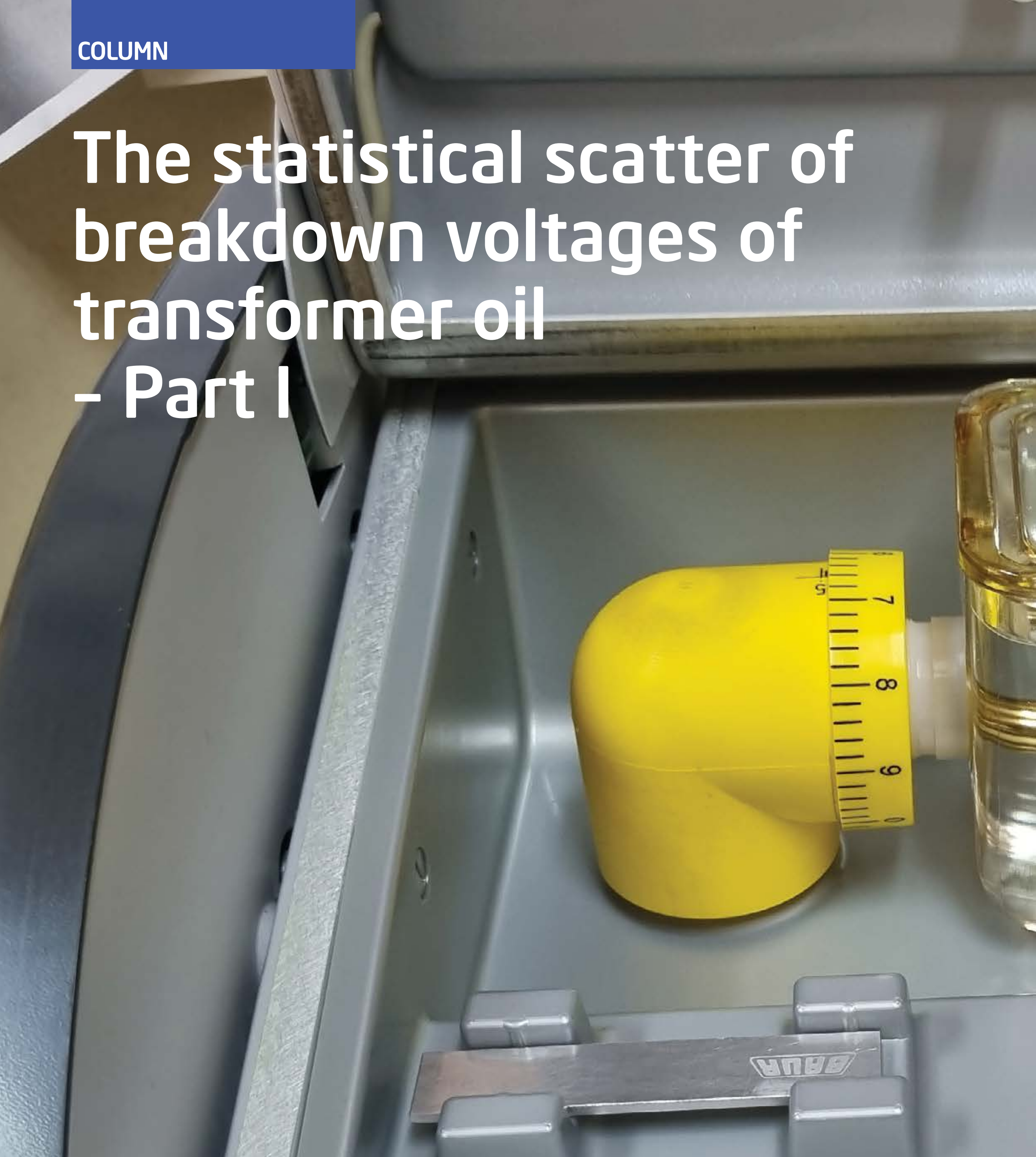
The statistical scatter of breakdown voltages of transformer oil – Part I



ABSTRACT

For the future statistical optimization of power transformer insulation design, more than two hundred publications on transformer oil breakdown voltage (BDV) were reviewed. Data were extracted where possible, and coefficients of variation (CV%) were calculated. The first part of the article discusses the conditions under which the test is considered valid, in accordance with ASTM D877, ASTM D1816, GOST 6581-75, and IEC 60156 standards, as well as the conditioning effect. The article is intended for young transformer engineers and for teaching undergraduate and postgraduate students about transformers in universities.

KEYWORDS:

ASTM, breakdown voltage, conditioning effect, coefficients of variation, ester, GOST, failure, IEC, MEGGER, power transformer, statistical scatter, transformer oil

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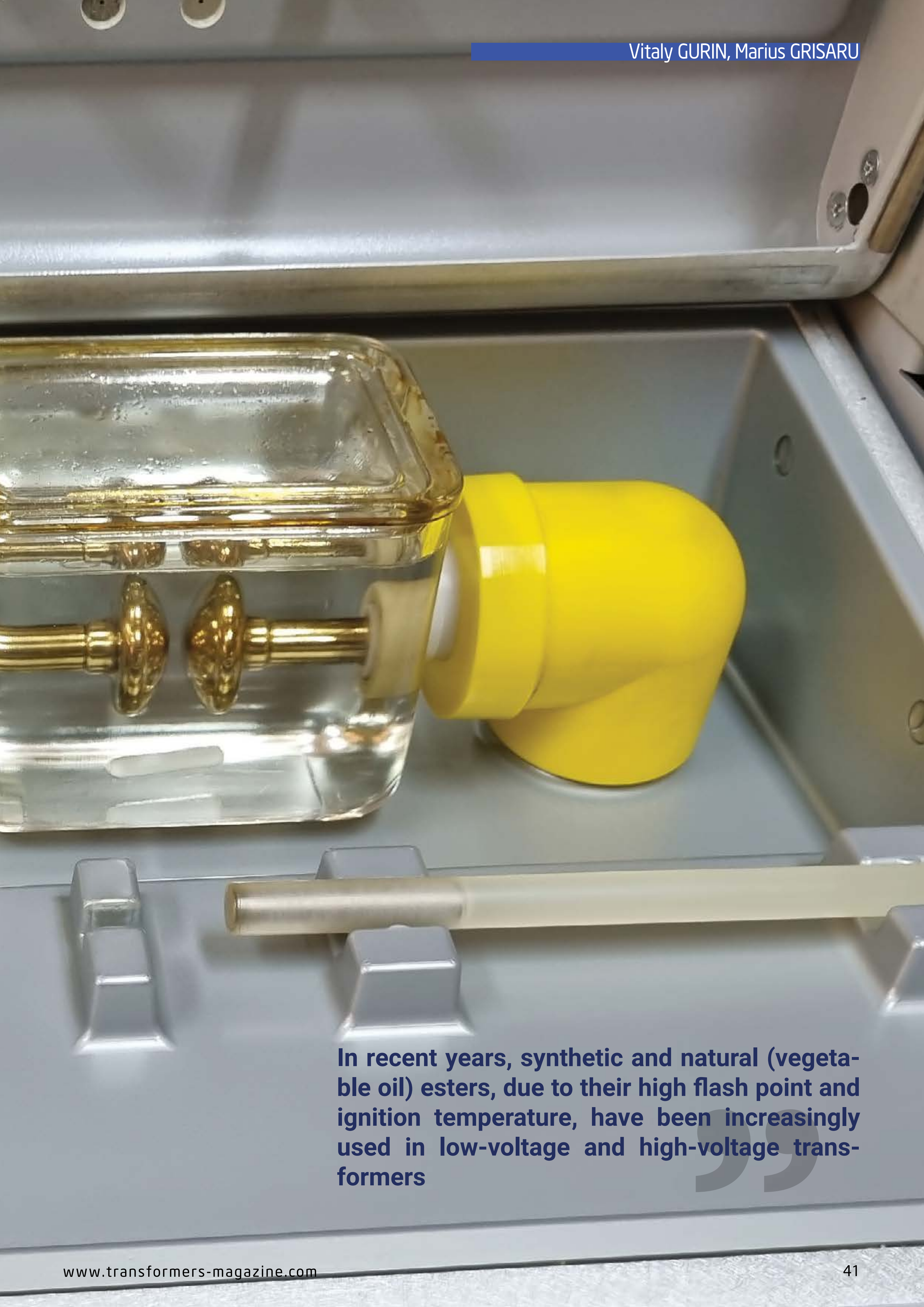


In recent years, synthetic and natural (vegetable oil) esters, due to their high flash point and ignition temperature, have been increasingly used in low-voltage and high-voltage transformers

The breakdown voltage of a transformer's insulation structure is a nonuniform, statistically distributed value corresponding to the probability of failure

1. Introduction

The first transformers built in the 19th century were of the dry type and very small [1]. In 1887, Elih Thomson patented the use of mineral oil in transformers to remove heat from the transformer core and extend its life. Thomson also realized that the solid insulation and anything that came into contact with live parts of the transformer also had to be impregnated and filled with oil. Mineral oil is derived from fossil resources and is a byproduct of petroleum with dielectric properties. It is processed and obtained by fractional distillation of crude petroleum oil. Oil is divided into four grades: aromatic, paraffinic, naphthenic and olefinic, where naphthenic is best suited for insulating and cooling transformers.

NOTE: *Mineral oil is flamable, and in the 1930s and 1940s, Askarel (a PCB-based insulating fluid) was used instead in mine transformers due to its low flammability and good dielectric properties. Subsequently, it turned out that the combustion products of Askarel are very toxic, and instead, high molecular weight hydrocarbons (HMHC) and silicon liquids began to be poured into fire-resistant distribution transformers that are installed indoors.*

In recent years, synthetic and natural (vegetable oil) esters, due to their high flash point and ignition temperature, have been increasingly used in low-voltage and high-voltage transformers. Synthetic esters are produced by reacting selected acids and alcohols, tailoring their properties to specific applications. Natural esters are obtained from oilseeds (soybeans, sunflowers, rapeseed, flax, olives, poppy seeds, etc.); their properties depend on the chemical process used to refine the base oil, as well as the declared and hidden additives. A promoting but controversial factor contributing to the popularity of esters in modern environmental conditions is their biodegradability (Fig. 1). Among the disadvantages of esters compared to other liquids are their initial cost, their dependence on stability, and varying properties based on the presence of additives, mixing effects, and other factors.

A century and a half have passed since the time of Thomson, but today and in the coming decades, insulation consisting of liquid and solid materials will predominate in large power transformers, with oil and cellulose remaining the main components in extra-high and ultra-high voltage transformers, although, throughout the ages, attempts have been made to use dry mediums such as SF_6.

One of the characteristic features of the modern development of transformer engineering is the transition to the optimization of their design. A review of the literature on power transformer optimization (161 sources) shows that, so far, optimization efforts have focused primarily on the parameters of the active part, excluding the insulation system. Since insulation cannot currently be determined by exact arithmetic values, it is considered a nonlinear optimization problem and a challenge for the future [2]. At the same time, optimizing the insulation would reduce the gaps inside the tank and thereby achieve a further reduction in the amount of steel and transformer oil. Instead of nonlinear optimi-

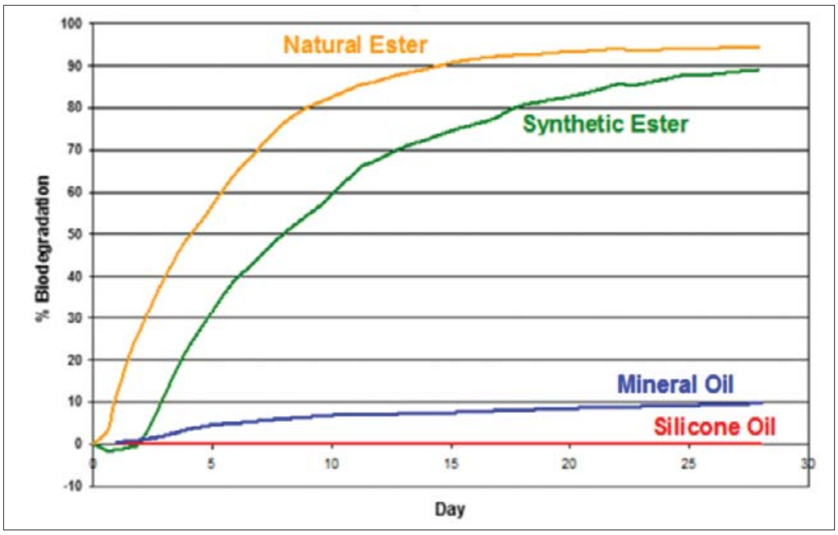


Figure 1. Biodegradability of various insulating fluids (Source: https://www.sciencedirect.com/science/article/abs/pii/S0378779622010033)

zation, statistical optimization can be applied, for which some groundwork already exists in practice. The breakdown voltage of a transformer's insulation structure is a nonuniform, statistically distributed value corresponding to the probability of failure. The probability of failure is a function of the applied electrical voltage, the distance and shape of the electrodes where the voltage is applied, and many other intrinsic parameters.

From a theoretical point of view, for a statistical approach to designing the insulation of power transformers, it is necessary to know the laws of distribution and coefficients of variation of electrical strength.

Transformer oil is the only part of transformer insulation for which standards exist that incorporate statistical methods to some extent

It is crucial to first collect the available data on transformer oil as it represents the most vulnerable and weakest link in the "oil-cellulose" system. We begin this work by estimating the scatter of the BDV of transformer oil. Historically, interest in the problem of BDV has shown two peaks: in the 1950s-70s and in the 21st century. The recent peak is attributed to the introduction of esters into practice, and their study is typically accompanied by a comparison with transformer oil.

Transformer oil is the only part of transformer insulation for which standards exist that incorporate statistical methods to some extent. These are standards that define the BDV at power frequency.

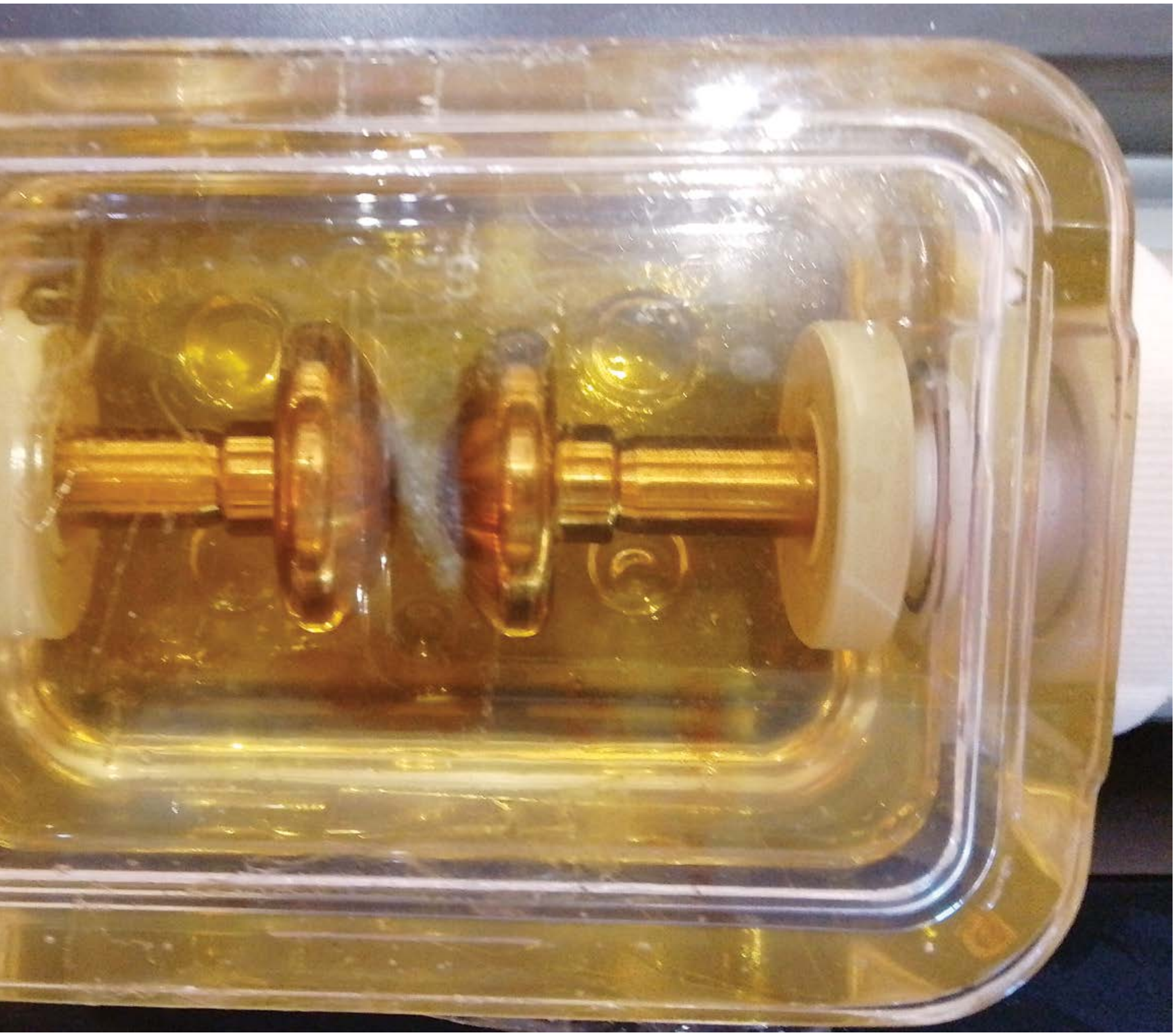
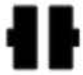


Table 1. The main differences between the ASTM and IEC standards acc. to MEGGER [3]

Standards		**ASTM D1816**	**ASTM D 877**		**IEC 60156**
			Procedure A	**Procedure B**	
Origin		USA	USA	USA	Europe
Electrodes	Shape				
	Gap size	2 mm or 1 mm*	2.54 mm	2.54 mm	2.5 mm
Oil sample stirring	Impeller	yes	not stirred	not stirred	optional
	Magnetic bead	no option			optional
Laboratory test temperature	Liquid	At ambient - must record	20 - 30 °C must record temperature as collected and when tested	20 - 30 °C must record temperature as collected and when tested	15 - 25 °C for referee tests
	Ambient	20 - 30 °C	Must record	Must record	Within 5 °C of oil sample
Outside test temperature	Liquid	At ambient - must record	Must record	Must record	15 - 25 °C
	Ambient	Referee tests 20 - 30 °C	Must record	Must record	Within 5 °C of oil sample
Test voltage	Rise rate	0.5 kV/s	3 kV/s	3 kV/s	2 kV/s
	Frequency	45 - 65	45 - 65	45 - 65	45 - 62
Breakdowns	Definition	<100 V	<100 V	<100 V	4 mA for 5 ms
	Number in sequence	5**	5*	1 - 5 different samples	6
	Time between breakdown	1 to 1.5 min	1 min	n/a	2 min
Test voltage switch off time following break-down	Normal (e.g. mineral oil)	Not specified	Not specified	Not specified	<10 ms
	Silicon oil	Not specified	Not specified	Not specified	<1 ms
Time between filling and start of test		3 - 5 min	2 - 3 min	2 - 3 min	2 min
Equivalent standards (adopted into)		None	None	None	BS EN 60156 CEI EN 60156 IRAM 2341 UNE EN 60156 FN EN 6056 SABE EN 60156 VDE0370 part 5 AS1767.2.1 PA SEV EN 60156 NRS 079-1* IS6729*
Notes on testing silicon oil		Can be used provided discharge energy in sample <20 mj		Can be used if modified in accord-ance with D2225 if procedure A cannot be used	OK if test instrument can comply with voltage switch off time requirements
Special conditions		* If breakdown does not occur at 2 mm, reduce gap to 1 mm ** Tests must be repeated if range of BD voltages recorded are more than 120% of mean with 1 mm electrode gap and 92% of mean with 2 mm electrode gap	*Tests must be repeated if range of BD voltages recorded are more than 92% of mean. If range of 10 BD voltages is more than 151% investigate why		Expected range of standard deviation/ mean ratio as a function of the mean provided as a chart
Comments		Test vessel requires cover or baffle to prevent air from contacting circulating oil	Used if any insoluble breakdown products in oil completely settle between breakdown tests	Used if any insoluble breakdown products do not settle between breakdown tests	*With some stand/stir timing differences. Test cell/vessel must be transparent. Reconditioned/reclaimed oil to BS148 is tested to IEC60156 following update in 2009.

Among the differences in the four main, we are primarily interested in the varying conditions for the scatter of mean BDV value

2. Standard methods for determining the BDV of transformer oil

There are many test standards, but the four most commonly used are the main ones. Two of them are from the USA (ASTM D877 and ASTM D1816, with the latest editions in 2013 and 2014, respectively), one is the Soviet GOST 6581-75 standard (last edition in 1988), and the international standard is the IEC 60156. The first edition of the IEC standard was issued in 1963, revised in 1995, and in 2018, and the third edition was released in 2018. A new version of IEC 60156 is expected to be published in the near future, which promises to be revolutionary in many aspects. In all these standards, the BDV of oil is determined in a semi-uniform electric field. The standards differ in test procedures and experimental settings. Table 1 provides a comparison between the ASTM and IEC standards. National standards in other countries are derived from these main ones. In practice, ASTM D-1816, IEC, and GOST are preferred over ASTM D877 because the electrode configuration in these tests is closer to real-world applications, and they are more sensitive to moisture than ASTM D877.

In many practical cases, the shorter Table 2, taken from [4]

Among the differences in the four main standards (electrode shape, gap size, number of consecutive breakdowns, etc.), we are primarily interested in the varying conditions for the scatter of mean BDV value that must be met for the test results to be considered valid. In ASTM D1816, tests must be repeated if the range of BD voltages recorded exceeds 120% of the mean for a 1 mm electrode gap and 92% of the mean for a 2 mm electrode gap. In ASTM D877 tests must be repeated if the range of BD voltages recorded are more than 92% of the mean value. If the range of 10 BD voltages exceeds 151%, further investigation is required to determine the cause.

In GOST, the limit value for the coefficient of variation (CV%) is set at 20%. If the CV% exceeds 20, the test cell is refilled with a portion of the liquid from the same vessel, and after mixing, six more samples are tested. To calculate the CV%, all 12 samples are taken into account. If the CV% again exceeds 20, the quality of the oil is considered unsatisfactory.

Table 2. Comparison of ASTM and IEC standards acc. to Suhaimi et al.

Standards	ASTM D1816	ASTM D877	IEC 60156
Description	Most widely used standard in North America	Older standard	Various countries have adopted it
Shape of electrodes			
Electrode material	Polished Brass	Brass	Brass/ Bronze/ Stainless Steel
Size of electrodes	Diameter: 36 mm	Diameter: 25.4 mm Thickness: ≥ 3.18 mm Sharp edges radius: ≤ 0.254 mm	Diameter: 12.5 mm – 13 mm
Electrode gap	2 mm/ 1 mm	2.54 mm	2.5 mm
Voltage rate of rising	0.5 kV/s	3 kV/s	2 kV/s
Time between breakdowns	1 to 1.5 minutes	1 minute	2 minutes
Stirring	Continuous with impeller (200-300 rpm)	None	Optional with a magnetic bar
Breakdown value	Mean of 5 measurements		

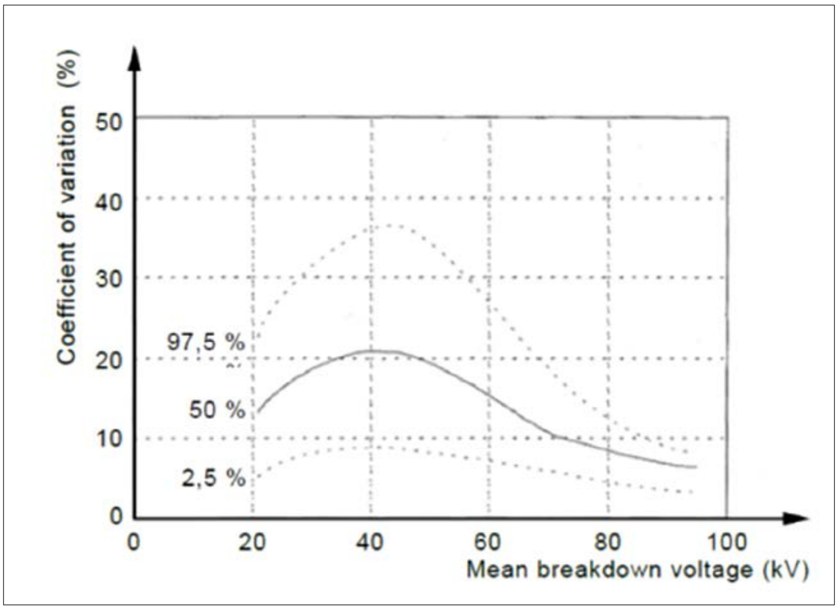


Figure 2. Graphical representation of coefficient of variation versus mean BDV of transformer oil acc. to IEC [6]. The solid line shows the distribution of the coefficient of variation as a function of the mean breakdown value. The dotted lines indicate the expected 2.5% to 97.5% range of values for the standard deviation (SD)-to-mean ratio as a function of the mean BDV.

The conditioning process refers to a gradual increase in breakdown strength observed with an increase in the number of measurements

In the current IEC version, the expected range of the standard deviation-to-mean ratio as a function of the mean is provided in a chart (Fig. 2).

Note that in Fig. 2, the peak of the 50% value of CV% is slightly above 20 and is located at a voltage slightly above 40 kV then, with increasing voltage, the scatter begins to decrease, and at voltages above 90 kV, CV% is less than 7.5.

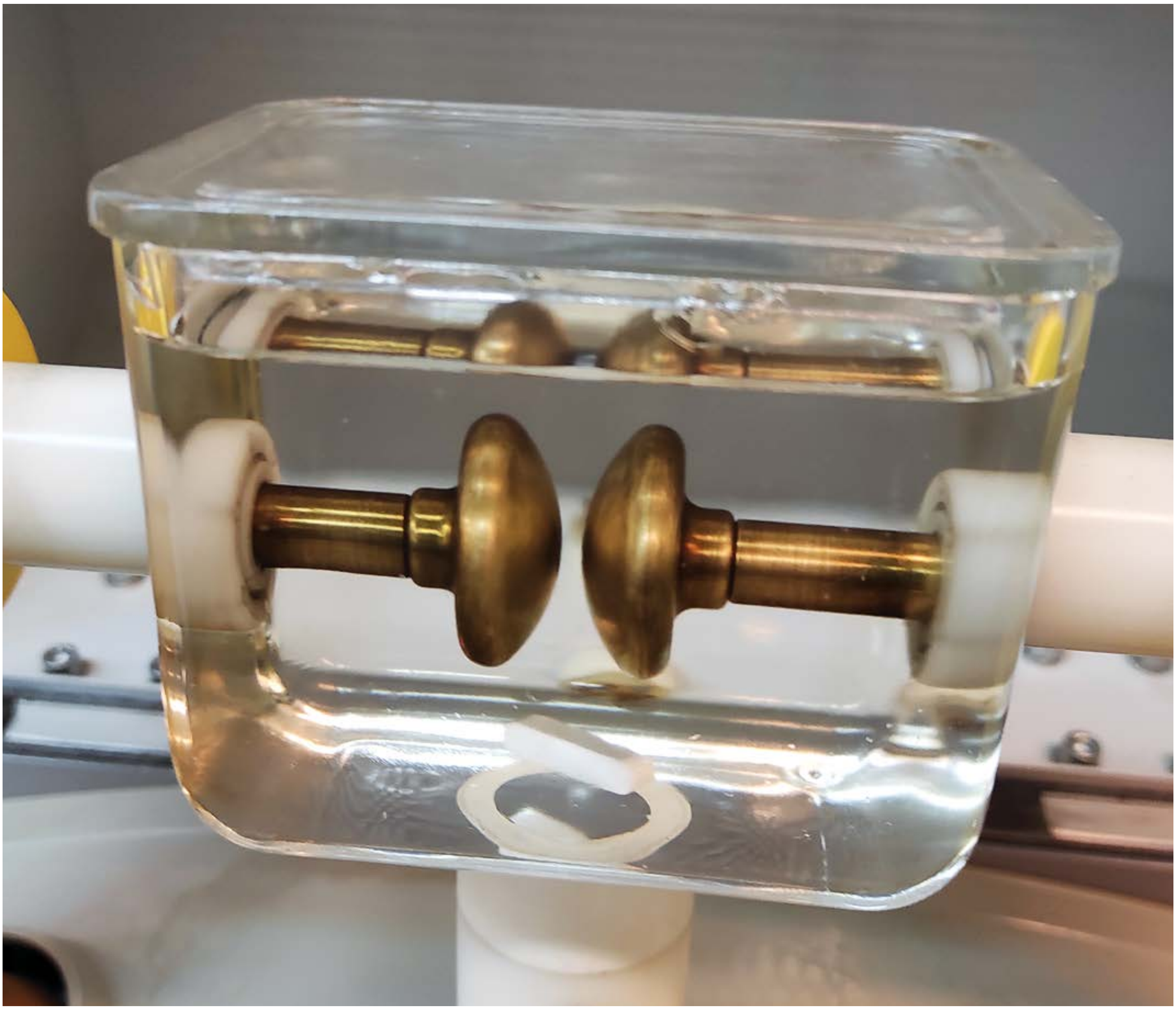
The latest version of the 2018 IEC 60156 standard recommends mixing the oil, which reduces the scatter of BDV [5]. This reduction is more noticeable when the BDV is lower due to the presence of contaminants (moisture, particles, sludge) in the fluid. Mixing efficiency is higher when the liquid flow between the electrodes is directed upward, which makes it easier to remove air bubbles.

3. Conditioning effect

The conditioning process refers to a gradual increase in breakdown strength observed with an increase in the number of measurements. In a number of cases, the "burnout" of impurities is noticeable already during the standard BDV test, along with a corresponding increase in BDV (Fig. 3). Therefore, reducing the spread of BDV values is sometimes achieved by increasing the number of tests in IEC 60156 to at least 25 [6].

However, as shown in [7, 8], 25 breakdowns may not be sufficient to "burnout" impurities.

Koch et al. (University of Stuttgart) measured the breakdown voltage of clean and contaminated oil (with varying humidity and acid levels) in a series of 400 tests [7]. They used a dielectric test system, Baur DTA 100 E, and obtained a very high scatter in the results (Fig. 4). The values in the first 40-100 breakdown tests were significantly lower than the values reached later. The authors attribute this



to the presence of particles in the oil and on the electrodes.

The authors of [8] determined the BDV with an even larger number of breakdowns (up to 8000). They used a cell containing 250 ml of oil, equipped with a spherical electrode system with a diameter of 12.5 mm and a separation distance of 2.5 mm. The oil temperature was equal to the ambient temperature. The spintermeter was programmed for oil breakdowns with a rest period of 30 seconds. As seen in Fig. 5, the BDV was initially much lower than the standard value of 70 kV. It then increased to 400 breakdowns, then decreased to 50 kV at 1000 breakdowns, before increasing again and stabilizing around 72 kV. Please note that the value required by the standard was only reached after 2000 tests.

Unfortunately, we didn't find source data in the literature from which it would be possible to calculate the BDV scatter and its change during the conditioning process.

Fig. 4 and 5 clearly show that impurities in the oil are the main factor determining the BDV value. Therefore, the study of impurities, including the determination of CV% and measures to combat them, seems inevitable on the path to improving the design of transformer insulation, and we will consider it in a separate article.

A list of factors affecting the breakdown strength of insulating oil and a detailed review of publications on this topic as of 2020 is given in the works of Danikas [9, 10, 11]. The total number of references in these reviews is 134 publications, but only some of them contain information on the scatter of BDV, from which the CV% can be determined. These and more recent works found on the Internet with useful information for calculating CV% will be discussed in the following parts of the article in relation to the influencing factors.

The standard BDV test of transformer oil at industrial frequency quickly provides beneficial information, but it needs to be improved

The values in the first 40-100 breakdown tests by Koch and al. were significantly lower than the values reached later

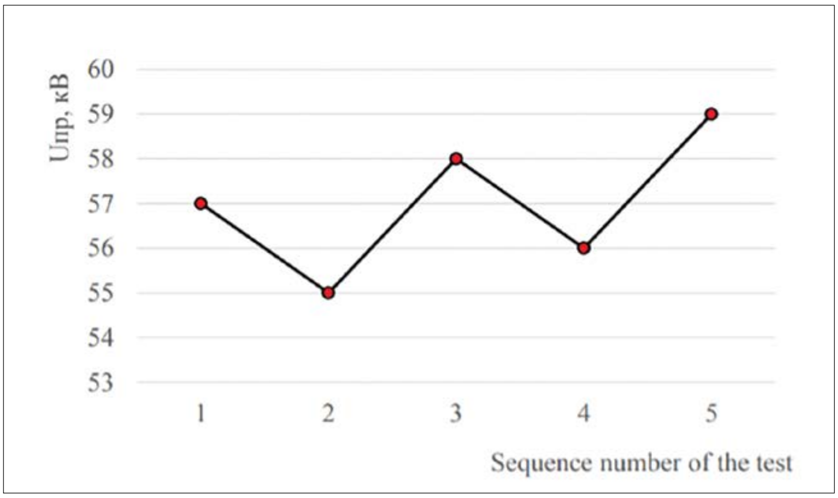


Figure 3. BDV of oil of transformer 63 MVA 110 kV (Source: O.Z. Toirov, Tashkent, Uzbekistan)

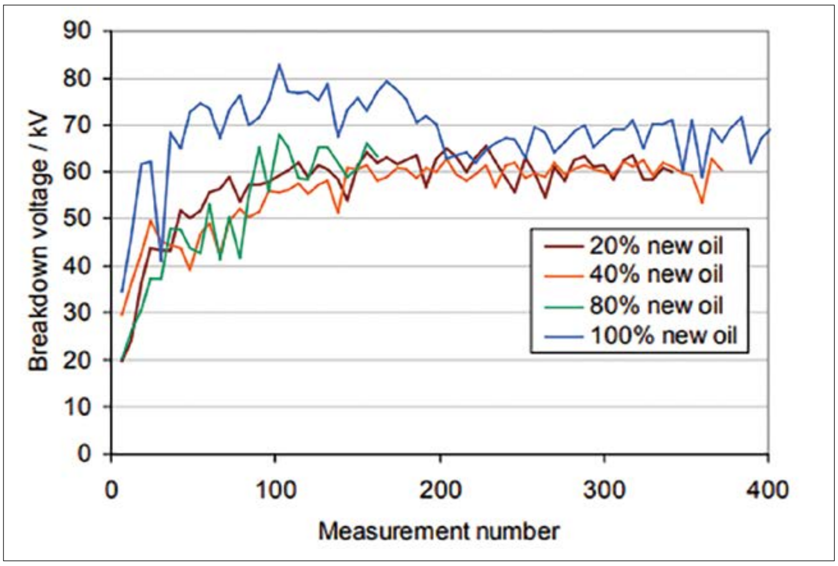


Figure 4. BDV depending on the number of breakdowns acc. to Koch et al.

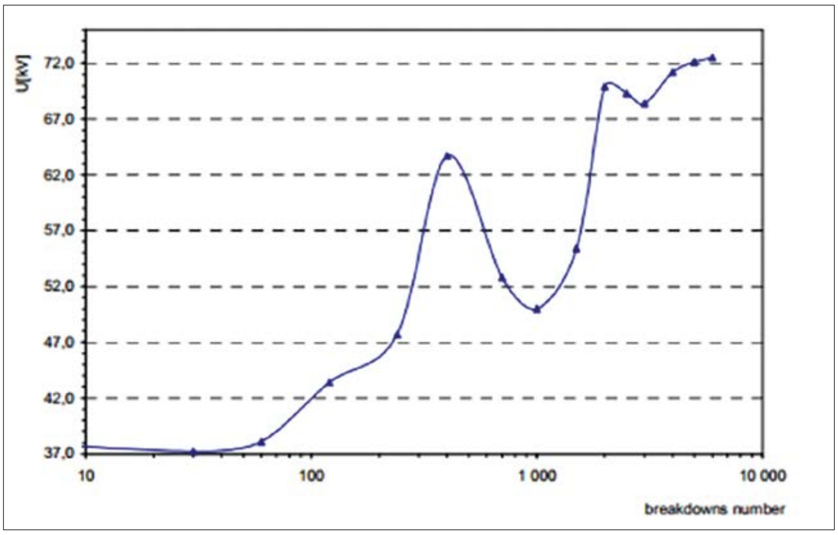


Figure 5. BDV depending on the number of breakdowns acc. to Benamar et al.

Conclusions to Part I

1. A review of more than two hundred publications showed that in practice, there is already a certain groundwork (dozens of publications) for studying the statistical scatter of the BDV of modern mineral insulating oil, a necessary step towards optimizing the internal insulation of power transformers

2. It is obvious and indisputable that it is impossible to do without knowledge of the BDV of insulating oil when designing power transformers.

3. The standard BDV test of transformer oil at industrial frequency quickly provides beneficial information, but it needs to be improved, which is beyond the scope of this article.

4. The use of BDV to assess the condition of a transformer during operation also requires separate consideration.

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Vitaly Gurin graduated from Kharkov Polytechnic Institute (1962) and graduate school at the Leningrad Polytechnic Institute. Candidate of technical sciences in the Soviet scientific system (1970). For 30 years he tested transformers up to 1.150 kV at ZTZ, including the largest one of that time in Europe, and statistically analysed the test results. For over 25 years he was the Executive Director of Trafoservis Joint-Stock Company in Sofia (the diagnosis, repair and modernisation in the operating conditions of transformers 20 – 750 kV). He has authored about 150 publications in Russian and Bulgarian, and is the main co-author of GOST 21023.

Marius Grisaru holds an MSc in Electro-Analytical Chemistry from the Israel Institute of Technology. He has almost 30 years of intense experience in almost all transformer oil test chains, from planning, sampling, and diagnosis to recommendations and treatments, mainly in Israel but also in other parts of the world. He is responsible for establishing test strategies and procedures and creating acceptance criteria for insulating liquids and materials based on current standardization and field experience. In addition, he trains and educates electrical staff on insulating matrix issues from a chemical point of view. He is an active member of relevant Working Groups of IEC, CIGRE, and a former member of ASTM. He is also the author and co-author of many papers, CIGRE brochures, and presentations at prestigious international conferences on insulation oil tests, focusing on DGA, analytical chemistry of insulating oil, and advantageous maintenance policy for oil and new transformers.