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ON – SITE PROCESSING OF INSULATION SYSTEM OF LARGE POWER TRANSFORMERS AND HOT–SPOT COMPUTER DETERMINATION

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1. Introduction

Recently on – site repair and refurbishment operations on transformers are more and more frequent because they are cost – effective alternatives, after all due to decreasing direct costs (cost of dismounting and transportation) and also shortening the repair time [4, 5, 10].

One of the most often operation performed on – site is oil processing and drying of transformer insulation. Water is one of the most dangerous agent of degradation of the paper – oil insulation system, influencing transformer reliability. Below, in the first part of the paper, two examples of transformer drying on – site are reported.

Hot – spot temperature of windings is another factor influencing ageing processes of winding insulation. Therefore precise determination of hot – spot is very important for controlling life of a transformer. In the second part of the paper some results of a computer calculation of the hot – spot are presented.

2. On-site processing of transformer insulation system

2.1. Autotransformer 500 MVA 410/245 kV

2.1.1. Source of moisture

Primary reason of autotransformer failure was a dielectric breakdown and then an arc in diverter switch of OLTC on phase A. The unit was switched off from both sides during approx. 60 msec.

The cover of the diverter switch was rapidly thrown out and the switch chamber walls were unsealed due to high pressure caused by the arc. After that the following events were happened:

- rapid increasing of pressure in the main tank,
- opening of one protecting pressure valve,

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- catching fire of oil in the diverter switch,
- activating a fire suppression water system.

The fire was extinguished but some volume of free water entered the main tank.

After some careful examinations, including an internal inspection no failure of windings was found. Consequently a decision on repair and drying the autotransformer on – site was taken.

2.1.2. Drying on – site

Because of relatively short time of exposing the insulation on wet oil and air (free water entered the main tank did not moisten the windings directly), rather small moisture contamination of insulation external layers was expected. A method of a number of successive cycles of vacuum and dry hot oil circulation was chosen.

Drying system and pre – starting preparation of the transformer

HV bushings were dismounted, coolers and conservator as well as all pipes were closed by vacuum proof valves. The main tank, including bushing chimneys, an additional oil container and an additional heater were thermally insulated and covered by water proof foil, to protect against heat dissipation and rain.

Schematic arrangement of devices used for drying is shown in Fig. 1 and a view of the on – site stand is presented in Fig. 2.

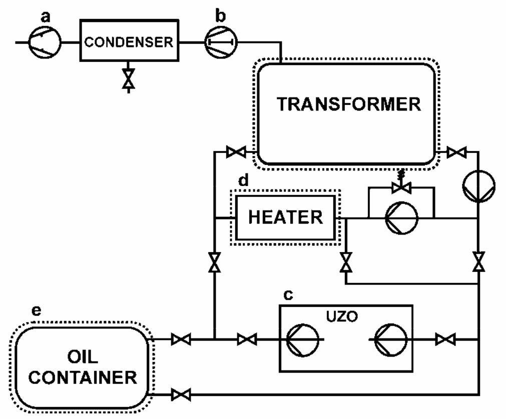

Fig. 1. Schematic arrangement of devices used for drying 500 MVA autotransformer.

Main elements of installation – Fig. 1.

a. Vacuum buster pomp with capacity 500 m^3/h.
b. Roots vacuum pomp with capacity 2000 m^3/h.
c. UZO 3000/6000 type oil treatment plant with maximum oil capacity 6000 m^3/h, heater 100 kW, and vacuum 0,1 mbar. Plant equipped with fine filter.
d. Additional heater 60 kW.
e. Oil container 50 m^3/h.

Drying process:

The process consisted of several stages:

I stage: Oil in the container was filtered, degassed and dried by means of the oil treatment plant till gas content below 0,5 %, water content below 5 ppm, and temperature approx. 80 – 85 °C were reached.

II stage: After closing the main tank, the vacuum pumps were activated to produce pressure at approx. 1 mbar level.

Fig. 2. View of the on – site drying stand. On the first plane – vacuum pump set

III stage: Oil filling. Clear, dry and degassed oil from the oil container was pumped to the main tank through the additional heater, up to the transformer upper yoke level.

IV stage: Heating – up core and windings. Hot oil, continuously heated by the oil treatment plant and the additional heater, was pumped through the tank till the winding temperature was approx. 90 – 95° C. Temperature of the inner winding was measured by means of the resistance method. Over the stage duration the vacuum pumps were in operation.

V stage: Drying under vacuum. Oil, during approx. 3 hours, was drain out from tank to the oil container and then vacuum of approx. 1 mbar was kept. Winding temperature, during approx. 40 hours, was slowly decreased up to approx. 60° C.

VI stage: Stages III ÷ V were repeated 4 times.

The last stage: Assembling. After last oil filling, the thermal insulation was partially dismounted. The bushings were installed and transformer was completely filled up by processed oil. Then approx. 20 hours processing of oil with continuous circulation trough the tank was applied.

2.1.3. Measurements during drying

During the drying process the following measurements were performed:

- temperature of winding (245 kV phase A) – the resistance method,
- tan d and C_2/C_{50} of insulation (inner, LV winding to grounded tank and core) – Fig. 3 and 4.

Before commissioning the autotransformer passed successfully the set of standard tests and additionally a prolonged 24 hours no – load test, supplied by an auxiliary small power source with an arrangement reducing the switching – on current [1]. Schematic supplying circuit is presented in Fig. 5. Resistors R were short – circuited approx. 15 seconds after switching – on supplying voltage.

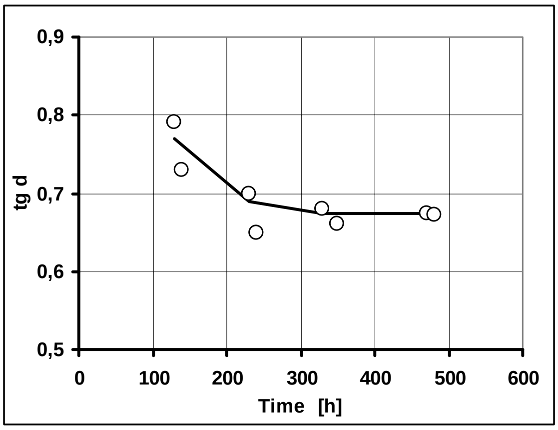

Fig. 3. tan d changes during drying of 500 MVA transformer.

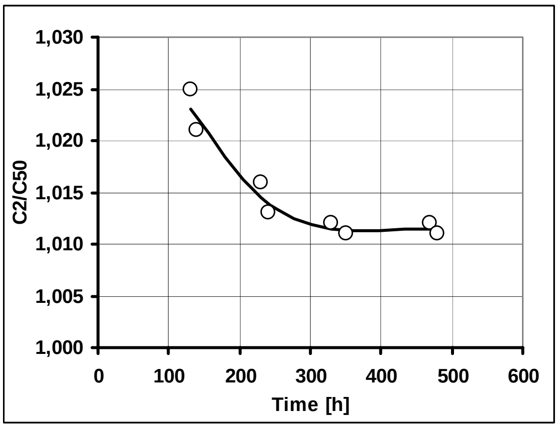

Fig. 4. C_2/C_{50} changes during drying of 500 MVA transformer.

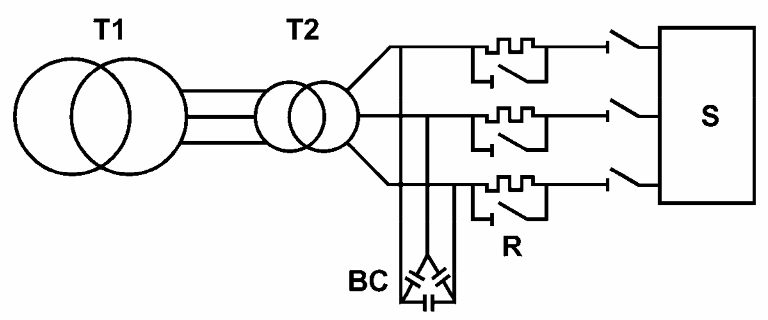

Fig. 5. Supply circuit for prolonged no – load test of 500 MVA, 410/245/15,75 kV autotransformer,
T1 – tested unit T2 – auxiliary transformer 630 kVA 15.75/0.4 kV
BC – capacitor bank 340 kVAr, 15.75 kV, R – resistors 3x0.2 Ohm
S – diesel generator 200 kW, U_n = 400 V, f = 50 Hz, cos φ = 0.8

During the test PD were measured by the acoustic method. Measured PD level was between 1500 and 2000 pC at the beginning of the test, and was going down during the test to 50 – 150 pC.

Before and after the test DGA were measured. Practically no changes were noticed.

2.2. Generator transformer 630 MVA, 400/22 kV

2.2.1. Reasons of water contamination

Large volume of hot water entered the main tank due to a failure of water – oil cooler caused by a human error. The transformer was equipped with the forced oil flow system (ODWF). Consequently oil pumps, before stopping, mixed the water with oil that gave a high moisture level in the insulation system. Drying so wet insulation should be performed very slowly to avoid deformation or even cracking paper and pressboard elements.

2.2.2. Drying on-site

Drying of the transformer was carried out in several stages.

Preliminary stage: Water and oil – water emulsion was removed to a container. Rest of wet oil was removed to another container. Windings and the core were washed with new dry oil and then the main tank was sealed and filled with dry nitrogen. Results of some measurements performed after switching off the transformer are given in Table 1.

I stage: The windings and the core were washed with new, dry oil by means of splashing nozzles installed in the top of the tank [3]. Then insulation was dried with dry air (dew point below -50° C). Process was repeated several times. Winding insulation resistance to ground was raised up to 1.5 Mohm (compare Table 1), and water content in paper and in pressboard was lowered below half of the beginning value.

Table 1. Results of measurements performed after failure of 630 MVA generator transformer

Insulation resistance	Testing connection	R_{300} Mohm	**Paper insulation**	Sample	Water Content ppm	**Oil**	Sample	Water Content ppm
	HV – LV, ground	0.1		Wire insulation	>9		Top	283
	LV – HV, ground	0.2		Insulation of leads	>9		Bottom	531
	HV – LV, screen	3.4		Pressboard 0.5…1.0 mm	6…7			

II stage: Vacuum drying without oil and with heating of winding. HV winding was heated by means of DC current and its temperature – measured by means of the resistance method – was stabilised on 80 –90° C level. Water content measured in 1 mm pressboard sample at the end of that stage was approx. 1%.

III stage: Vacuum drying with heating both windings. HV winding was heated as previously by means of DC current, LV winding and core were heated by means of hot oil (similar way as in stage IV and V of drying process of 500 MVA autotransformer). The process was repeated several times and finished when water content in paper/pressboard samples was below 0,5%. Changes of water content in these samples are given in Fig. 6.

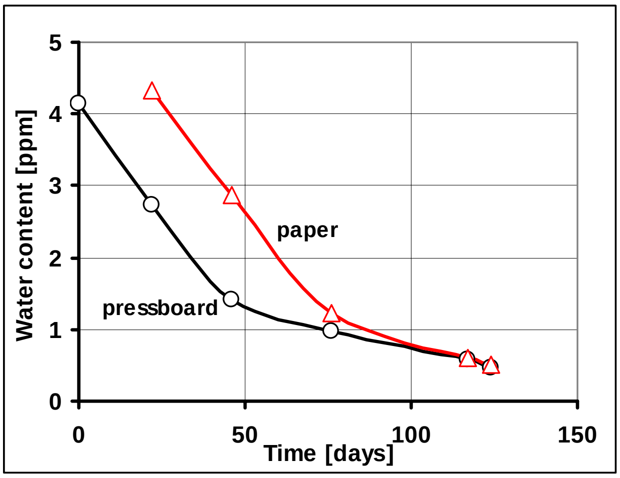

Fig. 6. Changes of water content in paper and pressboard samples during drying 630 MVA generator transformer.

Before commissioning the transformer passed successfully the set of standard tests.

3. Temperature distribution in a coil of a disc winding

A factor determining a lifetime of a transformer – "hot – spot" factor is a ratio of a hot – spot temperature rise and an average rise of a winding temperature [11, 12]. Hence a temperature distribution in the hottest coil shall be known in order to estimate the value of the coefficient. Consequently, precise and reliable method for calculation a temperature distribution in coil of the winding shall be used. It should also consider both radial and circumferential load distribution, and an uneven heat outflow from a cooling coil surface. Moreover, a form of the coil itself and its interconnections with neighbouring coils have to be taken into account. Generally the load distribution in the coil is not uniform because of an eddy current loss.

The elementary heat balance method was adopted for calculation the temperature distribution [7] that enables mapping a complicated structure of an analysed system. A passage of the heat to the surrounding oil is framed quantitatively by a convection coefficient. Commercially available packages could be used that calculate the convection heat exchange by means of the finite element method in Galerkin formulation employing equations of Navier – Stockes and Fourier – Kirchoff [2].

Below, results of sample calculations carried out on one coil of HV disc winding of 500 MVA, 400 kV autotransformer are shown. The coil with Chadvick interleaving wounded by a 'twin' wire has 18 turns. Dimensions of a single conductor are 2.8/14.4 mm.

An oil velocity is the most important factor influencing the discussed coefficient. Two sets of velocities expressed by Reynolds number were considered [8]:

R_e=100/10. An average value of Reynolds number in vertical cooling ducts (i.e. between a winding and neighbouring insulating cylinders) equals 100, at which an average oil velocity is equal to 31.2 mm/sec. The value for a horizontal cooling ducts (i.e. between neighbouring coils) equals 10. Therefore, the average oil velocity is equal to 5.14 mm/sec. Such set of values corresponds to natural, thermosiphon cooling of the windings (ON).

R_e=1000/200. Equivalent values are equal to 1000/312 mm/sec and 200/103 mm/sec, respectively. Such set represents a directed, forced circulation of the oil through the windings (OD).

Results of calculations for R_e=100/10 are presented in Fig. 7. The cooling efficiency is expressed as a non dimensional local value of Nusselt number. It depends on a distance from the oil inlet to the cooling duct expressed as non dimensional value equals to the real distance divided by a product of a hydraulic diameter of the duct, the average Reynolds number and Prandtl number.

Such method of presentation is commonly used in heat exchange problems because it enables quite simple transfer of results to another temperature and another thickness of the paper insulation.

A difference of the cooling efficiency at both surfaces is clearly visible. It rises with a reduction of Reynolds number (i.e. with decreasing the oil velocity). An inequality of the local value of Nusselt number is substantial particularly at higher value of Reynolds number. Significant disturbance of the said number takes place at the oil inlet and smaller one at the oil outlet. It is related to oil whirling in these regions particularly visible at an intake area and higher value of Reynolds number.

Sample calculation results of the eddy loss coefficient, shown in Fig. 8, are related to the following radiuses:

i) perpendicular to a main core axis, assuming equal distances to the tank wall – 'TAN',
ii) laying on the main core axis towards the reverse yoke – 'REV',
iii) as above, but towards a neighbouring winding – 'WIN'.

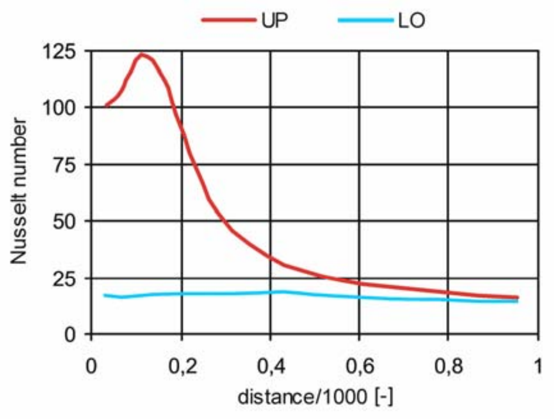

Fig. 7. The initial part of a local Nusselt number vs. a distance from an oil inlet to a duct between coils; Re = 100/10, ‘UP’ – upper, and ‘LO’ – lower cooling surfaces of the coil.

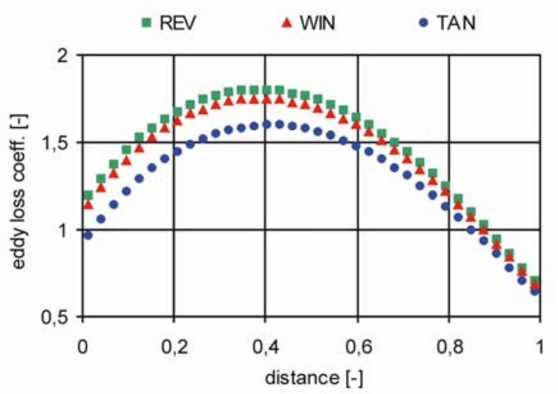

Fig. 8. Eddy loss coefficient vs. a distance from an outside edge of a coil. REV, WIN, TAN – see the text of this paragraph.

The distribution of the average temperature rise of subsequent wires remains a parabola – Fig. 9.

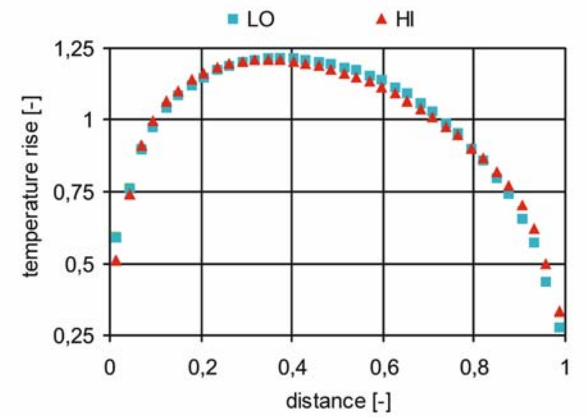

Fig. 9. The average temperature rise of wires of a coil vs. a distance from an outside edge of the coil. ‘LO’ – Re = 100/10, ‘HI’ – Re = 1000/200.

Both – the eddy loss coefficient distribution and its value as well as the cooling conditions – are reasons of the distribution character. A high temperature gradient at the coil edges is caused by the intensive heat flow from the external wires to the oil flowing in the vertical cooling ducts. A cooling surface of these wires in this direction is significantly larger than the surface in perpendicular direction. Moreover the heat flux from the external wires takes over heat from the neighbouring wires through paper insulation.

The above phenomenon may often reduce the hot – spot temperature. The character of the discussed temperature rise distribution practically does not depend on the oil velocity in the cooling ducts. However, the oil velocity influences on the cooling efficiency. Let us assume that in both selected sets of Reynolds number the hot – spot temperature is exactly the same. Under such assumption a passage from the set R_e=100/10 to the set R_e=1000/200 enables to increase of the current density by 26.5% causing a rise of the loss dissipated in the coil by 60%. Bearing in mind that it is a consequence of increasing of the oil velocity in the duct between coils about 20 times, mentioned above rise of the dissipated loss is not so high as it may be estimated at the first sight. An increase of a permissible value of the current density does not follow a rise of the local value of Nusselt number. This is because a convective temperature drop, influenced by the oil velocity, represents only a small part of copper – oil temperature drop.

4. Conclusions

On – site operation on transformers, including on – site insulation drying process, more and more stimulated recently by economic issues, supported by specialized apparatus are possible technologically with no decrease of the reliability of dried units. Presented on – site drying examples ensured low final moisture and high quality of insulation, comparable with quality obtained by means of advanced factory drying processes.

Advanced numerical methods are very useful for modeling local heat exchange phenomena, resulting in precise determination e.g. hot – spot factor with taken into account a majority of decisive factors met in practice.

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