EXTENDING TRANSFORMER LIFE THROUGH CONTINUOUS ON-LINE OIL CONDITIONING

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Figure 1: Desiccant Testing for Water Adsorption

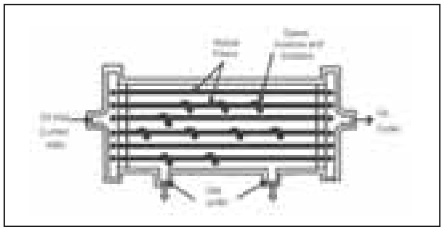

Figure 2: Diagram of Hollow Fiber Membrane Unit

The insulation system of high voltage power transformers consists of oil, paper and other cellulose based solids. Throughout their service lives these transformers are subjected to numerous stresses including high temperatures, vibration, electric fields, exposure to moisture, oxygen, acids and other chemical contaminants. As a result, over time a gradual loss in mechanical and dielectric properties will eventually compromise a unit's reliability. The degradation is primarily a chemical process that is substantially accelerated by heat and the presence of oxygen and moisture. Moisture is particularly detrimental to paper, as it will initiate hydrolysis and scission of the cellulose chain. Oxygen attacks both paper and oil producing a range of acids and other polar compounds that promote further degradation. Ideally these materials should be removed continuously so that accumulated levels do not reach the point where they can cause irreversible damage to the paper.

Researchers at Powertech Labs Inc. and EPRI undertook research, the objectives of which were to develop, build and evaluate on-line oil conditioning systems capable of continuously removing moisture, oxygen, and chemically active oil and paper degradation products including acids, polar oxidation products and dissolved metals from transformers.

TRANSFORMER LIFE EXTENSION FACTS

It is generally accepted that the useful life of transformers is determined by the residual strength of the cellulose insulation and not by its oil properties. This is because the oil can be reconditioned by conventional treatment or simply replaced, but the paper degrades through an irreversible process of depolymerisation. The paper and the oil aging processes also proceed at different rates and produce different chemical by products. Thus the timing of oil maintenance procedures may not coincide with requirements to preserve the paper insulation. Therefore, by maintaining the oil at near new conditions at all times, the transformer's life can be significantly prolonged and the risk of dielectric breakdown blamed for over 75% of extra high voltage (EHV) power transformer failures considerably reduced.

There are two approaches for protecting the oil/paper insulation. The traditional corrective approach is based on periodic oil reclamation and the preventive approach is based on the continuous oil reclamation process described here.

Based on the previous arguments, it is apparent that a continuous on line insulation conditioning system could provide real advantages over the traditional periodic oil reclamation using Fullers earth.

In particular,

a) oil and paper degradation products could be removed as they are formed, preventing their accumulation to harmful levels;
b) by maintaining the overall concentration of moisture and oxygen in oil low, the aging process in paper and oil is retarded;
c) auto catalytic oxidation and hydrolysis reactions are reduced and;
d) the migration of adsorbed products from the paper to the oil is promoted by maintaining a dynamic equilibrium between the two phases.

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IDENTIFICATION AND EVALUATION OF NEW ADSORBENTS

Since moisture is the most strongly adsorbed species, its presence in transformer oil will impair the adsorbent's capability to remove oil and paper decomposition products. To optimize the adsorbent's capacity for oil and paper decomposition products in the presence of moisture, two approaches were followed:

1. The use of strong desiccants to completely adsorb only water from the oil, combined with a hydrophilic adsorbent better suited for removing acids, polars, metals and other oil and paper decomposition products from the moisture free oil.
2. The use of hydrophobic adsorbent(s) with high adsorption capacities for oil and paper degradation products with low affinity to adsorb water.

A total of 25 adsorbents and ion exchange resins were investigated

Water Removal

Two approaches were investigated for the removal of moisture from transformer oil. The first used a desiccant and was aimed at obtaining treated oil virtually moisture-free The second approach was based on the use of the hollow fiber membranes already used for degassing /O2 removal. In this case, the moisture removal from the transformer oil per pass would only be partial (up to 50%).

The application of both methods in series was considered as a potentially advantageous option. This way, the incoming oil is partially dried and degassed using a suitable hollow fiber membrane module followed by an adsorbent with a high affinity for water to complete moisture removal. Only moisture free oil would pass through subsequent adsorption columns resulting in optimum adsorption capacity for oil and paper degradation products.

Several adsorbents were evaluated to selectively remove dissolved or dispersed water from aged transformed oil destined for reclamation. The results of water removal for the adsorbent of choice are shown in Figure 1. The initial water content in the feed oil was 250ppm, far above the equilibrium value for its temperature. We can see that the water content in the feed oil constantly dropped during the duration of the test yet the amount of H2O in the treated oil remained below the detection limit of the Karl Fischer Instrument.

Removal of moisture and dissolved gases by a hollow fiber membrane (HFM) is shown in Figure 2. In principle, as oil flows through the inside of the hollow fibers, dissolved gases permeate through the wall and into the housing (shell side). This continues until equilibrium is achieved at the operating conditions. If the gases and other products are continuously removed from the shell side by applying a vacuum or a stripping gas, equilibrium will never be achieved and the oil can be completely degassed. In order to determine its merits, the HFMs were evaluated in the laboratory in various modes including monitoring of dissolved gases, degassing, and dehydration of transformer oil. A US Patent has been issued for the use of the HFM for all three modes.

Eight commercial membrane modules were evaluated for degassing rate, moisture removal, leakage and swelling. Some HFM modules were especially developed for this application. The test results are presented in Table 1.

The results in Table 1 show that, with a satisfactory gas flux, two of the HFM candidates (#5 add #8) did not leak oil. As well, module #7 showed a promising degassing performance with almost negligible oil leakage.

Membrane Type	Oil Flow cc/min	Oil Temp. °C	% Removed per pass				Observed Oil Leak	Comments
			H_2O	O_2	N_2	CO_2		
1	145	39.4	60.5	35	12.5	32	no	not available
2	145	39.6	27.3	34.1	29.9	29	yes	
3	145	39	25	36.2	31.9	24.5	yes	heavy leak
4	145	33.5	22.7	47.7	42.3	28.7	yes	
5	14	38	13.1	15.5	11.6	13.5	no	small module
6	130	40	14.8	29.5	24.8	16.9	yes	eventually leaked
7	138	35	28.6	51.2	40.7	28.9	minimal	under evaluation
8	280	37	15.6	42	34.7	26.9	no	under evaluation

Table 1: The Evaluation of Hollow Fiber Membrane Modules - Amounts of Gas Removed From the Transformer Oil Per Pass Through the Membrane Module

	H_2O ppm	IFT Dynes/cm	NN mg/g	PF %	KV kV	Col	DBPC %
At inlet	23	42.6	-	0.288	36.1	-	-
Outlet	<1	45.2	-	0.03	65	-	-

Table 2: Properties of new Voltesso 35 oil before and after passing through the multipurpose on-line continuous oil conditioning system prototype -Mark I.

Volume treated Lit	H2O ppm	IFT Dynes/cm	NN mgKOH/g	PF %	Breakdown kV	Col	DBPC %	Cu ppm	T_o °C
Incoming Oil	3	38.8	0.014	0.935	32	1	0.22	0.07	51.9
110.7	<1	43.2	<0.01	0.042	57	1	0.23	0.001	51.9
375	<1	41.5	<0.01	0.079	42	1	0.23	0.01	41.5
799	<1	42.1	<0.01	0.051	60.9	1	-	0.008	55.5
1018	<1	41.6	<0.01	0.06	-	1	-	-	47.2

Table 3: Test results of the multipurpose on-line continuous oil conditioning system prototype installed in line on a 500 kV transformer.

Removal of Acids, Polar Compounds, and Dissolved Metals

Bench-scale experiments conducted to evaluate selected adsorbents consisted of cylindrical columns packed with the test adsorbent. The oil from the column outlet was collected and analyzed for acids, IFT, color, carbonyl compounds (by FTIR), furanic compounds, inhibitor content (DBPC), total polar compounds, and dissolved metals (Cu, Zn). The feed used for this evaluation also originated from in-service transformers and had been deliberately doped with propionic acid, 2-furaldehyde, soluble copper, and DBPC to give the full complement of contaminants and decomposition products as shown below.

H2O (ppm)	IFT (Dynes/cm)	Neut. No. (mgKOH/g)	FTIR (1860-1670)	DBPC (ppm)	2-Fur (ppm)	PF	kV	Color	Feed T (°C)
45	24.9	0.407	9.300	0.12	0.63	7.2	22	2.5	55-65

The DBPC concentration was monitored by FTIR at an absorbance of 3650cm-1and its concentration in the oil was not reduced by any of the adsorbents tested.

Development of a Multipurpose On-line Continuous Oil Conditioning System

The results of laboratory tests clearly suggested the need for a multi-adsorbent approach. A combination of five different adsorbents was found to be the most efficient in improving and maintaining the oil quality at near new conditions. They were contained in three different adsorbent beds connected in series. In addition, the system employed a hollow fiber membrane module in front of the adsorbent columns. The HFM module was designed to operate in two possible modes; a vacuum mode for oil degassing, and a pressure-vacuum mode in conjunction with a chiller for partial oil dehydration.

Figure 3 depicts the multipurpose on-line continuous oil conditioning system prototype. The system was instrumented with pressure and temperature gauges, thermocouples, temperature and pressure switches and plumbed with bypass and diverting valves to allow the system to operate in the degassing/ adsorption or only in the adsorption mode. Also the system was designed and equipped with fail-safe features and sample ports to allow periodic sampling from various locations.

After assembling the multipurpose on-line continuous oil conditioning system prototype (Mark I), functionality tests on all components and complete system were performed. Following successful functionality tests the system was further tested with new transformer oil to establish that it did not affect the new oil's properties. As can be seen from Table 2, the on-line continuous oil conditioning system prototype actually improved all the relevant transformer oil properties. Field trials of this prototype unit (Mark I) were carried out in our High Voltage Lab using a 500kV power transformer. The unit was connected at the bottom of the transformer and the oil returned in the conservator tank. Samples of oil were taken from the inlet and outlet of the unit and analyzed for property changes. Initially, the unit was evaluated with the transformer de-energized, and later with the transformer energized. The properties of the oil at the outlet of the conditioning unit, as a function of treated oil volume are shown in Table 3. We can see that the properties of the oil at the outlet of the unit are equal to or better than those of new oil. It is significant to notice that the DBPC inhibitor content is not depleted.

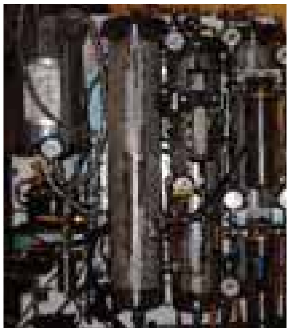

Figure 3: Multipurpose On-Line Continuous Oil Conditioning System Prototype Mark I

In addition, the HFM was tested in degassing mode by simply switching valves, without stopping or disturbing the system's continuous operation. In this mode, the HFM essentially extracts all dissolved gasses from the oil to some residual level and releases them to the atmosphere. To determine the efficiency of the HFM, the amount of gasses in the oil was measured before and after passing through the HFM. The test results of the HFM's efficiency are shown in Table 4.

The HFM module used for this evaluation worked satisfactorily in the degassing mode but developed a slight oil leak. To compensate for this, a subsystem for oil collection and retrieval was implemented. The need for the subsystem to handle the leaked oil, and the relatively high cost of this particular membrane motivated the search for an ìidealî membrane module that does not leak oil and is less expensive. Evaluation of the HFM in the dehydration mode was not possible since the moisture level of the transformer oil at the outlet of the system prototype was too close to the detection limit of the Karl Fisher instrument. However, the operational functionality of the system prototype in the dehydration mode, which involves the chiller and a vacuum/pressure pump, was proven to be working according to the design requirements.

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DEVELOPMENT AND EVALUATION OF DEDICATED UNITS

It was recognized that the flexibility and complexity associated with the multipurpose on-line continuous oil conditioning unit (Mark I) might not be needed in some cases. Therefore, it was anticipated that simpler or single purpose units might have equal or higher merit. Given the above, further efforts were focused towards the development of the following stand alone units; dehydration, decontamination, degassing/dehydration, oxygen scavenging unit

The main design features of these units were, weight reduction, easy installation and portability. A key feature of two of the above units require the use of an HFM module capable of degassing oil while remaining impermeable to oil and resistant to swelling. A satisfactory HFM module with a combination of such properties was not available. Therefore, at this point, efforts were focused on designing, building and implementing the first two units. Development of the other units was deferred until an appropriate HFM module was found or developed.

Dehydration Unit

A newly designed stand-alone dehydration unit (D1) was evaluated in our High Voltage lab by circulating the oil from a modified open transformer tank (used for bushing testing) containing 12,500 liters of transformer oil. The incoming oil contained 41ppm of moisture and had an electrical breakdown strength of 21kV. After passing through the dehydration unit, the oil's breakdown strength increased to 54kV and the water content reduced to below the detectable level (<2ppm). The unit was tested for more than 1700 hours. During this time, the moisture content in the outgoing oil stream remained below detectable levels regardless of flow conditions (see Table 5). However, at room temperature the pressure drop through the system increased from 5 psig to 17 psig as the oil flow increased.

After being successfully tested on the open transformer tank in our High Voltage Lab, the Dehydration Unit was installed on a 60kV in-service transformer containing 13,180L of oil (Figure 4 shows the unit connected to the transformer at the left). Its performance is being monitored and will be evaluated after the field test is completed.

Decontamination Unit -Mark II

A stand-alone decontamination unit (Mark II), has been designed, built and initially evaluated on an in-house de- energized transformer. Preliminary test results show that all measured properties of the outgoing oil have improved while the DBPC inhibitor remained unchanged (see Table 6).

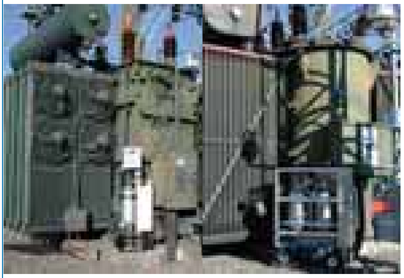

Figure 4: Dehydration Unit D1 (left) and Decontamination System Mark II (right) Installed on 60kV Field Transformers

The Decontamination System Mark II, fulfilled all its design requirements in being transportable, lightweight, easy to install, completely fail safe, and NEMA 4 compliant. After being commissioned, the unit was installed on a 60kV field transformer, which contains 12,700 L of oil. Figure 5, shows the unit connected at the transformer on the right. The unit's performance has been monitored by testing the incoming oil as a function of the treated transformer oil volume. The preliminary test results are shown in Table 7.

Membrane	Flow Rate	Oil Temp.	Vacuum	System Pressure	% Removed per pass					
Type	(L/min)	ºC	(in Hg)	(psig)	H_2	O_2	N_2	CO_2	CO	CH_4
CMC	0.450	67	-23.5	20.7	26.3	24.1	28.1	11	28	28.6

Table 4: HFM efficiency when employed in the degassing mode.

Oil Flow Lit/min	Volume treated Lit	Incoming Oil		Outgoing Oil	
		H_2O ppm	Breakdown kV	H_2O ppm	Breakdown kV
0.45	1863	41	21	<1	54
1.3	5811	30	-	<1	55
2	8757	29	-	<1	-
1	19923	18	-	<1	-
1	37916	10	-	<1	-

Table 5: Test Results of Dehydration Unit D1 Installed on an OpenTransformer Tank (12,500L)

	H_2O ppm	IFT Dynes/cm	PF %	Breakdown kV	DBPC %
Incoming Oil	3	37.6	0.325	51	0.23
Outgoing oil	<1	43.6	0.089	62	0.23

Table 6: Preliminary Results of Decontamination System (Mark II) on an Un-Energized Transformer .

Volume treated Lit	Incoming Oil					Outgoing Oil				
	IFT Dynes/cm	PF %	NN mgKOH/g	Polar	2Fural ppb	IFT Dynes/cm	PF %	NN mgKOH/g	Polar	2Fural ppb
342	26.8	3.06	0.044	3706	51	41.7	0.039	0.006	81.3	<10
6747	27.8	2.636	0.032	3064	35	30.8	1.633	0.02	2870	<10
13835*	28.2	2.636	0.08	-	27	20.6	2.134	0.02	-	18
17631	29.5	1.84	0.01	2514	25	31.6	1.22	0.01	2479	<10
12218	30	1.848	0.014	2546	19	30.8	1.318	0.01	2622	<10
10237	31.7	1.104	0.01	2483	<10	31.7	0.972	0.01	2487	<10

* after 12900 lit 2nd and 3rd columns replaced

Table 7: Field Results for the Decontamination System Installed on the 60kV Transformer.

DISCUSSION AND CONCLUSIONS

Laboratory tests have shown that a combination of desiccants, adsorbents and semi-permeable hollow fiber membranes is capable of restoring and maintaining transformer oil properties to near new conditions.

A multipurpose on-line continuous oil conditioning system prototype, Mark I, was tested in Powertech's lab on a 500 kV power transformer. The results showed that it dried the transformer oil to below the detection limits of H2O per pass, and at the same time removed most of the oil and paper degradation products.

Two less sophisticated and more economical prototype units, a Dehydra-tion and Decontamination Unit Mark II, were built and evaluated, first in the lab then in the field. Preliminary field testing of the decontamination system, Mark II, showed its capability to restore and maintain the transformer oil quality to near new conditions. Its capacity and long-term performance on in-service transformers has not yet been determined.

For more information on Powertech and EPRI's research on Continuous Oil Reconditioning of Power Transformers contact Nick Dominelli or Stevo Kovacevic of Powertech Labs in Surrey, British Columbia, Canada at (604) 590-7500. **ET**