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# FAULT DIAGNOSTICS OF TRANSFORMER WINDING IN TIME AND FREQUENCY DOMAIN

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Abstract

The paper presents basic overview of measuring methods and fault diagnostics on the power transformers and illustrating measurement on transformer winding using with methods of impact test and frequency response analysis (SFRA). Impact test and SFRA method are often used for analyzing of the insulation between coil threads or themselves of windings and for detection of the attenuated winding sections of transformers. There methods enable detecting early condition of the winding faults. In the paper is presented experimental measurement on distribution three-phase transformer 22/0.4 kV without operation by time and frequency domain by impact test and SFRA method. It was used comparison of measured curve for all phases using with mathematical statistical methods. It was found fault coil into primary winding of coil phase A.

Keywords: diagnostic methods, transformer winding, impact test, frequency method

## 1. INTRODUCTION

The important problem of actual energetic companies is that the data big number of measured parameters from the diagnostic measurements are not adequately further studied. Main technical problem is identification of power transformer condition, mainly in terms of their residual lifetime. The fault may occur in an unpredictable moment of transformer operation. The fault result may be the power breakdown for a short or long time.

It is necessary to analyze the measured values of transformer parameters, even for using monitoring. Therefore it is necessary based on knowledge of exposure to adverse influences of energetic phenomena, for example short-circuit currents, overcurrents or overvoltages. Achievements of these objectives by using suitable the diagnostics may help to identification the adverse effects of short-circuit and propose new measuring procedures. Moreover it is possible to identification forthcoming failure into transformer. Some steps are possible to propose in advance (e.g. repair of single parts of transformer) [1].

Except the winding faults (inter-turn short circuit, short time connection with the tank) it could lead to the tank destroy because of the arc pressure. The direct cause of the acting forces on windings is the action of the magnetic field with current paths. In the case of the transformer it is the field of the leakage flux. Normal conditions, when the currents in the transformer do not reach the rated one, the forces acting on the windings are generally small. On the contrary, the short circuit currents reach the values which are multiple of the rated one; these forces could be dangerous for the windings and fixing construction [2].

Forces are produced due to the interaction of the current and the magnetic flux density vectors. Thus, in general, the force vector can have any direction [3]. These forces can be radial (transverse) and axial (lengthwise), since these two components of the force can be calculated and analyzed independently [4]. Also, the two components have influence on different parts of the total transformer and it is necessary to obtain the two components for design purposes. The nomenclature axial and radial is applicable to concentric wound core type transformer.

Action of the forces on the windings could be separated to the radial and axial forces (Fig. 1). Both of these forces exist not only in the short circuit state but also in the rated state.

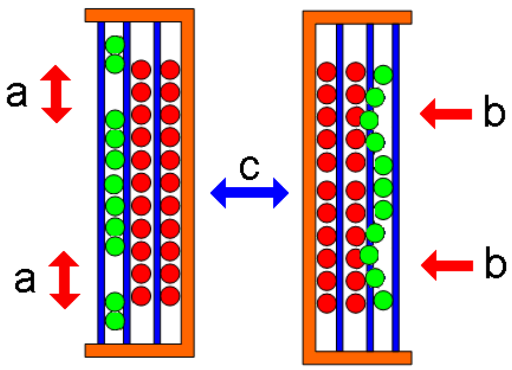



Fig. 1. Forces during short circuit on the winding of power transformer (a – axial effects, b – radial effects, c – rated state)

## 2. THE BASIC MEASURING AND DIAGNOSTIC METHODS FOR TRANSFORMER CONSTRUCTION

Considering the adverse effects of short-circuit forces which damage transformer construction parts (coils, magnetic construction and taps), the following analysis are be realized on disconnect distribution transformers:

- analysis of basic insulation parameters (winding resistances, permittivity, capacity and loss factor),
- measurement of transformer parameters in frequency dependence by Sweep Frequency Response Analysis method (SFRA),
- analysis of time response of transformer windings by impact test with using the high-voltage impulse source,
- analysis of insulating parameters by frequency dielectric spectroscopy method [5],
- measurement of winding parameters of power transformer at short-circuit state,
- combination of measuring methods according to the proposed diagnostic procedures.

The use of monitoring diagnostic methods and measurement procedures are useful for connected transformers on electric power. They belong here thermography and noise analysis and monitoring of basic insulating and mechanical parameters of transformers [6].

Adverse electromagnetic interference from transformer may to cause mechanical change into coil depending on the result of shift or inter-turn short-circuit of the winding [7].

Therefore it is possible use the following measurements of connected transformers will be realized using experimental apparatuses:

- thermography analysis [8],
- analysis of electromagnetic radiation from transformers,
- measurement of acoustic emission from generated at discharges, determination of energy magnitude, speed of exchange between energy of discharge and surrounding oil and localization of faulty state.

The proposed measurements allow us to detect the effects of short-circuit currents and over-currents. These effects can damage winding and magnetic circuit of the transformer.

The repair of transformer is costly and time-demanding. Measurement of frequency characteristics by the SFRA method, measurement of time response of windings by the high-voltage impulse source and measurement of parameters of windings at short-circuited state belong to non-invasive diagnostic methods of transformers.

There is no need of changing of the construction of the measured machine. Moreover they can be performed at disconnected transformer [9].

## 3. EXPERIMENTAL MEASUREMENT BY TIME DOMAIN

In the transformer diagnostics and analysis of winding quality is very important method by measurement in time domain using by impact test.

Impact test is often used for analyzing of the insulation between coil threads or themselves of windings and for detection of the attenuated winding sections of transformers. This method enables detecting early states of the winding faults. Short-time voltage pulses are applied to the winding in order to create a voltage gradient across the complete coil of the winding [10].

In the time intervals among pulses the winding react by damping oscillations with sinus form. Each machine winding has unique character of the respond, which could be analyzed by memory oscilloscope [11]. Wave form is influenced by transient circuit dependent on the winding inductance and inside capacity of the pulse generator.

Schematic diagram for the measured method of the impact test on three-winding power transformer is in Fig. 2.

In Fig. 3a is showed a comparison of time curves from pulse test measurement on the power transformer, where is possible to note time difference between by two coils. Amplitude decrease is involved by change of the resistance and capacitance of circuit due to damaged winding insulation. The measurement is carried on windings of two phases, where phase A is influenced by short-circuit and phases B and C are without fault.

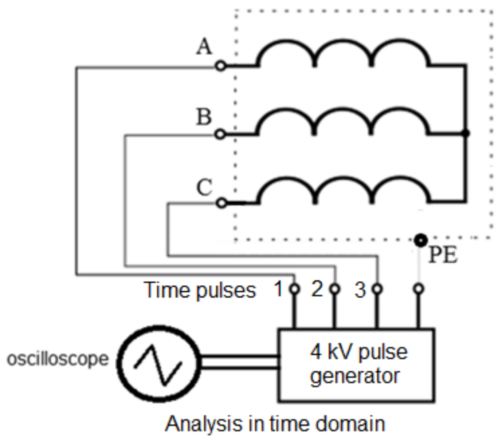
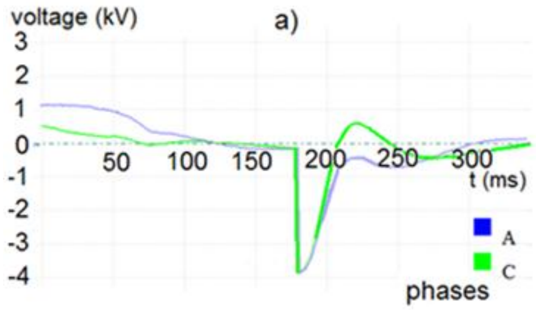



Fig. 2. Connection of transformer to impact test

For determine state of windings it is necessary to understand that single curves to each other overlap when coils are identical and not damaged. Mutually shifted dependents indicate damage on one of the coils; therefore it is handy to analyze time and amplitude differences in curves.

According to Fig. 3a defect can be located in the lower and upper part of the coil A.



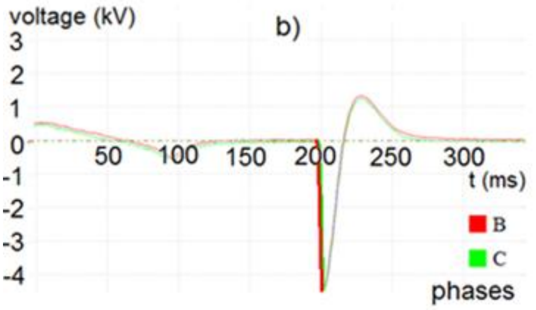




Fig. 3. Analysis of transformer windings by impact test: a) phase A has fault, b) phases B and C are good

Both impulses were analysed into two intervals: from 0 to 150 ms and from 151 to 350 ms. By dividing the pulses into intervals, a more detailed analysis is possible. Thus, each pair of curves is analyzed twice at intervals. The correlation analysis procedure is presented [12].

The amplitude analysis consists of three steps. The first step is to determine the fraction so that the individual rows of the measured pulse points X are divided by the corresponding rows of pulse Y using the relation

$$XY_i = \frac{k_\delta . \max(XY) + \mathrm{abs}(X_i)}{k_\delta . \max(XY) + \mathrm{abs}(Y_i)} \qquad (1)$$

where $k_\delta$ is the error coefficient whose inverse value is the maximum of the resultant ratio $XY_i$, $\max(XY)$ is the maximum positive value of the set of $XY$ and $\mathrm{abs}(X_i)$ values, and $\mathrm{abs}(Y_i)$ is the absolute value of the $X(Y)$ pulse in row i.

The waveforms of Fig. 4 belong to the resulting shares of $XY_i$.

The values of amplitude coefficient related to respective ratio in time intervals were showed in Fig. 4. For pairs of coils A-B and A-C in interval to 150 ms, the maximum value of ratio is equal to 5.47. In time interval from 150 ms, the maximum of ratio is equal to 8.11. The minimal amplitude of difference was for pair of fault-free coils B-C. The short-circuit as well as permanent deformation of coil of A phase were shown and proved in the results.

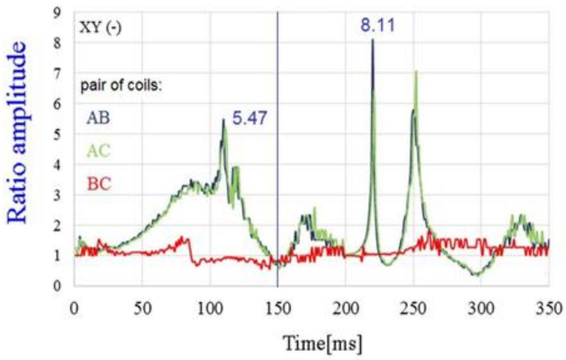



Fig. 4. Ratio of amplitude for pair of coils into measured transformer

## 4. EXPERIMENTAL MEASUREMENT BY FREQUENCY DOMAIN

In the transformer diagnostics and analysis of winding quality is very important and popular method by measurement in frequency domain using by analysing SFRA (Sweep Frequency Response Analysis) [13].

The power transformer diagnostics uses for a setting up of the frequency scale from 20 Hz to 10 MHz at source voltage 0.2 – 20 Vpp and output impedance 50 Ω for example using with the Megger FRAX 150 for frequency 20 Hz – 2 MHz (Fig. 5).

The Megger FRAX analyser is designed for detecting winding shifts and magnetic core defects in power transformers. The Megger FRAX finds curves describing a reduction that can easily be compared with the deviations given shift and deformation of transformer core, winding, tap or connection. The analyser can measure at sampling rate 100 MS/s with absolute accuracy ± 0.5 dB in dynamic range from +20 to -130 dB.

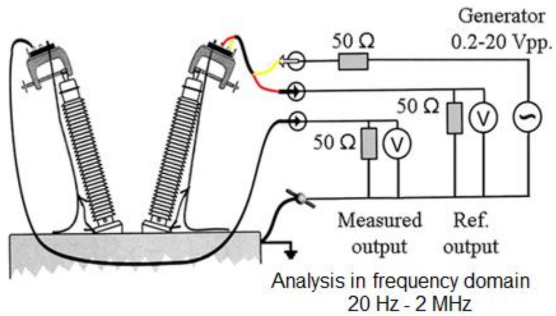



Fig. 5. SFRA measurement connection using the Megger FRAX

For different types of transformers, we can assume that they will have different frequency responses, because the frequency response of the transformer is significantly affected by the magnetic circuit and the winding arrangement.

As can be seen in Fig. 6, the frequency response can be divided into four areas, namely [63]:

a) low frequency area affected by the magnetic circuit,
b) the area of the medium frequency affected by the interaction of the windings,

c) the area of higher frequency, which is affected by the arrangement of individual windings as well as their internal interconnections,
d) the area of the highest frequency affected by the connection of the measuring cables.

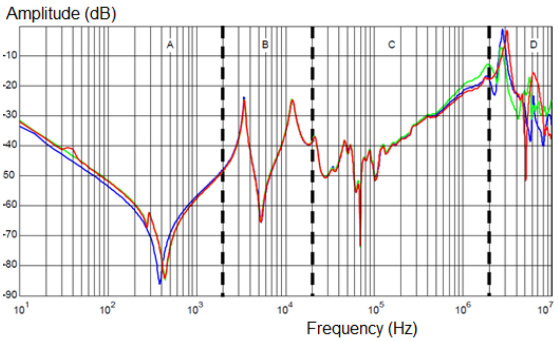



Fig. 6. Relationship between frequency response and transformer design

In the area of the magnetic circuit (<2 kHz), the response is influenced by the magnetization induction of the core and the majority of the capacitive reactances of the transformer. In three-phase nuclear-type power transformers, the middle phase in this region should have only one antiresonance, which is due to the symmetrical magnetic resistance paths that are guided by the middle phase of the magnetic circuit through the other two phases. The outer phases usually have two antiresonances because they have two different magnetic resistance paths, one through the near (middle) phase and the other through the more distant (outer) phase. The frequency response in this region is also affected by the residual magnetization of the magnetic circuit [63], [66].

The middle range of the frequency response (2 kHz - 20 kHz) is usually influenced by the coupling between the windings, which largely depends on the arrangement and connection of the windings, e.g. delta connection, stars, autotransformer winding connection, single-phase or three-phase transformer configuration [63].

The process of fault analysis on the transformer by measurement of the SFRA method with impact test is shown in Fig. 7. Differences between measured frequency curves are analysed by value of relative factor $R_{xy}$.

The winding state in primary or secondary part of transformer was detected by the short-circuit test. This test informed us about deformation of internal winding and their shifts as an activity of mechanical effect of short-circuit forces.

Impedance comparison of tests for no-load and short-circuit for undamaged windings are presented in Fig. 8.

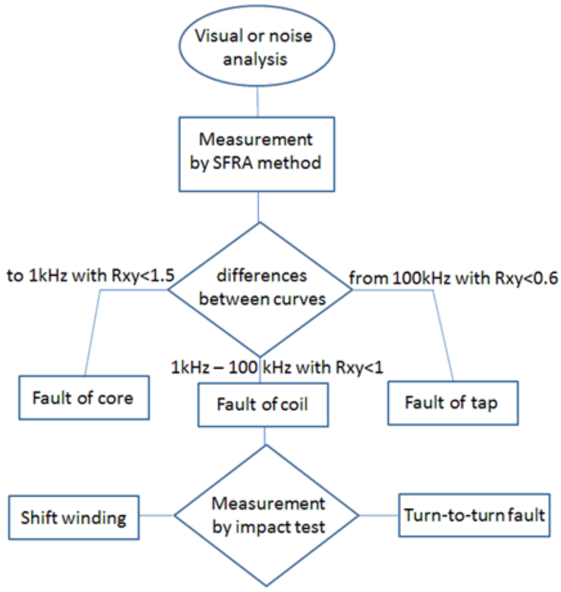



Fig. 7. The process of fault analysis of power transformer

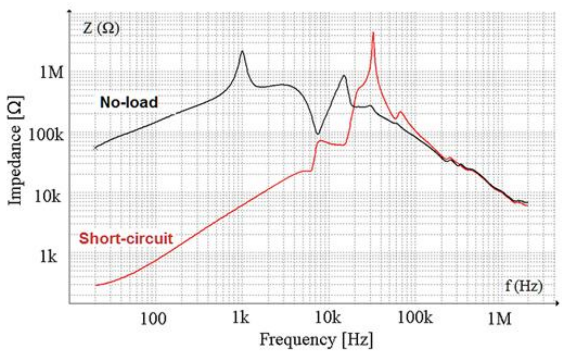



Fig. 8. Frequency dependencies of measured impedance for no-load and short-circuit states

Comparing the above graphs, clear difference is noticeable in curves from measurement of phase in relation to frequency (Fig. 9), which increases analysis accuracy when defining condition of the transformer.

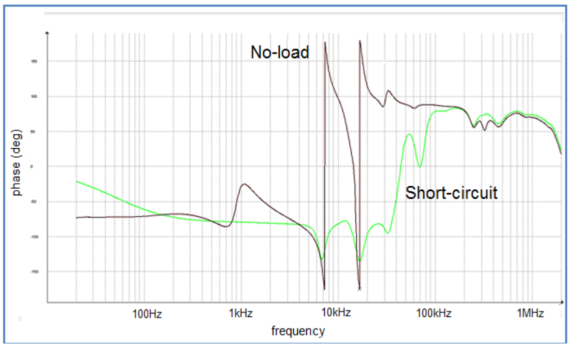



Fig. 9. Frequency phases of measured impedance for no-load and short-circuit states

Comparison of the measurements of attenuation and phase of three windings of the same transformer depending on the frequency for no-load test is presented in Fig. 10. The most difference curves between two coils of the same transformer is shown in the middle frequency (Fig. 10).

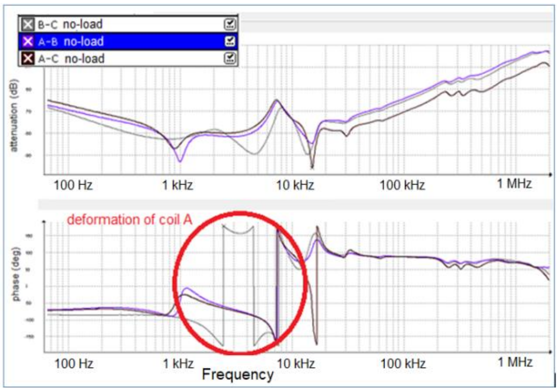



Fig. 10. Comparing the measured attenuation and phase of three windings of the same transformer in no-load test

Deformation of the coil A is displayed by dependence of the impedance and the frequency in the range 1-10 kHz (Fig. 10). If the windings of transformer are star connected, different curves between phases B - C means damage of other phase coil - coil A.

In order to analyse the measured results is possible to utilize normalized mathematical standard "DL/T 911-2004". This calculation method mathematically analyses differences between two curves (sequences) using relative factor $R_{xy}$ in equations (2), (3) and (4).

Calculation of the two sequences standard variance:

$$D_x = \sum_{K=0}^{N-1}\left[X(k) - \frac{1}{N}\sum_{K=0}^{N-1} X(k)\right]^2$$

$$D_Y = \frac{1}{N}\sum_{K=0}^{N-1}\left[Y(k) - \frac{1}{N}\sum_{K=0}^{N-1} Y(k)\right]^2 \qquad (2)$$

Calculation of the two sequences covariance:

$$C_{XY} = \frac{1}{N}\sum_{K=0}^{N-1}\left[X(k) - \frac{1}{N}\sum_{K=0}^{N-1} X(k)\right]^2 \times$$

$$\times\left[Y(k) - \frac{1}{N}\sum_{K=0}^{N-1} Y(k)\right]^2 \qquad (3)$$

Calculation of the two sequences normalization factor covariance:

$$LR_{XY} = \frac{C_{XY}}{\sqrt{D_X D_Y}}. \qquad (4)$$

Finally, from equation (9), relative factor $R_{xy}$ is determined [14].

Using the covariance factor calculation from equation (4), the difference between the two responses in the three frequency bands (1 kHz to 100 kHz, 100 kHz to 600 kHz, 600 kHz to 1 MHz) is determined, and each band is assigned a value of the relative factor $R_{xy}$.

The value of the factor $R_{xy}$ is assigned for each frequency band according to the degree of deformation of the winding and at the end the worst degree of deformation according to Tab. 1 [14].

Tab. 1 Relationship between relative factors and the degree of damage to the transformer winding

| Degree of winding deformation | Relative factor $R$ |
|---|---|
| Difficult (large) deformation | $R_{LF} < 0,6$ |
| Middle deformation | $1,0 > R_{LF} \geq 0,6$ or $R_{MF} < 0,6$ |
| Little deformation | $2,0 > R_{LF} \geq 1,0$ or $0,6 \leq R_{MF} < 1,0$ |
| Normal condition | $R_{LF} \geq 2,0$; $R_{MF} \geq 1,0$; $R_{HF} \geq 0,6$ |

where:

$R_{LF}$ is a relative factor in the low frequency band (1 kHz - 100 kHz), $R_{MF}$ in the mid frequency band (100 kHz - 600 kHz) and $R_{HF}$ in the high frequency band (600 kHz - 1 MHz).

For no-load tests the result of the calculation was the value for relative factor $R_{xy}$ = 0.35 in the low frequency range from 1 kHz to 100 kHz (Fig. 11). In this range the value of the inductive part dominated. The inductive part of impedance was depending on the geometry layout and deformation of the coil. This analyse represents deformation anomaly due to short-circuit in winding, thus damage of the phase coil A and permanent damage of the transformer.


Fig. 11. Finding of deformation of coil A by connection of frequency signals between the winding-phase A-C and B-C

## 5. CONCLUSIONS

We can diagnose transformer by means of time and frequency response of windings by the voltage impulses. Impact test and frequency response analysis indicate a significant sensitivity to a relatively small inter-thread deformation. These methods allow clearly analyzing of the short circuit impact in the transformer winding.

Although the relation between the response course and state of winding is clear, it is very complicated. It is impossible to expect, that from the found out difference in the course of response we can consider the concrete damage of the winding. As the result of measurement we can only observe, that the state of winding changed. Such result of using of mentioned above methods could be useful in decision making, whether it is necessary to open and examine the transformer.

Information and outcomes mentioned in the paper are the basis for future investigation, which will focus on enlarging the knowledge of and determining clear relation in time and frequency domain and condition of the transformer windings.

There measurement methods of ratio of amplitude for pair of coils works well when the two coils of the investigated transformer are in good state.

In the paper was showed fault state into transformer winding of phase A following possible short-circuit forces from energetic system.

There diagnostic methods of transformers considering the influence of short-circuit currents during the operation should be carried out to increase the reliability in real trouble-free process.

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Assoc. Prof. **Daniel Korenčiak**, PhD; Prof. **Miroslav Gutten**, PhD; University of Zilina (on the photo) - participating organization in its scientific and research activities is dealing for several years with the solution of the project and grant tasks in area of diagnostics of electrical equipment (electrical machines, automotive systems, electrical transfer devices). Head of research team and Department of Measurement and Application Electrical Engineering is