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Mechanical effects of short-circuit currents analysis on autotransformer windings

***Abstract**. This article deals with a description of methods of an experimental analysis (SFRA method, monitoring, thermovision) concerning the actual reliability of windings and magnetic circuit of the transformer, which is required in power transmission and power distribution companies all over the world.*

***Streszczenie.** Artykuł opisuje eksperymentalną analizę badania niezawodności uzwojeń i obwodu magnetycznego transformatora mocy. (**Analiza efektów mechanicznych przy występowaniu zwarcia w uzwojeniu autotransformatora**)*

Keywords: Transformer, diagnostics, SFRA method, monitoring, thermovision.
Słowa kluczowe: diagnostyka transformatora, termowizja.

Introduction

The short circuits in operation are commonly created by different line faults, etc. in mechanical damage of insulation, an electric insulation, an electric insulation breakdown on over voltage, wrong operation and in the next case row.

The meaning of short-circuit is a serious disrepair for the transformer, because there are high currents in it which are awfully rising winding temperature what can cause damage their insulation. Much more danger is high electromagnetic forces, which can be the reason for the devastation of transformer. On Fig. 1 is transformer which winding is damaged by short-circuiting forces.

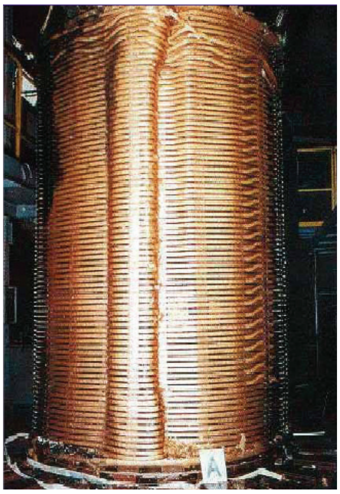

Fig.1 A view for damaged winding of autotransformer as a result effects of short-circuit radial forces [7]

Considering a significance of power three-winding autotransformers (see Figure 2) in the electric system, their price and possible damages arising in accidents, it is necessary to pay attention to higher prevention of these devices. Windings of the autotransformers should be designed to avoid various mechanical or thermal deteriorations caused by short-circuit currents occurring in operation.

Besides the permanent deformation effects of short-circuit current, there is also gradual aging process of the electrical device, which can worsen its mechanical properties. Heat shocks can cause decrease of mechanical strength of transformer and consequent unexpected damage of transformer during the operation.

To prevent a damage state of transformers, we perform different types of the measurements that should illustrate an actual condition of the measured equipment. It is therefore important to choose a suitable diagnostics for the right prediction of such conditions.

Fig.2 The autotransformer 400/121/34 kV

For a better comprehension this relation between transformer damage and short-circuits currents effects, we must focused on mechanical forces effect on transformer windings during short-circuit.

The theory of mechanical forces effect on transformer winding during short-circuit

The primary cause of the creation of forces, which effect on winding is effect of magnetic field on current flowing conductors. As to the transformer it is the field of stray flux.

In normal operation, when the currents in transformer do not exceed rating value, in general the forces effecting on winding are small. But at short-circuits, when the currents reach the multiple of rating values, these forces can become dangerous for windings or confirmative construction too.

We can divide forces affecting on windings into two groups [5] and [6]:

- radial (cross),
- axial (longitude).

Radial forces F_q are a result of lengthwise fields, which are paralleled to axis of transformer winding. These forces are dilating external windings and compressing internal windings, so air spaces are bigger in consequence of it.

The lines of force of magnetic stray flux are parallel with axis of winding and similar radial force effect on the each coil. The summaries of radial forces, which are signed as F_δ, lead up to increasing of space between windings δ (Fig.3).

Infinite small change of magnetic field energy adequate infinite small rising space $\partial\delta$ [5]

(1) $$\partial w = F_\delta \cdot \partial\delta \text{ , from } F_\delta = \frac{\partial w}{\partial \delta}$$

Magnetic fields energy:

(2) $$w = \frac{1}{2} \cdot i^2 \cdot \frac{1}{2\pi \cdot f} \cdot X_z$$

where: i – current momentary value at windings, X_z – leakage reactance in short of the windings, f – frequency,

so, force formula is:

(3) $$F_\delta = \frac{\partial w}{\partial \delta} = 2\pi \cdot (it)^2 \cdot \frac{l_{str}}{L_u} \cdot 10^{-7}$$

where: (it) – coil ampere-turn, l_{str} – average winding length in, L_u is height of winding.

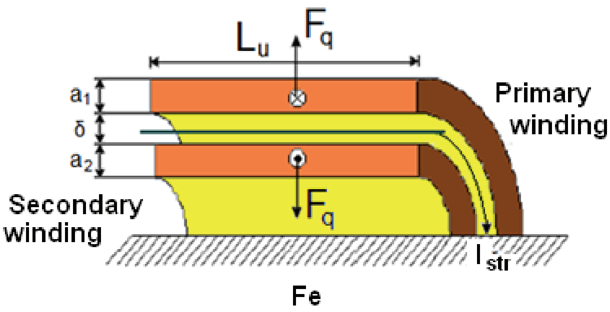

Fig.3 Radial forces Fq effect on transformer windings

The axial forces rise from the center to border of winding, where the magnetic field has the biggest cross component. In short-circuits axial forces can reach dangerous, so they can deform outer coil too.

As to asymmetric windings axial forces are dangerous. The forces which are created by a small displacement of both coils, try to make this displacement bigger. This displacement can be created by coils which are not totally similar. The asymmetry can be also created by insulation of high voltage coil because there are more insulators than in the lower voltage coil winding. But there is a possibility of retract any side of insulation in the totally similar coils. This retract can by caused by drying-out.

According to [2] we need to pay more attention to catching outer coil. In case of released coil, the axial forces F_d (Figure 4) can cause displacement of outer coils to the vertical sides (on Figure 4 is origination of empty spaces). The redundant pressure on spacers can press insulation and moved winding, what can cause seriously damages of transformer.

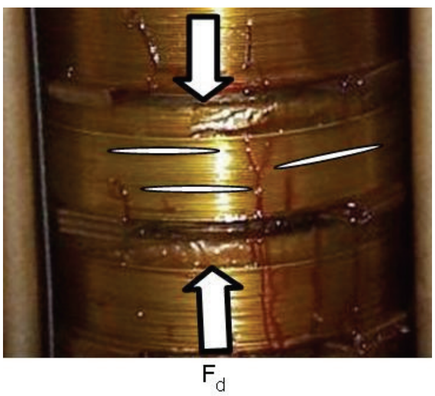

Fig.4. The pressurize the coil conductors by excessive effect of axial forces pressing (influence on the deformation of insulation)

On Figure 5 illustrates pitching of coil conductors by action of the excessive axial forces (effect to insulation compression).

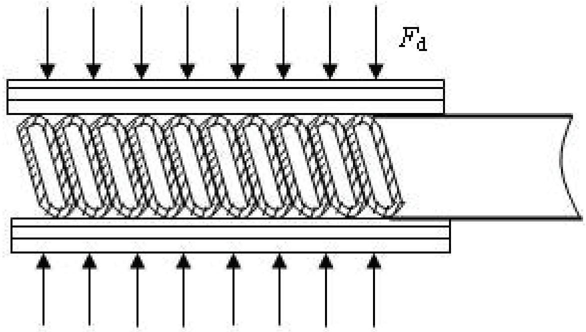

Fig.5. Pitching of coil conductors by action of the excessive axial forces.

Theory of SFRA method and its importance in transformer diagnostics

SFRA method belongs to current most effective analyses and allows to detect the influences of short-circuit currents, overcurrents and other effects damaging either winding or magnetic circuit of the transformer. This all can be performed without a necessity of decomposition of device and subsequent winding damage determination, which is very time consuming.

The method of the high-frequency analysis (Sweep Frequency Response Analyzer – SFRA [3]) is also one of the methods of undisassembling diagnostics of transformers. No intervention to the construction of tested device is demanded, the whole measurement is performed on detached device (not under the voltage). This method is applicable mainly for determination and measuring immediately after the manufacturing of device, i.e. for measuring of reference values. These parameters are consequently compared to the other measurements performed on the transformer, which is decommissioned, after the damages or revisions of transformer etc.

There is possible to detect by SFRA:

- a deformation of winding and its movements,
- a short-circuited turn or opened winding,
- a loose switching system,
- a damaged switching system,
- a core connection problem
- a partial breakdown of winding,
- a core movement or its wrong grounding.

Results measured on the new transformer can be used as the reference parameters for further comparison with values measured later after certain operation time of the transformer. They can be also compared with the test results performed after the transformer breakdown (or after the n-short-circuits) or repair or it can be used as a diagnostic test, when vibration sensors indicate some potential problem in transformer.

SFRA as a one of the most predictable methods is based on functional high-frequency generator and spectral recording analyzer principle, which are set up and controlled by computer. This method is used also by M5100 measuring system (see Fig.6) constructed by American DOBLE company [3].

According to [1] SFRA method determines the transformer responses in a time or frequency area. The time response measurement provides curve determination of the time response to the specific voltage impulse applied to winding input connection. The frequency response measurement consists in determination of amplitude eventually phase response to the harmonic voltage of variable frequency applied to winding input. While the time response is the record of time behaviour of voltage, frequency response is the amplitude response dependence on frequency.

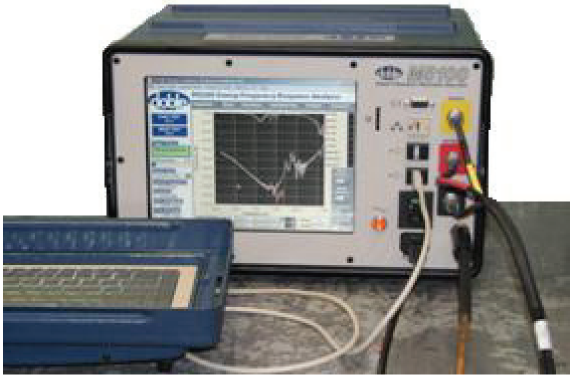

Fig.6. DOBLE M5100 measuring system

A relation between the response and the winding condition is definite, otherwise it is complicated. It is impossible to expect the assessment of concrete damage of winding from differences in response behaviours. The measurement results lead us only to a statement of the fact that some change of winding condition really occurred. Such test results are very helpful to decide, whether it is unavoidable to open and revise the transformer or not.

Measuring principles SFRA and experimental analysis of autotransformer

The behaviour of transformer winding response reflects e.g. electromagnetic couplings between the winding and transformer tank, also between the primary and secondary (eventually tertiary) winding, between the windings of particular phases or between turns themselves of particular windings.

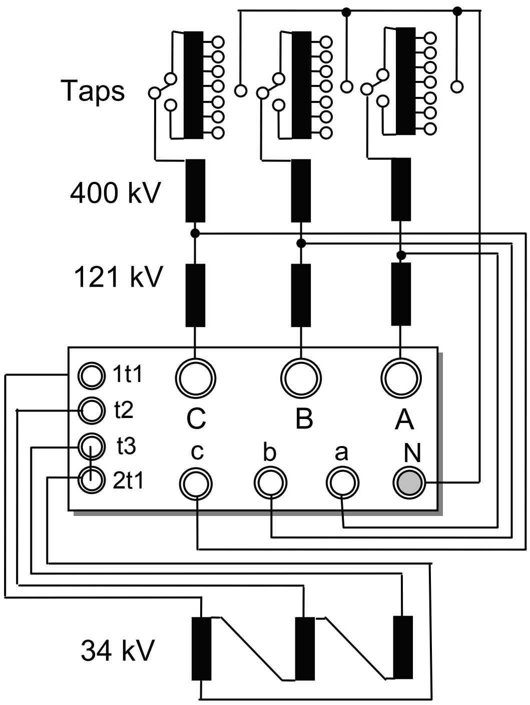

Fig.7 The three-winding autotransformer 400/121/34 kV tested by SFRA before its activation

Fig.8 Magnitude Chart of three-winding transformer (primary, secondary and tertiary windings)

The power transformer measurement requires a setting up of the frequency range from 10 Hz to 2 MHz (Fig.8), whereas there is necessary to follow the right measuring technique to prevent various inaccuracies and faults. According to [2] and [3], measuring technique of three-winding autotransformer 400/121/34 kV (Fig.7) is as follows (see Table1).

During the **open circuit tests** a mechanical condition of tested winding and ferromagnetic core is detected. The following curves typical for this measurement provide us important information about changes in the core, which are visible in low frequencies, while higher frequencies refer to problems such as winding movements or turn-to-turn fault.

Table 1

1. Open Circuit Tests								
Primary 400 kV			Secondary 121 kV			Tertiary winding 34 kV		
1	2	3	4	5	6	7	8	9
A – a	B – b	C – c	a – n	b – n	c – n	t3 – t1	t2 – t3	t1 – t2
2. Short Circuit Tests								
a-b-c short-circuited			t1-t2-t3 short-circuited			t1-t2-t3 short-circuited		
1	2	3	4	5	6	7	8	9
A – n	B – n	C – n	A – n	B – n	C – n	a – n	b – n	c – n

Figure 9 illustrates a simulation of gradual increase of turn-to-turn faults via open circuit test on autotransformer 400/121/34 kV (see Figure 7) at transformer taps of 1, 9, 13 and 17.

The application of analysis of phase attenuation depending on frequency (Figure 10) is suitable for more complete evaluation of winding condition. This analysis enables to assess the processes of winding movements during the particular short-circuits influences.

Problems with core grounding or shorted laminates in the core will typically change the shape of the lowest section of the curve (to 10 kHz). Mid frequencies (from 10 kHz to 200 kHz) represent axial or radial movements in the windings and high frequencies indicate problems such as e. g. winding knocking or problems with contacts.

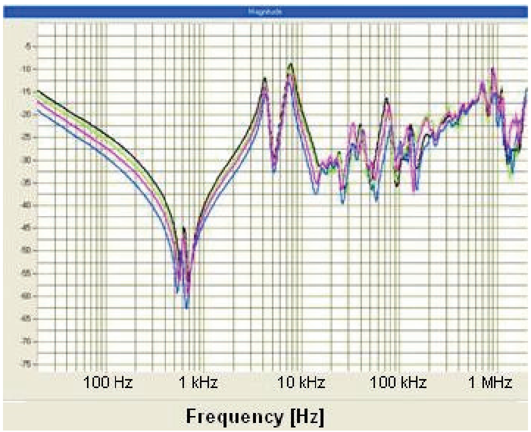

Fig.9 Simulation of turn-to-turn fault increase by open circuit test on autotransformer at transformer taps of 1, 9, 13 and 17

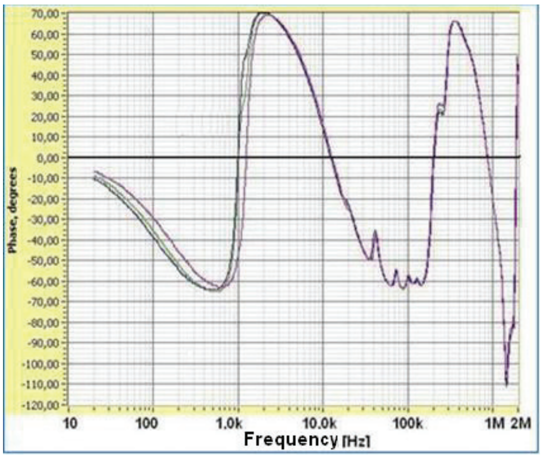

Fig.10 Magnitude Chart of transformer secondary winding

During the **short circuit tests** only the winding condition in primary or secondary part of transformer is detected. This measurement notifies reliably of deformation of inner winding and its movement as a result effects of short-circuit currents.

Conclusion

The state of the response depending up frequency is the image of geometrical winding movement and their construction in transformer. The change of this state depends on thermal and mechanical effects of short circuit currents.

Problem of the frequency analysis of transformers by SFRA method is very comprehensive and its application becomes interesting for many transformer manufacturers and operators. From the long-term point of view the SFRA method is supposed to be very useful and it provides enough information on tested transformers. These transformers have their reference data obtained by the manufacturers, suitable for the comparison with further data of particular transformer.

SFRA testing method represents one of the most effective alternative diagnostic methods compared to visual check. This method allows to detect the effects of the short-circuit currents, whereas we are able to evaluate the mechanical strength action on the transformer winding during previous operation It is also possible to identify the specific winding phase, which has been mostly influenced by the short-circuit currents, without a necessity of transformer dividing, which would be very time consuming.

There is also possible to identify the size of parameters of transformer **parallel circuit** as well as the position of its resonance frequency from particular curves (see Fig.11).

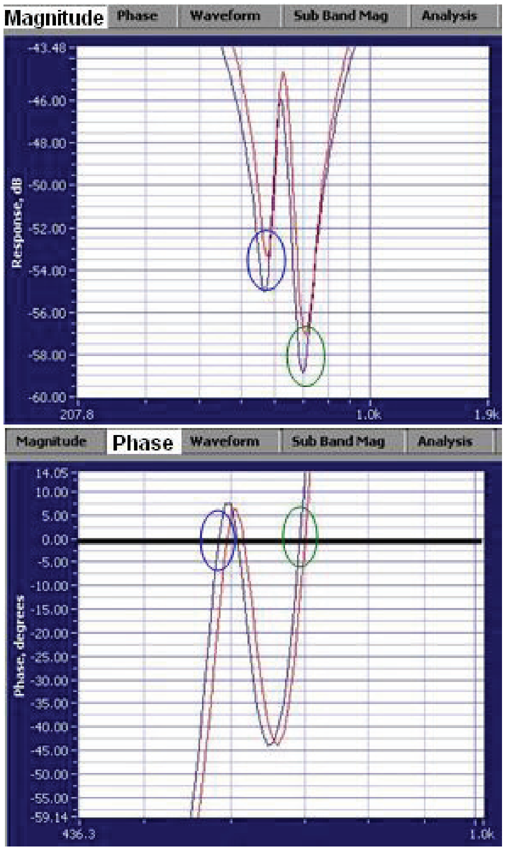

Fig.11 Comparison of amplitude attenuation [dB] and phase curve [°] in frequency dependence (measurement of the same transformer winding)

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