Improving the Quality Index of Insulating Oil in Transformers by Applying the Dehumidification Process

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Abstract: - The maintenance solutions applied to power transformers have been and are a current concern of major importance in extending the operating life but also in protecting the environment. This paper highlights the importance of the treatment/revitalization processes of used insulating oils, which aim to bring them within the parameters imposed by the standards, extend the life of the mixed insulation system and reduce the amount of oil considered waste. The paper presents the influence of humidity in the deterioration of the mixed insulation system of the power transformer and the effects of the treatment/revitalization process that lead to the improvement of the oil quality index.

Key-Words: - used oil, quality index, power transformer, revitalization, maintenance

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1. Introduction

The trend of treating/recycling/revitalizing waste oils from electrical equipment has gained momentum worldwide. According to Directive (EU) 2018/851 of the European Parliament and of the Council on waste, it requires the separate collection of waste oils in order to avoid their mixing with other types of waste or substances, ensuring that the best overall environmental outcome is achieved by their treatment [1-5].

In the management of waste oils, priority should be given to treatment/revitalization/regeneration processes, or other recycling operations that have an equivalent or better overall environmental outcome.

In the treatment of waste oils, priority should be given to regeneration or, alternatively, other recycling operations that have an equivalent or better overall environmental outcome than regeneration. In order to further improve the management of waste oils, the Commission should consider and, where appropriate, propose measures to improve the treatment of waste oils, including quantitative targets for their regeneration [4-9].

It was found that in the case of transformers, replacing used oil with new oil is not the best solution, because new oil takes both moisture and polar components from the solid insulation. In addition to this inconvenience, there is also the disadvantage of the high costs involved in this activity and the risk of environmental pollution.

Studies carried out in the field have proven that the operating life of transformers integrated into the energy system can be extended, guaranteed by applying treatment/ recycling/ revitalization processes. The factors that lead to the aging of the mixed insulation system can be electrical, thermal, mechanical or/and atmospheric [5-6].

The experience accumulated over time, in the maintenance process, tilts the balance towards adopting an optimal maintenance strategy to maintain and ensure the availability and reliability of the operation of the transformation units. To this end, it is necessary to carry out activities aimed at identifying possible operating anomalies from the early stage, in order to avoid major damage [7-9].

Humidity is the main indicator of the transformer's operating condition, a high water content requires the start of treatment/revitalization actions of the mixed insulation system [10], [11-16]. Transformer oil regeneration/treatment is an important preventive maintenance tool, and therefore transformer oil must be treated before it reaches the levels of deterioration known to cause transformer insulation damage.

The revitalization/ treatment/ regeneration processes, which aim to maintain the reliability in operation of transformers in service, are a support/ tool in protecting their mixed insulation system [5], [8-9].

Moisture is one of the major causes of insulation ageing, therefore in order to remove the cause and its effects, respectively, insulation treatment/ recycling processes are indicated, which lead to the improvement of physical-chemical parameters, as well as of the oil quality index [8-9], [11-13], [17-24].

The paper includes information on aging of insulation system, criteria for revitalization of power transformer insulation, case studies - treatment/ revitalization process - dehumidification of insulation system.

The obtained/presented results highlight the improvement of the physical-chemical parameters of the insulation and encourage the application of these treatment/revitalization/regeneration processes for prolonging the life time of power transformers. These treatment processes have a major contribution in protecting the environment.

2. Aging of the insulation system in live transformers

The insulation of power transformers is made up of two important organic components such as mineral insulating oil and solid cellulose insulation. During operation, the two components are subjected to a series of stresses and age together. The stresses that influence the reliability of transformer operation and cause their aging are (Fig.1) [11]:

- Thermal stresses such as oxidation, hydrolysis, overheating and current stresses;
- Electrical stresses such as partial discharges, transient overvoltages, energy discharges and even arcing;
- Mechanical stresses such as vibrations, cracks and current stresses;
- Stresses of the environment in which they operate such as ambient temperature, radiation, atmospheric pressure, humidity, oxygen and last but not least contaminants, gases, acids.

The insulating oil, under the effect of temperature, electromagnetic field and the catalytic action of metals, starts the oxidation process by creating radical molecules, i.e. some oil molecules lose a hydrogen atom. In this way, radicals are created that carry out the peroxide oxidation process, which with an unstable oxygen atom is an extremely active oxidant [11].

The process continues by creating new radicals, peroxides and oxides of various levels, which by continuing the oxidation process lead to the formation of acids. All these newly created molecules are polar.

Fig. 1. Transformer insulation ageing factors

The acids formed by the oxidation process "attack" metals and cellulose fibers, forming metal soaps, varnishes, aldehydes, alcohols and ketones, which deposit as acid sediment on insulation, tank walls, vents, radiator ribs, etc. Sediment formation is more rapid in overloaded and damaged transformers. Sediment increases oil viscosity and consequently decreases the heat dissipation capacity. In the electric field, it can cause partial discharge and, in severe cases, failure [12].

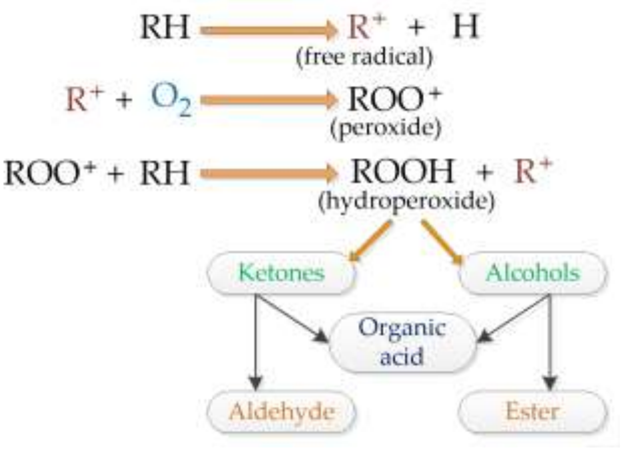

Fig. 2. Products of the oxidation process

Sediment causes reduction of insulating properties by abrasion of varnish and cellulose materials. Partially, it is also conductive, hygroscopic and thermally insulating. Sediment on the magnetic core and windings increases the operating temperature of the transformer.

Contamination of insulating oil is also possible due to external factors: improper pouring of oil, ingress of water from the atmosphere, ingress of dust, etc. [4-6], [16].

It has been found that the rate of oxidation of electrical insulating oil depends on the type of oil (paraffinic or naphthalene) and is also influenced by the concentration of antioxidants (inhibitors) in it. So, if an oil that was initially inhibited shows a decrease in inhibitor concentration, this is an indication that that oil shows an increasing oxidation reaction. A high oxidation rate leads to the formation of polar degradation compounds and subcompounds that affect the solid insulation and heat transfer properties of the electrical insulating oil.

In Fig. 3 it is schematically shown how the acids produced by oil oxidation and humidity are particularly dangerous elements for cellulose insulation, because they, through the hydrolysis process, lead to its degradation by breaking glycosidic bonds [12].

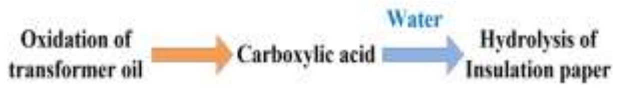

Fig. 3. Insulation oil oxidation that leads to the hydrolysis of insulation paper

The solid insulation of the transformer consists of cellulose. It consists of glucose molecules, polymerized in chains of molecules. Under the effect of high temperature, as the basic factor of degradation, the bonds on the polymer bonding produce irreversible breaks leading to permanent degradation of the insulation. By "breaking" the polymerized molecules, the paper loses its mechanical insulating properties. H_2O, CO_2, CO, CH_4 (water, carbon dioxide, carbon monoxide and methane) and furan compounds are released during this process.

Ageing products of the oil accelerate the degradation process of cellulose and vice versa. All the newly created compounds are, according to the law of equilibrium distribution between two media, arranged in solid and liquid isolation.

In order to prolong the service life of transformers in operation, i.e. to eliminate the effects caused by degradation of the mixed insulation system, the application of treatment/ revitalization/regeneration processes is indicated.

The decision on when to treat/revitalize oil is not simple. There are two important considerations involved that usually require a compromise. The first consideration is to examine the short-term risk of transformer failure, assessing whether the oil is in such poor condition that it poses a threat to the safe operation of the equipment over the next few months or years. The limits set in [7] provide a guide, although in different countries the limits applied may vary slightly.

The second consideration is for the longevity of the transformer insulation by evaluating the steps that are required to maintain the oil and paper in good condition to fulfill the expected lifetime of the transformer. Assuming this perspective will likely involve oil regeneration. In the latest editions of the oil maintenance standard in [2], there is a shift towards a longer term perspective with much more stringent requirements for several oil condition parameters.

3. Revitalization criteria power transformer insulation

The first step in deciding on revitalization is to measure the water content in both the insulation oil and the solid insulation.

The effect of water on paper ageing is significant and detrimental. The rate of paper degradation is directly proportional to the water content. For example, decreasing the water content of paper from 1.0% to 0.5% doubles the life of that paper.The permissible moisture content in paper is deduced from the values of the water content in the oil, assuming thermal stability and moisture balance between oil and paper (see Table 1).

The formation of soluble oxidation products begins to form in transformer oil as soon as the transformer is put into operation, due to the unavoidable presence of moisture, copper and iron as catalysts and also accelerators such as heat, acid, vibration, shock. load, surges and high electrical stresses. These soluble by-products of oxidation become insoluble as oxidation proceeds and eventually precipitate as sludge eventually resulting in a reduction in dielectric strength.

Table 1. Permitted moisture content in paper

Transformer rated voltage	**Water content in paper**
Up to 110 kV	2.5 %
110 ÷ 220	2.0 %
≥ 200 kV and above	1.25 %

The formation of soluble oxidation products begins to form in transformer oil as soon as the transformer is put into operation, due to the unavoidable presence of moisture, copper and iron as catalysts and also accelerators such as heat, acid, vibration, shock. load, surges and high electrical stresses. These soluble by-products of oxidation become insoluble as oxidation proceeds and eventually precipitate as sludge eventually resulting in a reduction in dielectric strength.

Polar compounds are formed when the neutralization number (NN) values are between 0,05 and 0,10 mgKOH/g oil, thus also resulting in a decrease in interfacial tension (IFT).

From an NN of 0.11 to 0.15 fatty acids coat the windings, the sludges in solution become insoluble and begin to precipitate during cold periods in the cooling fins and then accumulate in the insulation voids. From an NN of 0.16 to 0.20, sludge is precipitated in the cooling fins as well as on the core and coils, regardless of ambient temperature [17].

Once deposited, oxidation continues to harden the deposits. Nearly all transformers with neutralization index levels between 0.2 and 0.3 showed heavy sludge deposits on inspection.

Sludge deposits in transformers obstruct the heat exchange between the active parts of the transformer and the insulating oil and continue to embrittle the solid insulating materials by attacking the cellulose. Therefore, it is of utmost importance to keep a transformer free from sludge deposits. Oxides, in the initial oxidation phase, can be detected by measuring the neutralization index, the interfacial tension (IFT) and the dielectric loss coefficient (tanδ).

The limits of the mentioned indicators (Table 2) define the point at which it is necessary to start the treatment/revitalization (removal of oxidation products) of the transformer insulation system.

Table 2. Limits for starting the revitalization process

	Rated voltage (kV)		
	≤ 110	**110 ÷ 220**	**≥ 220**
IFT (mN/m)	≤ 30	≤ 30	≤ 30
NN (mgKOH/g)	≥ 0.1	≥ 0.1	≥ 0.1
tanδ at 90°C	≥ 0.3	≥ 0.2	≥ 0.1

Very important informations about the quality of the insulating oil (level of degradation) are signaled by the value of the oil quality index (OQI) which is given by the ratio of the interfacial tension (IFT) to the neutralization index (NN). The usual OQI value for a new oil is 1500 (see eq.1) [24].

$$OQI = \frac{IFT}{NN}; \quad OQI = \frac{45.0(\text{typial new oil})}{0.03(\text{typial new oil})} = 1500 \quad (1)$$

The correlation between oil health and OQI is shown in Table 3, and the limits for starting the treatment/ revitalization process are given in Table 4. Each of the above limits informs us that the insulation is at risk and precautionary measures must be taken to stop accelerated aging. According to the standards the oil must be regenerated without unnecessary delay when any of the following criteria are applicable to the degraded oil:

- The acid number is 0.10 mg KOH/g or greater;
- Interfacial tension less than 32 mN/m (this is also the IEEE limit for the highest tension class);
- Dielectric loss coefficient is greater than 5% at 90ºC (this is also the IEEE limit for the highest voltage class);
- When the "oxidation index" (interfacial voltage divided by the acid number) is below 300.

Table 3. Condition of insulating oil

OQI	**IFT [dyne/cm]**	**NN [mgKOH/g]**	**Oil condition**
560 - 312	> 28	0.05 – 0.09	Good oil, oil functions are good
240 - 187	24-28	0.1 – 0.15	Satisfactory oil, sludge can be identified in solution, cooling function is low
147 - 120	22-24	0.15 – 0.2	Bad oil, sludge on windings and other transformer parts
< 110	< 22	> 0.2	Very poor oil, deteriorated insulation, poor cooling efficiency

			and operation at high temperatures

Table 4. Limits for starting the treatment/revitalization process

	Rated voltage		
	≤ 110 kV	110 ÷ 220 kV	≥ 220 kV
OQI	≤ 300	≤ 300	≤ 300

After determining the start of revitalization of the insulation system, it is necessary to define the limits of the insulation parameters after treatment/ revitalization. These limits guarantee that the process has been carried out properly, i.e. that the insulation oil is regenerated and the solid insulation is dried and thoroughly purified (Table 5). All ageing processes will thus be delayed [7-9].

Table 5. Required oil characteristics after revitalization

Oil Characteristics	Voltage (kV)		
	≤ 110	110 ÷ 220	≥ 220
IFT (mN/m)	≥ 35	≥ 38	≥ 38
NN (mgKOH/g)	≤ 0.03	≤ 0.03	≤ 0.03
tanδ at 90°C	≤ 0.01	≤ 0.01	≤ 0.01
Water content (ppm)	≤ 20	≤ 15	≤ 10

For solid insulation, the limits after the treatment/ revitalization process are as follows:

- Water content in the solid insulation:
  - up to 110 kV ≤ 2.0 %;
  - 110 kV – 220 kV ≤ 1.5 %;
  - 220 kV and above ≤ 0.7 %.
- The increase of furan compound (2-FAL) content may be maximum 0.1 ppm per year.

The revitalization process of power transformers is the regeneration of oil and the drying and purification of solid insulation. New trends encourage the use of synthetic adsorbents in the insulation revitalization process, they retain both aging products and water, and can be reactivated in case of saturation. Oil losses are negligible, less than 1% [18-20].

The process of replacing the insulation oil is not a viable option due to the fact that there is a severe amount of pollutants in the solid insulation which dissolve in the new oil and deteriorate its characteristics. Also 95% of the water in the transformer will remain in the solid insulation.

4. Case studies for on-site drying of insulation using adsorption technology

In order to establish how the process of treatment/revitalization of the insulation system with synthetic adsorbents positively influences the parameters of power transformers and at the same time prolongs their lifetime and reliability, case studies were carried out.

In the following, the measurements/results obtained for two transformers that underwent the treatment/revitalization process are presented.

The four transformers with the following general characteristics: Tr-1 and Tr-2 have TTUS-ONAF, 40 MVA, 110/6.3 kV, 50 Hz; Tr-3 and Tr-4 TTUS-ONAF 25 MVA, 35/6.3 kV. The values of the measurements before and after treatment of the above mentioned transformers are shown in Table 6 and Table 7.

Table 6. Presentation of measurements performed before and after treatment - transformer TTUS-ONAF 40 MVA, 110/6.3 kV

Parameters	Unit of measure	Tr-1		Tr-2	
		Before	*After*	*Before*	*After*
Oil					
Water content	ppm	38.75	4.28	24.26	3.37
Dielectric strength	kV/cm	178.4	305.31	184.17	314.2
Interfacial tension	mN/m	22.035	42.75	20.71	44.08
Acidity index	mgKOH/g	0.0834	0.045	0.0812	0.045
Oil quality index		234.91	950	255.04	979.55
Tan δ at 90°C		0.095	0.051	0.098	0.053
Particles		46025	4670	28550	4857
Solid insulation					
Water content	%	3.67	1.57	3.24	1.34

According to the data presented in Table 6 and Table 7, following the dehumidification process, a substantial improvement of the measured parameters was observed.

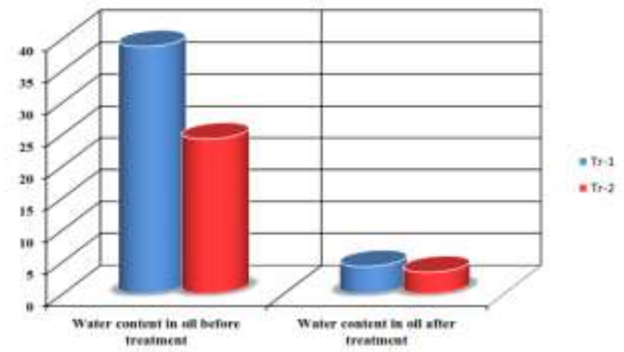

Fig. 4. Water content in oil before and after treatment

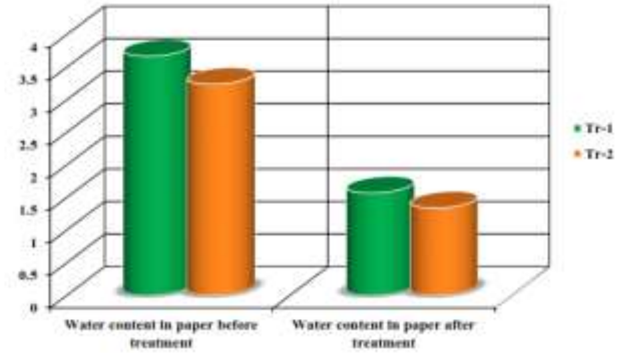

Fig. 5. Paper water content before and after treatment

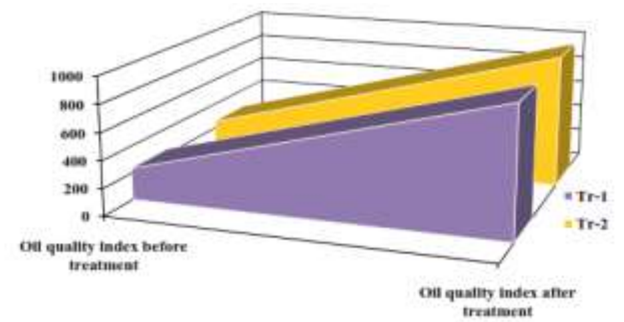

Fig. 6. Quality index improvement

Passing the oil through adsorbers resulted in filtering the oil from the transformers, reducing the number of particles.

The initially measured water content in the oil for the first transformer decreased from 38.75 ppm to 4.28 ppm, and for the second transformer from 24.26 ppm to 3.37 ppm (see Fig. 4).

There is also a decrease in the moisture in the solid insulation, for the first transformer from 3.67% to 1.57%, and for the second transformer from 3.24% to 1.34% (see Fig. 5). The values measured after the dehumidification process for dielectric strength and interfacial tension recorded a considerable increase (see Table 6).

The adsorbent material used in the treatment process led to the elimination of polar degradation byproducts, thus improvement of oil quality index is seen. OQI for the first transformer increased from 234.91 to 950, and for the second transformer from 255.04 to 979.55 (see Fig. 6).

Table 7. Presentation of measurements performed before and after treatment - transformer TTUS-ONAF 25 MVA, 35/6.3 kV

Parameters	**Unit of measure**	**Tr-3**		**Tr-4**	
		Before	***After***	***Before***	***After***
Oil					
Water content	ppm	37.4	2.81	39.65	3.05
Dielectric strength	kV/cm	176	311.2	160	302.4
Interfacial tension	mN/m	23.5	45.56	20.8	47.23
Acidity index	mgKOH/g	0.103	0.087	0.094	0.072
Oil quality index		228.15	523.67	221.27	655.97
Tan δ at 90°C		0.096	0.0047	0.09	0.0043
Particles		32152	4057	28078	3509
Solid insulation					
Water content	%	3.6	1.46	3.9	1.28

The initially measured water content in the oil for the third transformer decreased from 37.4 ppm to 2.81 ppm, and for the fourth transformer from 39.65 ppm to 3.05 ppm (see Fig. 7).

There is also a decrease in the moisture in the solid insulation, for the third transformer from 3.6% to 1.46%, and for the fourth transformer from 3.9% to 1.28% (see Fig. 8). The values measured after the dehumidification process for dielectric strength and interfacial tension recorded a considerable increase (see Table 7). The improvement of oil quality index for the third transformer increased from 228.15 to 523.67, and for the fourth transformer from 221.27 to 655.97 (see Fig. 9).

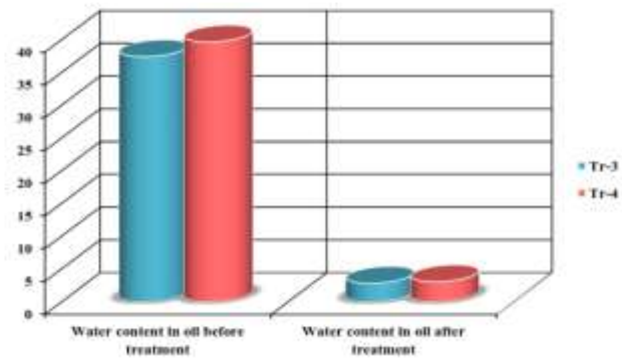

Fig. 7. Water content in oil before and after treatment

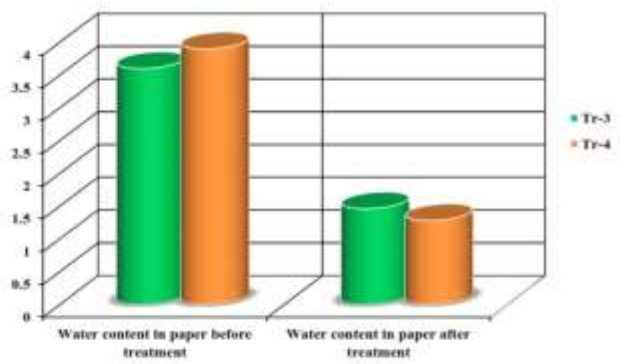

Fig. 8. Paper water content before and after treatment

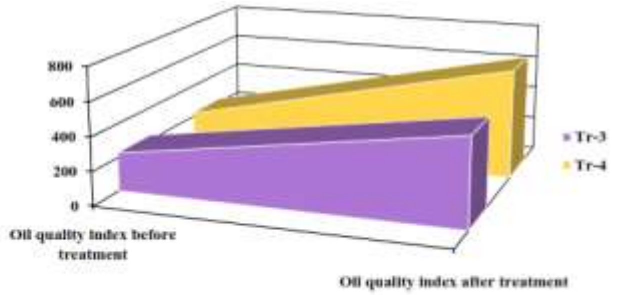

Fig. 9. Quality index improvement

The results obtained for the above-mentioned transformers showed a remarkable capacity of the adsorbent used for drying both oil and solid insulation, and spectacular recovery of the paper-oil insulation parameters, with relatively low costs compared to those of classical processes.

5. Conclusions

Transformer oil regeneration/treatment is an important preventive maintenance tool, and therefore transformer oil must be treated before it reaches levels of deterioration known to cause transformer insulation damage.

If an oil maintenance program is followed, the accumulation of moisture and sludge in the solid transformer insulation can be prevented.

The results obtained from the case studies, presented in this paper, revealed that by applying the process of revitalization of transformer insulation during operation using synthetic adsorbents, the physicochemical properties of the oil improved qualitatively and the paper insulation remains dry and purified. The life extension of transformers by applying this procedure is significant.

Revitalization of the insulation of power transformers at present has no alternative. Economically and technically revitalization compared to oil replacement has considerable advantages.

The maintenance strategy should include compliance with the mentioned criteria to ensure reliable operation of the transformers, and the use of online and on-site treatment methods are indicated to avoid premature decommissioning.

By applying revitalization processes based on adsorption, oil regeneration is ensured in the first place, but also environmental and human protection, since synthetic adsorbates are reactivable (they are not a source of pollution).

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