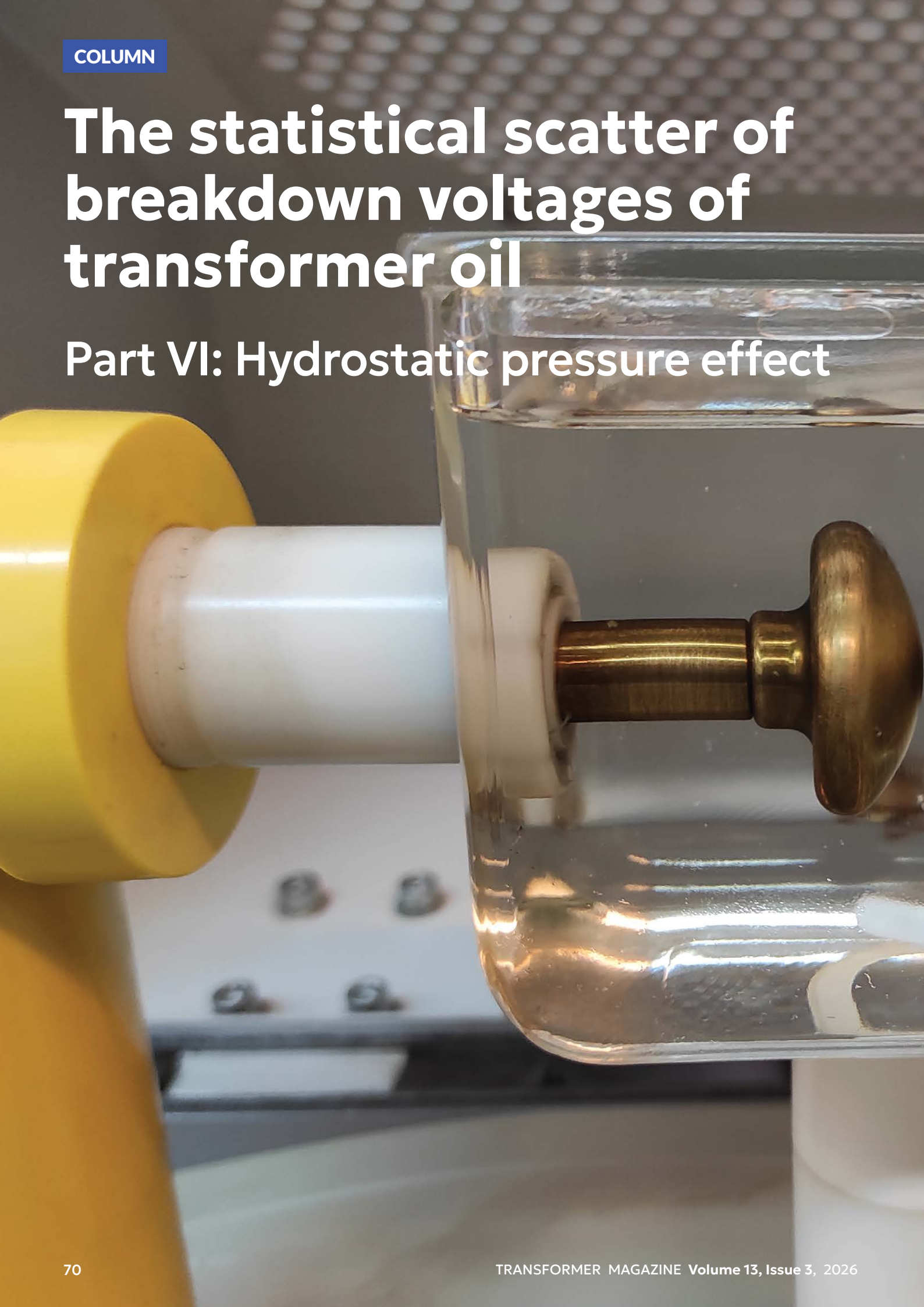
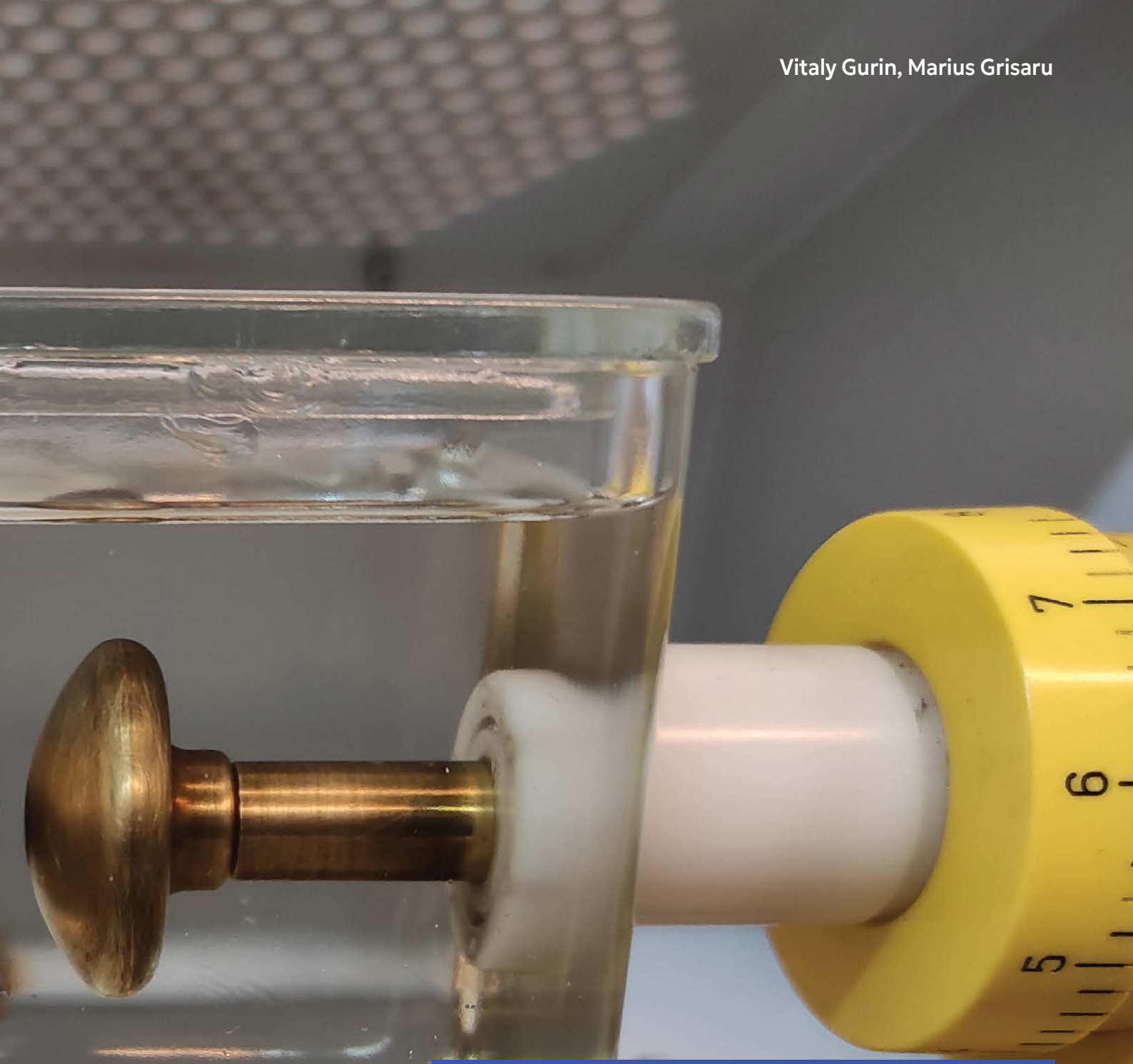
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The statistical scatter of breakdown voltages of transformer oil

Part VI: Hydrostatic pressure effect





ABSTRACT

Part VI of the article explores the limited studies focusing on how hydrostatic pressure impacts the breakdown of transformer oil and other liquid dielectrics. Preliminary analysis suggests that the relationship between breakdown voltage (BDV) and the coefficient of variation (CV%) with pressure can be represented using a semi-logarithmic plot, applicable to various test voltages used in power transformers and pulse power supply systems. However, additional research is required to substantiate these findings. The observed patterns are likely associated with the formation of gas bubbles and streamers during the pre-breakdown phases.

KEYWORDS:

breakdown voltage, bubble, coefficients of variation, electric strength, pressure effects, pulsed power systems, transformer oil

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Advances in modern high-speed electro-optical technologies are now facilitating faster progress toward developing a comprehensive theory of liquid breakdown

Introduction

In a power transformer, the oil pressure typically ranges between 15 to 35 kPa during regular operation at sea level, where atmospheric pressure is considered standard at 1.013 bar (101.3 kPa or 760 torr). These fluctuations are attributed to changes in oil temperature: as the transformer operates, the oil heats up and expands, leading to increased pressure within the tank. Conversely, during cooling, the oil contracts, causing a drop in pressure. Transformers with a capacity of 1 MVA or higher are equipped with protective devices designed to safeguard the tank in case the internal pressure surges above 50 kPa.

The relationship between breakdown voltage (BDV) and oil pressure becomes particularly significant for transformers operating under conditions where atmospheric pressure deviates from the standard. These include:

a) High-altitude locations, where atmospheric pressure is lower than sea level average.

b) Offshore applications, such as oil production platforms or wind power installations, as well as underwater environments like data processing centers or subsea electronics, where atmospheric pressure exceeds the standard.

Mineral oil is commonly utilized in power transformers and other high-voltage electrical equipment, as well as in pulsed power systems, including applications like plasma generation. Its role in these systems has driven increased interdisciplinary research over the past two decades to better understand the breakdown mechanisms in dielectric liquids. Advances in modern high-speed electro-optical technologies are now facilitating faster progress toward developing a comprehensive theory of liquid breakdown.

This discussion aims to examine existing data on the effects of pressure on the breakdown voltage (BDV) of mineral oil across these applications.

Standard test voltages in accordance with IEC

Half a century ago, Bell identified pressure as a key factor influencing the breakdown strength of dielectric liquids. He noted that increasing hydrostatic pressure typically enhances the strength, although this trend may not apply universally, particularly in the case of degassed liquids [1].

Research conducted by Badent and colleagues from the University of Karlsruhe in Germany focused on the breakdown behavior of Shell Diala D oil. Their study examined the oil saturated with nitrogen under alternating current conditions, as well as at standard impulse 1.2/50 µs [2].

Fig. 1 illustrates the relationship between breakdown voltage and pressure in a weakly non-uniform field, as defined by VDE 0370. It is evident that for all gap widths ranging from 0.5 to 1.25 mm, the breakdown voltage rises consistently with increasing pressure. The authors have approximated these behaviors with nearly linear trends.

In a non-uniform field with a gap width of 7 mm and pressures of 0.1, 0.5, 1.0 and 1.5 MPa, the authors provide the initial data, by which CV% was calculated. In Fig. 2, it is clear that the average BDV value also increases with increasing pressure, and CV% has a clear downward trend.

A pivotal study on the impact of pressure on BDV under standard test conditions was conducted a decade later at the University of Stuttgart [3]. This research examined two types of mineral oils: the newly developed Nynas Nytro 3000 and the service-aged Shell K 6 SX from 1964, using three distinct experimental setups across varying pressure ranges. For oil pressures between 1 and 21 bar, as well as 1 to 100 bar, specialized measurement cells were designed. Additionally, the automated testing system Baur DTA 100E, equipped with a modified test cell, was utilized to analyze pressures ranging from 0.1 to 1.5 bar.

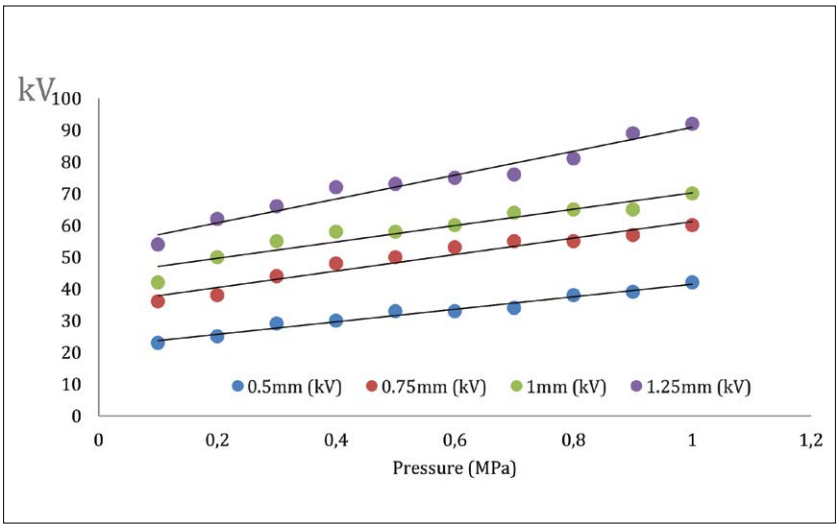


Figure 1. AC voltage stress vs. pressure, uniform field by Badent et al., 1994 [2]

Half a century ago, Bell identified pressure as a key factor influencing the breakdown strength of dielectric liquids

The study findings indicated that rising oil pressure leads to an increase in breakdown voltage until it approaches an asymptotic maximum. Conversely, under-inflation contributes to a reduction in breakdown voltage. Fig. 3 provides a clearer illustration of the low-pressure range due to its logarithmically scaled x-axis. The lower graph in this figure portrays the variation of CV% as calculated during our analysis.

In Fig. 3, within the pressure range of 0.1 to 100 bar, the BDV rises by a factor of 2.4 (134/55), while the CV% shows a more pronounced decrease, dropping by a factor of 3.6 (21.8/6). The potential physical mechanisms underlying the observed BDV-pressure relationship are analyzed in the subsequent discussion.

Types of voltages used in pulsed power systems and liquid breakdown studies

Generating plasmas with specific properties, such as density, temperature, or composition, requires high-power impulses of varying shapes, including rectangular, triangular, and sinusoidal forms. These impulses are characterized by short durations ranging from nanoseconds to seconds and can feature both low amplitudes (hundreds of volts) and high amplitudes (kilovolts, kiloamperes). In studying liquid breakdown phenomena, a variety of voltage types—alternating current (AC), direct current (DC), and impulse voltages—are employed. These impulses can have rise times lasting tens of nanoseconds and durations extending up to several thousand microseconds.

The extensive body of literature addressing the specified topics contains minimal information on the dependence of the oil BDV on pressure. Furthermore, no sources were identified that discuss the coefficient of variation within this context.

In a study by authors [4] affiliated with the Center for Pulsed Power and Power Electronics, Electrical Engineering Department at Texas Tech University in the USA, pre-breakdown processes in Univolt 61 transformer oil under DC conditions with highly non-uniform fields were examined. Fig. 4 from their research highlights a distinct dependence of the BDV on polarity.

Rising oil pressure leads to an increase in breakdown voltage until it approaches an asymptotic maximum

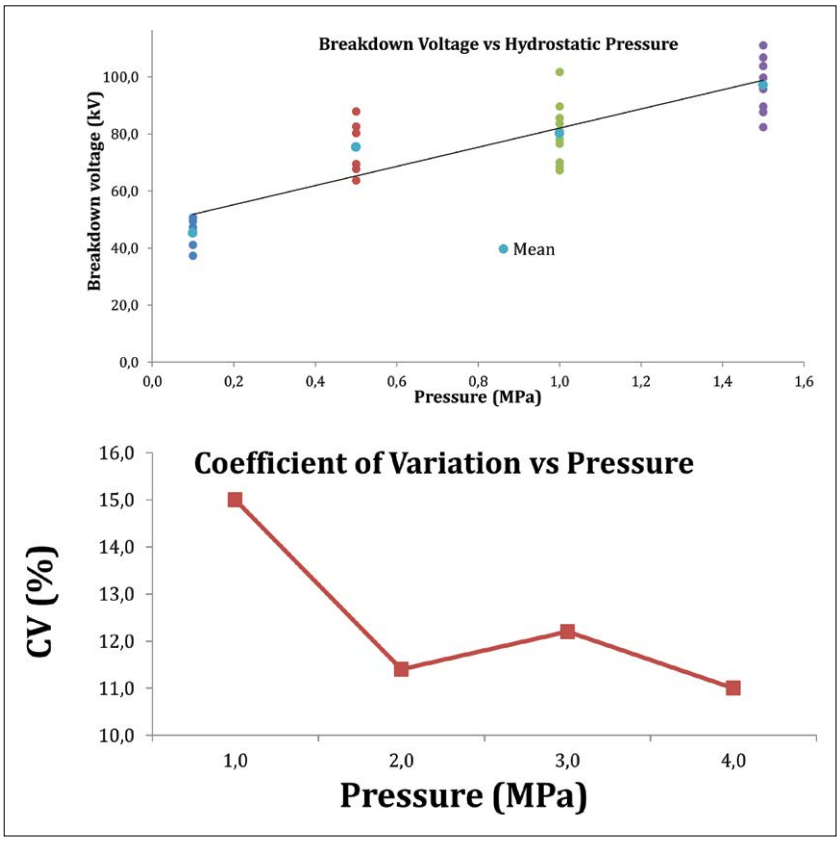


Figure 2. AV voltage stress, point-to-plane configurations with a gap width of 7 mm by Badent et al. [2]

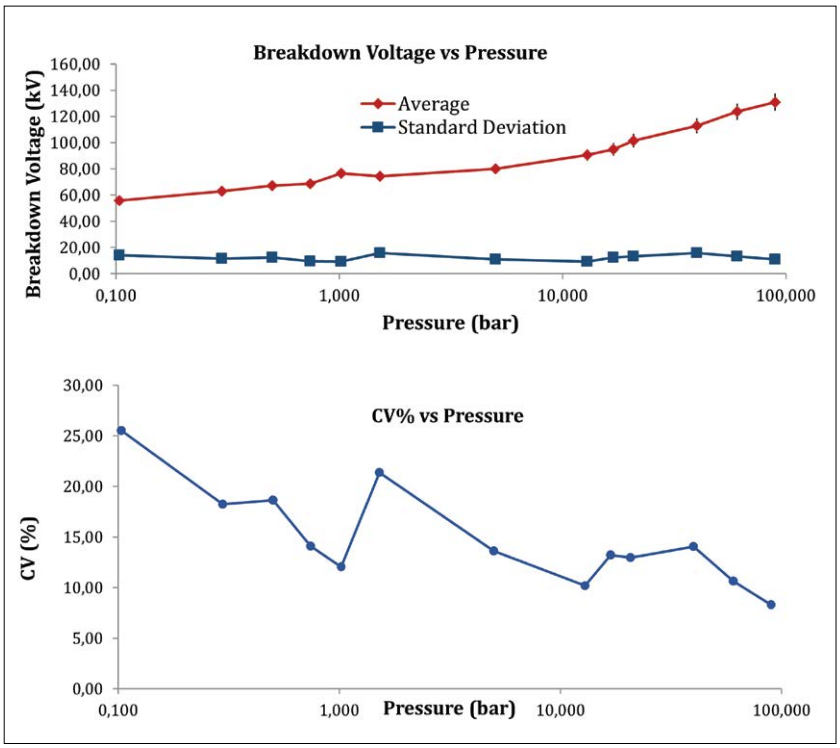


Figure 3. BDV and CV% of insulation oil as a function of pressure by Koch et al., 2007 [3]

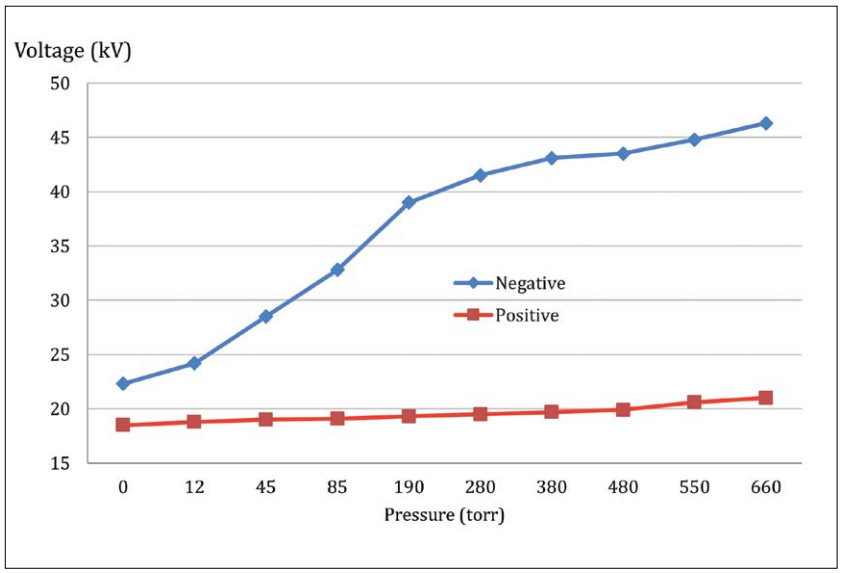


Figure 4. Breakdown versus pressure curves for positive and negative polarity. Point/plane geometry. Gap = 2:5 mm. Open symbols = positive. Closed symbols = negative [4]

The breakdown voltage for negative needle-to-plane configurations shows a significant sensitivity to pressure changes

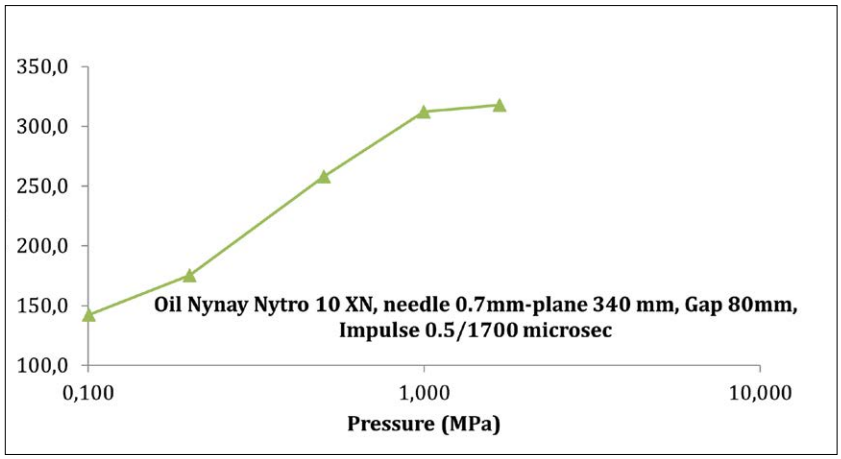


Figure 5. BDV of transformer oil as a function of pressure (based on Linhjell et al., 2019) [5]

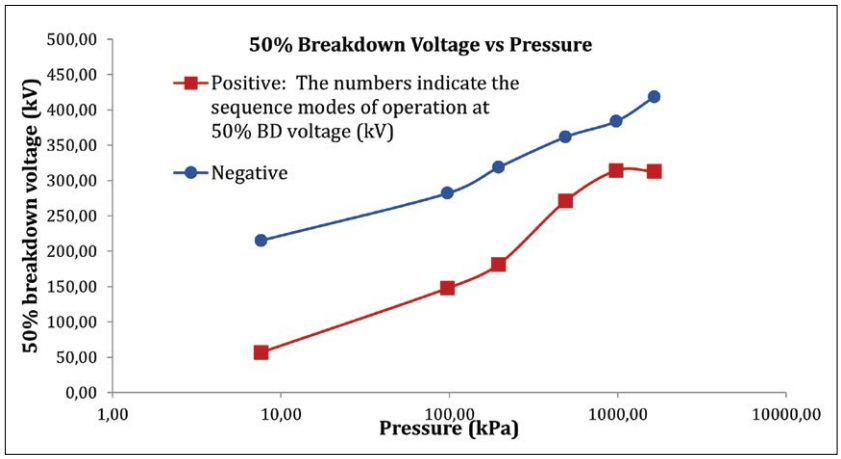


Figure 6. 50% breakdown voltage vs. pressure by Linhjell et al., 2020 [5]

The breakdown voltage for negative needle-to-plane configurations shows a significant sensitivity to pressure changes, with a 50% reduction observed as the hydrostatic pressure drops from atmospheric levels to several hundred mtorr. In contrast, under positive polarity, the breakdown voltage experiences a much smaller decrease of approximately 10%.

The studies conducted by Linhjell et al. [5, 6] explored the effects of 0.5/1700 µs impulses of both polarities. In the first study [5], the researchers examined the development of positive streamers in transformer oil within a non-uniform field, under pressures ranging from 0.1 to 1.7 MPa. Their finadings demonstrated that as pressure increases, the breakdown voltage rises correspondingly. This trend is illustrated in Fig. 5, which was created based on the data from Fig. 3 in the original study.

The curve depicted in Fig. 5 exhibits a behavior that closely aligns with a logarithmic trend. As detailed in the second study [6], the logarithmic rise in BDV corresponding to increasing pressure is a defining characteristic observed for both polarities (Fig. 6).

Physics BDV versus pressure

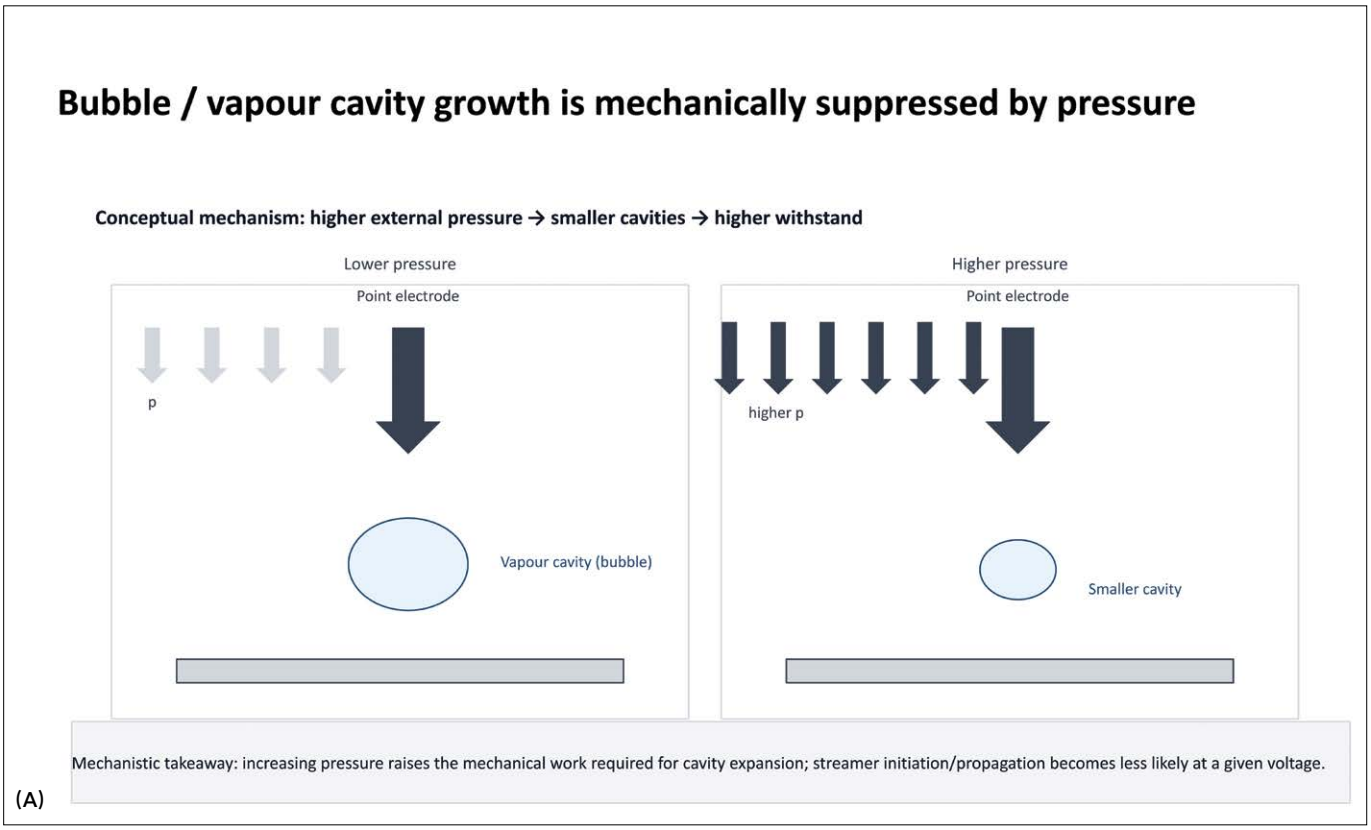
The relationship between BDV and pressure, as observed by various researchers, can be effectively explained using the bubble theory of liquid breakdown. In technically pure liquids, impurities—including solid particles or/and dissolved gases—act as initiation points for charge generation under the influence of an electric field. This process leads to the formation of microscopic gas bubbles, predominantly composed of hydrogen. These bubbles exhibit lower breakdown strength compared to the liquid itself, making them more conductive to electricity.

As the electric field becomes stronger, the generation of gas increases, causing these bubbles to expand. This expansion eventually results in the development of streamers—localized channels of ionized gas that traverse the liquid between electrodes. Such streamers create conductive paths for current flow, triggering a chain reaction or avalanche process that culminates in complete breakdown of the liquid.

Pressure plays a crucial role in influencing the formation of bubbles, streamers, and the breakdown voltage (BDV). At a certain critical pressure level, bubble formation begins to exert a notable impact. Below this threshold, the conduction current rises sharply due to an increase in both the quantity and size of bubbles. As pressure increases, it suppresses the generation and growth of bubbles, while simultaneously enhancing the electrical strength of the gas within these bubbles, consistent with Paschen's law.

The influence of pressure on streamer formation and development, however, follows a more intricate mechanism that largely depends on the specific properties of the liquid. Typically, streamers become shorter as pressure increases, and at sufficiently high pressures, they may completely disappear. These pressure-driven changes in bubble and streamer behavior often result in a higher BDV.

Figure 7 summarizes two practical conceptual consequences of pressure and liquid-condition effects on breakdown. In aged oils, oxidation products can reduce



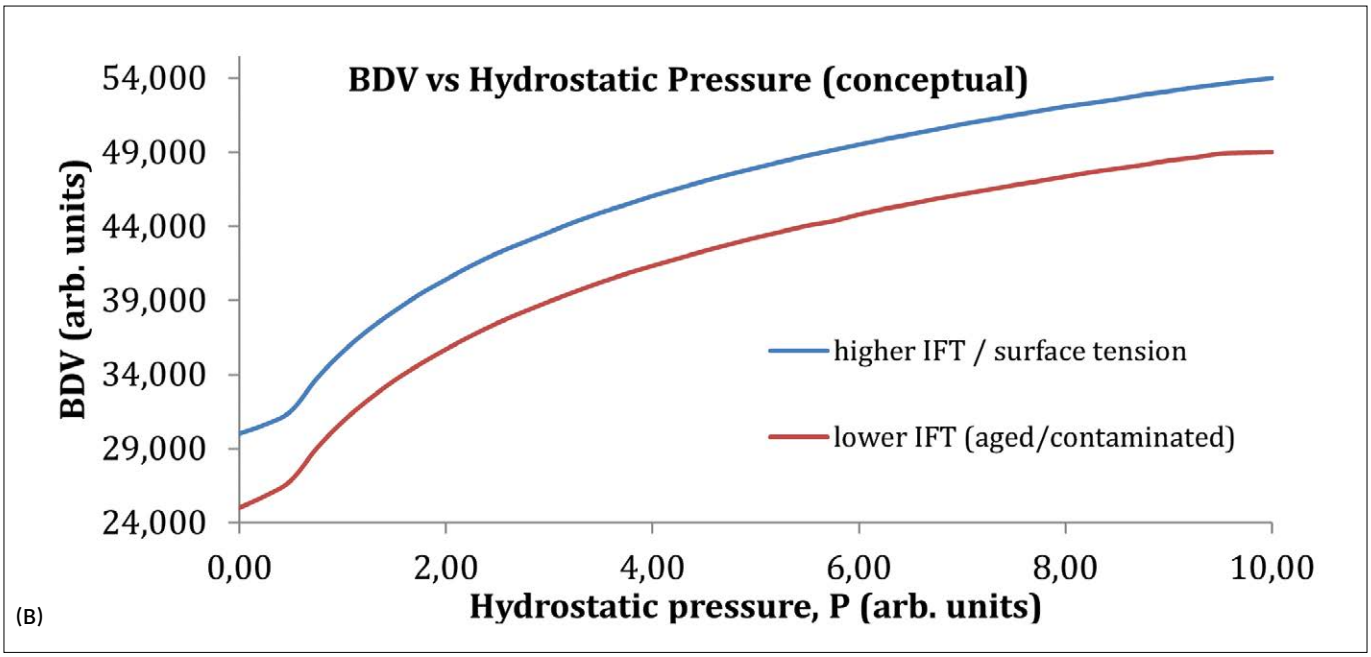


Figure 7. (A) Conceptual bubble suppression by hydrostatic pressure (mechanisms discussed in [3], [6], [10]); (B) conceptual: lower IFT shifts the pressure–BDV curve downward (grounded in [10], [11])

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Generating plasmas with specific properties, such as density, temperature, or composition, requires high-power impulses of varying shapes, including rectangular, triangular, and sinusoidal forms

interfacial tension and promote bubble evolution, so the pressure–BDV curve is expected to shift downward for the same pressure level [11].

NOTE: High pressure can sometimes facilitate the formation of streamers, highlighting the importance of ongoing research into the breakdown mechanisms of dielectric liquids.

Practical consequences for power transformer design and maintenance

The literature indicates that pressure influences both the mean BDV and its statistical dispersion (CV%). The implications below translate the laboratory findings (mineral oil, impulse, long gaps) and the broader liquid-dielectric evidence into transformer-engineering actions [2]-[13].

Additional evidence from the references reinforces and extends the conclusions: (i) impulse BDV and time-lag components exhibit polarity-dependent pressure sensitivity (Wang et al.) [8]; (ii) the pressure effect is time-dependent and interacts with voltage duration and rise rate (Kao & McMath; Koo) [9], [10]; (iii) in pressurised-flowing synthetic hydrocarbons (PAO), pressure increases the delay-to-breakdown and reduces breakdown scatter, supporting a kinetic-control interpretation [7]; (iv) the same cavity/streamer logic applies to ester liquids, but moisture state must be treated via relative saturation and sealing philosophy, not ppm alone [12], [13]; and (v) extended pressure/temperature studies (Imbert thesis) support the need to treat pressure, temperature, and conductivity/chemistry as coupled variables [15].

Conclusions

Hydrostatic pressure emerges from this review as a controllable parameter that systematically increases the breakdown voltage of mineral insulating liquids while simultaneously reducing statistical scatter, and this behaviour is well approximated by semilogarithmic BDV–pressure trends over wide ranges of voltage types, geometries, and pressures. The evidence is consistent with bubble and streamerbased breakdown physics: elevated pressure suppresses bubble nucleation and growth, shortens or extinguishes streamers, and thereby shifts both the mean BDV upward and



the CV% downward, whereas low interfacial tension, ageing products, and reduced ambient pressure all act in the opposite direction and effectively lower the pressure–BDV curve for inservice transformer oils.

From a practical standpoint, temperaturedriven pressure fluctuations inside operating transformers can locally reduce the instantaneous BDV, increasing the probability of bubbleassisted initiation during cold night periods or rapid load changes, especially in aged, low IFT oils. In parallel, published impulse and DC studies indicate that pressure not only modifies the 50% breakdown level and scatter but also affects the time lag between voltage application (or front arrival) and breakdown inception, reinforcing the view that pressure acts on the underlying bubble and streamer kinetics rather than merely shifting a static threshold.

These findings suggest that future dielectricliquid and transformer test standards should explicitly require the reporting, and, where feasible, control, of the testcell pressure for BDV measurements, since this parameter measurably influences mean BDV, CV%, and timelag characteristics and is essential for comparing results between laboratories, voltages, and liquids. For transformer engineering

Pressure plays a crucial role in influencing the formation of bubbles, streamers, and the breakdown voltage (BDV)



Hydrostatic pressure emerges from this review as a controllable parameter that systematically increases the breakdown voltage of mineral insulating liquids while simultaneously reducing statistical scatter

Theme	Consequence	Recommended practice
Thermal cycling / night cooling	Internal pressure dips can reduce impulse margin and increase bubble-assisted initiation probability.	Trend internal pressure (where available) and correlate with DGA and BDV; check sealing integrity and relief settings [8], [9].
Oil ageing / low IFT	Lower IFT can shift the pressure–BDV curve downward and potentially increase sensitivity to pressure dips.	Monitor IFT alongside acidity and DDF; prioritize treatment when IFT collapses or when multiple indicators deteriorate [3], [10], [11].
Altitude / site pressure	Lower ambient pressure at high altitude increases bubble risk and reduces baseline headspace pressure.	Record site altitude; ensure pressure management philosophy (sealed/N_2 cushion/conservator) is adequate; review alarm thresholds [14].
Ester-filled transformers	Higher water solubility and different gas behaviour change “dry/half-dry” interpretation and bubble kinetics.	Use relative saturation (Aw/RS%) rather than ppm alone; maintain sealing/oxygen control; tailor treatment to liquid and paper condition [12], [13].
Testing protocol and comparability	BDV mean and CV% depend on handling, settling, degassing history, and test pressure.	Standardize sampling/handling, degassing, temperature, and any applied pressure; report CV% with BDV where possible [3], [7], [10].

practice, the combined pressure temperature chemistry perspective argues for integrating pressure trending with conventional diagnostics (DGA, IFT, moisture, acidity and BDV with CV%), so that design choices, sitealtitude corrections, and maintenance decisions can more reliably manage bubble risk and preserve insulation strength under real operating conditions

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Author



Vitaly Gurin graduated from Kharkov Polytechnic Institute (1962) and graduated from 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.