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ACCELERATED DEGRADATION OF TRANSFORMER INSULATION BY IMPACT OF POLAR PARTICLES AND METHODS OF RETARDATION OF THIS PROCESS

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SUMMARY

Preventive monitoring of insulation condition is discussed. The decision to use intervention measures is facilitated by using the analysis of obtained results. The paper presents the mechanism of insulating system degradation during transformers operation, which is discussed as a unique one consisting of two materials: cellulose and oil which are quite different in regard of their chemical stability and characteristics.

The paper offers the presentation of our approach to solution of insulation aging problem. When solving the problem of quality maintenance of insulation system our starting point was the fact that the process of degradation of cellulose and insulating oils in conditions of transformers operation could not be stopped, which results in constant formation of degradation products.

The examples of practical application of new method of maintenance or refurbishment of transformer insulating system, which is possible on site, too, are presented. The employment of a new adsorbent with selective adsorption effect on carbonyls, water, and gases is proposed. The adsorbent is meant to be regenerated, which is of special importance from the point of view of environment and use on the site. The principal solution to the apparatuses and methods for presented procedure is proposed as well.

Keywords

Transformer - Insulation - Degradation - New Adsorbent - Regeneration - Ecology

1. INTRODUCTION

For quite a number of years we have been studying degradation of transformer insulating system during its operation in our power grid of 400, 220 and 110 kV. There are installed instrument and power transformers of 20 to 725 MVA. Except a small amount of current transformers of 400 kV which are insulated by SF6 gas, the others are constructed by use of oil- paper insulation.

We have started monitoring of the insulation condition during the transformer manufacture and final acceptance tests. The results obtained give the initial parameters necessary for prophylactic tests in the period of service. We have developed the testing methods and criteria of quality. The new methods of insulation testing are introduced when the need appears, and all the testing results are processed statistically.

It is well known that with transformer being in operation, various electrical fault and full loaded currents take place as well as electric and magnetic field effects and different sorts of overheating, which induce the aging process of insulation that could manifest by change of oil characteristics and reduction of dielectric properties of solid insulation. This interferes with the functioning of the transformer and may cause problems.

The products of degradation of insulation are divided between fluid and solid insulation, regardlessly of its origin, following from the process of diffusion and circulation of oil through cellulose. Their presence in oil is the main cause of fall of insulating characteristics of oil but by their measurement in oil it is possible to diagnose the state of transformer insulation. Degradation products are molecules of remarkably polar character and being such they can be factors of harmful currents in electrical and magnetic field in transformer insulating system.

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2. PREVIOUS EXPERIENCE OF INSULATION MAINTENANCE

The process of insulation degradation is monitored and the results of prophylactic tests and defined criteria are used to decelerate that process. The decision of precautions which is necessary to carry out in order to decelerate the insulation system degradation is made in accordance with analysis of obtained results.

We have got the instrument transformers in substations with insulation system closed and separated from environment influence for more then 20 years. The degradation of general condition of insulation system has been not caused by impact of outside factors any more but by aging processes only. This is the reason that the electrical and chromatographic checks are proceeded in longer periods of time.

The problems with current transformers we are dealing with are caused by faults in manufacture and design. The first problem is appeared during paper insulation building due to use of inadequate glue, and the second one due to overvoltages of high frequency which may initiate the resonance phenomenon. These faults are present even 20% with our apparatuses. Partial discharges testing through piezo- converter, which ultra sound transfers into electrical value that is analyzed through oscilloscope and computer, is the method to start the current transformer selection. This method is used for setting aside units which have to be tested by chromatographic analyses of gases in insulating oil and to make the definitive decision. The problematic units are sent to be repaired selectively, when the paper insulation is replaced and with some units the electrostatic shields geometry, too. In that way we have prevented the insulation breakdown followed by explosions.

We have proceeded the actions for stopping the accelerated degradation of power transformer insulation or for small repair works on the site whenever it is possible, in order to save the time and resources. The failures that have been developed gradually or those which switched off the transformer from the operation are given in percentages, relating different parts:

- Overheating of shields and iron parts 21%;
- Short circuits of laminations and end frames 19%;
- Winding failures 14%;
- An inadequate work of protection 10%;
- Failures of OLTC 10%;
- The breakdown or overheating of bushings 9%;
- The breakdown of HV leads 7%;
- The disconnection of grounded parts 6%;
- Rest failure reasons 4%.

Any internal fault may be the cause of degradation of insulation system. Entering of any insulating material into insulation system carry to different electric field distribution. Inadequate glue may influence the changes in insulation and be the cause of increased partial discharges and considerable insulation damages, which follow to breakdown finally. We have found the X wax in such places as well as carbonized traces, while cutting the paper insulation of current transformers, as a result of disassembled products of insulating oil. Except partial discharges, all kind of overheating including those caused by leakage flux, connections in magnetic circuit and insufficient good contacts, may influence the accelerated insulation degradation.

We shall present our experience concerning the overhaul of insulation condition in the cases of stopping of accelerated insulation system degradation during operation or in the cases of repair works. The samples of paper and oil are sent for testing. The paper is tested on degree of polymerization and the oil on physical, chemical and electrical properties. The state and dirtiness of winding (insulating- cooling) ducts caused by carbonized and metallic particles as well as by the oil sediment, are established by direct examination or endoscope. Except the oil tests according to standards of quality and when was the impact of electrical arc, the samples of oil are passed though fine filters of 5μm and below and particles on filter are examined by microscope. In many cases the carbonized fiber-particles of cellulose were found as well as metallic balls with diameter below of 1μm, which were carried by oil circulation and found in any level of insulation system. These particles must be eliminated from the windings and oil before the transformer putting into operation, for they may influence the conductive paths on insulating surfaces in the direction of electrical field. This process may lead to insulation breakdown again and be the cause of very serious damages of transformer in some period of time. We reached the best effects of particles elimination from insulating system when we pumped the insulating oil through insulation system and adsorbent at the same time, when first the cleaning and drying process of solid insulation was done. The adsorbent that we used, has been found in the nature in the pure condition so called 'tuff'. This adsorbent through their own active surfaces also units the polar molecules such as carbonyls, carboxyl groups etc., which appeared by the aging process of insulating oil and paper. The products of aging have also been removed by using of much more active adsorbents, which have reclaimed the insulating oil very effectively.

Insulating oils that we use, are mostly with inhibitor and it is removed by adsorption process. The inhibitor is got back in pure oil up to necessary percentage (0.3%). In addition to described procedures for removing polar molecules of oxidation, water etc. while failure elimination and for returning of insulation system into correct condition, the similar processes are necessary to be performed on the transformers that are continuously in operation, whenever the testing results have pointed to that. Prophylactic testing of transformers in service includes the periodical tests such as infra- red spectroscopy (IR), gas chromatography, physical, chemical and electrical checks of oil and complete insulation system. We have come to realization for the

free electric charges inside of insulating system through analysis of curve of insulation loading under d.c. voltage. The introduction of liquid chromatography of insulating oil is in preparing in order to complete the picture of processes of degradation inside of transformers. We have noticed through repetition of periodical tests, that the process is accelerated during the service with approximately the same condition of transformer exploitation.

In accordance with available data regarding the present state of techniques and technology, the search for a solution of how to maintain insulation system has developed in two directions:

- Retardation of insulation degradation by adding inhibitors;
- Products of oil and cellulose degradation removing by an adsorption method.

Our investigations are being pursued intensively, especially to materials which might reclaim oil of a transformer in service, without taking it out of operation.

3. OUR APPROACH TO SOLVING THE INSULATION DEGRADATION PROBLEM

When solving the insulation degradation problem, we started form the basic facts, such as:

- The insulating system must be considered as a whole;
- The insulating system is composed of two materials: cellulose and oil. Their chemical stability and physical properties are entirely different. The process of the degradation during transformer operation cannot be stopped;
- The inhibitor which is added to oil only decelerates but does not stop the process of degradation, it is being spent permanently during the operation of transformer, and the oxidation process is accelerated. Kinetics of this process is not possible to be foreseen;
- Products of insulation disintegration are disposed between liquid and solid insulation, regardless in which they appeared, and this is the consequence of process of diffusion and oil circulation through cellulose. According to our analysis the percentage of cellulose particles is very high, even up to 80%. Their presence in oil is the basic cause of reduction of insulating oil dielectric capacity, It should be pointed out that the products of degradation are molecules of clearly polar character and as such, they can be factors of harmful currents in electrical and magnetic field in transformer insulation system.

It is necessary to remove from oil all products of degradation, all kind of particles, water, gases, in order to preserve the require characteristics of insulation system and through it provide reliable functioning of transformer system on the whole. These points confirm that the regeneration of transformer oil is the complex problem which cannot be solved in one step by the existing technology and adsorbents.

The removal of products of insulation degradation, water and gases, has been done by adsorption process and by vacuum processes independently. The most frequently used adsorbents for this process are natural materials such: Fuller's earth, alumina, zeolite, active bentonite clay etc. The obtained results prove that the problem can be solved only partly by this technological procedure. The unsolved problem is how to find out or synthesize an adsorbent of such properties and how in one process to remove the most of products of insulation disintegration.

As the aim of our explorations, the synthesis of the new type of adsorbent, defining of macro and mezzo porous structure, specific surface and energetic characteristics, is set, which may completely solve the complex regeneration problem.

4. CHARACTERISTICS OF THE NEW ADSORBENT

As the aim of our first part of the work, the synthesis of the new adsorbent is set. The solution has been searched in simple and familiar systems in which the synthesizing process can influence for getting of desired properties of adsorbents.

The essence of the process is in defining of concentrated relations of exterior characteristics of hydrothermal procedure for getting of active alumino-silicate, of maximum adsorption capacity in relation to all degradation products. These processes on the surface are performed parallel and competing in compliance with some molecular groups and energetic character of the surface.

In all cases it is obvious that the presence of carbonyl group influences to increase of hydrophilic property of oil. Electrical oil characteristics are directly dependent on appearance of carbonyl groups. The supposed optimal characteristics which an adsorbent should have, as well as the obtained values of the new adsorbent, are shown on the Table I.

TABLE I: Characteristics of the New Adsorbent

No.	CHARACTERISTICS	SUPPOSED VALUES	OBTAIN. VALUES
1	Specific surface m^2/g	150- 250	150- 240
2	Middle pore radius r- ^oA	50-70	50- 80
3	Total pore volume cm^3	0.35	0.40
4	Static sorption water capacity %	min. 22	24
5	Static sorption capacity of aliphatic carbonyls %	12- 16	13.5
6	Static sorption capacity of furan and homologies %	10- 14	11
7	Form of adsorbent sphere, mm	0.5- 1.5	0.5- 1.5

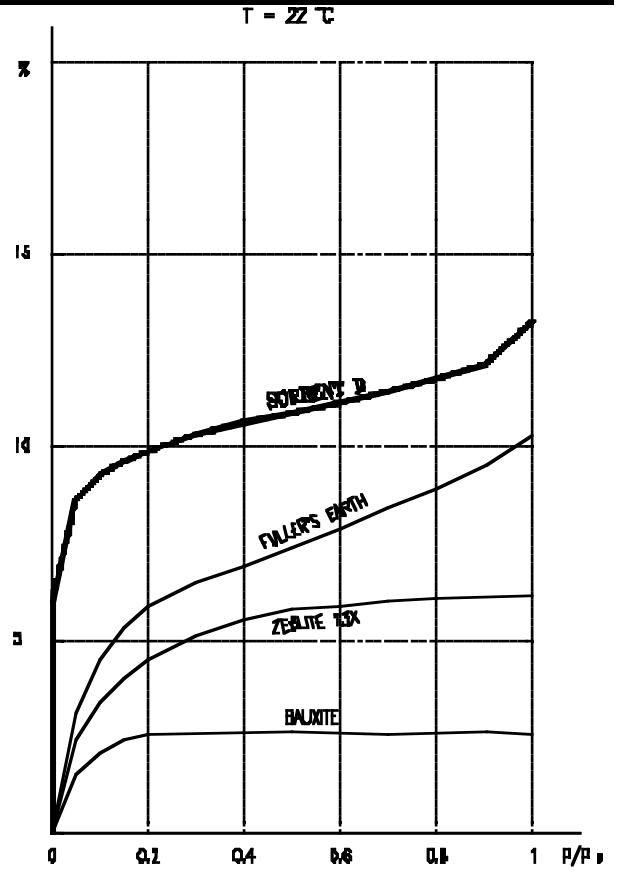

FIGURE 1: Isotherms of Ethylaldehyde (Carbonyl) Adsorbents

Besides the data of the new adsorbent presented on the Table I, we have got the diagrams which characterize its porous structure. The diagrams showed:

- Adsorptional/ desorptional nitrogen isotherm;
- BET isotherm- specific surface;
- Pore arrangement in differential form;
- Pore arrangement in integral form.

Adsorption characteristics of the obtained adsorbent are investigated for some number of compounds which may appear as products of insulation system degradation. The results obtained are shown as adsorption isotherms, and are compared with the same characteristics of up-to- now used adsorbents for oil regeneration.

Figure 1 shows isotherms of carbonyl adsorption (ethylaldehyde). Based on the results obtained, the new adsorbent D shows a greater adsorption capacity than Fuller's earth, zeolite, or bauxite.

Figure 2 shows water adsorption on examined adsorbents. The adsorption zeolite capacity is dominant, especially for lower relative pressures, which is essential for effective removal of low water concentrations from oil. It was expected for zeolite. Our adsorbent D with exception of zeolite, has better adsorption properties then the others currently on the market.

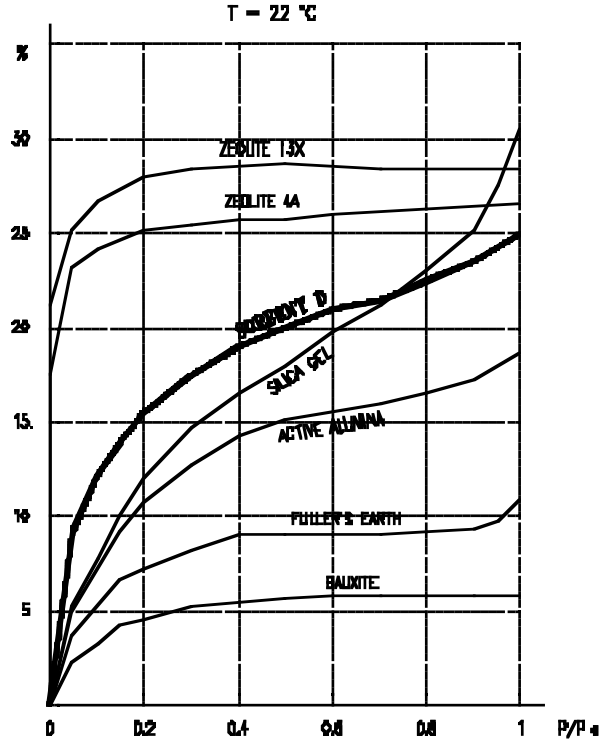

FIGURE 2: Isotherms of Water Adsorption of Different Adsorbents

We have also got the adsorption isotherms of lower carboxyl on new adsorbent D and Fuller's Earth as well as adsorption isotherms 2- furaldehyd on adsorbent D, zeolite 13x, Fuller's earth and adsorbent A- 4M of Russian production.

Based on analysis of the obtained results it may be concluded that the new adsorbent has quite a number of advantages in comparison to adsorbents currently in use, some of them are important:

- A larger adsorption capacity of 30- 50% to adsorbents known;
- Optimal relation of porous structure and specific surface;
- Favorable kinetic parameters for the process of adsorbent diffusion;
- A high thermal stability and chemical inertia:
- The adsorption process of all examined components has the character of physical adsorption and it means that the process is completely reversible.

Our general conclusion is that the high adsorption activity of adsorbent D to polar compounds of acid character should be imputed to the great number of active centers present on its surface.

Based on these characteristics, the procedure of adsorbent regeneration has been developed. This procedure contains two main operations: extraction and thermal activation.

In our investigation, the processes repeated many times and the results obtained are shown on Figure 3.

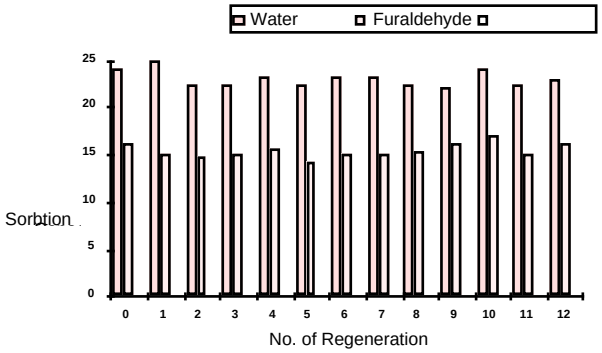

FIGURE 3: Change of Adsorption Capacity Depending on the Number of Regeneration

As the example of thermal stability, compared review of porous structure change and specific surface may be used. After ten regenerations only small changes have been noticed. For this purpose we formed the diagrams which show the porous structure change and specific surface in dependence on regeneration.

It should be stressed that the regeneration problem is specially important from economic and environmental point of view.

5. MAINTENANCE OF INSULATION SYSTEM BY USE OF ADSORBENTS

Our attitude in connection with monitoring of insulation system led to discovering some number of transformers which definitive required replace of insulating oil together with washing and drying of solid insulation. The decided way of drying on side (oil spray, heating with own oil, vacuuming etc.) requested that all transformers should be prepared in such way to be able to withstand full vacuum in their own tanks. Further process of insulating oil replaced by new oil after washing and drying of solid insulation has been proved as insufficient because for short period of time, out of solid insulation by diffusion and by oil circulation, the elements of previous state have passed into new oil. This is after Henry's law. Distribution of water concentration and aging products between oil and cellulose are constant. This is the base of accelerated aging process which starts by breakdown of polymerisated paper molecules and thus it is being continued by acting of aging paper products onto oil and vice versa.

Confirmation of above stated has been found in investigation of coefficient of paper polymerization on quite a number of transformer samples where it is easy to find out that the paper next to the conductor is very often in better condition than the one which is in the outside layer.

After oil replacing procedure we had, in the period less than one year, to repeat the process of oil pass through absorbent in order to eliminate polar molecules and at the same time, to apply repeated accelerated aging of the new oil under the influence of these oxides.
Very soon we concluded that from economic point of view it is far more justified instead of oil replace to proceed adsorption first and other works perform in the same manner.

Natural adsorbents we dealt with are used up to 20% of the treated oil mass. In case the oil was too much aged and consequently require more adsorbents to be taken into state to function properly we didn't treat the oil on the side but such transformer was removed from the network.

The further decision about the matter should be made later on. This was the way that same 100 or more transformers were treated during the regular maintenance or fault elimination. After determining the new method of refurbishment of insulation many works on side were widened.

Initially and based on testing results the insulating oils in our transformers are grouped in for quality categories.

After many years in experience of fault elimination in insulation system we have, at the moment in transformers only first and second group of quality, i.e. oil which is relevant to international standard for 400 kV network.

The used adsorbent was burnt in thermal power stations, in cyclonic furnaces respectively. The solution of adsorbent regeneration in mobile installations makes this process much easier. We started to explore the new effective adsorbents and belonging structures of mobile devices suitable for on site use.

Table II shows comparative results obtained by adsorbents so called 'tuff' and new one presented in this paper.

Almost all insulating oils during adsorption treatment are in very good condition with use of 5% adsorbent mass value. This will enable to achieve the effective regeneration of adsorbent on side and its repeated continual use.

TABLE II: Testing Results of Insulating Oil Before and After Use of Old and New Adsorbent

	Before Revitalis. 20% of Old Ad./ 6% of New Ad.	After Revitalis. 20% of Old Ad./ 6% of New Ad.
tan δ %	9.02/ 11.65	2.10/ 0.22
Specific Resistance GOhm m	2.2/ 2.1	21.1/ 190.0
Interfacial Tension mN/ m	15.1/ 17.77	30.2/ 33.75
Neutralization Value mg KOH/ g	0.08/ 0.22	0.03/ 0.01
Sediment	Yes/ Yes	No/ No

TABLE III: Technical Characteristics of Devices of Type A and Type B

	Type A	Type B
Capacity of Treated Oil l/ h	600	1200
Treated oil mass Capacity* t	50	100
El. Power Consumption kW	0.6	1.1
Length mm	750	750
Width mm	600	650
Height mm	400	800
Mass kg	60	95

* Oil containing 100 ppm of water come to oil containing less than 10 ppm in one pass, at 10 C.

Installations with thermal adsorbent treatment are widely used in many countries.

Besides the work on the new adsorbents we have constructed a number of devices on site use. For example devices for gas removing, dehydration and insulating oil treatment have technical characteristics as shown in the Table III.

Types A and B are for filtering and dehydration. Adsorbent regeneration is carried out in the device in the period less than one our time. Type B can be used for gas removing. Twenty (20) devices of the kind are at the moment in experimental work and in workshops.

Similar devices with increased capacities are constructed for the use of new adsorbent D. Possibilities of the new adsorbents enable system maintenance control of transformer insulation from the moment of putting into operation until its lasting life.

Replace of column with new adsorbent can be done without interrupting transformer operation. Having in mind considerable capacities and their regeneration possibilities, we can conclude that maintenance of such column systems with bigger transformers is no problem at all. A benefit is great because duration of insulation life is prolong with increased security in operation with elimination of polarized elements- water and particles.

In all our experience we found no harmful reactions in the tested adsorbents during insulating oil treatment while it can be applied to standard physical treatment (heating - vacuuming). Improvement of adsorbents and devices for its application include improvement maintenance of other kinds of insulation such as gas SF6.

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