minor faults including a few turns. As a result, the magnitude of the induced voltage in such cases may be negligible and undetectable.

Over-fluxing of the transformer generates leakage flux, where passes through the mentioned sensors to produce an output voltage and reveals a false internal fault.

In this paper, a novel Linkage Flux Based (LFB) method is proposed to protect power transformers using some single/multi turns sensors (named "Search Coil" or SC), which are located and turned around the grounded core, or between LV and HV windings (on the LV winding). The linkage flux lines, normally, induce a voltage in the SCs. Comparing the output voltage of the identical SCs on any phase (transformer leg) reveals the flux linkage asymmetrically. In other words, any absolute difference between induced voltages in identical SCs can be concluded as a difference in the related linkage flux lines, which is impossible in normal condition. Using the proposed approach, TTFs with any number of turns involved in, are easily identified. This means that even TTFs including few turns are detectable, fast and with high reliability. Furthermore, unlike the conventional transformer protection schemes (differential current based protective relays), presented method doesn't have mal-operation during energizing (due to inrush current) or in abnormal condition (due to over flux).

To validate the feasibility of the proposed method in different operating condition, a finite element method (FEM) based study is carried out on a sample power transformer with 50KVA rating and turns ratio 20/0.4 kV. All simulation studies are performed on ANSOFT MAXWELL® [9] software environment. This paper is organized as follows: Section II, provides a brief overview on the fundamentals of linkage and leakage flux analysis in power transformer; and a short review on FEM is provided in Section III. Various simulations to analyze case studies are done in Section IV. The proposed method to find the fault location is described in Section V, and finally, Section VI concludes the paper.

2- FUNDAMENTALS OF LINKAGE AND LEAKAGE FLUX ANALYSIS AND INDUCED VOLTAGE

The proposed method in this paper is based on the magnetic flux continuity law [10] which states the magnetic fluxes are continuous and enclosed lines, which do not originate nor terminate at a point. Moreover, flux is determined by applied voltage, and when some turns are shorted, the flux in them tends to reduce.

Linkage flux in power transformers passes through the both primary and secondary windings. This sinusoidal flux (φ_{link}) induces voltage (E_{ind}) in any windings according to Faraday's law as equation (1), where N is the number of the related winding.

$$E_{ind} = N\frac{d\varphi_{link}}{dt} \tag{1}$$

In addition to the linkage flux, there is a miniature flux in normal conditions that passes through the air and is called the leakage flux. This flux doesn't create any linkage between transformer windings, and only reduces the voltage in the primary and secondary windings proportional to the load [11], as shown in Figure 1.

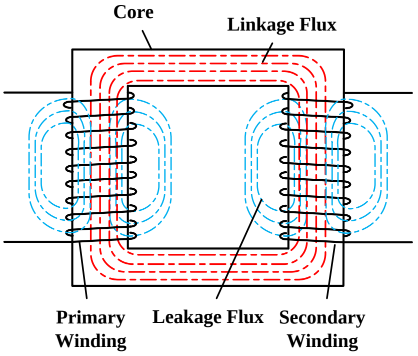

Figure 1. Linkage and Leakage fluxes in transformer

Against the normal conditions, whenever an internal TTF occurs in transformer:

- Passing flux through the faulty section tends to change its own path from the core to the outer, i.e. the linkage flux reduces, and inversely the leakage flux increases.
- Symmetrical flux lines will be disturbed, and their density will be varied along the faulty transformer leg.
- Flux density in the transformer tank (that is about zero in normal condition) will be raised when a TTF occurs

In this paper, the difference mentioned above in the linkage flux during TTFs is detected via inserting some SCs on the transformer legs. The related voltages are used as sensitive criteria not only for the fault detection and transformer protection, but also to determine the fault location during the repair process.

For further explanations, a three phase transformer core is considered as shown in Figure 2. Four series HV winding disc are considered on each leg and then, five SCs by regular intervals are located on each one, to measure the linkage flux at their place (HV discs are located between SCs).

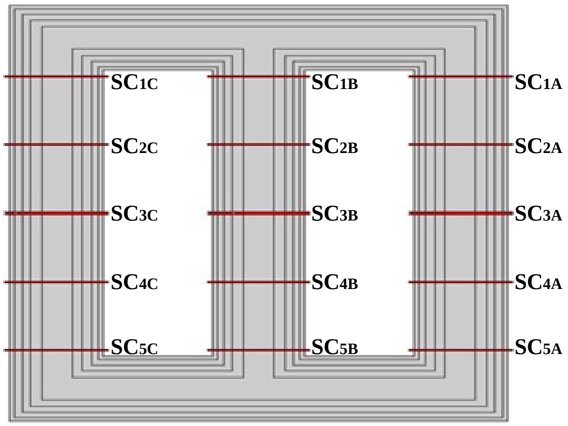

Figure 2. Location of SCs on transformer core

In normal operation (healthy condition), SCs on each leg sense equal and similar variation of linkage flux, i.e. equal voltages induce in all SCs on each leg. Similar flux with 120° difference in phase will pass through other SCs on the adjacent legs, simultaneously. This is expected that the output voltages of the SC_{1A} and SC_{5A} to be exactly the same. SC_{2A} and SC_{4A} should also exhibit similar induced voltages at their outputs. Therefore:

$$\begin{cases} E_{SC_{1x}} - E_{SC_{5x}} = E_{SC_{2x}} - E_{SC_{4x}} = 0 \\ \qquad x = A, B, C \end{cases} \tag{2}$$

And also:

$$\Delta E_x = \left(E_{SC_{1x}} - E_{SC_{5x}}\right) + \left(E_{SC_{2x}} - E_{SC_{4x}}\right) = \left(\underbrace{E_{SC_{1x}} + E_{SC_{2x}}}_{\substack{Sum\ of\ upper\ SCs \\ \Sigma E_{ux}}}\right) - \left(\underbrace{E_{SC_{4x}} + E_{SC_{5x}}}_{\substack{Sum\ of\ lower\ SCs \\ \Sigma E_{lx}}}\right) = 0 \tag{3}$$

Or by summation of similar ΔE_x at three legs:

$$\Delta E_A + \Delta E_B + \Delta E_C = 0 \tag{4}$$

Moreover, on the basis of 120° difference in the phases of the fluxes in three legs:

$$\begin{cases} \underbrace{E_{SC_{kA}} + E_{SC_{kB}} + E_{SC_{kC}}}_{\substack{Sum\ of\ similar\ SCs\ at\ three\ phases \\ SE_k}} = 0 \\ \qquad k = 1, \cdots, 5 \end{cases} \tag{5}$$

Or by summation of similar SE_k at five stages:

$$\sum_{k=1}^{5} SE_k = SE_1 + SE_2 + SE_3 + SE_4 + SE_5 = 0 \tag{6}$$

Either of the equations (4) or (6) can be considered as a criterion to detect TTFs. They are named in this paper as "Crt_DIFF" and "Crt_SIG", respectively.

When a TTF occurs, for example near the SC_{1A}, the linkage flux passing through the mentioned sensor will be reduced (or ideally will become zero). However, because of shorting some turns, the applied voltage to the remaining turns raises and therefore:

$$\begin{cases} \left| \underbrace{E_{SC_{1A}}}_{\approx 0} - \underbrace{E_{SC_{5A}}}_{\leq normal\ value} \right| > 0 \\ \Rightarrow \left| \underbrace{\Delta E_A}_{\neq 0} + \underbrace{\Delta E_B}_{\approx 0} + \underbrace{\Delta E_C}_{\approx 0} \right| > 0 \end{cases} \qquad (7)$$

It is noticeable that for severe TTFs, the increasing component of leakage flux in a phase can link with adjacent windings, and then ΔE will be raised in them, too.

There is an exception to occur a TTF exactly in the middle point of the winding. In such case, although ΔE will become zero for all phases and Crt_DIFF cannot exhibit the fault occurrence, Crt_SIG can show the abnormal condition, as well. In other words, in such case as the worst condition, the value of SE_3 will be increased, when other SEs may be remained at zero.

3- A REVIEW ON FEM

Any idea and its results should be evaluated using simulation, before they are applied on the expensive devices. Analysis of a faulty transformer is very complicated, and cannot be done using a simple differential equation. Such problems need powerful techniques, such as FEM.

FEM is a well-known numerical based technique to solve the complicated simulations. It is a powerful tool to achieve a precise description of the electromagnetic behavior of the magnetic components, such as transformers [12].

FEM divides the element into a large number of triangular parts, called ‘mesh’. Electromagnetic fields inside the element under study are calculated using the following nonlinear differential equation [13]:

$$\nabla \times \frac{1}{\mu} \nabla \times A = \overline{J_e} - j\omega\sigma \overline{A} + \omega^2 \overline{A} \qquad (8)$$

Where $\overline{A}$ represents the magnetic vector potential, and μ , σ and ω are permeability, electrical conductivity and power angular frequency, respectively. Similarly, $\overline{J_e}$, $j\,\omega\sigma\overline{A}$ and $\omega^2\overline{A}$ represent the source current density, the induced current density and the displacement current density, respectively.

Using the finite element to solve problems requires three stages [14].

a) Meshing the problem space into contiguous elements of suitable geometry and assigning appropriate values of the material parameters (conductivity, permeability and permittivity) to each element.

b) Excitation of the model by the initial conditions.

c) Specification of the boundary conditions for the problem. The values of the potentials are suitably constrained at the limits of the problem space.

The finite element method has the advantage of geometrical flexibility. It is possible to include a greater density of elements in regions where fields and geometry vary rapidly.

There are two different approaches to couple finite element models with circuit equations [15]. One is direct coupling and the other is indirect coupling. In direct coupling, the circuit equations are directly incorporated into the field calculation and solved simultaneously. In indirect coupling, the field calculation is performed by a free standing program, while circuit simulation and coupling between field and circuit models are handled in a separate program. ANSOFT’s Maxwell Software adopted the indirect coupling method.

The FEM has a great advantage of geometrical flexibility. It is possible to include a greater density of elements in some regions, where fields and geometry vary rapidly [12].

In this study, an FEM based analysis is carried out on a sample transformer in order to simulate internal TTFs and generate induced voltage in SCs based on the linkage flux variation in the transformer core.

4- SIMULATION

To investigate the proposed method, a sample transformer is simulated in ANSOFT MAXWELL [9], which its technical specifications are shown in Table 1.

TABLE 1. TECHNICAL SPECIFICATIONS OF THE MODELED TRANSFORMER

Rating Power	50 kVA
Vector Group	Yzn5
Voltage Ratio	20000/400
SC Impedance	4.03%
Frequency	50 Hz
HV Turns	4155
LV Turns	2*48
HV Nominal Current	1.44 A
LV Nominal Current	72 A

A. TRANSFORMER MODEL AT NORMAL CONDITION

Figure 3 shows the flux distribution in the transformer structure at an arbitrary time instant. As shown, linkage flux has a symmetrical and unique form from the top to bottom of the legs. Likewise, with respect to 120° phase difference between the fluxes passing the legs, sum of three phase fluxes is equal to zero and no flux bypasses through the tank (shell).

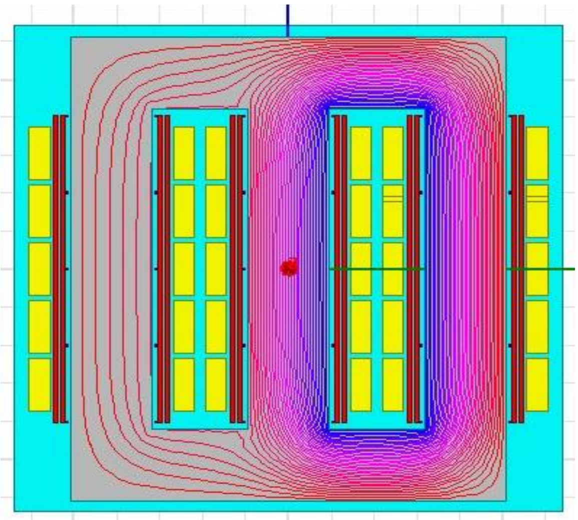

Figure 3. Flux distribution in transformer during normal condition

B. TRANSFORMER MODEL AT FAULTY CONDITION

The most common internal faults occur in HV side of the transformers, because the probability of insulation deterioration is more than that of the LV side. Then in this case, the model is run under the faulty condition, where a quintuple TTF is applied on HV side at t=550msec, between SC_{2A} and SC_{3A}. Figure 4 shows the flux distribution in the transformer core from 540msec (10msec before the fault occurrence) up to 600msec (50msec after happening instant of the fault) with single cycle steps. As shown, although all SCs (on each leg) observe equal fluxes before the fault, the passing flux lines from various SCs on the right faulty leg (phase A) varies after the fault such that approximately no flux passes from the SC_{1A} at t=560msec, when the passing flux from the SC_{5A} slightly (or no) changes, and therefore ΔE_A will be raised. Accordingly, the previous linkage flux escapes from the shorted turns region, and appears as leakage flux that can pass through adjacent phase B. It can induce the voltage in some SCs on phase B, and then ΔE_B will be increased, too, as shown in Figure 5. This process creates a bigger Crt_DIFF value than the normal condition, as the first TTF detector (Figure 6). Moreover, the flux passing through the tank is not zero, because the symmetry form of the three phase fluxes is destructed. Then summation of identical SCs on three phases is not zero and accordingly, the Crt_SIG as the second TTF detector, takes a bigger value than the normal one (Figure 6). Indeed, this criterion shows the flux balance in three legs (phases) of transformer.

By changing the number of faulty turns at the mentioned location, the values of Crt_DIFF and Crt_SIG can be obtained as recorded in Table 2. As shown, it can be concluded that the proposed flux-based method in the worst case can detect the single TTFs in the HV side of the transformer. There is 4155 turns in HV side and therefore, even the smallest TTFs (at 0.024% of the winding) are detectable using the proposed algorithm.

C. TTF IN THE MIDDLE POINT OF THE WINDING

To check such a case, a quintuple TTF is simulated in the middle point of the winding A, in vicinity of SC_{3A}. As aforementioned, such TTFs cannot be observed by Crt_DIFF. But, it is expected that Crt_SIG is able to detect them. Variations of the mentioned criteria are shown in Figure 7. As shown, against Crt_DIFF, Crt_SIG detects such small TTFs in the middle points.

It can be concluded that Crt_SIG can be introduced as the proposed flux based scheme to protect transformer against the internal TTFs.

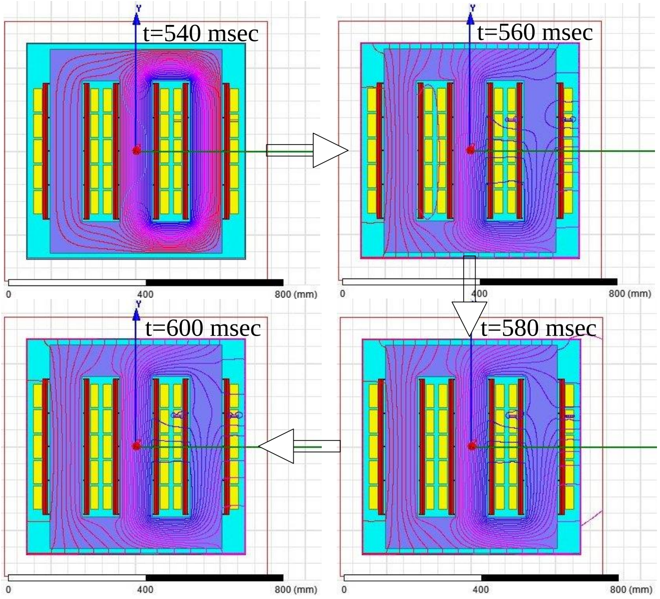

Figure 4. Flux distribution in transformer core from healthy state (540 msec) up to 2.5 cycles after fault occurrence (with single cycle steps)

5- FAULT LOCATION

As shown in both Figure 6 and Figure 7, when a TTF occurs, the induced voltage in the closer SCs will be reduced more than the further ones. This phenomenon can help technicians to find the TTF location, by comparing the induced voltage in the SCs, or by measuring the differential value of the sequential SCs on the faulty leg. The faulty leg can also be found by comparing three values ΔE_A, ΔE_B and ΔE_C when a safe voltage is applied to the transformer LV windings, separately (single phase excitation with equal amplitude) or simultaneously (three phase excitation). Therefore, installed cheap and simple SCs can be used not only to protect the transformer, but also to repair the faulty transformer. Then the proposed method can be introduced to the industrial manufacturers as an economic and justified procedure.

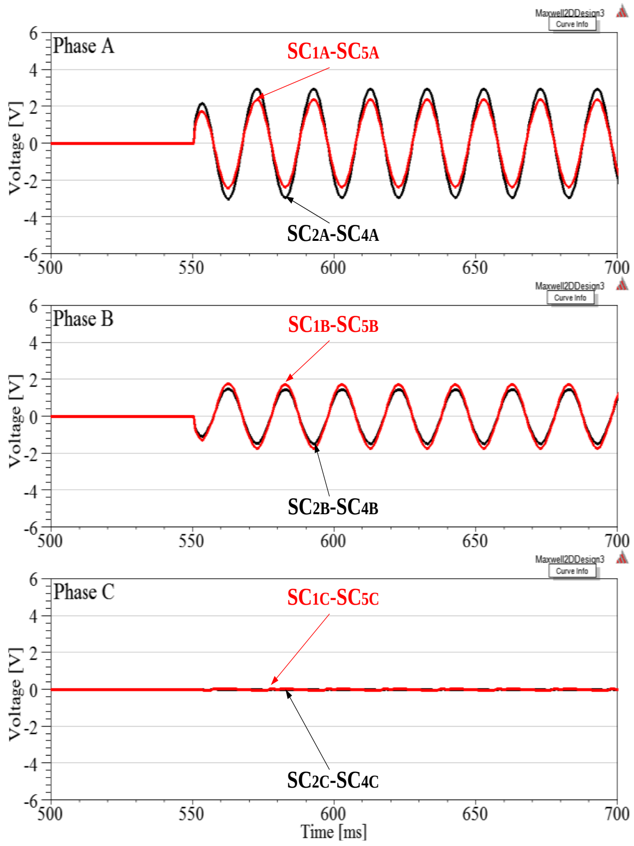

Figure 5. SCs induced voltages in three phases during a TTF

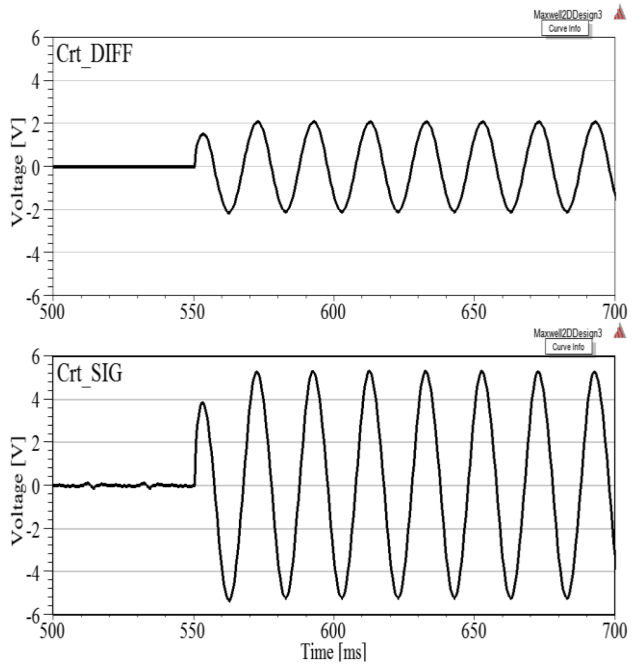

Figure 6. Variations of Crt_DIFF (Top) and Crt_SIG (Down) due to a quintuple TTF on phase A of HV winding between SC2A and SC3A at t=550msec

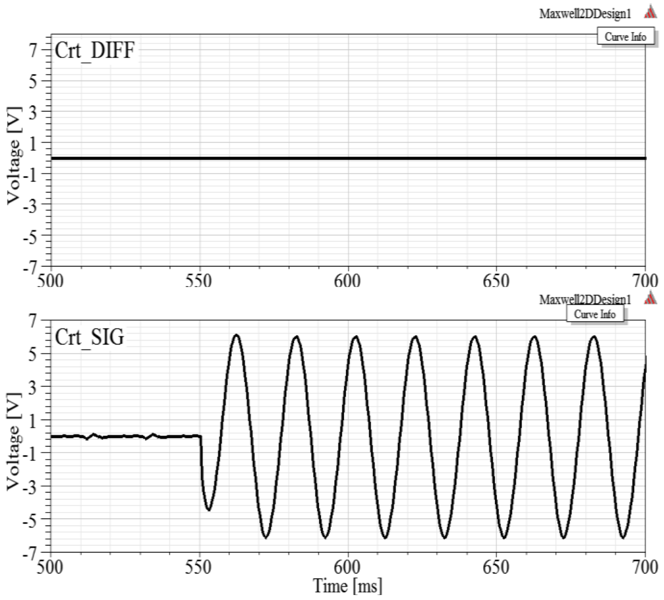

Figure 7. Variations of Crt_DIFF (Top) and Crt_SIG (Down) due to a quintuple TTF on the middle point of phase A of HV winding at t=550msec

TABLE 2. INDUCED VOLTAGES IN SCS DUE TO VARIOUS TTFS ON PHASE A, BETWEEN SC_{2A} AND SC_{3A}

Induced Voltages (V)	Number of Faulty Turns			
	1	**5**	**10**	**20**
SC_{1A}-SC_{55}	0.336	4.72	6.14	6.28
SC_{2A}-SC_{4A}	0.420	5.88	7.68	7.88
SC_{1B}-SC_{5B}	0.124	3.44	4.48	4.66
SC_{2B}-SC_{4B}	0.210	2.92	3.8	4
SC_{1C}-SC_{5C}	0.002	0.28	0.35	0.54
SC_{2C}-SC_{4C}	0.002	0.28	0.35	0.54
Crt_Diff	**0.297**	**4.15**	**5.4**	**5.65**
Crt_SIG	**0.875**	**10.54**	**11.2**	**12.2**

6- CONCLUSION

In this paper, a novel transformer protection and fault location scheme are proposed to detect TTFs by inserting several SCs on the core legs, in order to measure the linkage flux at various locations. Two fault detector criteria as Crt_DIFF and Crt_SIG (based on difference and summation of the SCs induced voltages, respectively) are introduced to monitor the TTFs via the variation in the linkage flux, and it is shown that they are able to precisely detect the faulty conditions (even due to single turn short circuits). Also it is shown that unlike Crt_DIFF, Crt_SIG can sensitively observe TTFs at the middle point of the winding. Finally, it is concluded that Crt_SIG can be introduced as the proposed flux based scheme to protect the transformer against internal TTFs.

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