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Verification of On-Site Oil Reclamation Process by means of Polarisation / Depolarisation Current Analysis

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***Abstract*: This paper starts with the reasons why on-site oil reclamation processing was required for two 250MVA 3-ϕ banks of single-phase transformers. It reviews the results of routine diagnostics and describes the application of a new off-line diagnostic tool, Polarisation / Depolarisation Current (PDC) Analysis in the verification of the effectiveness of the oil reclamation process. The moisture in insulating paper of each unit as assessed by the new tool is reported, in addition to various insulation properties such as oil conductivity, insulation resistance, polarisation index and recovery voltage. Finally, the comparison of PDC analysis result before and after oil reclamation indicates the degree of improvement in the insulation system and the final condition of the transformers.**

INTRODUCTION

Power transformers serving a large city like Sydney often operate under heavy loads. For preventive maintenance, periodic in-service diagnosis such as oil analysis is therefore essential to assess their internal condition. This normally includes Dissolved Gas Analysis (DGA), Moisture in oil, Dielectric Dissipation Factor (DDF), Resistivity (RES), Dielectric Breakdown Voltage (DBV), Acidity, Interfacial Tension (IFT) and Furans Analysis. If the result shows that corrective maintenance is required, the treatment procedure is carried out on-site, bearing in mind that the unit can be called back into service at any time.

The two 250MVA, 330/132/16 kV 3-ϕ banks of 1-ϕ three-winding autotransformers aged between 30yrs and 36yrs that are discussed in this paper are in similar condition. After many years in service, the oil in these six 1-ϕ units required refurbishment. The analysis of oil samples revealed that the main-tank oil of each unit had high levels of deterioration products (both acid and non-acid type polar molecules) which led to very high DDF, very low RES, high acidity and low IFT. The worst one was Transformer No. 1 blue phase (T1B) with DDF 0.1714 at 90^{o}C, RES 2.2 GΩ-m at 90^{o}C, Acidity 0.13 mg KOH/g. and IFT 23.5 mN/m. The major cause of the aging of oil inside the main tank was the contamination of the oil from the on-load tap changer, as detected by DGA result. In addition, the main-tank oil of Transformer No. 1 red phase (T1R) had 30 ppm of moisture content, and required dry out for continued operation.

The refurbishment of these six units was carefully planned to meet the network requirements. Network operational issues meant that the treatment time for each transformer had to be limited to only five days. With the limited outage time, only on-site reclamation of the main-tank oil was considered and the acceptable limits for reclaimed oil properties were readjusted for this project (moisture content in oil 15 ppm max, acidity 0.05 mg KOH/g max and IFT 30 mN/m min). The off-line process was chosen in order to avoid any risk due to either static electrification (charge separation in case of turbulent flow) or partial discharges to floating particles. The oil was pumped out from the transformer through the conservator into the oil treatment plant and returned to the transformer at the bottom drain valve, at the flow rate of about 1,000 litres per hour.

To verify the efficiency of the oil treatment, the reclaimed oil was sampled at the end of the process for laboratory analysis and the result is shown in Table 1 (discussed in section 5). In addition, the new on-site off-line non-destructive technique called Polarisation / Depolarisation Current (PDC) Analysis [1] – [5] was applied, in order to assess the condition of the insulation system between the windings. The PDC evaluation results include conductivity of oil in the main duct, moisture in pressboard, capacitance and dissipation factor, resistance and polarisation index (P.I.) and the recovery voltage polarisation spectrum. As the outage time could not be extended, it was not possible to test every unit both before and after oil reclamation. Results of tests conducted are shown in Table 2.

PDC MEASURING CIRCUIT

Figure 1 shows the PDC measuring circuit and Figure 2 shows the principle of this technique [1]. In this test, the insulation between the auto-windings (terminal HV, MV and N) and the tertiary winding (LV) was continuously charged by the dc voltage step of 500 V for 10,000 s. A long charging time is required in order to assess the solid insulation. The tank was directly earthed and excluded from the current measuring circuit. In this connection, the polarisation (or charging) current was the combination of absorption current (due to polar aging molecules) and the conduction current (mostly caused by free water).

Table 1
Oil Analysis Result of Transformer Bank No. 1 and No. 2 after On-Site Oil Reclamation

After reclamation		Transformer Bank No, 1						Transformer Bank No, 2					
Oil Property	Unit	Red (T1R)		Yellow (T1Y)		Blue (T1B)		Red (T2R)		Yellow (T2Y)		Blue (T2B)	
		just after	1month after	just after	1month after	just after	1month after	just after	1month after	just after	1month after	just after	1month after
Oil temperature	^oC		23		23		23		23		23		23
DBV(IEC60156)	kV	67	81	77	81	68	84	63	65	69	71	70	76
DDF (IEC60247)			0.0172		0.0213		0.0526		0.0190		0.0173		0.0193
RES(IEC60247)	GΩ-m		24.3		28.2		30.3		28.3		26.5		24.0
H_2O	ppm	6	8	6	6	9	6	14	9	14	10	14	9
ACID	mgKOH/g	0.01	0.05	0.01	0.05	0.01	0.05	0.01	0.04	0.01	0.04	0.01	0.04
IFT	mN/m	41.5	28.3	41.5	28.4	41.5	28.1	44.1	33.0	43.6	33.0	43.9	32.0

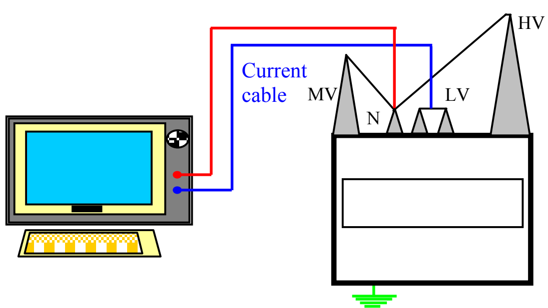

Figure 1 - Measuring circuit for PDC analysis of a single-phase autotransformer

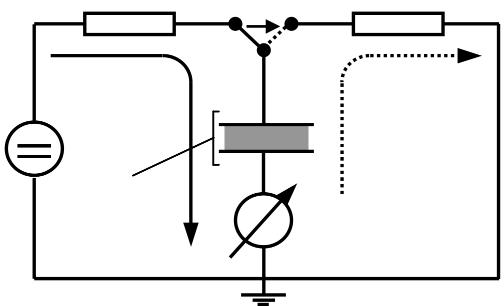

Figure 2 - Principle of test arrangement for the PDC technique [1]

At the end of the preset charging time, the circuit was automatically switched over to disconnect the insulation from the dc supply and replaced with a short-circuit for another 10,000 s. The depolarisation (or discharging) current measured during this duration consists only of the absorption current as conduction current exists only when there is power supply. The absorption current during the depolarisation has the same magnitude as the absorption current during the polarisation, but with reverse polarity. If the insulation system is dry, the conduction current will be very small. The polarisation current and the depolarisation current will then be nearly equal within about 1/10 of the charging period.

PDC MEASUREMENT RESULTS

Some PDC measurement results of Transformer Bank No.1 and No.2 are shown in figure 3. The initial time dependence of these relaxation currents (<100 s) is very sensitive to the oil conductivity while the moisture content of pressboard influences mainly the shape of the current at much longer time [4] - [5] (e.g. > 5,000 s). When the oil has good quality or low conductivity, the initial currents will be low such as in the case of T1R after oil reclamation. The initial currents before oil reclamation of T1B were the highest among all units in the same bank, so the oil condition of T1B was the worst, which was also confirmed by DDF and RES of oil at 90^{o}C.

For each unit, the polarisation current and the depolarisation current up to 100 s are almost identical. This means the oil was much more influenced by polarisation processes (polar molecules) than by conduction (water).

The last two charts of figure 3 show the comparison of T1Y and T2Y before and after oil reclamation, which reflect the improvement of oil quality by the process. Comparing also the PDC measurement results of T1R (top right of figure 3) and T1Y after the treatment, the measured current curves are very similar. It can be concluded that the units in the same bank had quite similar insulation condition after oil reclamation.

RESULTS OF PDC ANALYSIS

From the PDC measurement results, the software developed for the PDC Analyser evaluated oil conductivity, moisture in pressboard and various dielectric responses. Details of the PDC evaluation can be found in [1]-[5]. Table 2 summarizes the insulation properties analysed by the PDC software for each test. Figure 4 and 5 show the comparison between before and after oil reclamation of some dielectric responses. It can be seen from all results that the quality of oil in both units improved after reclamation although the degree of improvement was moderate: oil conductivity > 1 pS/m, tan δ at 1 Hz > 0.0005 (or 0.5%) and insulation resistance at 60 s < 10 GΩ. (Reference [2] presents some superior insulation properties assessed by the PDC technique after transformer refurbishment).

RESULTS OF OIL ANALYSIS

As mentioned in section 1, oil samples were taken at the end of oil reclamation process for laboratory analysis. The first samples were taken just after the reclamation. The results of these samples represent the quality of the oil before the transformers were switched back in service. The results in Table 1 show that the quality of the oil was improved by the treatment and met the utility specification for this contract.

In these units where paper dry-out was not applied and the oil was not totally drained out of the transformers, there was some amount of oil, which was absorbed by the pressboard and might not been reclaimed. The polar molecules in this portion of the oil gradually mingled with the reclaimed oil when the units were reenergized.

Samples were then taken about 1 month after the transformers were back to service. At this time, the reclaimed oil and the remaining oil absorbed by the paper were well mixed. The results in Table 1 show that the quality of the oil mixture was not as good as just after the reclamation process. Actually, the improved but moderate quality had already been observed by the PDC analysis before the units were returned to service.

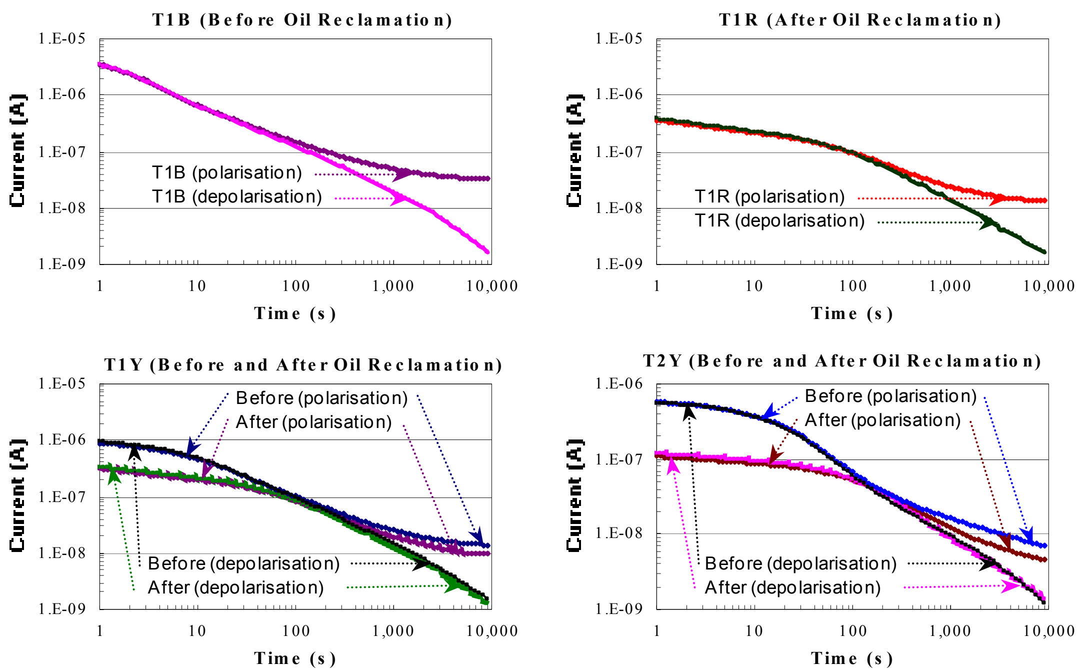

Figure 3 - The measured Polarisation and Depolarisation Currents of Transformer Bank No. 1 and No. 2

Table 2
Summary of PDC analysis results for Transformer Bank No. 1 and No. 2

PDC Analysis	**Transformer Bank No. 1 (core type)**				**Transformer Bank No. 2 (shell type)**			
Description	**Blue (before)**	**Yellow (before)**	**Yellow (after)**	**Red (after)**	**Blue (before)**	**Yellow (before)**	**Yellow (after)**	**Red (after)**
Average oil & winding temperature (^{O}C) during test	26.2	23.6	23.7	25.9	23.6	25.5	23.6	22.5
Moisture in pressboard..% wt.	2.5-3.0	2.5	2.0-2.5	2.0-2.5	2.0	2.0 +	2.0	2.0 -
Oil conductivity at 20°C (pS/m)	**30.53**	7.079	1.953	1.624	7.865	9.029	1.888	1.903
Capacitance at 50 Hz (nF)	15.09	15.06	14.99	15.63	3.310	3.278	3.248	3.267
C at 10^{-4} Hz / C at 50 Hz (pol.)	10.23	7.15	5.67	5.75	18.09	20.62	14.26	13.54
C at 10^{-4} Hz / C at 50 Hz (depol.)	10.69	7.55	6.11	6.25	19.11	20.73	15.28	14.54
DDF or tan δ at 1 Hz (%)	**11.9**	2.32	0.90	1.12	4.34	6.08	1.23	1.15
Insulation Resistance at 60s: R_{60} (GΩ)	2.47	3.50	4.45	4.04	4.92	4.58	7.90	7.86
Insulation Resistance at 600s: R_{600} (GΩ)	8.47	15.3	18.8	15.9	31.1	24.5	29.5	33.9
Polarisation Index (P.I.): R_{600} / R_{60}	3.42	4.36	4.23	3.93	6.32	5.34	3.73	4.31
Charging time at 1st peak of polarisation spectrum (s)	**2.8**	20	160	150	39	29	210	190
Maximum Recovery Voltage (V)	84.9	81.4	91.1	90.9	132.8	132.6	123.3	126.1
Initial slope at Max. Recovery Voltage (V/s)	**93.79**	15.22	3.46	3.36	36.28	49.76	7.43	7.97

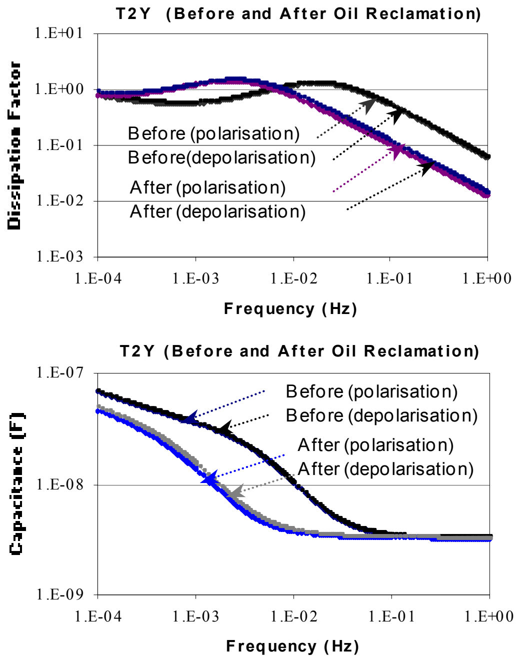

Figure 4 - Frequency scans of Dissipation factor and Capacitance of T2Y before and after refurbishment

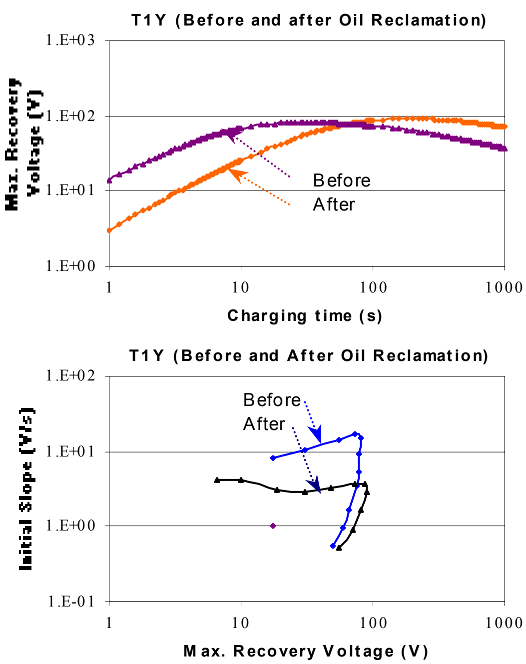

Figure 5 - RVM Polarisation Spectrum and the so-called "Guuinic representation" of T1Y before and after oil reclamation

CONCLUSION

In the case of Sydney two 250MVA, 330/132/16 kV 3-ϕ banks of single-phase autotransformers, PDC analysis carried out before oil reclamation process reveals that the oil was in poor condition but the moisture in pressboard of every unit was still acceptable. It also identified that the majority of oil enemies in these units were polarisation (such as polar aging molecules dissolved in the oil) rather than conduction (mostly caused by water). The PDC analysis in combination with the oil test results provided a clear indication that the contamination from tap changer had enormous effect on oil aging. The blue phase of Transformer No. 1 was the worst.

After the oil reclamation, PDC analysis revealed improvement of the oil by the following insulation characteristics, although the suggested criteria as shown in each parenthesis would have been preferred if the outage time could have been extended:

- The decrease of oil conductivity (suggest < 1 pS/m).
- The decrease of DDF at 1 Hz (suggest < 0.5%).
- The first peak of RVM Polarisation Spectrum appears at longer charging time (suggest > 500 s) and the so-called "Guuinic representation" curve appears at lower initial slopes.
- The increase of insulation resistance at initial time e.g. up to 60 s (suggest > 10 GΩ at 60 s).
  Note: The P.I. (R_{600} / R_{60}) is not necessary to be higher [2].

Finally, the slight improvement of solid insulation was also verified by the PDC analysis:

- The slight decrease of moisture in pressboard.
- The decrease of capacitance at very low frequencies e.g. at 10^{-4} Hz.

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