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Effects of ageing and maintenance practice on winding performance

On-site replacement of OLTC, drying of winding insulation, induced voltage test with PD measurement of 250 MVA, 400/110 kV, 40 year old transformer

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SUMMARY

The On-Line Tap Changer (OLTC) was damaged beyond repair, but winding insulation has not been significantly aged in 250 MVA, 400 kV network transformer, despite more than 40 years of service. The transformer maker does not manufacture his type of OLTC any more, and it was replaced by MR equivalent. To determine the winding-insulation condition induced-voltage test was performed up to 110% U_n, by energizing the tertiary winding from mobile motor-generator set operating at a higher frequency. Insulation of 400 kV winding revealed Partial Discharge (PD) level between 1200 and 1800 pC but no specific PD source was identified. Water content in the winding insulation amounted to 1.1% prior to the OLTC replacement. Very compact design of the tank required an assessment of dielectric stress around the leads from tap-winding to the tap-selector. These leads had to be extended, and clamping the joints and wrapping tape insulation in the cramped space required highly skilled craftsmen. The single access porthole has been sealed when no people were inside the tank, to limit ingress of air. An internal polymeric-membrane was installed inside the tank to separate the working area from the windings, where a small overpressure was kept with synthetic dry-air. Despite such precautions some moisture was absorbed by the winding-insulation surface during the OLTC replacement. To dry this insulation the transformer was heated by filling the tank with new oil warmed up by 65ºC, then draining the oil and lowering the pressure to less than 1 Tor (133 Pa) for 24 hours. The moisture was extracted from the insulation outer-layers and lower than 1% content was measured using RVM and PDC methods, which are sensitive to the moisture trapped in the insulation surface, and to the moisture averaged over the whole insulation-volume, respectively. The induced-voltage test was repeated after completion of the OLTC replacement, and PD level in 400 kV winding insulation was reduced by an order of magnitude, and DGA indicated content of Hydrogen 3.5 ppm, Methane 0.35 ppm and no Acetylene. The transformer was put in service after 72 hour trial run. The successful on-site OLTC replacement in the large transformer manufactured in Japan 40 years ago confirmed feasibility of such operation. This meticulously prepared on-site operation, highly skilled engineers and technicians, as well as advanced instruments to assess the winding-insulation condition were the essential factors to extend the technical life of this strategically important and costly transformer.

KEYWORDS

High-Voltage, Power-Transformer, On-site-OLTC-replacement, On-site-HV-Test, On-site-Drying.

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1. INTRODUCTION

Drying technology of HV power-transformer solid-insulation has been developed and implemented by manufacturers for a century [1], but on-site transformer-drying is relatively new. Several factors have to be considered when the mature technology well established in transformer factory is adapted to the conditions prevailing in HV station [2]. The drying process of new transformer-insulation that was not oil-impregnated is different, in fact simpler than in the case of already oil-impregnated paper and pressboard. Extraction of water trapped in oil-impregnated pressboard is a much slower process [3].

Moisture content in cellulose increases with years of operation at an elevated temperature. Usually the short-time of transformer unavailability is the most important requirement imposed on the on-site repairs. However, an accelerated moisture extraction may damage the laminated structure of pressboard, since rapid evaporation of water trapped inside the pressboard may create voids that take a long time to be filled with oil [4].

In older transformers accessories often have to be replaced, and to remove old and install new on-load tap-changer or HV bushings the oil is drained, and tank access-cover open to let the service man enter and work inside the tank. An ingress of atmospheric moisture to the tank and absorption of water by the outer surface of cellulose insulation is unavoidable. Obviously, an attempt is made to minimize the insulation wetting by scheduling the work at dry-weather period, covering the access port when possible and trying to keep a small overpressure in the tank. Transformer repair teams are familiar with these precautions, but there is no way to eliminate absorption of moisture from atmospheric air.

A decision to replace ageing accessories or to repair minor damages in an old transformer is based on cost analysis that takes into account an expected extension of the technical life. This depends on the cellulose degree of polarisation (DP), on the core-loss of steel available at the time of manufacturing, on insulation safety margin applied by the designer, who optimised his transformer to make it competitive on the market, or to ensure a high reliability required by the buyer [5]. Such factors as brittle cellulose, windings bent by short-circuit current usually decide on scrapping the old transformer.

The traditional winding drying technology involves heating the active part by flooding or spraying with hot oil, and reducing the pressure to evaporate and extract the water trapped in cellulose. Such process is relatively slow since diffusion of water vapour from high-density, massive pressboard may take days. Vapour-phase process accelerates drying and helps to clean old transformers contaminated by soot and sludge, but the large volume of highly flammable solvent is considered as potential danger of fire. Handling the solvent is well controlled in the factory, but the danger of accidental ignition is much higher in HV station [6]. Heating of transformer windings by circulation of low-frequency current was developed and implemented first in factories making distribution transformers. Recently, this technology was applied to large power transformers on-site [7, 8]. It offers an advantage of shorter drying-time and a smaller energy needed to warm-up only the winding rather than core and tank [9]. However, the strictly controlled timing of the low-frequency current circulation and lowering the pressure cycle is critical and easier to implement in a factory than on-site. To prevent wire-insulation overheating the winding hot-spot temperature shall be strictly kept under pre-determined limit, since the heat transfer is much lower under vacuum than in an oil-filled tank [10]. Use of natural esters rather than mineral oil has been considered owing to esters more effective moisture absorption [11], but other factors precluded their wider use for transformer drying.

The on-site replacement of OLTC in 400 kV, 250 MVA transformer presented in this paper was undertaken after an in-depth analysis of the technical and economic factors.

2. DECISION TO REPLACE THE DAMAGED OLTC

The original OLTC has been damaged beyond repair [12] and a temporary fixing enabled continued operation until the network conditions permitted to take the transformer off service.

An internal inspection of the transformer revealed the damage of the OLTC fixed and moving contacts in all three-phases, as well as destruction of the contact support and insulation structures. It became obvious that the tap changer has to be replaced, but this model (LRY-01) has not been manufactured in Japan for several years, and the cost of making custom-made one-copy was prohibitively high. After consultation with the leading supplier of tap changers from Germany a suitable replacement OLTC (VRD1300) was found, although its physical dimensions are different.

The internal inspection gave positive answer to the question of sufficient space inside the tank to install the new OLTC and to connect its selector to the tap-winding. Besides, the cellulose samples taken from the outer winding surface indicated a low DP that predicted a long-enough technical-life. On another hand the transformer was built in Japan, and local workers must have been physically smaller than average Polish technician charged with extension of leads connecting OLTC tap-selector to the tap-winding.

A comparison of the on-site OLTC replacement-cost against savings due to postponed investment in a new transformer for several years, convinced the transformer owner to take the risk of such unprecedented operation in Poland.

3. ASSESSMENT OF TRANSFORMER TECHNICAL CONDITION BEFORE COMMENCING OF OLTC REPLACEMENT

To assess insulation condition the induced-voltage test was performed using a diesel-engine and three-phase 300 kVA generator with frequency regulation. This mobile motor-generator set was rented from Hungarian enterprise that has operated this equipment The generator output-voltage excited the transformer tertiary-winding through a step-up transformer [13]. At 60 Hz the test voltage attained 110% of the rated 31,5 kV of the tertiary and 400 kV of the primary winding. Measuring equipment of this mobile unit included 9-channel 12 bit analogue-to-digital (A/D) converter with measuring channels to record the supplied voltage and current, as well as 6-channel PD measuring system type MPD 600 with PARD algorithm to locate PD source inside the transformer [14]. Besides, an acoustic PD localisation system type PDL 650 and Tettex 9124 conventional PD meter were included.

Table I. Measurement of PD in the transformer before OLTC replacement. U tertiary voltage

U [kV]	400kV winding			120kV winding			31,5kV winding		
	phase A [pC]	phase B [pC]	phase C [pC]	phase a [pC]	phase b [pC]	phase c [pC]	phase a [pC]	phase b [pC]	phase c [pC]
5	25	20	30	25	18	22	30	30	32
10	25	20	32	25	20	25	30	35	32
20	500	500	800	150	180	190	250	250	150
31,5	1000	1200	1800	400	500	550	500	500	400
34,6	1200	1600	1800	500	600	600	600	600	400
19	PD onset voltage								
12	PD extinction voltage								

Despite a relatively high PD level shown in Table I, no specific discharge source was located in the transformer during the induced-voltage test carried out before OLTC replacement.

Fig.1. Mobile motor-generator set on a trailer and Partial Discharge level measured by Tettex 9120.

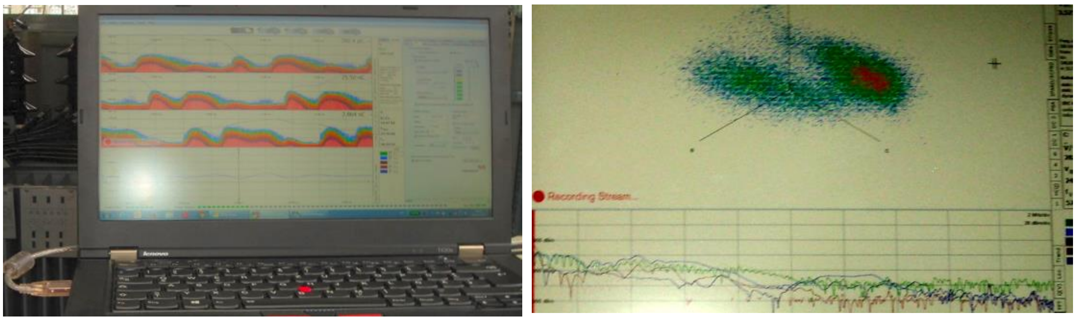

Fig.2 Partial Discharge pattern recorded by MPD 600 instrument and analysed with PARD algorithm.

4. PROTECTION OF THE INTERNAL INSULATION AGAINST ATMOSPHERIC MOISTURE AND CONTAMINATION

Absorption of atmospheric moisture by outer-layer of cellulose insulation depends critically on its time of exposure. Time taken by removal of the old and installation of the new OLTC, as well as by clamping and insulating connection of the leads from the tap-winding to the OLTC tap-selector was minimized by careful planning and preparation of the required parts, tools and insulating material.

Only one access-port to the tank has been open during the disassembly of the original OLTS and connecting the new extension of the leads. In front of this access port a lock was built and its entrance doors was closed after the service man crawled into the lock. A clean working suit was compulsory to all persons entering the tank. A polymeric membrane was wrapped around the winding insulation to separate it from the OLTC working area.

A small over-pressure inside the tank was kept by a generator of dry synthetic-air yielding 35 m^3/hour, equipped with an air-filter that stopped particles exceeding 1μm. The dry air was injected into the active part protected by the membrane and into the work area. Obviously, Nitrogen cannot be used since people have been working inside the tank. In the work area only two people only were allowed wearing clean working-suit and face mask to reduce air humidity and contamination. Once the old OLTC was lifted up and removed a transparent cover was installed over the opening in the tank cover to let sunlight into the working area. The new OLTC was dried and oil impregnated together with prefabricated connections.

No welding, soldering or filing is allowed inside the tank, and the lead connections were made by pressing joints of 2x240 mm^2 Multiflex copper-conductor with a special tool. Insulating spacers made of phenolic-paper and epoxy reinforced glass-fibres were installed between the OLTC leads to keep their distance calculated for the respective tap-selector voltage, and to ensure required dielectric strength. Although tedious and skill demanding work has taken time, but the strict working procedures were enforced and controlled. At this stage one can say that "Devil is in the Details" has not lost its novelty.

Fig. 2 Leads connecting OLTC selector to the tap-winding. Joints between original lead and its extension were clamped and insulated with wrapped tape, inside the tank. Spacers ensured the distance between the leads calculated according to their respective voltage-difference.

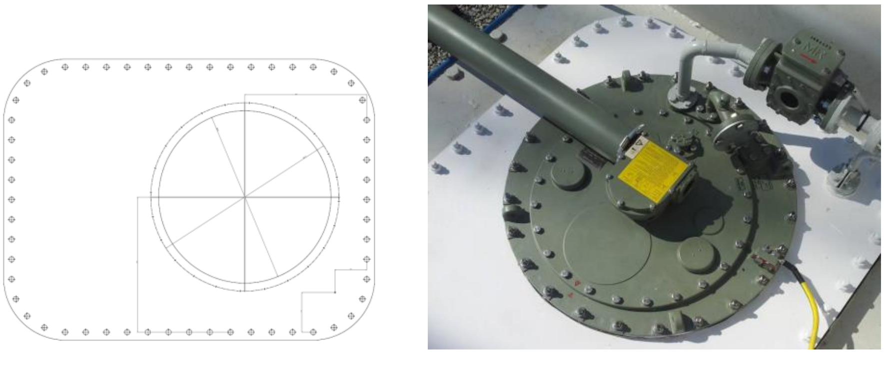

Fig. 3. Installation of the new OLTC required machining of the cover that fits to the existing opening and accommodates the new OLTC flange with its drive angle-transmission

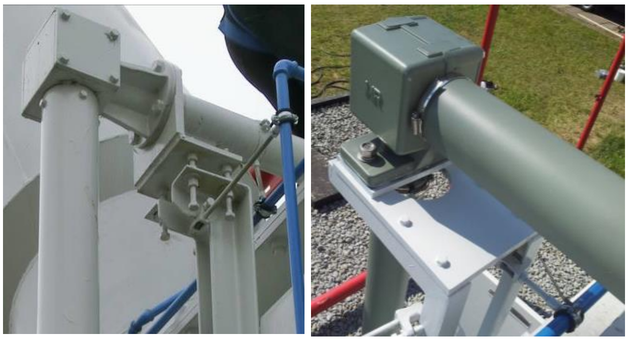

Fig. 4. Original and replaced angle-transmission of OLTC drive.   The new OLTC drive.

5. HEATING AND VACUUM DRYING OF THE TRANSFORMER.

Once the new OLTC connections were checked the transformer insulation was subjected to the heating and vacuum drying, since the new lead insulation was not oil impregnated and despite all precaution the winding insulation-surface may have absorbed some atmospheric moisture. Two series connected oil-processing systems MAS 600 with total heating power of 200 kW were employed to warm-up the oil by 65ºC and to circulate the hot oil through the transformer then through the filter and degassing chamber.

Fig. 5. MAS-600 oil processing system warming up oil that circulated through the transformer.

The two oil processing system allowed for two-stage warming the transformer active part as well as oil de-gassing and drying.

The next step consisted in draining the hot oil and lowering pressure in the tank to less than 1 Tor for 24 hours. The long thermal time-constant of the transformer kept its temperature and allowed for effective extraction of moisture trapped in the insulation surface layers.

Water content in cellulose was recorded using two methods: Polarisation-Depolarisation-Current (PDC) and Recovery Voltage Measurement (RVM), since the first indicates an average moisture content in the whole insulation volume, and the second reveals wet surface layer of the cellulose.

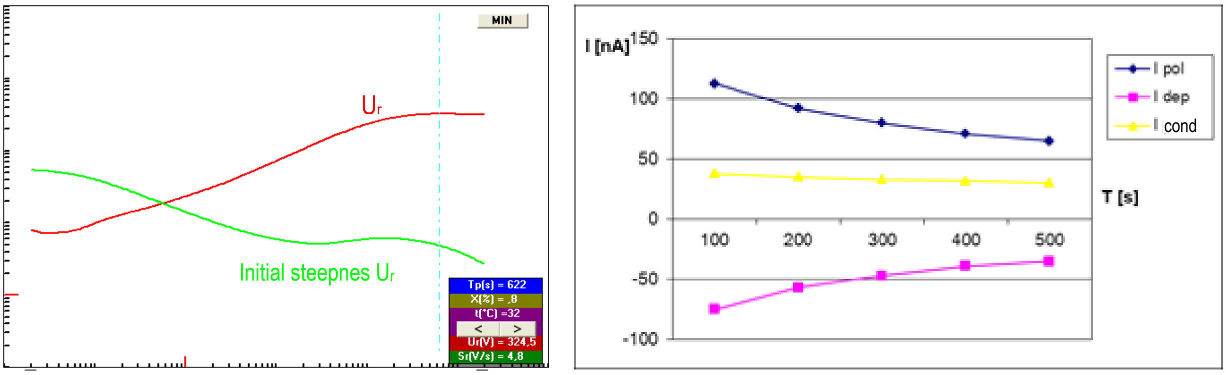

Fig. 6. Recovery Voltage characteristics (left) and polarisation-depolarisation current record (right) taken at the final stage of transformer drying have indicated the same water content of ~1%.

Such result confirms a uniform moisture distribution in the transformer insulation.

6. FINAL INDUCED-VOLTAGE TEST AND DISSOLVED GAS-IN-OIL ANALYSIS (DGA)

The most important check of the transformer insulation strength was the induced-voltage test carried out in the same way as before OLTC replacement but performed at all regulation-winding taps to confirm the sufficient withstand-voltage of all new connections. Charge of partial discharges measured up to 110% of the transformer rated voltage is indicated in Table II.

Table II. Measurement of PD in the transformer after OLTC replacement. U tertiary voltage

U [kV]	400kV winding			120kV winding			31,5kV winding		
	phase A [pC]	phase B [pC]	phase C [pC]	phase a [pC]	phase b [pC]	phase c [pC]	phase a [pC]	phase b [pC]	phase c [pC]
5	9	25	20	30	25	18	22	30	30
10	9	25	20	32	25	20	25	30	35
20	9	50	50	80	35	38	39	35	35
31,5	9	100	100	90	40	50	55	50	50
34,6	9	100	110	90	50	60	60	60	60

A comparison to PD charge readings taken before and after insulation drying reveals wet insulation as the main cause of high PD level shown in Table 1. This observation is confirmed by the PD distribution spread over the whole insulation that was revealed by PARD algorithm during the initial induced- voltage test.

Dissolved gas-in-oil analysis was performed before and after the induced-voltage test and the obtained gas concentration in parts per million (ppm) is given in Table III.

Table III. DGA readings taken before and after the Induced-Voltage Test (IVT)

#.	Gas	Polish standard same as IEC	Typical values by IEC	Units	Readings before IVT	Readings after IVT
1.	Hydrogen H_2	PN-EN 60567	50 – 150	ppm	0	3,5
2.	Methane CH_4	PN-EN 60567	30 – 130	ppm	0,3	0,35
3.	Ethane C_2H_6	PN-EN 60567	20 – 90	ppm	0	0,63
4.	Ethylene C_2H_4	PN-EN 60567	60 – 280	ppm	0	0,12
5.	Acetylene C_2H_2	PN-EN 60567	2 – 20	ppm	0	0
6.	Propane C_3H_8	PN-EN 60567	-	ppm	8,7	6,7
7.	Propylene C_3H_6	PN-EN 60567	-	ppm	6,6	4,8

Low level of dissolved gas-in-oil confirms absence of significant partial discharges in the HV insulation.

The complete series of low-voltage electrical measurements was performed before and after OLTC replacement. Their readings allowed switching the transformer on for trial 72-h operation.

As no problems have been reported the transformer was brought back to regular service, and performs satisfactorily till now, according to the owner.

Fig.7. 250 MVA 400 kV transformer after the acceptance tests.

7. DISCUSSION

On-site OLTC replacement of an old transformer was decided after an economic analysis of savings due to postponed acquisition of a new unit and the cost of preparation and execution of this rather-complex operation. A detailed schedule of the subsequent operations, co-ordination with all involved parties, as well as skilled craftsmanship and accumulated experience in drying transformer-insulation were the crucial elements of this venture. It is expected that similar assignments will be allocated by the HV transmission- system operator, since the number of older transformers is growing and there are limits to the budget allocated to their replacement by new units.

8. ACKNOWLEDGEMENTS

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