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Analysis of mechanical effects of short-circuit forces on transformers

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Abstract

This paper is focused on analysis of mechanical effects on transformers. The analysis was performed by means of a DST system. Transformer manufacturers can use this system for the quality check of their products, repair companies for repairing advantageousness evaluation and measurement of transformer new parameters after the repair. If the DST is included in the entrance firm control, it is possible by means of it to verify the parameters given in the transcript of the new transformer measurement supplied by its manufacturer.

Keywords: short-circuits, radial forces, axial forces, transformers, winding, SFRA method, frequency.

Analiza mechanicznych oddziaływań sił zwarciowych na transformatory

Streszczenie

W artykule przedstawiono wyniki nowoczesnej analizy mechanicznych oddziaływań na transformatory sił zwarciowych, którą wykonano za pomocą systemu DST. Producenci transformatorów energetycznych mogą wykorzystać ten system do kontroli jakości nowych jednostek, natomiast zakłady naprawcze do zawansowanej oceny stanu technicznego i uzyskania nowych parametrów bazowych po naprawach i kapitalnych remontach. System DST może być stosowany do kontroli stanu transformatorów energetycznych użytkowanych prze spółki dystrybucyjne. Ma to szczególne znaczenie podczas dokonywania decyzji remontowych oraz wymianie starszych jednostek. W artykule przedstawiono teorię powstawania sił podczas zwarć w transformatorach i opisano składowe oraz koncepcję zaprezentowanego systemu DST. Wykorzystywane pomiary do diagnostyki transformatorów to: pomiary rezystancji uzwojeń z analizą czasową napięcia, pomiary napięcia indukowanego, pomiary przekładni, pomiary zwarciowe, SFRA **(Sweep Frequency Response Analysis)**, pomiary rezystancji izolacji. W artykule wymieniono zalety systemu DST, ze zwróceniem szczególnej uwagi na metodę SFRA, przydatnej w diagnostyce eksploatacyjnej z długoterminowego punktu widzenia.

Słowa kluczowe: zwarcia, odkształcenia promieniowe, odkształcenia poosiowe, transformatory, uzwojenie, SFRA, częstotliwość.

1. Introduction

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 result of short-circuit is a serious disrepair of a transformer, because there are high currents in it which rise the winding temperature considerably, which can cause damage of the insulation. High electro-magnetic forces which can be the reason for devastation of a transformer are much more dangerous. Fig. 1 shows the transformer whose winding is damaged by short-circuiting forces.

When considering a significance of power three-winding autotransformers 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 during 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 in the transformer mechanical strength and, consequently, unexpected damage of the transformer during the operation.

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

For a better comprehension of the relation between transformer damage and short-circuit current effects, we must focus on the effect mechanical forces effect on transformer windings during the short-circuit.

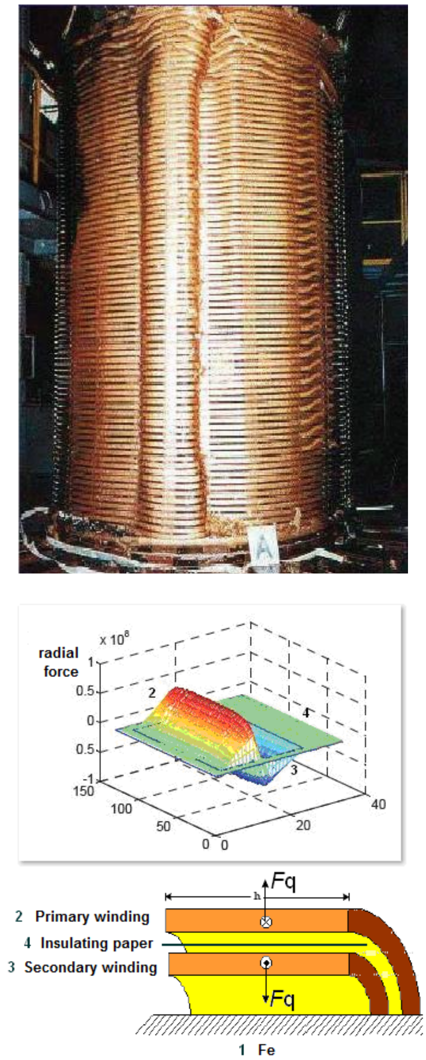

Fig. 1. A view of the autotransformer damaged winding due to short-circuit radial forces [7]
Rys. 1. Uszkodzone uzwojenie autotransformatora w wyniku oddziaływania promieniowych sił zwarciowych [7]

2. The theory of mechanical force effect on the transformer winding during short-circuit

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

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

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

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

Radial forces F_q are a result of lengthwise fields which are parallel to the axis of the transformer winding. These forces dilate the external windings and compress the internal ones, so the air spaces become bigger in consequence of it.

The lines of the magnetic stray flux force are parallel to the winding axis and the similar radial force affects the each coil. The sums of radial forces, denoted by F_δ, lead up to increase in the space between the windings δ (Fig. 1).

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

The axial forces are dangerous to asymmetric windings. 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 the 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 be caused by drying-out.

According to [2] we need to pay more attention to catching the outer coil. In case of a released coil, the axial forces F_d can cause displacement of outer coils to the vertical sides. The redundant pressure on spacers can press insulation and moved the winding, which can cause serious damages of the transformer.

Fig. 2 illustrates the pitching of coil conductors by action of the excessive axial forces (effect of insulation compression).

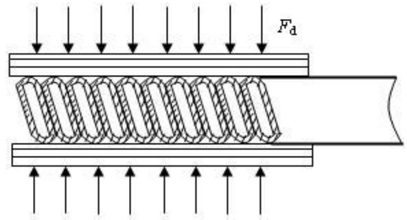

Fig. 2. Pitching of coil conductors by action of the excessive axial forces
Rys. 2. Wychylenie przewodów w cewce wskutek oddziaływania sił poosiowych

3. Basic information about the system DST and its use for analysis of short-circuit forces

The DST measuring system of transformers developed at the University of Žilina, in cooperation with the firm Lambda Control Ltd. Liptovský Hrádok and with delivery of apparatuses from EN-CENTRUM Ltd. Praha, is certain for transformer manufacturers and for organizations working at transformers maintenance. Transformer manufacturers use the system for the quality check of their products, repair companies for repairing advantageousness evaluation and for measurement of transformer new parameters after the repair. If the DST is included in the entrance firm control, it is possible by means of it to verify the parameters given in the transcript of the new transformer measurement supplied by its manufacturer.

The DST measuring system of transformers can be used for complex measuring of different types of transformers.

According to the analysis of short-circuit forces - the system DST is dedicated to:

a) direct analysis of:
  - winding resistances with time analysis of voltage,
  - induced voltage test,
  - voltage ratio,
  - short-circuit measurement with analysis of short-circuit voltage,
  - SFRA method.

b) indirect analysis of:
  - no-load measurement,
  - insulation resistance,
  - separate-source test.

The transformer diagnostic system DST is completely designed and supplied additionally from the source part (Fig. 3 - right box). It includes the following electrical accessories:

- single – phase testing transformer BEZ Bratislava 30 kVA, 0,4/100 kV,

- single – phase testing transformer BEZ Bratislava 5 kVA, 0,4/3 kV,
- high voltage 150 kV voltage divider DVR150F HIGH VOLTAGE,
- three – phase oil autotransformer TTW PDOR72 72 kVA, 0-400 V,
- impedance – matching transformer BEZ Bratislava 100 kVA, 400/1000 V,
- frequency converter 400 VAC, 0 - 500 Hz, 18,5 kW.

There are also in the measuring and controlbox DST (Fig. 3 - left box):

- insulation tester C.A 6549 - to 5 kV,
- winding resistance meter Raytech WR50-12 - to 50 A [5],
- ratio measuring meter Raytech TR–Spy Mark II - to 100 V [6],
- three–phase high precision power analyzer Fluke Norma 4000,
- voltage transformers 1000/100 V,
- current transformers 50/5A, 20/5A, 5/5A,
- SFRA analyser Doble mod. M5000 or frequency RLC meter

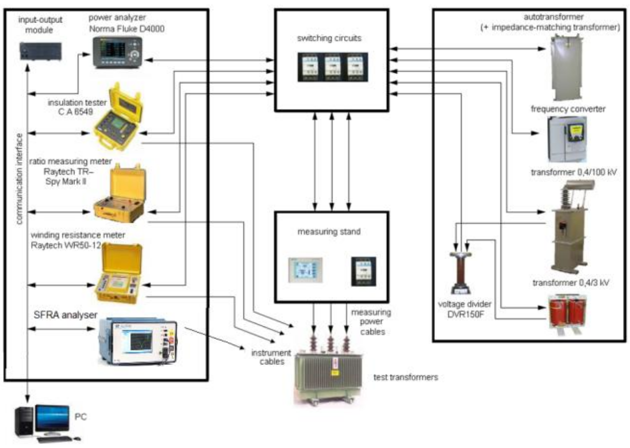

Fig. 3. Block diagram of the system DST
Rys. 3. Schemat blokowy system DST

4. Experimental analysis by means of the system DST

A program for diagnostics of transformers DST works under the operating system Microsoft Windows. The program is controlled by standard components of the Microsoft Windows operating system, therefore it is user friendly. Most of operations are done using a mouse and clicking the left button over the desired control object (button, scroll bar, menu item, text box, …). Input and modification of the data in the text box is done by easy overwriting of the chosen value using a keyboard. The program DST6 is designed for automatic diagnostics, complex measurements and verification of operating parameters of distributive transformers using particular measurements, which are divided into groups.

After the startup and also before a measurement the program DST tests all necessary devices like measuring instruments, sources, input and output states and error states. The program verifies the correctness of settings which are stored in external files. In the case of an error the error message appears on the screen.

Individual measurements and also their results are in the transparent form placed and viewed in bookmarks of the program main window. Except text printout, the results and the state of individual measurements are also in the graphic form. In the bookmark General evaluation the states of particular measurements are clearly viewed. The scheme of transformer connections for a particular measurement will appear in the measurement window, after opening, in the upper part. This scheme is displayed also on the graphic panel of the measuring stand as a help for connecting the measured transformer with the system DST. During the measurement the measured values are graphically visualized in the measurement window and individual steps of the measurement are available in the numerical and text form. Thanks to it the operating staff of a measuring workstation has all the time information about the immediate state and the operation of the system DST. The program automatically graphically indicates and warns the operating staff about the measured values which are out of the range. For simpler observation of the system DST operation the program is equipped with a sound background which indicates the activity of the measurement, the error states and the reports.

Partial results of individual measurements together with the entered card data are possible to be stored in the archive of measurements. The complete results of the measured parameters of transformers may be stored in the database of measurements. The database enables easy searching and viewing of the stored results of measurements.

4.1. Sample of measurement by the self-discharging voltage method

In system DST this method is possible to be realized during a measurement of the winding resistance. The self-discharging voltage method is a highly sensitive method which is based on assessment of the quality changes of material aftermath operational aging.

After the defined time of the inter-coil capacitance charge the transformer is unplugged from a DC supply and we measure the discharging process of winding insulation through the leakage resistance. Faster decreasing of self-discharging voltage is caused by a smaller value of the insulating resistance. Discharging process is affected by irreversible degree of degradation of material, too.

The graph of the voltage on the transformer inter-coil capacitance after unplugging is shown in Fig.4. The discharging time grows with rise in the quality of winding insulation.

We can observe the differences between each phase of the transformer in t_2 time in this measurement.

This difference is an important sign of degradation of the state of winding insulation mainly by the effect of short-circuit currents.

We checked 9 randomly selected transformers which were used in a distribution network of power in the range from 30 kVA to 1 MVA and we acquired the discharging time for each phase (Tab.1). The results of measurements were a partial image of short-circuit stresses of the transformer in the operating time. The coils were not changed before the test.

In Tab. 1 there are values obtained by measuring the self-discharging voltages on the primary HV coils. Comparison of the different phases shows asymmetry of the insulation quality on transformers 1 and 4.

Tab. 1. Results of discharging time measurement
Tab. 1. Wyniki pomiarów czasów rozładowywania

No.	Type	*S*	A - B	A - C	B - C	IΔt_v.100I	**Note**
		(kVA)		t_v (s)		(%)	
1	kTO 253/22	30	48	34	48	**21,54**	***a**
2	aTO 294/22	100	98	82	96	**10,87**	
3	aTO 294/22	100	114	98	103	**8,57**	
4	aTO 294/22	100	103	131	156	**20,77**	***a**
5	aTO 334/22	250	152	131	159	**11,09**	
6	aTO 334/22	400	68	71	69	**2,40**	
7	aTO 374/22	630	135	107	123	**12,05**	
8	aTO 374/22	1000	76	60	63	**14,57**	
9	kTO 350/22	400	165	165	171	**2,40**	

*a – **huge inter-coil difference**

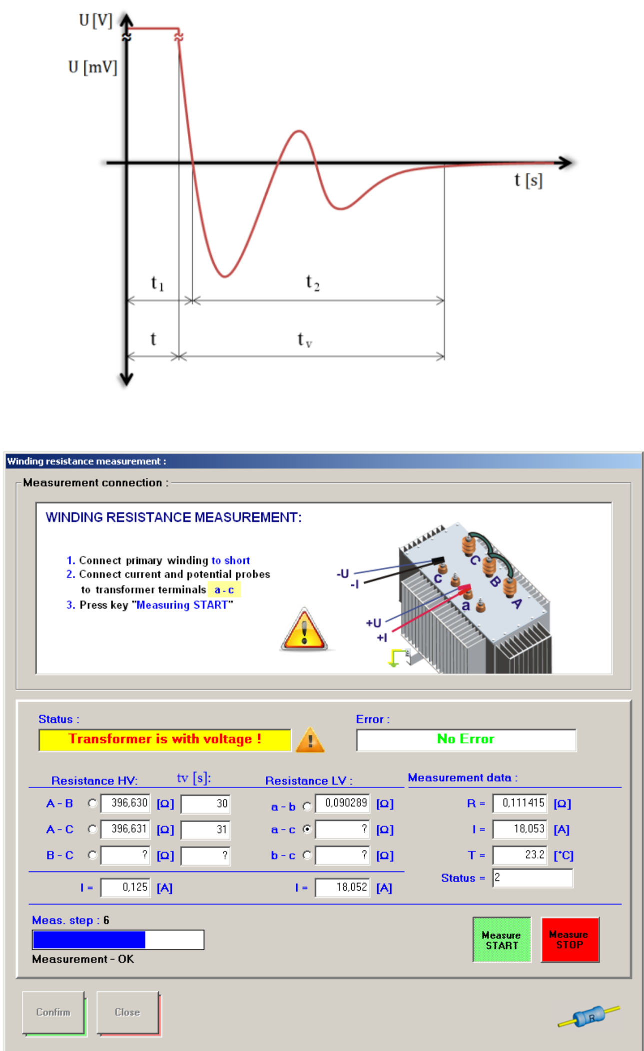

Fig. 4. The discharge process of the transformer after disconnection from a DC supply and the dialog window of the DST system

Rys. 4. Proces rozładowywania transformatora po odłączeniu napięcia stałego i widok okna systemu DST

4.2. Sample of measurement – the SFRA method by RLC meter

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

The SFRA as one of the most predictable methods, can be based on passive parameter measurement method depending on frequency 20Hz – 200kHz (see Fig. 5 – the measured values for a distribution transformer 22/0,4 kV by RLC meter).

During these measurements there are detected mechanical states of the tested winding and ferromagnetic core. The obtained curves typical for this measurement provide the important information about the changes in the core, which are visible in low frequencies, while higher frequencies are associated with problems such as winding movements or turn-to-turn fault.

The application of analysis of phase or tgδ (dissipation factor) attenuation depending on frequency (Fig. 6) is suitable for more complete evaluation of the winding condition. This analysis enables assessing the processes of winding movements during the particular short-circuit influences.

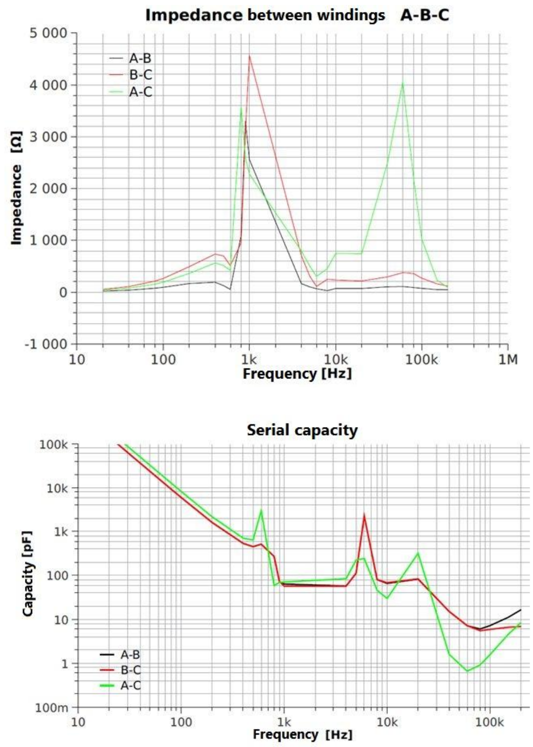

Fig. 5. Dependence of the impedance and capacity on frequency, measured with RLC meter for transformer 22/0,4 kV

Rys. 5. Zależność impedancji i pojemności od częstotliwości, zmierzone miernikiem RLC dla transformatora 22/0,4 kV

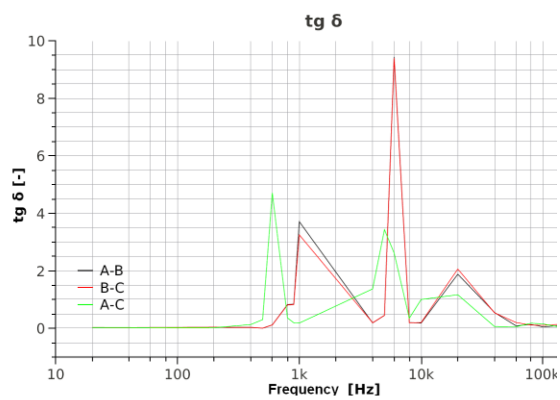

Fig. 6. Dependence of tgδ on frequency measured for transformer 22/0,4 kV

Rys. 6. Zależność tgδ od częstotliwości zmierzona dla transformatora 22/0,4 kV

5. Conclusion

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

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

The problem of the frequency analysis of transformers by the 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 the tested transformers. These transformers have their reference data obtained by the manufacturers, suitable for the comparison with further data of a particular transformer.

The SFRA testing method, the self-discharging voltage method, the analysis of short-circuit voltage and others represent one of the most effective alternative diagnostic methods compared to a visual check. These methods allows detecting the effects of the short-circuit currents, whereas we are able to evaluate the mechanical strength action on the transformer winding during the 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.

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