

Influence of transformer oil particle contamination on its dielectric hardness

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Influence of particles of metal and non-metal origin, generated during transformer production and exploitation, on transformer oil dielectric hardness is investigated in this paper. For that purpose, particle analysis and dielectric investigations were performed on samples of new oil and oil taken during transformer exploitation, both before and after filtration. Samples were taken from particular levels of the transformer. Sampling and all measurements were made in accordance with valid ISO standards for oil testing. Based on the obtained results, it has been concluded that parameters defining statistical distribution of the random variable "breakdown voltage" are dependent on the concentration of particles in oil. The reason for this is found in local destruction of insulating oil, produced by highly non-homogeneous electric field surrounding particles of metal origin. Reversibility of transformer oil dielectric characteristics after electric breakdown is also considered.

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1. Introduction

Insulating system of a power transformer, beside its basic functions (insulating and cooling), also presents a medium which enables state analysis and regular work of the transformer itself. Investigation of the correlation between oil electrical characteristics and its contamination, arising during transformer production and exploitation, is therefore of particular interest. Dielectric hardness is the most important electrical characteristic of insulating oils, and there are numerous methods for its determination.

Establishing the influence that purity of transformer oil exerts on its dielectric hardness is of great importance. During the production of transformer inner structure a certain quantity of conducting and non-conducting particles is generated. The majority of these micro-particles are removed by the first filtration of insulating oil. However, electro-dynamical stresses, especially during transformer activity, release particles transfixed in certain transformer parts, leading to the increase of their concentration in oil. In exploitation conditions, concentration of the particles is proportional to the magnitude of electric field, and has a maximum value at the place where electric field is strongest. This leads to local increase of electric field, which could give rise to micro-discharge phenomena. The micro-discharges thus occurring generate new particles in the zone of maximum electric field, inducing destruction of oil. The positive feedback of the process finally leads to breakdown. As a consequence, presence of conducting and non-conducting particles in transformer oil causes a decrease of its dielectric hardness [1,2].

However, in practice it is not always possible to establish instantly which mechanism has led to dielectric breakdown. This especially holds for particle breakdown mechanisms, because the particle concentration is dramatically increased after the breakdown. Despite this, in the case of transformer oil breakdown, the theory of the particle-induced breakdown is often accepted as a probable one, since no alternative theory yet exists.

The aim of this paper is: 1. to determine the influence of particles appearing during transformer production and exploitation on the dielectric hardness of insulating oil, as well as to investigate a possible connection between the presence of conducting and non-conducting particles in insulating oil and the degree of its dielectric hardness reversibility; 2. to demonstrate that ISO testing standards for transformer oil are partly inadequate for the testing of power transformer oil and insulating oil intended for use in high voltage pulse power equipment.

2. Experimental

In order to research the influence of particle oil contamination on dielectric hardness, investigations were performed on samples of pure oil (sample 1), contaminated oil (samples 2a and 2b) and filtrated oil (samples 3a and 3b). Marks a and b designate levels in the transformer at which oil was taken (a - lowest level, b - medium level). Filtration of contaminated oil sample was accomplished by passing it through the zeolyte 4 (alumo-silicate with the following characteristics: $Al \div (Al + Si) = 0,5$, main cation Na^+ , channel length $4 \cdot 10^{-3}$ mm, primary application in adsorption [3]), i.e. the procedure by which most polarized particles are removed.

Furthermore, based on particle type determined by subsequent particle size analysis, and the fact that the contaminated sample was taken from the transformer after a long exploitation period, it can be stated that in this way almost all particles are removed. Experimental procedure itself consisted of two steps. The first step was to perform particle size measurements of particles present in all the processed transformer oil samples. The second step was to determine transformer oil dielectric and physical characteristics. Measurements were performed on all samples.

2.1. Particle size analysis of transformer oil particle content

Microscope particle size measurements by application of skewed (not straight) light were used for determining the quantitative and qualitative content of particles in oil samples. Particles with a diameter larger than 20 μm were first separated by oil filtration through filters of appropriate density. Results of particle size analysis were expressed by using the five-class division, in accordance with the standards for classification of transformer oil purity.

2.2. Measurement of transformer oil dielectric and physical characteristics

For each sample a series of 100 breakdown voltage measurements was performed. Before and after each series of measurements, other important dielectric and physical parameters of the sample were also determined.

The sampling and examination were conducted in accordance with the valid standards [4, 5, 6]. The volume of the examined samples was 450 ml. The samples were poured down a glass stick into the examination vessel and left for fifteen minutes, for all the air bubbles created by pouring to disappear. Chromatographic analysis was carried out on oil samples before each measurement series. On the OPG-100 device for automatic examination of insulating oils, a 30 second period of mixing was set, followed by a 3 minute pause after mixing (the walls of the vessel are transparent, so that any remaining air bubbles may be observed). The rate of the voltage rise was 2 kV/s. The spark gap between elliptic electrodes was 2,5 mm. A constant micro-ambience was maintained during the examination of each sample. All measurements with a certain sample were performed in the course of one day and without interruption. Temperature was $25 \pm 2^\circ\text{C}$ and relative humidity $40 \pm 5\%$ during all measurements, so that the influence of temperature and humidity could be reduced to a minimum. The examined samples of insulating oil were kept in opaque, bottles, closed with a plastic cap.

3. Results and discussion

3.1 Results of particle size analysis

Mechanical impurities were determined by the optical-electronic procedure, along with classification of

impurities found in fractions. 73% of particles detected in sample 2 (contaminated oil) were of metal origin. The remaining particles (27%) were silicate polymers, predominantly cellulose fibers. The majority of particles were asymmetrically shaped and many of them were rounded. Fig. 1 shows a photo of particles in contaminated oil, zoomed 100 times.

Result of particle size analysis are presented in Table 1. In Table 2 the categorization of the transformer oil samples according to the valid standards is presented. (It is important to notice that GOST 17216-71 refers to Государственный Общий Стандарт Технический (former Soviet Union, now Russia), which corresponds to IEC 296) [7].

Table 1. Results of the particle size measurement analysis.

Class in μm	Number of particles in 100 cm^3		
	Sample 2a	Sample 2b	Sample 3a
1 to 5	518100	260700	462000
5 to 10	62700	39600	29700
10 to 20	26400	16500	6600
20 to 50	465	345	330
50 to 100	115	95	90
> 100	95	60	45
Fibers	20	25	20



Fig. 1. The photo of particles with zooming 100.

With the given range of classes it is not possible to deduce the type of particle size distribution. The concentration of particles is highest in sample 2a, while it is significantly lower in samples 2b and 3a, especially in classes covering the range from 5 to 50 μm . The particles were mostly round-edged. It could be stated, based on the presence of rounded particles, that local micro-discharges had been occurring in transformer during exploitation. The concentration of particles below 1 μm is high and approximately invariant in all samples.

3.2 Results of dielectric examination

Fig. 2 shows chronological sequences of the random variable "breakdown voltage" for samples 1, 2b and 3a.

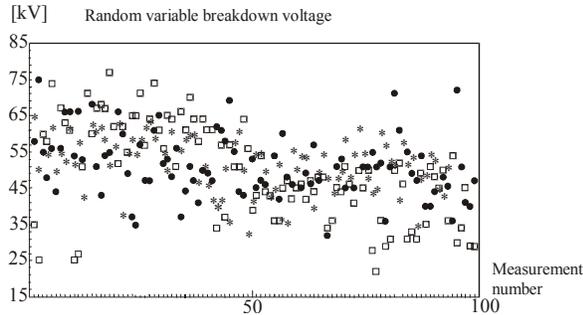


Fig. 2. Chronological sequences of random variable "breakdown voltage" for samples 1, 2b and 3a (Legend: ● – sample 1, □ – sample 2b, * – sample 3b).

Fig. 3 shows a chronological sequence of the average breakdown voltage calculated on the basis of six successive measurements (according to the standard) for samples 1, 2b and 3a, together with the corresponding average values of the whole measurement of 100 values of breakdown voltage for all three samples.

Table 2. Categorization of transformer oil according the standards.

Class in μm	Particle number	IEC 296 GOST 17216 – 71
1. Sample 2a		
5 to 10	62700	12
10 to 20	26400	12
20 to 50	465	10
50 to 100	115	11
> 100	95	12
Fibers	20	12
Average value of purity class		11.5
2. Sample 2b		
5 to 10	39600	12
10 to 20	16500	12
20 to 50	345	9
50 to 100	95	10
> 100	60	12
Fibers	25	13
Average value of purity class		11.3
3. Sample 3a		
5 to 10	29700	11
10 to 20	6600	10
20 to 50	330	9
50 to 100	90	10
> 100	45	11
Fibers	20	12
Average value of purity class		10.5

Table 3 gives the values of dielectric parameters ($tg \delta$ - dielectric loss factor, ϵ_r - relative dielectric permittivity, ρ - specific electric resistance) and physical parameters (σ - surface tension, φ - water content) for samples 1, 2b and 3a.

Table 3. Values of dielectric and physical parameters for the sample 1, 2b and 3a.

	Sample 1	Sample 2b	Sample 3a
$tg \delta$	$0.39 \cdot 10^{-3}$	$7.75 \cdot 10^{-3}$	$71.7 \cdot 10^{-3}$
ϵ_r	2.14	2.10	2.15
ρ (G Ω m)	130	80	95
σ (Mn/m)	44.34	34.33	41.37
φ (ppm)	38.47	35.18	30.93

In Fig. 2, showing breakdown voltage chronological values, substantial fluctuations are observed for all samples. This phenomenon is most pronounced for sample 2b. A similar phenomenon is seen in Fig. 3, where a decrease of average breakdown voltage is observed, as a result of irreversible changes occurring in insulating oil during the examination, which suggests inadequacy of the method defined by the standard. Fig. 4 presents the histograms of random variable "breakdown voltage" for samples 1, 2b and 3a, with the corresponding statistical distribution (Weibull distribution fit) [8, 9].

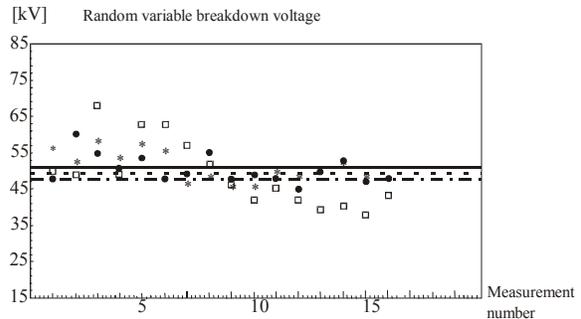


Fig. 3. Chronological sequences of random variable "breakdown voltage" average values calculated according to standard for samples 1, 2b and 3a. (Legend: ● – sample 1, □ – sample 2b, * – sample 3b).

Diagrams in Fig. 4 demonstrate that statistical distributions of the random variable "breakdown voltage" for pure and filtrated oils are very similar, to the point that the sample of filtrated oil could be said to have better characteristics, i.e. larger dielectric hardness, than the new unused oil. However, when all other relevant characteristics are taken into account, this conclusion is only of general relevance. Lower dispersion of the random variable "breakdown voltage" in the sample of filtrated oil points to a lower content of water and particles in oil achieved by filtration.

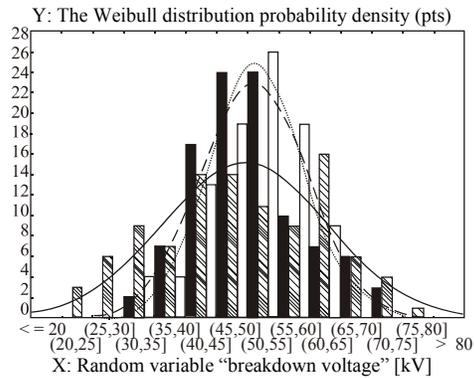


Fig. 4. Comparative showing of the random variable "breakdown voltage" in histogram form i.e. fitted by Weibull distribution for the samples 1, 2b and 3a.

(Legend: ■ – sample 1, ▨ – sample 2b, □ – sample 3a).

On the other hand, the difference between contaminated oil and new (filtrated) oil is clearly visible. It is obvious from graphs and tables that during the process of transformer exploitation degradation of insulating oil dielectric characteristics occurs. This conclusion is additionally backed up by parallel comparison of dielectric hardness measurement results with the results obtained by particle size analysis (Tables 2 and 3). A qualitative cause-effect connection between transformer oil contamination by humidity and particles (occurring during exploitation) and its dielectric characteristics is thus determined.

Physical mechanisms governing the influence of oil particle contamination on its dielectric hardness are too complex to be clasped by a unique physical model, which could provide a one-way method for establishing acceptable limiting levels of particle concentration in insulating oil. Nevertheless, information on particle concentration and their classification according to size can be very useful in discovering deviations from expected values, which may present a danger to the transformer. New and improved examination techniques should be pursued, which would give a better estimation of risk arising from the existing uncertainty in particle distribution by size and type. Development of a method for direct estimation of breakdown voltage fluctuations is also necessary, along with a more precise method for determination of the damage factor.

4. Conclusion

In case of high voltages, based on experiences obtained working with transformers and according to researches results, the content of water and particles in insulation oil has a significant influence on dielectric hardness. This paper suggests some necessary improvements of oil examination techniques, which would be useful both to the manufacturer and the user, with the main purpose of predicting the risk of particle oil contamination and providing efficient decision-making criteria regarding insulation replacement.

The obtained results show that more attention should be paid to stochastic nature of the random variable "breakdown voltage". The degree of dielectric hardness reversibility introduces uncertainty into research results, when measurements are performed according to procedures prescribed by the valid standards (breakdown voltage is determined as the average value of a series of six successive measurements, a series with standard deviation larger than 25 % is discarded).

It can also be concluded that the valid standards do not recommend limiting levels of oil contamination. The investigation points out that the standard test procedures should be improved. It was possible, based on the results obtained from chromatographic analysis, to exclude the influence of gases dissolved in oil on the measurement. On the other hand, the 3 minute pause after the mixing of oil may not be long enough for extraction of gas micro-bubbles. It would be suitable if the oil could be depressurized and left at a lower pressure for several hours before the breakdown tests are performed. Our opinion is that it would be useful to make an additional effort on establishing an improved protocol for oil diagnostics.

While standard procedures may be applied immediately after filtration, they are of no help in determining the distribution of particle size or shape in used unfiltered transformer oil. Statistical distribution of the random variable "breakdown voltage" can provide information on the condition of transformer insulating oil, and timely indicate the need for its replacement.

Acknowledgement

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