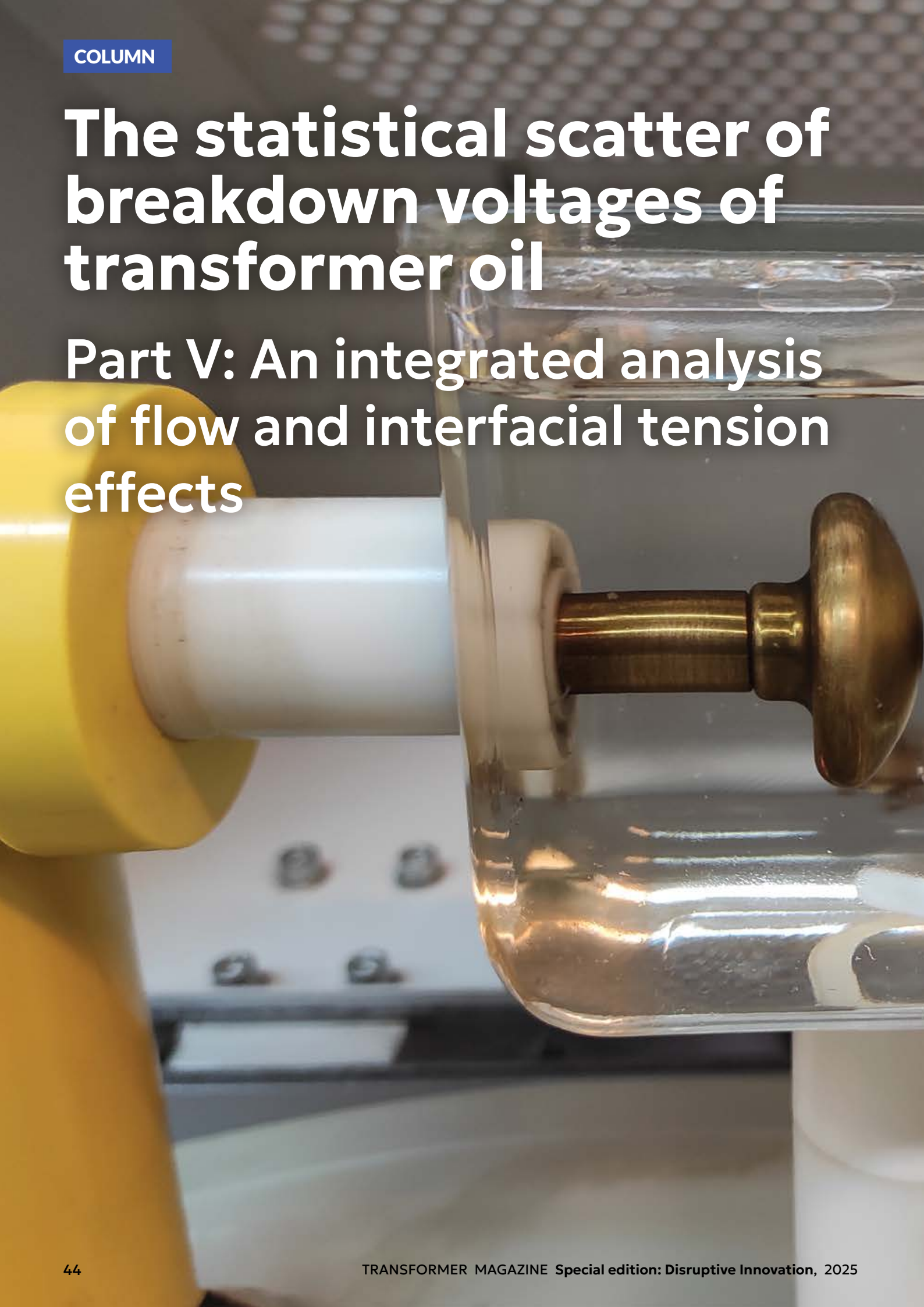
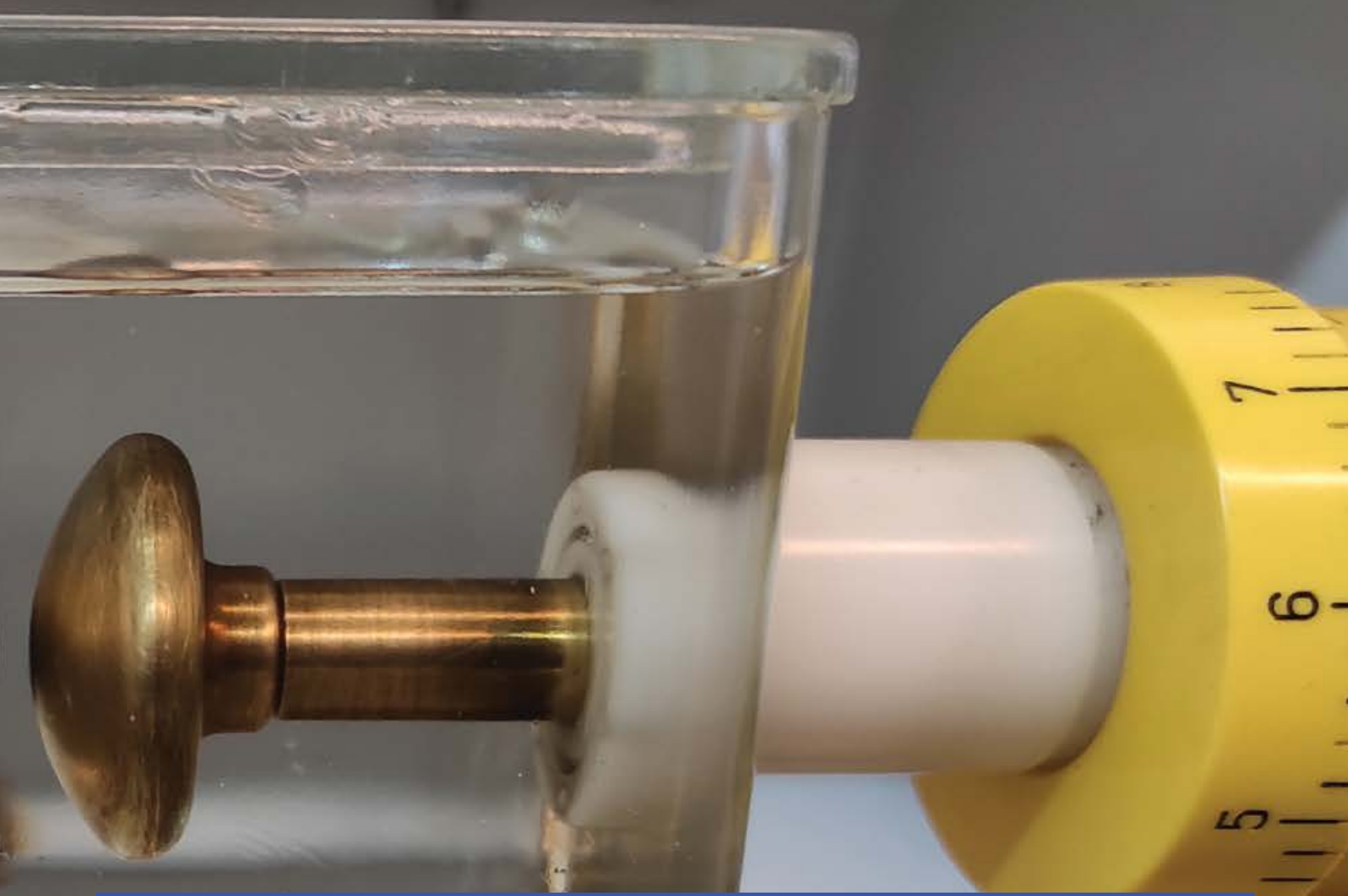


The statistical scatter of breakdown voltages of transformer oil

Part V: An integrated analysis of flow and interfacial tension effects





ABSTRACT

The fifth part of the column presents an integrated analysis of how breakdown voltage (BDV) values in transformer oil are affected by dynamic conditions, including flow, stirring, and fluid type. Drawing from multiple experimental studies, the analysis highlights the significance of oil movement in both laboratory testing and actual transformer service. A central theme is the critical role of **interfacial tension** (IFT), which governs the stability of bubbles and contaminants under electrical and mechanical stress. Particular emphasis is placed on the behavior of low-IFT fluids, such as ester-based or aged oils, which tend to form and retain microbubbles under agitation, leading to significant BDV depression. The statistical nature of dielectric breakdown is also addressed, showing how flow conditions alter the distribution type and variability of test results. In the context of modern transformer design, where directed oil flow and compact insulation geometries prevail, understanding these dependencies is essential. The study concludes with diagnostic and design recommendations, emphasizing that the selection of stirred or static BDV testing must be context-specific—tailored to the insulating liquid, its IFT, moisture content, aging level, and operational regime. It advocates for more nuanced testing protocols and calls for industry standards to evolve accordingly.

KEYWORDS:

BDV testing, breakdown voltage, bubble formation, contaminants, dielectric strength, esters, flow dynamics, interfacial tension, moisture, oil flow effects, stirring, streaming electrification, transformer oil

Breakdown voltage is a fundamental parameter for assessing oil dielectric integrity, making BDV testing a cornerstone of quality assurance and in-service diagnostics

1. Introduction

Transformer oil fulfills the dual functions of insulation and cooling in high-voltage electrical equipment. Its breakdown voltage (BDV) is a fundamental parameter for assessing its dielectric integrity, making BDV testing a cornerstone of quality assurance and in-service diagnostics. However, a critical and often overlooked aspect of this testing is the decision of whether to perform it with or without oil stirring.

In most factory and field settings, BDV is measured with stirring to simulate the in-service conditions of large power transformers where oil is in constant motion due to natural convection or forced circulation. This motion influences the distribution of impurities, the behavior of gas bubbles, and electro-

static charge patterns, all of which affect breakdown performance [1]. Nevertheless, the decision to stir should not be automatic. It must be a contextual choice dependent on the purpose of the test, the type of electrical equipment, and the properties of the insulating fluid itself.

For instance, stirred testing is appropriate for evaluating the in-service performance of an energized transformer. In contrast, static (unstirred) testing may be more suitable for assessing the intrinsic quality of new oil or the condition of oil in offline components like bushings and tap changers, where localized contaminants or bubbles pose the primary risk [2]. The effect of flow is further complicated by the oil's **interfacial tension (IFT)**, which governs the stability of gas bubbles and contami-

nants. Low-IFT fluids, such as aged mineral oil or natural esters, are particularly susceptible to performance degradation under flow [3].

This paper provides an integrated analysis of the relationship between oil flow, IFT, and dielectric behavior. By synthesizing theoretical principles and experimental evidence, it establishes a rationale for selecting the appropriate BDV test configuration and underscores the need for context-sensitive diagnostic approaches in transformer engineering.

2. Fundamental mechanisms of dielectric breakdown in insulating liquids

Dielectric breakdown in transformer oil is an inherently statistical process governed by the presence of "weak links", which are localized regions where impurities like moisture droplets, solid particles, or gas bubbles reduce the fluid's ability to withstand electrical stress [4]. The stability of these weak links, particularly bubbles and water droplets, is fundamentally controlled by the liquid's interfacial tension. A low IFT reduces the energy required to create

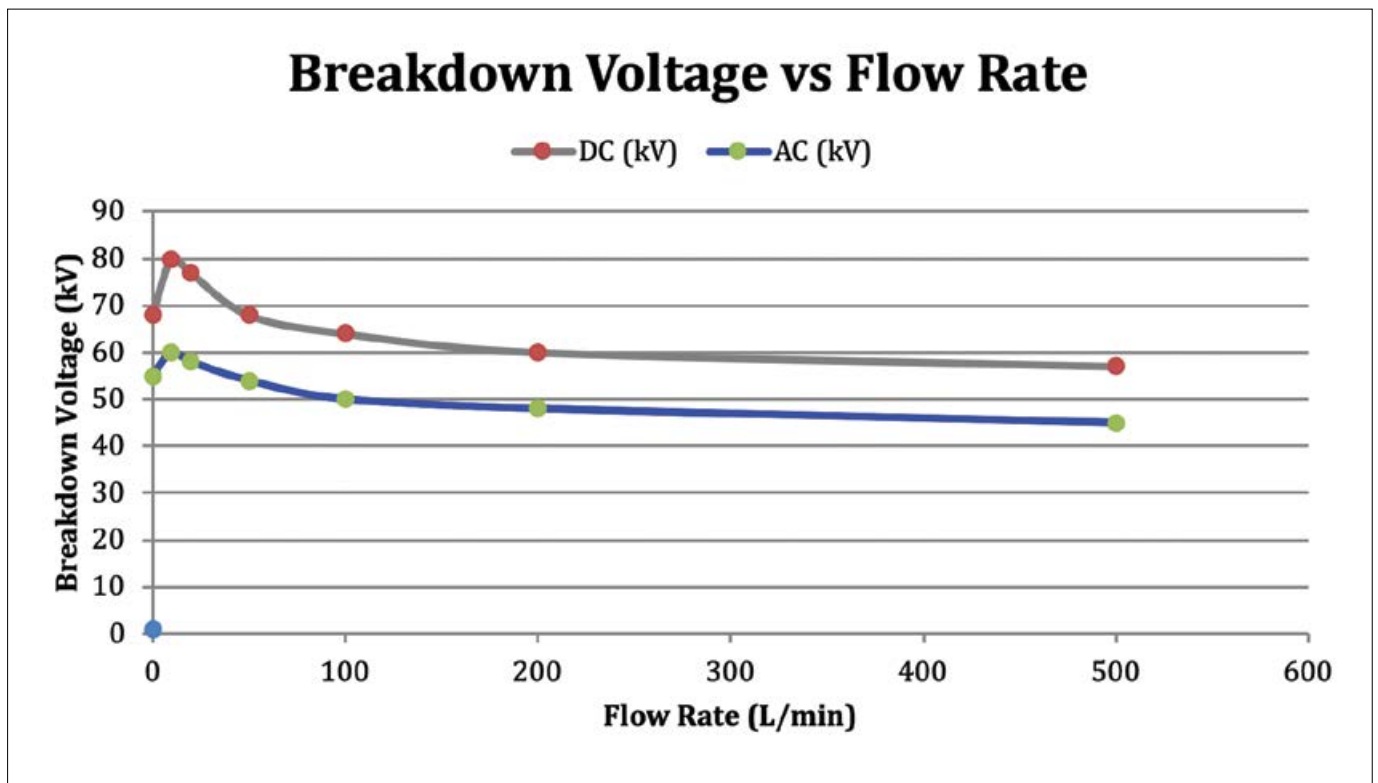


Figure 1. Flow effect on breakdown voltage of transformer oil by Ikeda et al. [1]

or deform an interface, making such weak links more susceptible to elongation and disruption under an electric field, which can initiate the breakdown cascade [5]. The probability of encountering a critical weak link increases with the volume of stressed oil and the area of the electrodes, a phenomenon known as the “volume effect” or “electrode area effect” [6].

The dynamics of these weak links under an electric field determine the statistical nature of the breakdown. In static (unstirred) oil, impurities can accumulate, making the breakdown event dependent on the “first defect encountered”. This typically results in BDV values that follow a Gumbel (extreme-value) distribution, characterized by a higher probability of early failures [7].

In contrast, stirring or flowing oil homogenizes the fluid, dispersing weak links more evenly. A single dominant defect no longer governs breakdown but becomes a volume-averaged event. Consequently, BDV measurements in stirred oil tend to follow a Gaussian (normal) distribution with a lower coefficient of variation (CV%). This shift from a defect-limited to a volume-averaged breakdown mechanism is a key reason why stirring can increase both the mean BDV and the repeatability of the test. The Weibull distribution can also be used to model this behavior, where the shape parameter (β) indicates the failure type: $\beta < 1$ suggests initial (defect-driven) breakdown, while $\beta \approx 1$ indicates random (volume-averaged) failure [1].

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3. The influence of fluid dynamics on breakdown voltage

Experimental evidence has consistently shown that oil motion has a profound and complex effect on its dielectric strength.

3.1. Effect of flow velocity

The relationship between flow velocity and BDV is nonlinear. Pioneering work by Ikeda et al. [1] demonstrated an “arch curve” behavior for AC and DC voltages. As shown in their findings, BDV initially increases with velocity, peaking

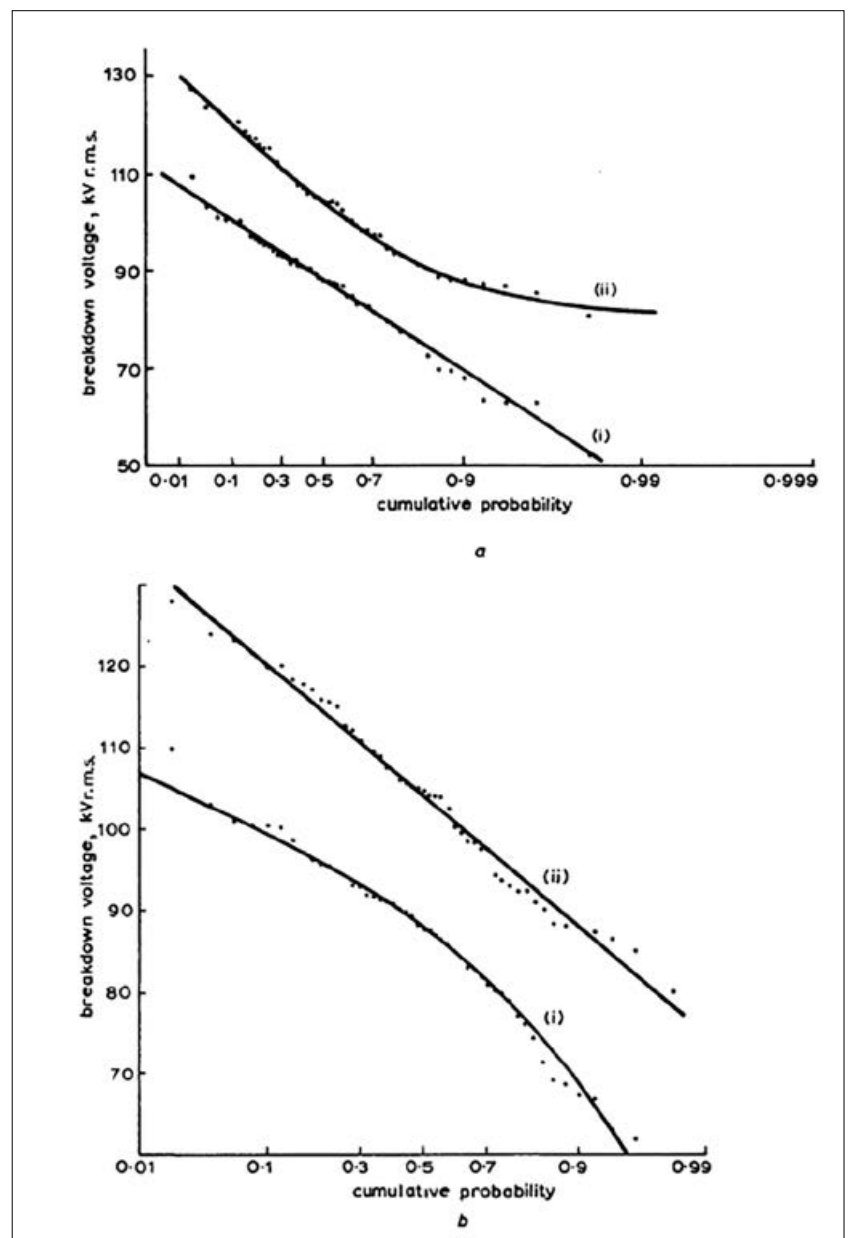


Figure 2. Cumulative probability for stationary- and circulating-oil samples by Nelson et al. [7]

Table 1. Distribution indices for stationary and circulating oil by Nelson et al. [7]

	Power frequency		1/50 μ s impulse		Gaussian	Extremal
	Stationary	Circulating	Stationary	Circulating		
Mean stress, kV/mm	7.3	8.9	18.9	19.6		
Standard deviation, kV/mm	1.2	1.1	2.3	3.2		
Coefficient variation %	16.5	12.2	12.4	16.4		
Skew	-1.38	0.09	-0.64	-0.74	0	-1.29
Kurtosis	5.97	2.32	2.92	3.53	3	5.4

Research by Qin et al. [3] demonstrated that the presence of air bubbles can reduce the BDV of transformer oil by nearly 50%

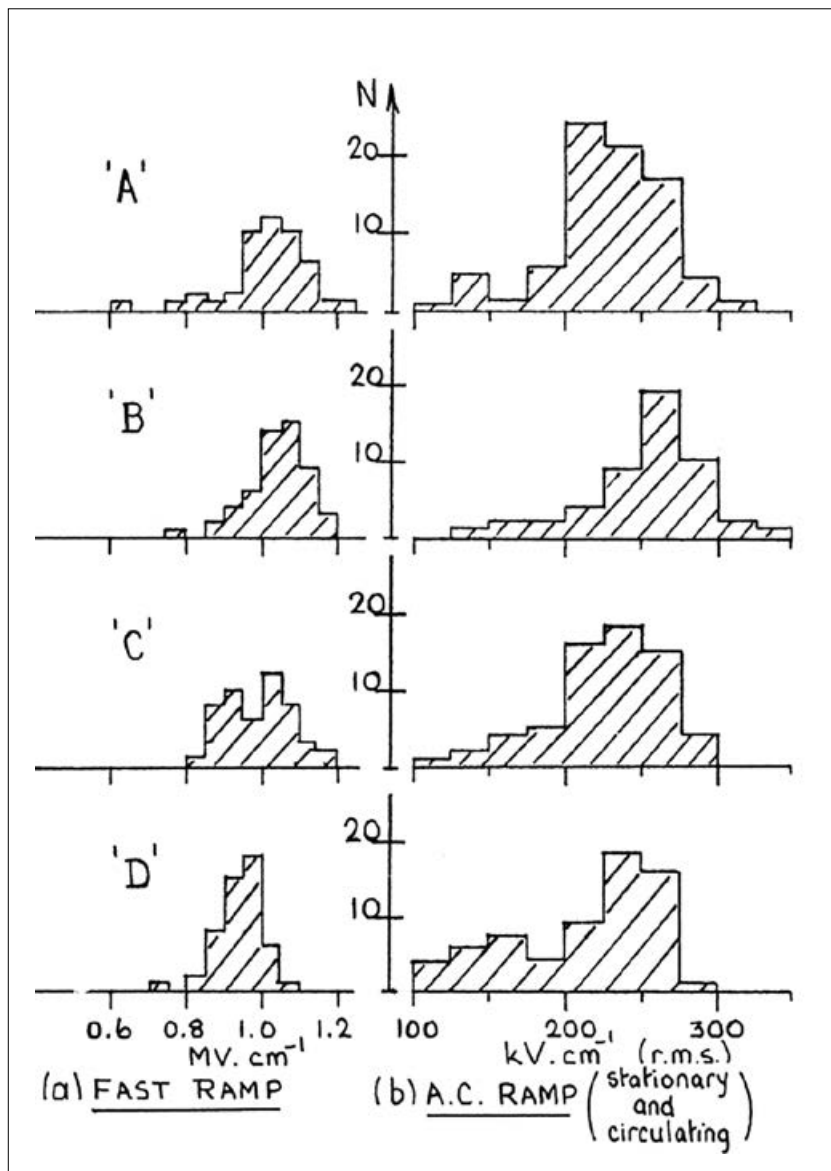


Figure 3. Distributions of breakdown strengths for four electrode areas by Bell [8]

at around 3–5 cm/s, as the gentle flow flushes contaminants from the high-field zone. However, as velocity increases further (e.g., >100 cm/s), turbulence, bubble elongation, and streaming electrification become dominant, causing the BDV to decline, often below the value for stationary oil.

This establishes a critical velocity range where flow is beneficial. The established relationship is: **BDV of slow-moving oil > BDV of stationary oil > BDV of fast-moving oil**. This effect is not observed under impulse conditions, where the short duration of the voltage application prevents significant particle or bubble movement [1].

3.2. Statistical distribution and contaminant behavior

Nelson et al. [7] provided further insight by investigating the statistical distribution of breakdown events. Their work confirmed that circulating oil at a modest velocity (3 mm/s) not only increased the mean AC breakdown strength but also transformed the statistical distribution from Gumbel (for stationary oil) to Gaussian (for circulating oil). This change highlights a fundamental shift in the breakdown mechanism, from being defect-limited to volume-averaged.

Bell's research [8] also examined the effects of electrode area and gap spacing, confirming their significant impact on BDV. While his findings on the statistical distribution under circulation differed slightly from Nelson's, he reinforced the principle that external physical factors, including oil motion, are critical and

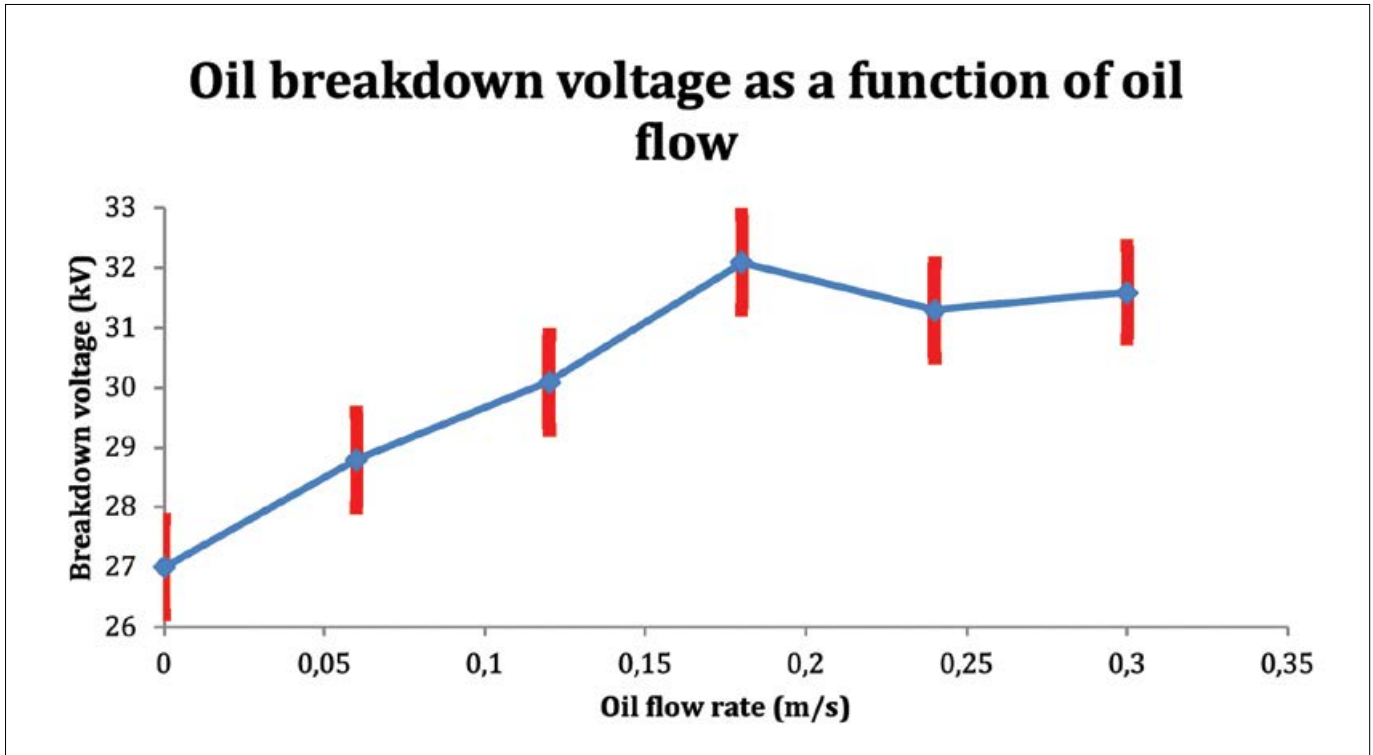


Figure 4. Oil breakdown voltage as a function of oil flow by Zhang et al. [9]

must be specified when reporting BDV values.

3.3. Bubble dynamics and gas inclusions

Gas bubbles are one of the most detrimental types of contaminants. Research by Qin et al. [3] demonstrated that the presence of air bubbles can reduce the BDV of transformer oil by nearly 50%. However, their study also showed that oil circulation can partially mitigate this effect. An increase in flow rate from 0 to

Huh et al. [10] showed that electrostatically charged oil consistently exhibits a lower BDV than uncharged oil, regardless of flow velocity

0.18 m/s improved the BDV of bubble-contaminated oil by 15.4%, as the flow disrupts the alignment and elongation of bubbles in the electric field, preventing them from forming a conductive path.

The mechanism involves the deformation and growth of bubbles under AC stress, which accumulate charge and initiate partial discharges, eventually leading to a full breakdown [4].

Table 2. Breakdown fields of mineral oil under 50/60 Hz AC voltage

Electrode configuration	Gap separation (mm)	Oil status	Breakdown field (kV/mm)
Sphere-plate	12	Stationary, without bubbles	4.16
		Stationary, with air bubbles	2.11
Hemisphere-hemisphere	8	Stationary, without bubbles	13.25
		Stationary, with air bubbles	9.25
Sphere-sphere	2.5	Stationary, without bubbles	>14.5
Plate-plate	10	Stationary, with bubbles	2.73
		Flowing, with bubbles	2.94–3.1

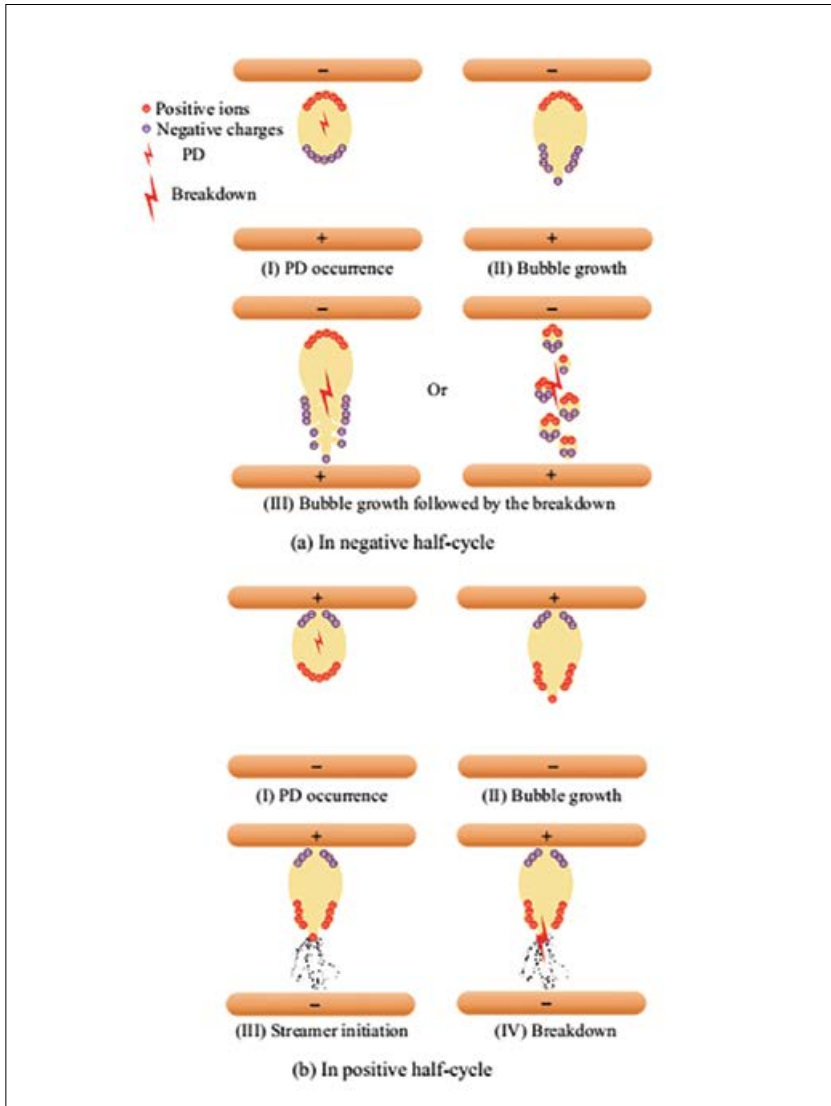


Figure 5. Illustration showing bubble dynamics before the breakdown by Zhang et al. [9]

3.4. Charging effects

In addition to mechanical effects, oil flow can introduce electrostatic phenomena. Streaming electrification, caused by friction between the oil and insulating surfaces, can lead to charge accumulation. Huh et al. [10] showed that electrostatically charged oil consistently exhibits a lower BDV than uncharged oil, regardless of flow velocity. This is because the excess free charges can more easily trigger electron avalanches. The negative impact of charging is exacerbated at higher velocities and temperatures, making it a critical consideration for large, high-flow transformers.

3.5. The critical role of interfacial tension (IFT)

The impact of flow on BDV is significantly modulated by the oil's interfacial tension.

IFT represents the energy required to form an interface between the oil and another phase (like water or gas) and is the primary force resisting the deformation of bubbles and droplets. The balance between the disruptive electrical stress and the stabilizing force of IFT is described by the dimensionless **Weber number (We)** [5]:

$$We = \frac{2r\epsilon_{oil}\epsilon_0 E_0^2}{\sigma}$$

where r is the droplet/bubble radius, E_0 is the electric field strength, ϵ_0 represents permittivity, and σ is the interfacial tension. This relationship mathematically shows that as IFT (σ) decreases, the Weber number increases, indicating a greater tendency for a bubble or droplet to deform, elongate, and ultimately initiate a breakdown.

The lower the IFT, the more sensitive the oil's BDV becomes to the effects of flow, as the motion can continuously supply the high-field region with breakdown-initiating bubbles

Fluids with **high IFT**, such as fresh mineral oil (typically >40 mN/m), have strong cohesive forces that resist bubble formation and entrainment. In contrast, fluids with **low IFT**, such as aged mineral oil or natural esters (often <25 mN/m), have weaker cohesive forces. Under the mechanical agitation of flow or stirring, these low-IFT fluids are much more prone to forming stable microbubbles and emulsions that become entrained in the fluid [3, 5]. These suspended bubbles act as persistent weak links, dramatically increasing the risk of a dielectric failure. Therefore, the lower the IFT, the more sensitive the oil's BDV becomes to the effects of flow, as the motion can continuously supply the high-field region with breakdown-initiating bubbles [4].

4. Comparative analysis of different insulating liquids

The response of an insulating liquid to flow is highly dependent on its chemical nature and resulting IFT.

- **Mineral oils:** Fresh mineral oils possess a high IFT (>40 mN/m) and generally show a predictable and positive response to moderate flow, with increased BDV and reduced variability. For these oils, stirred testing is often a reliable representation of in-service conditions. However, as mineral oil ages, oxidation byproducts lower its IFT, increasing its susceptibility to flow-induced BDV degradation.
- **Synthetic esters:** These fluids have an intermediate IFT (typically 25–35 mN/m) and exhibit a more variable response to flow. While fresh synthetic esters may benefit from stirring, aged or wet esters can show fluctuating

BDV readings as flow interacts with microbubbles or emulsified water. The decision to stir must be made on a case-by-case basis.

- **Natural esters:** With a very low IFT (typically 15–25 mN/m), natural esters are highly susceptible to stable bubble entrainment [5]. Stirring or flow often leads to a *decrease* in BDV, sometimes by as much as 30–40%. The agitation can mask the true dielectric weakness by keeping bubbles suspended.

Stirring or flow often leads to a decrease in BDV, sometimes by as much as 30–40%

Further complexity in the relationship between IFT and BDV is highlighted in studies comparing fresh mineral oils and vegetable oil esters. Research by Baruah et al. on Pongamia oil methyl ester (POME) showed that while the ester's IFT was less than half that of mineral oil (21.2 mN/m vs. 47 mN/m), its AC breakdown voltage was more than double (82 kV vs. 35 kV) [11]. This apparent contradiction is explained by the different moisture saturation capabilities of the fluids. Due to their polar molecular structure, esters can hold significantly more water in a dissolved state, where it is less dielectrically harmful. In contrast, mineral oil has a very low saturation point, meaning excess moisture readily forms free water droplets that act as potent weak links, severely depressing the BDV [11]. This underscores that while low IFT increases susceptibility to contaminants, other properties like moisture tolerance can dominate the breakdown performance in fresh, well-processed fluids.

5. Implications for transformer design and reliability

The relationship between oil flow, IFT, and dielectric strength has direct consequences for the design of modern power transformers. The trend towards more compact designs with reduced oil volumes and directed-flow cooling

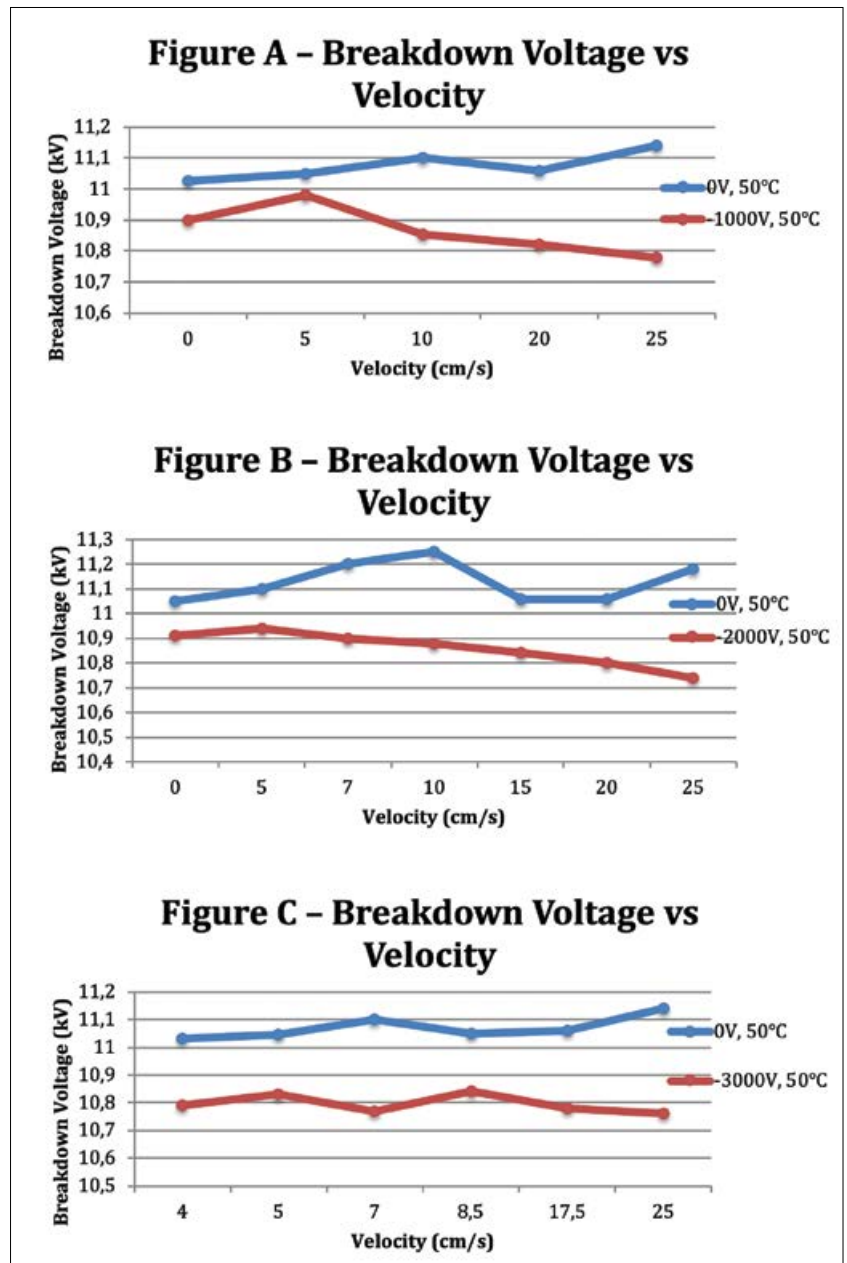


Figure 6. AC breakdown voltage vs charged oil by Huh et al. [10]

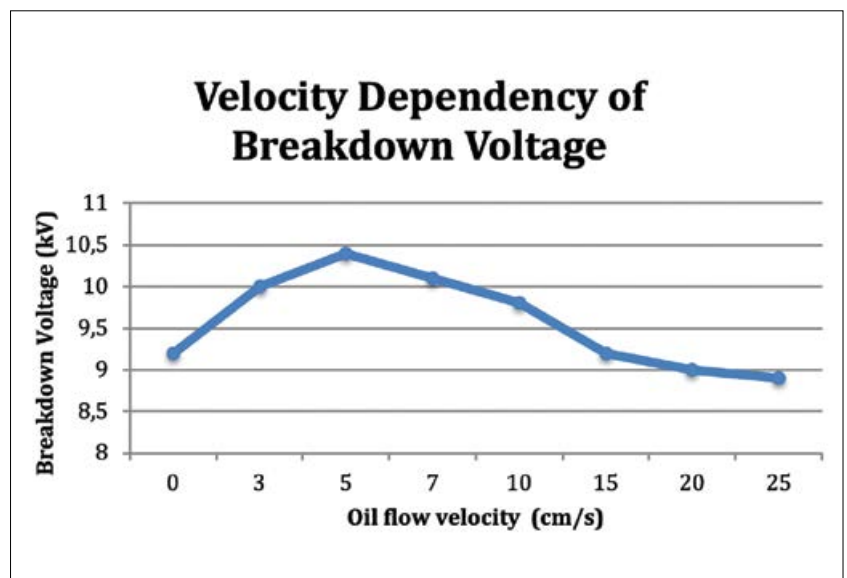


Figure 7. General effect of oil velocity on uncharged oil by Huh et al. [10]

Table 3. Recommended BDV test modes and flow response by liquid type [11]

Characteristic	Mineral Oil (MO)	Pongamia Pinnata Oil (PPO)	Pongamia Oil Methyl Ester (POME)	Natural Ester FR3™
Density, kg/m³	0.825	0.93	0.9	0.91
Kinematic viscosity at 27 °C, cSt	11.25	32	14	59
Interfacial tension at 27 °C, mN/m	47	20	21.2	20.6
DDF at 90 °C	0.0089	0.008	0.0045	0.00863
Water content, ppm	25	1080	586	53.4
AC breakdown voltage, kV	35	89	82	83

An oil with a high static BDV may be unsuitable if its dielectric strength degrades significantly at the flow rates present in the cooling ducts, especially if its IFT is low

systems increases the volumetric electrical stress on the insulation. In these high-power-density units, oil is an active dielectric component whose performance is intrinsically linked to its flow dynamics.

Design engineers must consider the stability of the insulating liquid under operational flow conditions. An oil with a high static BDV may be unsuitable if its dielectric strength degrades significantly at the flow rates present in the cooling ducts, especially if its IFT is low. This requires an **alignment** between laboratory testing protocols and in-service flow regimes. Failure to account for flow-dependent weaknesses can lead to insufficient safety margins and

an underestimated risk of failure, particularly during transient overvoltage events.

6. Recommendations for BDV testing protocols

The choice between stirred and unstirred BDV testing is a critical diagnostic decision that must be guided by the test objective, the equipment's function, and the fluid's properties. A one-size-fits-all approach risks either overestimating the dielectric strength (by masking defects with stirring) or being overly conservative.

The following table summarizes the key considerations for selecting the appropriate test configuration.

Based on this analysis, the following recommendations are proposed:

- 1. Specify the method:** BDV testing protocols must always specify whether stirring was applied to avoid misinterpretation and ensure valid comparisons.
- 2. Context is key:** The interpretation of BDV results must consider the oil type, IFT, moisture level, and the operational context of the equipment.
- 3. Default to static for low-IFT fluids:** For ester-based liquids or service-aged oils with known low IFT, static BDV testing should be the default method unless the test is specifically intended to simulate a high-flow design.
- 4. Integrate into design:** Transformer designers should couple electrical field simulations with oil flow modeling to identify regions where flow-dependent dielectric weakening may occur, paying special attention to the IFT of the selected fluid.
- 5. Update standards:** Standards bodies (e.g., IEC, IEEE) should develop

Table 4. A Summary guide for stirred vs. unstirred BDV testing

Test configuration	When to use	Advantages	Limitations/risks
With stirring	Energized transformers, flow simulation	- Simulates service flow - Disperses impurities - Improves repeatability	- May mask defects - Risk of bubble retention in low IFT oils - Induces charging
Without stirring	Static equipment (OLTCs, bushings, storage), aged/ester oils	- Detects localized weaknesses - Reveals worst-case dielectric behavior	- Higher CV% - May overestimate risk in flow-based systems

guidance for flow-sensitive BDV testing that explicitly incorporates IFT as a critical decision parameter.

7. Conclusion

The flow of transformer oil is a critical parameter that significantly influences its measured breakdown voltage. This influence is fundamentally modulated by the liquid's interfacial tension (IFT). While stirring during BDV testing can improve repeatability for high-IFT fluids by simulating in-service conditions, it can also mask serious dielectric weaknesses in low-IFT fluids like natural esters or aged oils, where it promotes the retention of breakdown-initiating microbubbles. The decision to use a stirred or static test must be a deliberate, purpose-driven choice based on the fluid's properties and the diagnostic objective. As transformer designs become more compact and reliant on forced oil flow, a deeper, more nuanced understanding of the interaction between fluid dynamics, IFT, and dielectric strength is essential for ensuring long-term reliability and preventing unexpected failures.

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