

CONSIDERATION in ON-LINE PROCESSING

By

VICTOR SOKOLOV

**SCIENTIFIC AND ENGINEERING CENTER
ZTZ-SERVICE**

INTRODUCTION.OBJECTIVES OF PROCESSING. TYPICAL CONDITIONS OF A TRANSFORMER.TREATMENT METHODS ON ENERGIZED TRANSFORMERS.ESTIMATION OF TIME AND PARAMETERS TO BE MONITORED.SAFETY PROBLEMS.REFERENCES.

INTRODUCTION

In recent years there has been considerable interest in the subject of On-Line Processing of Power Transformers, particularly in reclamation of oil, drying out and regeneration of insulation. In 1992 nine Doble's Clients responded that they perform reconditioning on units while they are energized.

(Questionnaire 1992)

Now one can see an obvious tendency towards implementation of On-Line procedures on the transformers up to 500 kV .

Plain economical benefit encourages fast developing processing technique. Besides traditional processing equipment, some special Processing systems have appeared: Fluidex, Pall, Velcon,"Dry Keep",etc.

Some processing methods have had a positive experience during the last 25-40 years

In the former Soviet Union the permanent regeneration system (cartridges filled with silica-gel) have been specified for all transformers above 2.5 MVA; Autotransformers 1150 kV and some special transformers 750 and 500 kV (with elevated intensity of electrical stresses) have been equipped with the permanent filter systems) which has been in operation over 25 years.

The first positive experience with On-Line drying out of 500kV transformers was introduced in the USSR in early 70th (utilizing molecular sieves).

There has been a positive experience with On-Line degassing of 330-750 kV transformers in some Ukrainian utilities (Donbassenergo, Dneprenergo).

However there are several relaxing factors, which make some technical and psychological obstacles to wide implementation of On-Line procedures:

- *Risk of failure due to possible introduction into the tank air, bubbles, particles or other impurities; loss of oil level; occurrence of static electrification*
- *Risk of failure while processing “unhealthy” transformer*
- *Very long time (in some cases) of treatment (very costly process); e.g. drying out may last several months, and accordingly cause a high costs of processing procedures*

However, generally it may be argued that if a transformer keeps functional serviceability any improvement of its condition may be performed without de-energizing. The problem is only whether safety measures are sufficient ones. The objective of this paper is to highlight some problems referring to On-Line processing and to stimulate CIGRE study in developing Processing and particularly On Line Processing Techniques.

OBJECTIVES OF PROCESSING

RECONDITIONING THE NATURALLY DETERIORATED TRANSFORMERS:

-
- Aged oil,
- Contamination of cellulose insulation with oil aging products
- Saturation with air
- Moisture contamination
- Particles contamination
- Elimination of PCB

REHABILITATION OR MAINTAINING THE FAIRLY GOOD HEALTH OF DEFECTED TRANSFORMERS

- Having a source of gas generation (e.g., localized overheating)
- Having source of particles (carbon, metal) contamination
- Having severe moisture contamination of solid insulation
- Having severe contamination with sludge or other aggressive oil aging products

REHABILITATION OF THE INSULATION SYSTEM AS A PART OF LIFE EXTENTION PROGRAM

Such a program shall include set of procedures to restore dielectric safety margin by means of drying, cleaning and degassing the insulation system and reducing the rate of future deterioration by means of evacuation aging products and oxygen out of oil and solid insulation particularly

Some general considerations in processing program could be advised:

- *The effective processing program shall base on the relevant results of the condition assessment*

- *The most important procedures with the goal to Extend the Life are extraction of moisture and particles, extraction of aggressive aging products from oil, and (particularly important) desorption and extraction of oil aging products from solid insulation.*
- *In some cases (aging the oil particularly) a modeling the process is necessary to select the optimal and efficient technology (For example, selection of the type, and amount of the clay)*
- *The process is always can be minimized if the real condition of the transformer is taken into account*

CONDITION OF A TRANSFORMER

Water, oxygen, oil aging products (acids particularly) and particles of different origin are agents of degradation, which can shorten transformer life significantly under impact of thermal, electric, electromagnetic and electrodynamic stresses.

Processes of insulation deterioration involve slow diffusion of water, gases, and aging products and therefore affect basically only a part of insulation structure, so called “thin structure” (paper insulation of turn and coils, pressboard sheets, etc., which comprises typically 40-60% of the total mass. “Active portion “of insulation is typically much lesser in transformers 35-110 kV than in 160-400 kV. Simplification of a transformer to just of two-component system (mass of oil – mass of solid insulation) leads to overestimation of a problem.

For instance solid insulation in LTC consists basically of waterproof material and ingress water remains in oil predominantly. Few people are trying to predict water content in solid insulation of LTC using moisture equilibrium data.

A similar picture is in the most 35 -69 or even 110 kV transformers where an amount of water- adsorbing- insulation is relatively small. Thus, 30 ppm of water in oil at 20 C dos not really mean that water content in insulation is over 5 %. That is practically impossible. This water has been rather accumulated in oil or “waiting” on the bottom of the tank.

Rate of cellulose deterioration (depolymerization) is proportional to water content and acid number. Thus, estimation of “Loss of Life” is sound only if both of these factors are taken into account.

It is impossible to restore aging decomposition of cellulose insulation, but it is quite feasible to recover reversible change in the insulation condition and practically restore the initial safety margin.

It is also possible to reduce the rate of further insulation deterioration. It is apparent that Rehabilitation means in the first instance cleaning and cleansing the transformer body, namely removing moisture, particles, aging by-products and absorbed gases.

It ‘s always important to distinguish between a natural deterioration (under impact of temperature, oxygen, mechanical friction, ingress of air and moisture through the breathing system provided by design) and Abnormal deterioration when a defect is involved. In the latter case identification of the defect and its correction (or advisement to correct) is important.

The following typical cases would occur:

- *Elevated water in oil associated with ingress of free water through insufficient sealing (e.g. draw lead bushings). Tightness test by means of producing some extrapressure is a good tool to assess and eliminate the problem.*
- *Excessive aging of oil (particularly in sealed transformer) can be associated with local or general overheating. DGA test may recognize the problem.*
- *Presence of metal particles and carbon is typically caused by wearing the pumps or localized overheating. DGA, vibration and acoustic tests may help to recognize the problem.*

Assumption of high water content in solid insulation may be confirm or rejected by means of Water Heat Run Test [14]. This method is very useful in-service tool to recognize condition of equipment and to select a proper processing.

Fairly bad condition of a transformer should not be an obstacle to perform On-Line processing with the goal to improve its condition. If a transformer is in operation and stands operational stresses, improvement of its condition can not bring any harm. The question comes only: how thoroughly precaution measures have been foreseen..

TREATMENT METHODS ON ENERGIZED TRANSFORMERS

One should consider that practically all impurities are distributed in certain proportion between oil and solid insulation. Significant amount of gases and oil aging products are concentrated in cellulose.

Oil is a water-transferring medium. Water presents in oil in soluble form and also in “hydrate” form being absorbed by polar aging products (aromatics) and particles. However using Karl Fisher method we measure practically only dissolved water not bounded water. Thus we typically underestimate water content particularly in aged oil.

Sometimes just only thoroughly filtering the oil may reduce water content. Dielectric safety margin of both major and minor insulation of a transformer contaminated with water is determined by dielectric strength of the oil. Dangerous effect of soluble water is a sharp reduction of dielectric strength of oil with increasing saturation percent due to increasing conductivity of the particles available. The fewer particles content the weaker effect of water on dielectric strength of oil.

The effective processing shall incorporate drying and filtering procedures simultaneously

If to come from the worst to the better from point of view improvement of the dielectric safety margin I would advise the following ranking:

- **Do not allow bubbles**
- **Remove free water**
- **Remove particles, particularly large and conductive ones**

- **Remove dissolve water**
- **Remove oil aging product**

Water in turn insulation accelerates aging decomposition. Depolymerization of cellulose is proportional to water content. This process becomes much more dangerous in presence of acids and non-acid polar. Elimination of aging products being adsorbed with insulation may significantly reduce dangerous effect of water, namely, the temperature level of bubble evolution. If a utility is going to overload transformer, please strongly advise reconditioning the insulation system

Thus a treatment program shall consider as a rule a simultaneous complex of procedures: drying, filtering and extraction of aging products.

The following procedures have been experienced and may be performed on energized transformer

- Drying of oil
- Oil degassing
- Oil reclamation
- Oil filtering
- Purification of insulation through filtering of oil
- Drying of insulation through drying of oil
- Regeneration (desludging) insulation using oil as a solvent
- PCB elimination

One can distinguish passive and active methods of treatment

Active methods incorporate force moving the oil through filter, vacuum-degassing machine, fuller's earth towers, etc. This approach allows to monitor and accelerate the process but have some disadvantages (adjustment, maintenance, operator's service, loss of power)

Passive methods incorporate typically a system of some cartridges filled with sorbent and connected to the tank or to the coolers (see "Dry Keep"). The passive process is much more economical but lasts longer.

Let us discuss general effectiveness of processing a transformer filled with oil and comparative effectiveness of On-Line and Off-Line procedures.

*Effectiveness of methods depend on physical effect chosen for processing
Methods based on diffusion processes: reclamation, vacuum degassing-diffusion through oil film-, drying out of cellulose, etc. are more effective at high temperature;*

Methods based on adsorption processes: drying oil trough adsorption (e.g., paper) filter, restoration of color, etc. are more effective at low temperature

Drying and Degassing oil using thermal-vacuum process

The process incorporates removing from the oil the certain volume of gas: (air) and water vapor. Parameters of the process (oil flow rate, residual pressure and temperature) shall be coordinated with characteristics of vacuum pump (displacement) to remove amount of air and vapor available Oil typically contains 9-11% of air and 3-5% of water vapor

10ppm (g/to) of water is equal to (1.2-1.3)% of volume concentration.

1 gram of water at residual pressure of 1mm Hg takes approximately 1 m³ of volume (at 0.5 mm Hg-accordingly 2 m³)

To remove 11% of dissolved air and 50 PPM of water at 60C and 0.5 mm Hg, using flow rate 5m³ per hour, the displacement of vacuum pump must be more then 1080 m³ per hour.

Parameters of the process shall be monitored in such a way to remove the desirable amount of “water-gas” mixture per one pass

Degassing process may be optimized using the most effective stage of the process.

One can define two degassing stages in vacuum degassing plant

- Intensive extraction from the oil under vacuum dissolved air and water inevitably cause foaming, which provides intensive diffusive emission of gas, and vapor out of oil. This is the most effective stage of degassing. It does not require high vacuum and high temperature.
- Relatively slow gas diffusion out of flowing layer while oil is flowing down from spray nozzles or spraying to produce the mist. This process needs in comparatively high temperature and vacuum.

However its important not to allow the foam get out of vacuum chamber.

Typical volume of oil foam is 8 times as large as volume of the oil itself and time constant of foam sedimentation is about 60 sec.

One can show that to meet above mentioned requirements flow rate of the oil shell be equal to 8 of volumes of vacuum chamber.

However foaming tendency of different oils is rather different. Some general guidelines has been suggested by Doble which does not recommend to use the oil having foaming tendency more then 150 ml (test by D892)

Drying and degassing of oil does not require very high temperature and vacuum. Average oil temperature 40-50C and vacuum 1-0.5 mmHg are sufficient to reach adequate dryness.

Effectiveness of both On-Line and Off-Line procedures are practically equal

An important advantage of On-Line Processing is possibility to use internal losses of the transformer. Thus this process may be more economical then off-line treatment when oil needs typically in addition heating.

DRYING OUT OF INSULATION THROUGH DRYING THE OIL

This process needs in essentially higher temperature then drying the only oil

Really, to get low moisture content one must maintain a very low relative saturation of oil.

Water content in oil is directly proportional to relative water concentration (relative saturation) up to saturated level. It's very important to consider solubility characteristics of the oil

Water saturation – temperature [$W_s - T$] relation is expressed by form

$$W_s = W_0 \exp. (- B / T)$$

Where W_0 and B are constants, which are typically different for different oils, mainly due to difference in aromatic content. Some information about estimated solubility constants and saturated water content are shown in the Table beneath

Knowing the aromatic content one can easily select the parameters of solubility

Oil #3 may use as prototype of aged oil.

One can see that for oils #1 and #2 50 ppm of water at 20C is over then saturated level

However at 40C 50ppm corresponds to $\approx 50\%$ of relative saturation, and at 70C only to 16-18%.

# Oils*	Aromatics $C_A, \%$	W_0	B	Solubility, PPM		
				20 °C	40 °C	70 °C
1	5	$16.97 \cdot 10^6$	3777	42.8	97.5	279
2	8	$23.08 \cdot 10^6$	3841	46.8	108	316
3	16	$22.76 \cdot 10^6$	3783	56.2	128.3	369.2
4	21	$13.16 \cdot 10^6$	3538	75	162	436
5	Silicon-oil	$1.9525 \cdot 10^6$	2733	174	314.7	675.4

To get water content in cellulose about 2%, relative saturation of the “hot” oil shall be $\phi < 8\%$. Assuming maintaining water content of oil within the transformer 15 PPM, e.g. for oil # 2 we may estimate the starting temperature of drying process:

$$T = \frac{(-B)}{\ln\left(\frac{W_{oil}}{\phi \cdot W_0}\right)} = \frac{(-3841)}{\ln\left(\frac{15}{0.08 \cdot 23.08 \cdot 10^6}\right)} = 328K (\approx 55^\circ C)$$

One can show then to achieve moisture content in cellulose of 1% the drying temperature shall be over 70C and process shall allow maintaining water content in oil less then 10 ppm.

Experience has shown that drying out of insulation really contaminated with water by means of circulating oil through dehydrator needs high temperature and very long time and practically much less effective and efficient than methods of drying out of transformer free of oil.

On the other hand, On-Line procedures are definitely more efficient then Off-Line because of possibility to utilize internal losses of a transformer as source of heating.

On-Line processing may be really very efficient in case using “passive methods” [1]. Two cartridges filled with molecular sieves of 200 kg may

extract during several months about 40 kg of water, so that to dry effectively a transformer rated 200-300 MVA.

Oil filtering

Particle contamination is practically the main factor of degradation of dielectric strength of transformer insulation and accordingly, elimination of particles is the most important objective of oil processing.

The most dangerous are conductive mode particles (metals, carbon, wet fibers, etc.)

CIGRE working group "Particles in oil" (WG 12.17) has found that a lot of failures on HV transformers has been associated with particles contamination". Traditional dielectric breakdown test is not sufficient to identify the problem and particles counting method has been advised as monitoring tool. Denomination of typical contamination level including possible dangerous level has been advised.as well using classification of NAC standard:

4-6	Normal	Contamination level typical for transformer in service
7-9	High	Possible transformer malfunction
10-12	Very high	The condition strongly indicative of transformer malfunction

High level means presents of 32000-64000 particles of 5 µm and above and 8000 particles of µm in 100 ml of oil.

It's apparent that improvement of transformer condition in-service is mandatory and On-Line filtering process is particularly desirable.

Both Off-Line and On-Line procedures are practically equal, however the latter does not need in additional heating to reduce viscosity of oil'

There are some technical problems with oil purification, which have to be considered:

- Filtering of small particles, particularly carbon needs in very thin filter elements
- It's difficult to remove small particles (e.g. clay crumb). Due to miserable mass they are swimming in the oil following convection flow. This is really disadvantage in comparison with purification the oil being draining out of the transformer tank.
- Filter (particularly paper mode) can be a source of particles generation itself. Useful life of filter shall be considered particularly for On-Line application.

OIL Reclaiming

Similar to drying of oil this is a widespread processing method for both Off-Line and On-Line application.

On-line procedures are more efficient because of possibility to use internal losses of a transformer to heat the oil

One must consider some disadvantages of the methods:

- A large amount of waste

- Loss of oil during reclamation (what is more sensitive in case of energized unit)
- Limited amount of oil processed with one charge
- Risk of introduction the clay crumb into the tank (more critical for energized unit)

Passive mode methods with installation of some cartridges filled with adsorbents could be sometimes much more efficient and safe.

Experience has shown a very good effectiveness of so called "reclaiming without waste" using Fuller's earth reactivation technology. In Czech Republic e.g. several of tens transformers have been reconditioned up to the level better than a quality of new oil (what is really feasible). About 30% of the units have been processed On-Line.

INSULATION REGENERATION (DESLUDGING)

This is a critical process to extend the Life. Experiments have shown that extraction of aging products from cellulose may result at least in doubling the life span.

Sludge is the most dangerous enemy of transformer insulation:

-as impurity, sludge reduces oil dielectric withstand strength (like particle)

-as semiconductive sediment, sludge reduces impulse strength of oil-barrier insulation and LTC insulating components

-as extreme sour, sludge is effective killer of a new oil and cellulose.

Sludge acidity may vary in the wide range up to 30-300 mg KOH/g, so that aggressiveness of sludge is more important than its quantity.

On the other hand, sludge may occur at comparatively low oil acidity (0.04-0.07 mg KOH/g).

Old empirical rule states that a substance is dissolved in a similar solvent.

Transformer oil can dissolve oil-aging products to some extent.

Solvent action of the oil depends on aromatic content (the more, the better); molecular weight (viscosity-the less, the better); presence of some tarry products.

Detergency of operating oil can be improved by means

- of some cleaning additives;
- lowering concentration of oxidation products in oil (by reclaiming);
- maintaining a high temperature of oil to improve its solubility.

There have been two positive experiences:

Off Line Desludging as a part of rehabilitation process utilizing regenerative oil (method ZTZ-Service)

Desludging by means of desorption of aging products into oil being freshly regenerated through adsorbed percolation columns, maintaining the oil temperature above its aniline point (method Fluidex). Energized transformer to use loading heat is preferable.

ESTIMATION OF TIME OF PROCESSING AND PARAMETERS TO BE MONITORED

A process of gradual improvement of the transformer condition by means of circulating oil through processing equipment is of exponential mode.

Three parameters shall be considered:

- Ratio of final and initial concentration of contaminant;
- Ratio of flow rate and total volume of oil in the transformer;
- Ratio of inlet and outlet concentration of contaminant per one pass of treatment into the processing machine

The most important parameter, which determines effectiveness of the process is relative rate of contaminant, removed per one pass, namely:

Ratio of input and output water, ratio of particles, ratio of oil aging characteristics (Neutralization Number, interfacial tension, PF, Resistivity)

For example, if the system reduces the water content from the input 50 ppm to output 10 ppm per one pass with flow rate 2 m³ per hour, the time to reduce water to 10 ppm in the transformer of 20 m³ will take 20 hours. That is equal to processing two volume of oil in the transformer). If processing equipment removes only 50% of input contaminant per one pass such time will take 32 hours.

Another important parameter to be monitored is ratio of flow rate and the volume of oil to be treated.

Both of abovementioned parameters are variable that's why it is very important to arrange On-Line monitoring of processing characteristics.

I would recommend the following approach:

- *Check the initial condition (concentration contaminants to be removed;)*
- *Define the desirable final condition;*
- *Define the optimal parameters of processing: flow rate, temperature, and vacuum, which give the maximal rate of removing contaminant;*
- *Estimate the time of process;*
- *Evaluate the possible life of adsorbents and filters elements to be replaced during the total time of processing;*
- *Arrange monitoring of abovementioned basic parameters of processing and auxiliary parameters (temperature, flow rate, vacuum.)*

Utilization of On-Line sensors is of importance:

- Water sensor.
- Resistivity sensor; I believe that that is the most convenient characteristic to monitor oil reclaiming process.
- Gas sensor to monitor degassing of transformers having excessive gas (faulty gases) concentration.

Special study [15,16] has shown that reclamation process is the most effective if to reclaim the oil, which have few nonacid polar, independently of the IFT and Neutralization Number reached during service aging.

It should be also considered that low value of NN and high value of IFT does not guaranty good behavior of the oil after reclamation if nonacid polar are presented.

SAFETY PROBLEMS

The main disadvantage of On-Line Processing is a risk of failure due to unintentional impairment transformer condition. Different precaution measures centered to minimize the risk are presented in [1,2,,35,6,8,10,11,13,]

Recommendation referring to some safety measures is presented beneath

How to minimize the risk of reducing dielectric withstand strength due to possible introduction into the tank foreign impurities

- *The system shall not incorporate a vacuum process*
- *Do not allow air permeate into the tank:*
- *Do not allow oil to splash.*
- *Do not allow foam ingress into the tank*
- *Do not allow particles ingress into the tank*
- Consider static electrification [2].
- Do not allow the turbulence of oil

Partial Discharge activity will not bring a critical harm if to limit time of their acting.

How to minimize the risk to loose of oil during processing

Consider minimal volume of oil in the transformer, taking into account possible loss of oil during reclamation (replacement of waist clay)

Watch oil level; consider the oil level gauge

Consider in some case arrangement of a metal standpipe to minimize the loss of oil

Consider automatic shut down controls

How to minimize the risk of failure during processing defective transformer

In general any defective transformer which on operation could be processed without de-energizing if adequate measures to prevent impairment of its condition are taken

However lack of the necessary diagnostic characteristics precludes often determination of real technical condition of the unit.

Two options could be recommended:

- Processing only definitely undefected transformer,
- Assessing the condition prior to processing

Consider possibility to overheat transformer during the process

Processes, which need in high temperature (drying out, insulation regeneration) may affect thermal behavior of the transformer.

Recommendation on the base of CIGRE WG 12.09 study could be advised .

REFERENCES

- 1.Sakkie van Wyk, Rotek Engineering(South Africa)
“Dry out systems and techniques for Power Transformers” Proceedings of the EPRI 1998 Conference.

2. Abel Pereira, Bonneville Power Administration.
"Safe handling Procedures for insulating oil with High Concentration of combustible gases"-Proceedings of the DOBLE 1996 Conference, Sec 5-7
3. Larri Christodoulou, United Power Services, Bruce Baranowski, Baron USA, Inc.
"On-Line Energized Oil Processing of Transformers a Perspective of System Manufacturer and Service Company", Proceedings of the 1995 DOBLE Conference, Sec.5.7
-
4. Myers, S.D., "Transformer Life can be extended", Minutes of the 1982 DOBLE Conference, Sec 6.6
7. B. Pahlavanpour, et al., "Extension of Life Span of Power Transformer by on-site improvement of insulating oil
8. P. Luccioni, et al., "On-Line Processing of Transformer Oil", Proceedings of 1995 DOBLE Conference, Sec.5-8
9. J.J. Kelly, S.D. Myers, Inc "A discussion of the on-line Oil Processing papers, Proceedings of the 1995 DOBLE Conference, Sec.5-9
10. M. Girard (Electricity de France), "On-Line Processing of Transformer Oil," Minutes of the 1997 EuroDOBLE Colloquium"
11. P.W. Brunson, et al. "On-Line degassing of EHV power transformers", Minutes of the 1990 DOBLE Conference, Sec.6-11
12. J. Laakso, British Columbia Hydro and Power Authority, "Discussion of the P. Brunson paper", 1990 DOBLE Conference, Sec.6.11.1A
13. Minutes of the 1998 FALL Meeting of DOBLE Clients
14. V. Sokolov, B. Vanin "Experience with in-field assessment of water contamination of large power transformers", Proceedings of EPRI 1999 Conference
15. C. Lamarre, et al. "Optimum Reclamation Time for Insulating Oils", Proceedings of the 1988 DOBLE Conference, Sec.10-6
16. A. Bassetto, et al. "Assessment of the optimum reclamation time for uninhibited oil by infrared spectroscopy, Proceedings of the 1991 DOBLE Conference, Sec.10-4
17. Alberto Herreno Rocha, Inteconexion Electrica S.A. (ISA), Colombia "On-line reclamation of power transformer insulating oil", Proceedings of 1999 DOBLE Conference, Sec.5-6

