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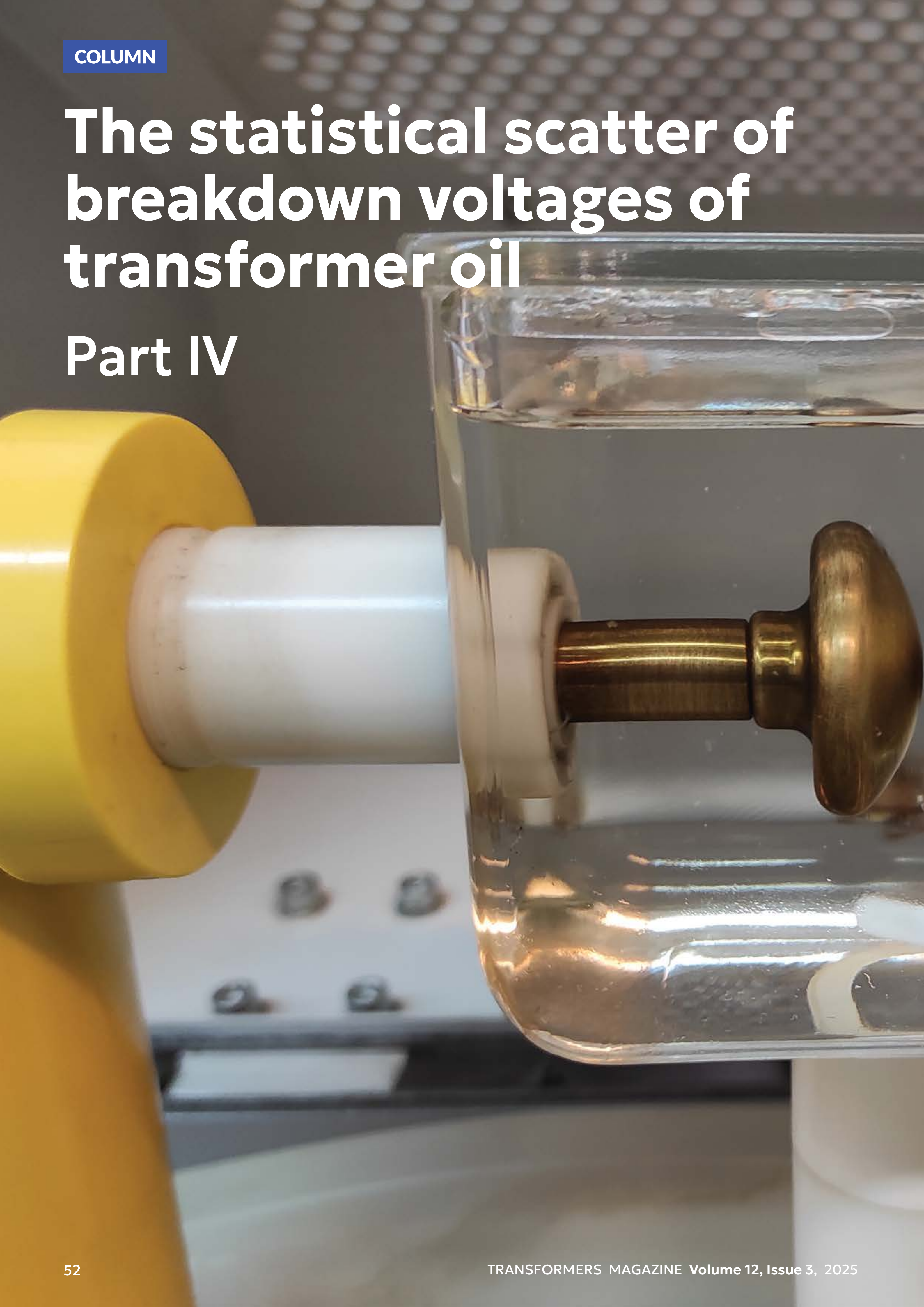
The statistical scatter of breakdown voltages of transformer oil

Part IV



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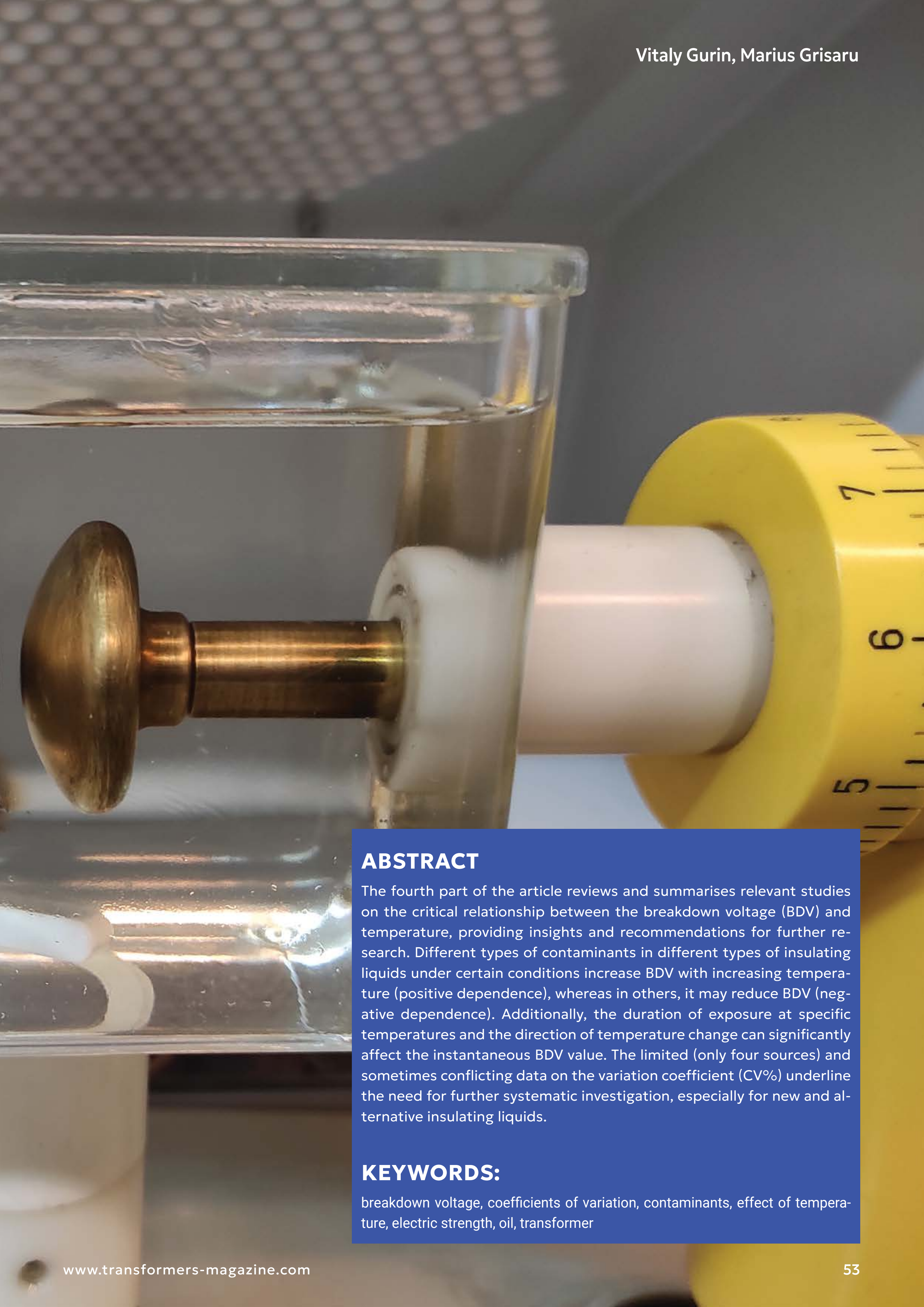

ABSTRACT

The fourth part of the article reviews and summarises relevant studies on the critical relationship between the breakdown voltage (BDV) and temperature, providing insights and recommendations for further research. Different types of contaminants in different types of insulating liquids under certain conditions increase BDV with increasing temperature (positive dependence), whereas in others, it may reduce BDV (negative dependence). Additionally, the duration of exposure at specific temperatures and the direction of temperature change can significantly affect the instantaneous BDV value. The limited (only four sources) and sometimes conflicting data on the variation coefficient (CV%) underline the need for further systematic investigation, especially for new and alternative insulating liquids.

KEYWORDS:

breakdown voltage, coefficients of variation, contaminants, effect of temperature, electric strength, oil, transformer

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The main reason for performing the BDV test of insulating oil is to try to predict the probability of its occurrence, and the temperature effect is one of the main factors that must be taken into account

1. Introduction

In the scenario of transformer failure due to any internal cause, it always ends with a breakdown voltage. The main reason for performing the breakdown voltage (BDV) test of insulating oil is to try to predict the probability of its occurrence. The temperature effect is one of the main factors that must be taken into account by the designer of optimal power transformer (PT) insulation.

When a power transformer is operating, the oil temperature inside the tank changes dynamically due to changes in its load regime and/or weather conditions.

NOTE: *It should be noted that there is "hysteresis" in the change in oil temperature with load, since as the transformer heats up, water evaporates from the paper into the oil much faster than it can be absorbed by the paper from the oil as the transformer cools down. This is of little importance to the transformer designer, but is one of the problems with the BDV method as a diagnostic tool.*

Under normal operating conditions of block transformers, the temperature can reach 70-80°C, and in critical situations (temporary overload), sometimes even more than 100°C. Network transformers are usually loaded much less, and their oil temperature can even be lower than 40-50°C. According to standards, factory tests of transformer insulation are carried out at room temperature, and the suggested maximum oil temperature during a long-term emergency of 1-3 months is 115°C according to IEC (110°C according to IEEE). Therefore, when optimising insulation, the designer needs to know the dependence of BDV and CV% on temperature at least in the range of 20-115°C. Factory tests of transformer insulation, including oil for breakdown voltage according to all standards, are carried out at room temperature to homogenise the results and to be able to perform a trend under similar conditions. Sometimes, this required temperature stabilisation to cool down or to warm up to room temperature. This is because the breakdown voltage is highly influenced by temperature.

When optimising insulation, the designer needs to know not only the maximum permissible temperature from the point of view of aging considerations and as a key factor influencing insulation breakdown, but also to know the dependence of BDV and CV% on temperature in the range of at least 20-115°C. With the introduction of new insulating liquids, it is increasingly important to examine their behaviour at extreme temperatures, considering both intrinsic impurities and substances that may form rapidly due to degradation triggered by external factors such as heat, oxygen, moisture, and other contaminants.

Although most published studies of oil have been conducted at room temperature, there is considerable literature on the complex temperature dependence of BVD, which was discovered more than half a century ago, but only a few publications provide the raw data for determining CV%.

2. Physics of the effect of temperature

In the literature, many authors usually explain their results on the effect of temperature on the dielectric strength of mineral oil using one of two theories. One is that temperature changes affect breakdown voltage due to physical processes such as viscosity, interfacial tension, and density. Another is that the dielectric strength of oil is a function of the humidity of the oil and the presence of contaminants in it, which determines the temperature dependence of the BDV.

2.1. Behaviour of BDV at constant moisture

A prominent representative of the first group is Jayaram (University of Waterloo, Ontario, Canada), whose work was funded by NSERC (Natural Sciences and Engineering Research Council of Canada) [1]. The author investigated the dielectric strength of Voltesso 35 mineral oil using ASTM D1816 with varying flow rates (from 0 to 65 ml/s) and in wide temperature ranges (20-105°C). An important feature of the work was maintaining a virtually constant moisture content in the oil (Fig. 1).

The BDV values obtained by the author as a function of temperature and flow rate are shown in Fig. 2.

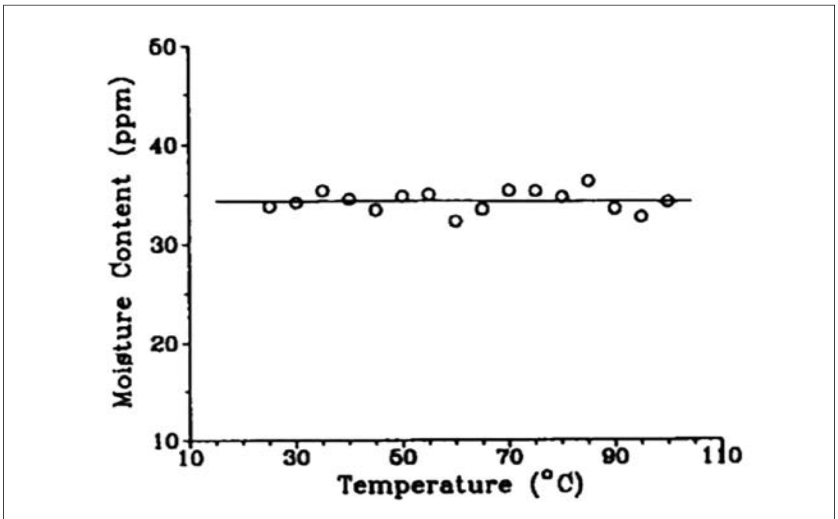

Figure 1. Variation of moisture content in oil with temperature in Jayaram's experiments

As can be seen from this figure, the BDV at different flow rates (from 1 to 5 ml/s) increased to 80˚C and then decreased (on average by about 15% near the temperature of -100˚C), which the author explains by the evaporation of water in the oil. Regardless of the flow rate, there was a peak in the BDV at a temperature of about 80˚C. The breakdown voltages of the oil with flow were slightly higher (up to 10%) than those measured for stationary oil.

2.2. BDV versus moisture content

In real transformers, naturally, the moisture in the oil does not remain constant, as shown in Fig. 1, but there is a constant redistribution of moisture content between the solid insulation and the oil due to temperature changes with changes in load and atmospheric conditions, as a result of which the electrical strength of the oil changes.

The "vanguard banner" of the second theory's supporters is Fig. 3 from the dissertation in German by Karl-Heinz Holle at the Technische Hochschule Braunschweig, 1967. Here is the link to the dissertation: https://vufind.techlib.cz/Record/000464396, which can't be downloaded.

This dependence of the AC BDV on temperature at different values of oil humidity has received wide attention, often without reference to the original source.

55 years later, in an article by Polish and French university scientists Rozga et al. [2], curves E (kV/cm) of uninhibited mineral oil Nytro Draco depending on

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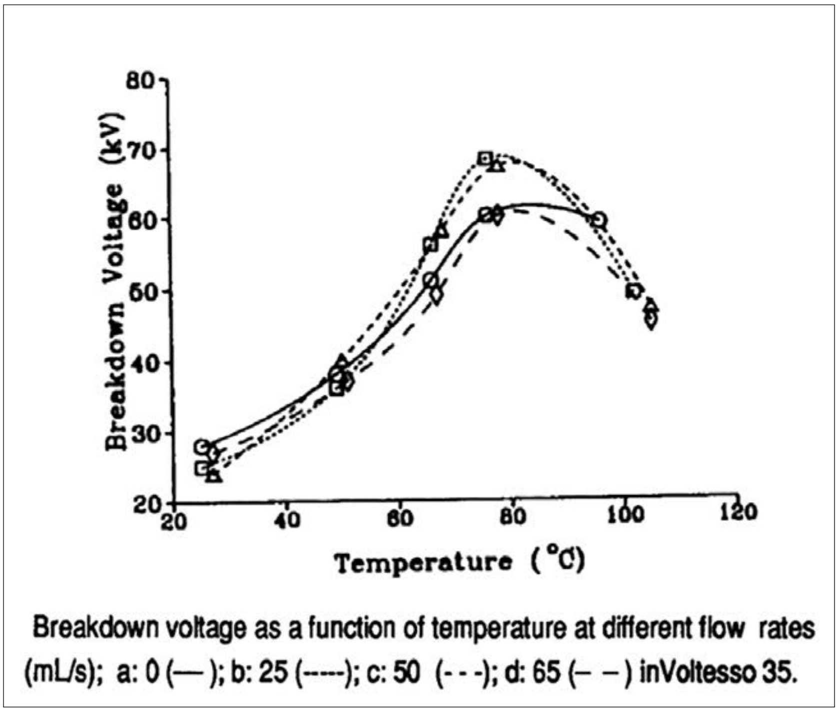

Figure 2. AC breakdown voltage as a function of temperature at different flow rates according to Jayaram

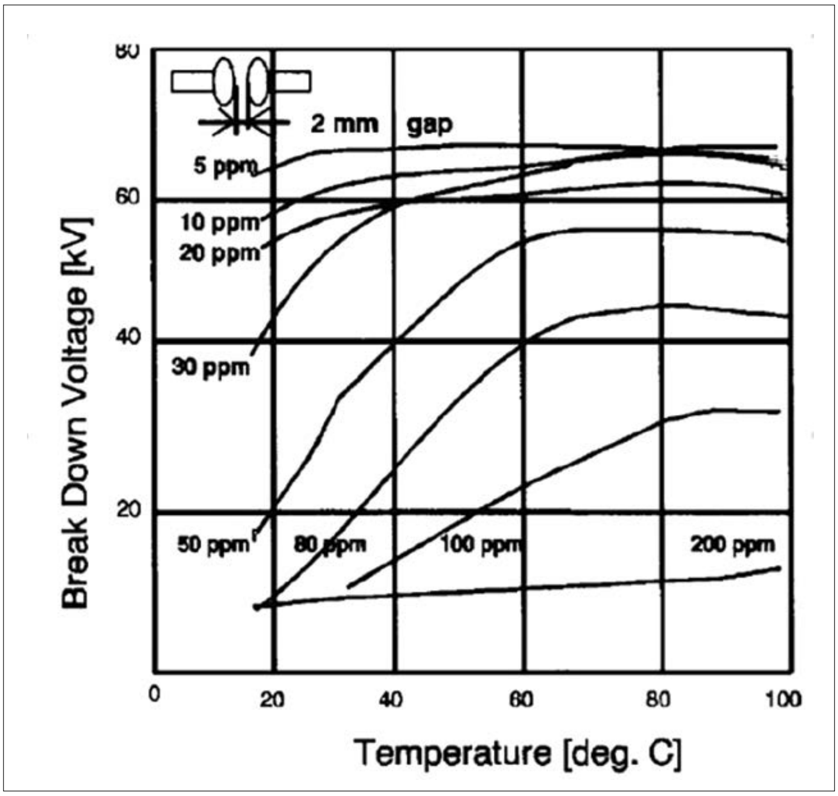

Figure 3. Effect of temperature on the breakdown voltage of an insulating oil with different water content (Source: Karl-Heinz Holle, 1967)

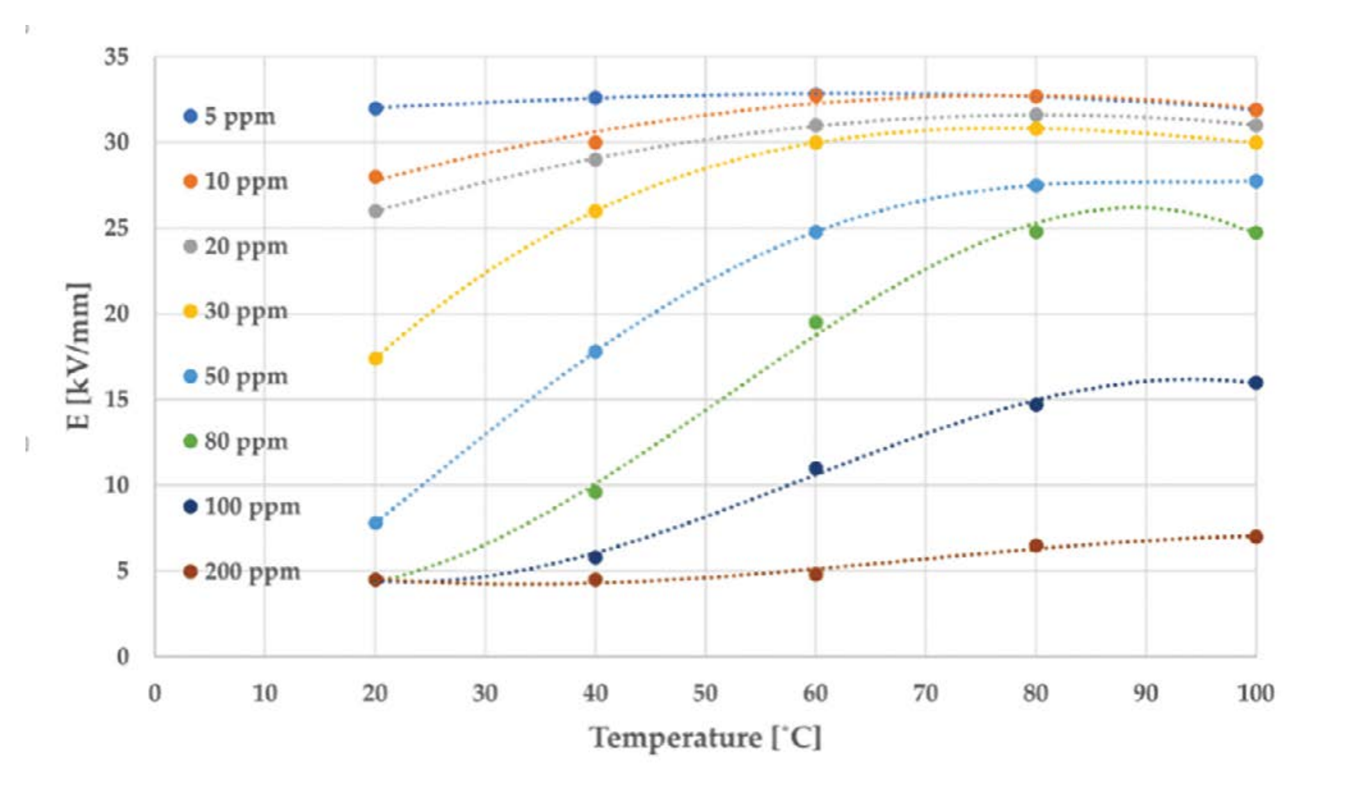

Figure 4. Relationships between the electric strength of mineral oil and temperature at different levels of moisture content in oil according to Rozga et al.

Oil that contains medium water content shows an initial increase in BDV as it is heated from ambient into the 60–80°C range due to the "drying" effect of high temperature

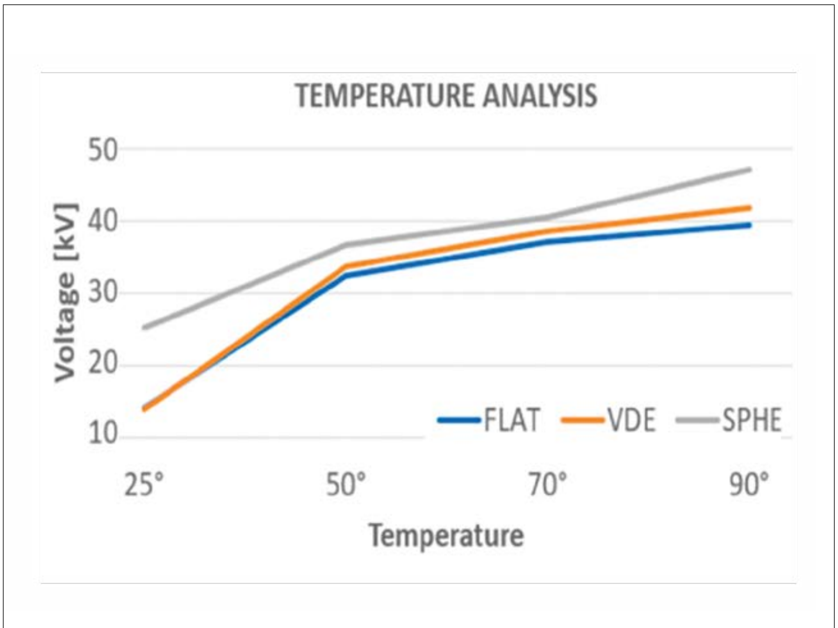

Figure 5. The dependence of breakdown voltage of three different electrode shapes on temperature, according to Gonzalez et al.

temperature (Fig. 4) are presented, similar to Hall curves. The authors say that this figure was developed based on data obtained from [3].

As follows from Figs. 2-5 oil that contains medium water content shows an initial increase in BDV as it is heated from ambient into the 60–80°C range due to the "drying" effect of high temperature. Additionally, oil viscosity decreases strongly with heating, which makes it easier for impurities to move, but on the other hand, allows any gas bubbles or moisture to disperse out of the gap more easily. The net effect at moderate to high temperatures (50–80°C) in a contained sample often still favours higher BDV if moisture was present, as long as no new contaminants are introduced.

Essentially, heating removes moisture (possibly some dissolved gases), restoring the oil's BDV to its dry value. This illustrates that raising the temperature can be beneficial up to a point for wet oil. Indeed, it's common practice to heat and dry transformer oil to improve its dielectric strength.

NOTE: *We must emphasise the seemingly paradoxical fact: a transformer designed* *and tested at ~ 20 °C at the factory has greater electrical strength in operation*.

3. BDV by electrode type.

In a study done by researchers of [4] it seems that the dependence of breakdown voltage and temperature is independent of electrode shape as in Fig. 5.

In this study, the breakdown voltage (BDV) of insulating oil increased with temperature. This positive correlation was consistently observed across all electrode types—flat, VDE, and spherical. The highest BDV values were recorded at 90 °C, with reduced dispersion, indicating more stable dielectric behaviour at elevated temperatures. ANOVA-based models confirmed temperature as a statistically significant factor, with positive coefficients in all regression equations. These findings emphasise that elevated temperatures, within the studied range, enhance the dielectric strength of insulating oils, likely due to reduced viscosity and improved charge dispersion.

4. High-temperature behaviour of BDV (Ambient up to ~120 °C)

Both in Fig. 2 (the first breakdown theory) and in Fig. 3, 4, etc., the BDV peak is near a temperature of about 80 °C. (The peak is most clearly expressed in Fig. 2, at a moisture content of ~35 ppm). Therefore, it is logical to assume that the processes underlying the two theories apparently occur simultaneously in a real transformer.

With a further increase in temperature, as many researchers note, the BDV often decreases. This is explained by the fact that water in the oil evaporates, bubbles are formed, and due to the decrease in the viscosity of the oil, the formation of conductive "bridges" from moisture, impurities and bubbles is facilitated.

Here is an interesting result obtained by Nelson back in 1971 [5]. Among other things, he (see [6]) also studied the effect of the nature of the dissolved gas (oxygen, air, nitrogen) on the electrical strength of oil in large-area cylindrical electrodes during oil circulation, depending on the temperature. We quote Nelson:

The highest BDV values were recorded at 90 °C, with reduced dispersion, indicating more stable dielectric behaviour at elevated temperatures (Gonzalez et al., 2025)

«*The increased electric strength occurring as a result of the circulation was not maintained for temperatures in excess of about 60°C. Above this temperature, a rapid and reproducible drop in strength was observed, together* ***with an increase in the coefficient of variation*** (emphasis added)». Nelson explains this phenomenon by the formation of microbubbles. Unfortunately, he did not provide the initial data to calculate the CV%.

However, very high temperatures (approaching 100–120 °C and above) can introduce new limiting factors for BDV. If the oil is saturated with water or if the temperature exceeds the boiling point of water (~100 °C at 1 atm), any additional heating can cause water to evaporate within the oil, forming vapour bubbles. Unlike dissolved moisture, gas bubbles in oil are extremely detrimental to dielectric strength.

Bubbles create low-density, gas-filled regions that withstand much lower voltages before ionising, and if an oil is hot and wet, its BDV will plummet due to bubbling

Bubbles create low-density, gas-filled regions that withstand much lower voltages before ionising. Thus, if an oil is hot and wet (unable to hold all water in solution), its BDV will plummet due to bubbling.

This scenario can occur in aged transformers: for example, a transformer with wet insulation can experience bubble formation in hot spots above ~110 °C, leading to sudden dielectric failure. It is a known risk that high temperature plus moisture can trigger bubble-induced breakdown, underscoring again the importance of keeping moisture low.

Even for dehydrated oil, extremely high temperatures tend to reduce the intrinsic dielectric strength. Thermal agitation and energy can lead to increased ionisation of oil molecules and the generation of decomposition products. As one source notes, when oil temperature becomes sufficiently high, the oil molecules themselves can crack (thermally decompose) and ionise, providing charge carriers that initiate breakdown; simultaneously, the low viscosity at high T means those charged particles move faster, further lowering the breakdown voltage.

In other words, beyond a threshold, temperature rise inherently weakens the liquid's dielectric strength. Empirically, above about 100°C, many oils begin to show a gradual decline in AC breakdown strength if dry, owing to these effects (and the onset of any oil degradation). At 130-150°C, oil will start to decompose significantly (e.g., breaking C–H bonds to produce combustible gases like ethylene and acetylene).

Such thermal decomposition not only generates flammable gas bubbles in the oil but also yields polar oxidation products, both of which drastically reduce BDV. Thus, an aged oil at 120 °C may have lower BDV than at 80°C, especially if degradation or gas evolution has started. In practice, transformers are rarely operated above ~110°C continuously for these reasons: insulation life is compromised, and the risk of dielectric failure increases as oil heats. To summarise, heating a contaminated oil initially improves BDV by dissolving moisture, but excessive heating will eventually reduce BDV once boiling of volatiles or oil breakdown commences.

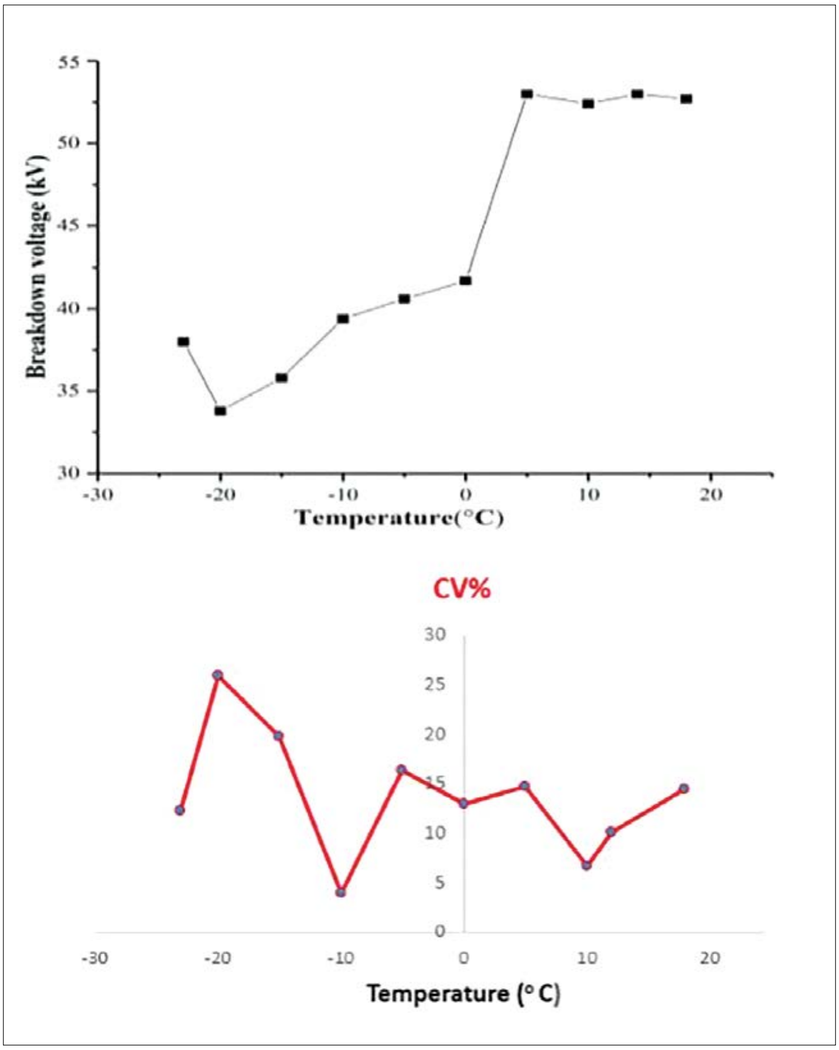

Figure 6. Temperature change curve of breakdown voltage and CV% by [7]

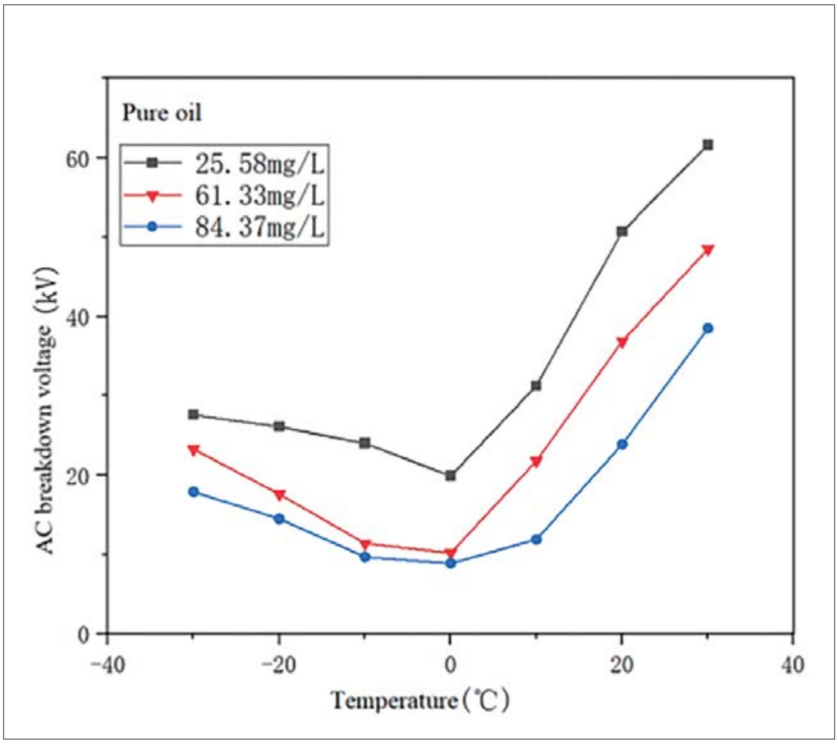

Figure 7. BDV vs temperature at different moisture content according to Qin et al.

In the absence of water, cooling generally increases oil viscosity and slightly increases the dielectric strength, since electron mobility and impurity motion are reduced

5. Behaviour of BDV at low temperatures

5.1. The dry oil

For very dry or new oil (with negligible water), the low-temperature BDV might not decrease much, or even at all (Fig. 6). In the absence of water, cooling generally increases oil viscosity and slightly increases the dielectric strength, since electron mobility and impurity motion are reduced.

Thus, a dry oil's BDV is relatively insensitive to low temperature or could even improve when cold.

The behaviour of CV% is apparently influenced not only by physics but also by chemistry. For the increase of CV%, the responsible factor is probably the homogenisation parameter, which is influenced by the viscosity, which increases, and this means that each time there is a different matrix of oil contamination, and the contaminants are less soluble in the liquid.

As temperature goes from 20 to 60 and 80°C, dispersed water becomes dissolved water, which improves the BDV because dissolved moisture, while still detrimental, is far less dangerous than free water droplets

5.2. Oil that contains water

Mineral oil's properties with ppm greater than 10 change significantly at elevated temperatures. First, oil can dissolve much more water at high temperatures: for example, the moisture saturation limit of a typical new mineral oil triples as temperature rises from 20°C to ~46°C (from about 47 ppm to 141 ppm) [8] and continues rising exponentially with temperature. Thus, heating the oil will drive those water droplets back into the solution (up to the saturation limit) if the oil contains some moisture. As temperature goes from 20 to 60 and 80°C, dispersed water becomes dissolved water, which improves the BDV because dissolved moisture, while still detrimental, is far less dangerous than free water droplets [9]. This study represents a U-shaped curve of dependence of BDV vs temperature as in Fig. 7.

Below 0°C, the droplets freeze into ice, which does not elongate in the electric field and thus causes less field distortion, resulting in rising BDV

According to bridge theory, at 0°C, moisture exists as suspended droplets that align under the electric field and form conductive bridges, causing a sharp drop in BDV. Below 0°C, the droplets freeze into ice, which does not elongate in the electric field and thus causes less field distortion, resulting in rising BDV. Above 0°C, water remains dissolved and minimally affects the electric field, leading to higher BDV.

The presence of moisture primarily causes the pronounced BDV reduction around 0°C. In summary, cold temperatures can be problematic for aged or moist oil, as the precipitation of water droplets at low temperatures markedly lowers the BDV. This is why guidelines stress minimising moisture in transformers that must start or operate in freezing conditions.

NOTE: Conclusion for Practical Use

Moisture control is essential in transformer oils, particularly near 0 °C, where BDV reaches its minimum. In cold climates, regular drying and monitoring of oil moisture content is crucial. Higher BDV performance and stability is maintained with lower moisture content across all temperatures.

6. Behavior of CV% with temperature change

Apart from Fig. 6, we found data on how the BDV scatter changes with temperature only in the following three sources.

6.1. Data by Rajňák et al., 2020

Slovak scientists from the Technical University of Košice provide graphical data on the BDV of transformer oil Mogul Trafo CZ-A, in a homemade container with hemispherical electrodes with a radius of 5 mm and a distance between them of 0.35 mm [10]. The volume of oil was about 85 ml. The filled container was first heated to 80°C, exposed to an external infrared heater. Then the tests were carried out at temperatures from 80°C to room temperature (about 23 °C). 30 tests were performed at each temperature indicated in Fig. 8. The time delay between successive measurements was about 2 min, during which the oil was stirred for self-healing.

The statistics we calculated are shown in Fig. 8. As seen in the data, the mean of BDV increases monotonically; while CV%, on the contrary, first decreases from 19.4 to 8.1 with a tendency to stabilise, and at 60°C (possibly due to the beginning of water evaporation) it sharply increases to 15.6, then decreases again.

Summary table of BDV vs low temperature at different moisture levels in transformer oil

Parameter	Low moisture (25.58 mg/L)	High moisture (84.37 mg/L)
Temperature range	−30°C to +30°C	−30°C to +30°C
BDV trend	U-shaped curve	U-shaped curve
Minimum BDV	At 0°C	At 0°C
Max BDV	At +30°C	At +30°C (lower than low-moisture sample)
Low temperature effect	Ice crystals cause less field distortion → BDV rises again	Similar trend, but BDV still lower overall
At 0 °C	Suspended water → conductive bridges → Lowest BDV	More suspended water → sharper BDV drop
Above 0 °C	Water dissolved → weak field effect → Higher BDV	Water still affects breakdown → Lower BDV

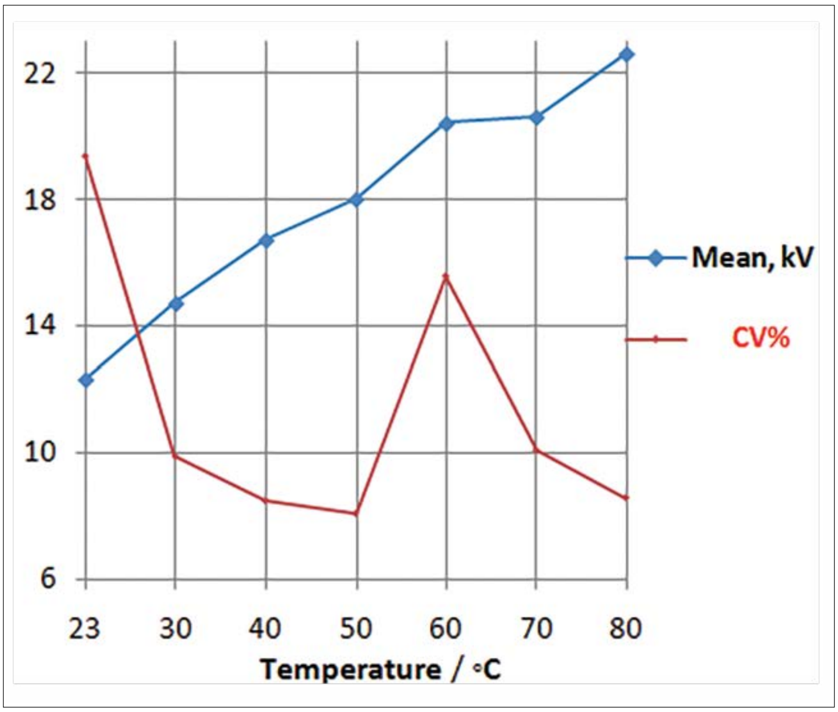

Figure 8. Effect of temperature according to Rajňák et al.

The paper by Rozga et al. also presents the results for LI BDV, which initially increase with increasing temperature and then tend to decrease

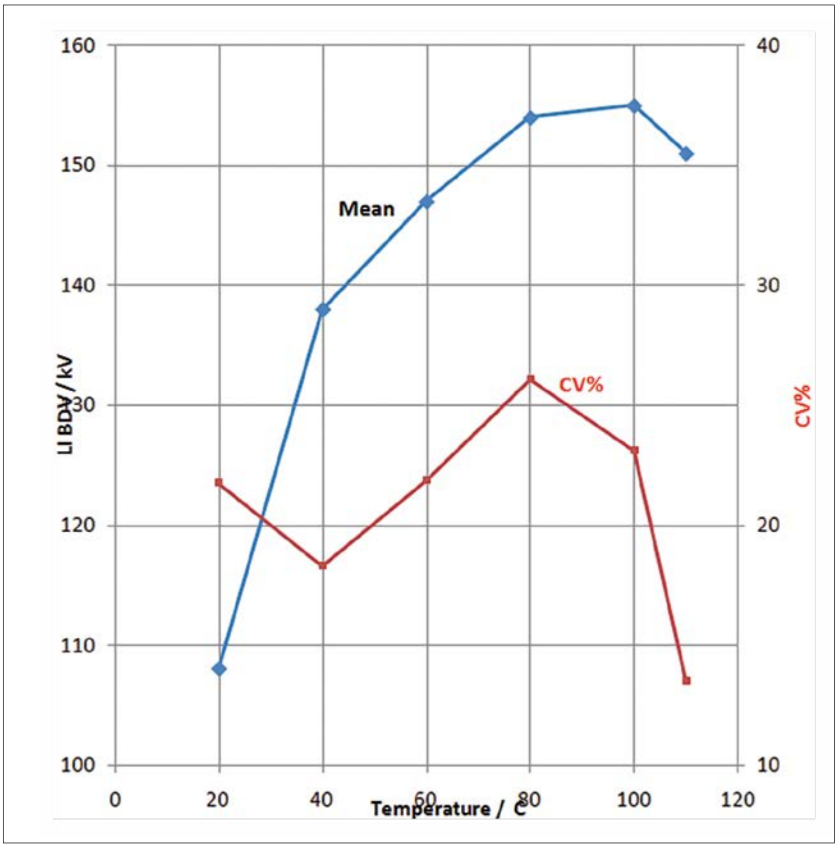

Figure 9. Effect of temperature for a standard lightning impulse in a highly non-uniform field according to Rozga et al.

The paper by Rozga et al. also discusses the effect of temperature on the breakdown voltage of a standard negative polarity lightning impulse (LI BDV) in a non-uniform electric field "point-to-plane 25 mm" for temperatures of 20, 40, 60, 80, 100 and 110°C. The results showed that LI BDV, like AC BDV, initially increases with increasing temperature and then tends to decrease (Fig. 9). Note that in the broken curve of the dependence of CV% on temperature that we constructed, CV% initially increases slightly on average, and starting from 80°C, it decreases significantly.

Data by Yahya et al. show that the mean of BDV and CV% monotonically increases up to 60°C, after which the mean stabilises, while the CV% drops sharply

6.2. Data by Yahya et al., 2023

The [11] shows BDV tables (sample sizes = 5) according to IEC for Diala-B oil in the range 30 ÷ 100°C, from which we calculated the statistics shown on Fig. 10. As seen in the data, the mean of BDV and CV% monotonically increases up to 60°C, the mean then stabilises, while the CV% drops sharply.

7. Behaviour of insulating liquids under varying moisture levels

This question under low-temperature conditions was studied in Jovalekic et al. [12]. The following summary analyses the breakdown voltage (BDV) performance of three types of insulating oils—Mineral Oil (MO), Natural Ester (NE), and Synthetic Ester (SE). The focus is on BDV behaviour under low-temperature conditions and varying moisture levels.

1) Mineral oil (MO)

- Remains liquid down to −35°C.

- BDV decreases steadily with temperature drop.

- BDV is significantly reduced at −35°C.

- Moisture has a strong degrading effect on BDV at all temperatures.

- Behaviour is linear-like and sensitive to water content.

2) Natural ester (NE)

- Similar BDV to MO at room temperature.

- As temperature drops to −25°C (gel-like state), BDV increases.

- BDV peaks at −25°C, then drops at −35°C when solidified.

- BDV is high and not affected by moisture at low temperatures.

- Shows non-monotonic, U-shaped BDV behaviour.

3) Synthetic ester (SE)

- Turns gel-like at −35°C.

- Room temperature BDV is similar to MO and NE.

- Incomplete data at −25°C, but BDV decreases at −35°C.

- Performance appears intermediate between MO and NE.

4) The influence of moisture by oil type

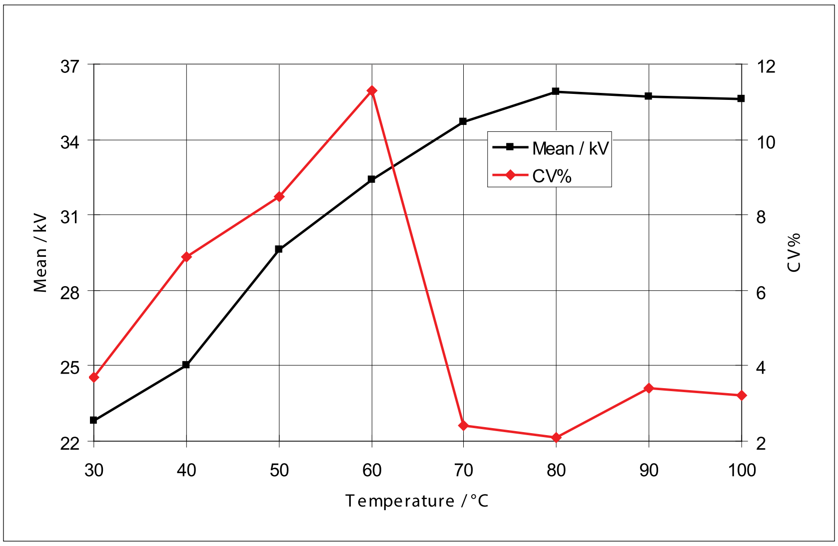

Figure 10. Effect of temperature according to Yahya et al.

The limited (only four sources) and sometimes conflicting data on the variation coefficient CV% underline the need for further systematic investigation

Summary of how moisture affects each oil at various temperatures:

Conclusions

1. Understanding the BDV vs temperature relationship is essential for transformer design and risk assessment under varying thermal and load regimes.

2. The electrical strength of pure and dry mineral oil (ppm ≤ 5) changes little with temperature.

3. For mineral oil containing more than 10 ppm water, BDV increases with temperature up to approximately 80 °C, after which it begins to decrease. This trend appears consistently across multiple independent studies. The observed peak near 80 °C is attributed to the improved solubility of water at elevated temperatures, which reduces the disruptive effect of free water droplets. However, at higher temperatures, evaporation, bubble formation and reduced viscosity facilitate the emergence of conductive paths and a decline in BDV. Although most studies agree on the existence of a peak, the precise temperature at which it occurs and

Oil type	Room temperature	−25°C	−35°C
Mineral oil (MO)	BDV ↓ with moisture	Still decreases	Very low, sensitive to water
Natural ester (NE)	BDV ↓ with moisture	BDV high, no water effect	BDV drops, no water effect
Synthetic ester (SE)	Likely reduced	Data not available	Reduced in gel state

the shape of the curve vary depending on oil type, moisture content, and testing conditions.

4. The limited (only four sources) and sometimes conflicting data on the variation coefficient CV% underline the need for further systematic investigation, especially for new and alternative insulating liquids.

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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.