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Breakdown and acceleration voltage of biodegradable liquid made in GTL technology at positive lightning impulse voltage

Abstract. *This paper compares the lightning properties of the inhibited biodegradable insulating fluid produced using Gas-to-Liquids (GTL) technology, which was designated GTL-I-BIO, with conventional transformer fluids such as uninhibited mineral oil (UMO) and synthetic ester (SE). The comparative analysis was performed for two parameters: lightning impulse breakdown voltage (LIBV) and acceleration voltage (V_a). The tests were performed at the standard lightning impulse voltage under positive polarity for two inter-electrode gaps: 25 mm and 40 mm. The highest LIBV value was recorded for UMO. However, the highest V_a value was obtained by GTL-I-BIO.*

Streszczenie. *W artykule porównano właściwości udarowe inhibitowanego biodegradowalnego płynu izolacyjnego wytworzonego w technologii Gas-to-Liquids (GTL), który oznaczono GTL-I-BIO, z konwencjonalnymi cieczami transformatorowymi, takimi jak nieinhibitowany olej mineralny (UMO) i ester syntetyczny (SE). Analizę porównawczą przeprowadzono dla dwóch parametrów: udarowego napięcia przebicia (LIBV) i napięcia przyspieszenia (V_a). Badania przeprowadzono przy udarowym napięciu piorunowym normalnym o biegunowości dodatniej, dla dwóch odległości międzyelektrodowych: 25 mm i 40 mm. Najwyższą wartość LIBV odnotowano dla UMO. Natomiast najwyższą wartość V_a, uzyskał GTL-I-BIO. (**Napięcie przebicia i przyspieszenia cieczy biodegradowalnej wytworzonej w technologii GTL przy dodatnim napięciu udarowym piorunowym**).*

Keywords: GTL, positive polarity, breakdown voltage, acceleration voltage.
Słowa kluczowe: GTL, biegunowość dodatnia, napięcie przebicia, napięcie przyspieszenia.

Introduction

Transformers are one of the most important components of the electric power system. Most of them are paper-oil insulated units. The transformer windings are immersed in a tank filled with an electrically insulating liquid. It performs very important functions because it ensures an appropriate level of insulation, impregnates the paper insulation and is responsible for dissipating the heat generated in the transformer. For this reason, it is necessary to ensure the highest possible quality of the fluids used. The most popular type of dielectric fluids are mineral oils produced from petroleum distillates in accordance with the requirements of standards such as PN-EN IEC 60296 or ASTM D3487. The constant increase in demand for electricity means that more and more transformers operate in difficult environmental conditions (e.g. very low/high temperatures), in which conventional mineral oil does not perform well. Modern transformers are smaller, but operating higher voltages meaning oils are under greater stress than ever before. Therefore, more and more alternative fluids are being created. Another aspect of why new transformer fluids are being developed is the increase in global environmental awareness and in the field of sustainable development. Therefore, transformer manufacturers, as well as customers, are increasingly seeking to ensure that the insulating materials used in their products have a positive impact on these areas. Any leaks of mineral oil are dangerous to the natural environment, which is why fluids are developed in which attention is paid to their biodegradability. As a result, natural or synthetic esters, hydrocarbons of biological origin or hydrocarbons created on the basis of GTL are produced. It is important that the introduction of dielectric liquids to the market that are consistent with the concept of sustainable development does not reduce their quality [1-4].

The base oil used in Gas-to-liquids (GTL) technology is a hydrocarbon (usually with an isoparaffin structure) obtained from natural gas, not from crude oil. The GTL process consists of three stages which is schematically shown in Figure 1. In the first stage natural gas is partially oxidized to create a mixture of hydrogen and carbon monoxide which is then known as synthesis gas or syngas. Impurities are removed from the syngas. The second stage converts the synthesis gas into liquid hydrocarbons using the Fischer-Tropsch process. In this stage a liquid is formed which looks and feels like wax at room temperature. The final stage is cracking and isomerization which cuts the molecule chains into shorter lengths. This yields high-quality liquids such as diesel, kerosene, lubricant oil and transformer liquids [5-10].

GTL products are colourless, odourless liquid hydrocarbons a very high quality that have very low levels of impurities like sulfur, aromatics and nitrogen. An extra benefit of having less sulphur is that it greatly lowers the chance of copper corrosion, extending the life of transformers. Oils produced using GTL technology can be mixed and combined with conventional hydrocarbon liquids, and certain mineral oils can benefit from the addition of GTL liquids to enhance their characteristics. The previously described properties of natural gas-derived fluids can have a substantial impact on transformer dependability and lifespan [5-10].

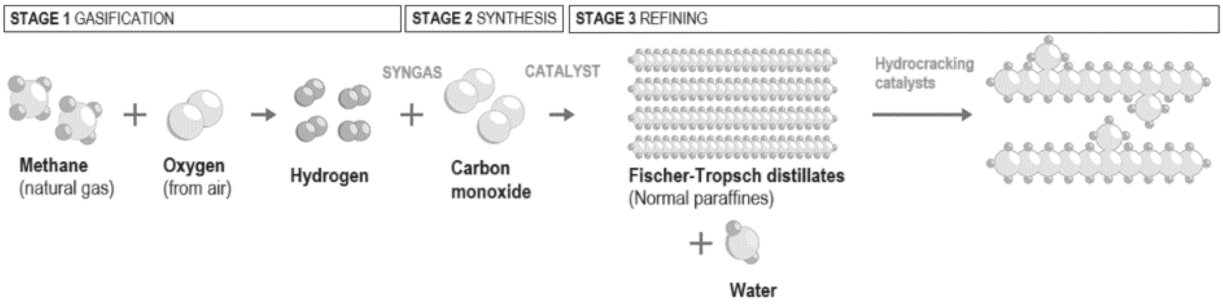

Fig. 1. Diagram of the GTL process

As previously mentioned, the paper compared lightning properties of a biodegradable, inhibited fluid made using GTL (GTL-I-BIO) technology with uninhibited mineral (UMO)oil and synthetic ester (SE). The basic parameters of tested liquids are presented in Table 1.

Table 1. Basic parameters of the tested liquids

Properties	UMO	SE	GTL-I-BIO
Density in 20°C [kg/m^3]	879	970	816
Kinematic Viscosity in 40°C [mm^2/s]	11	27.2	7.4
Kinematic Viscosity in -30°C/ -20°C* [mm^2/s]	1700	1170*	253
Flash point [°C]	146	255	161
Pour point [°C]	-57	-57	-52
Dielectric Dissipation Factor (DDF) in 90°C	0.0006	0.2854	0.0001
Moisture content [ppm]	9.9	66.0	9.2
AC BDV [kV]	79.6	70.2	71.8

The testing liquids were of high grade. The AC breakdown voltage (AC BDV) was measured in compliance with standard IEC 60156 before to the commencement of the tests. The values obtained were greater than 70 kV, indicating that the fluids utilised were in good condition [11].

Measurement system and measurement methodology

The measurement system used was the same as in the authors previous works [8-10, 12-13]. The source of the lightning impulse voltage was a 6-stage lightning impulse Marx generator. It produced a positive standard lightning impulse voltage 1.2/50 µs. The peak value meter with a resistive voltage divider was used to measure the peak value of lightning impulse voltage. The oscilloscope was used to record the voltage time courses, as well as time courses of the light pulses accompanying the discharges. The measurement of the light emitted during discharge was measured using a photomultiplier. This was possible thanks to the use of transparent organic glass for the construction of the test cell. An optical fiber was connected to the photomultiplier with a spectral range from 300 to 850 nm. Measurements of light emitted during discharges are needed when analysing data on pre-breakdown phenomena [10]. However, they are not subject of this paper and will not be analysed here. The peak value meter, oscilloscope and photomultiplier with accessories were enclosed in a Faraday cage. The measurements were performed in a test cell with a point to sphere electrode system. The high voltage point electrode was made of tungsten and its radius of curvature was 50 µm, while the diameter of sphere electrode was 13 mm. The tests were carried out for two electrode gaps: 25 and 40 mm.

The measurement of LIBV was carried out using the step method, which is suggested in the standard [14]. A standard lightning impulse voltage of 1.2/50 µs was applied to the electrode system, increasing the voltage by ΔU equal to 5 kV at each step. Value of initial voltage was determined experimentally. There was a 1-minute break between successively applied voltage impulses, while after breakdown oil was stirred and then waited 30 minutes before starting next test. Series included 10 measurements of LIBV. In order to be considered correct, the measurement had to occur 3 discharges before breakdown occurred.

Standard lightning impulse voltage was also used to determine the acceleration voltage (V_a). This voltage is where the transition from slow to fast discharges occurs in the sequence of propagation. Fast discharges are distinguished by a discharge channel that is more energetic, has a higher temperature, greater ionization level, and exposes more of the insulating system solid insulation. Greater acceleration voltage values suggest that a particular dielectric liquid is more resilient to formation of fast discharges [1, 10, 13, 15-16]. Initial voltage was previously determined LIBV. Then voltage was increased with a ΔU step of 5 kV until time to breakdown was significantly shortened. As in previous studies, a 1-minute break was maintained between successive lightning impulses. Two measurement series were performed for each of tested liquids. A 30-minute break was carried out before starting the second series. Figure 2 shows how the time to breakdown was determined for slow discharges, and Figure 3 for fast discharges.

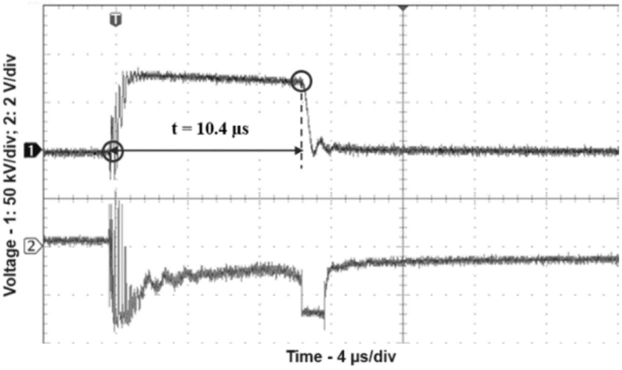

Fig. 2. Example of a slow discharge oscillogram for a positive polarity: U = 80 kV, oil type – GTL-I-BIO, 1 – voltage, 2 – light, time base: 4 µs/div, volts/div: 50 kV

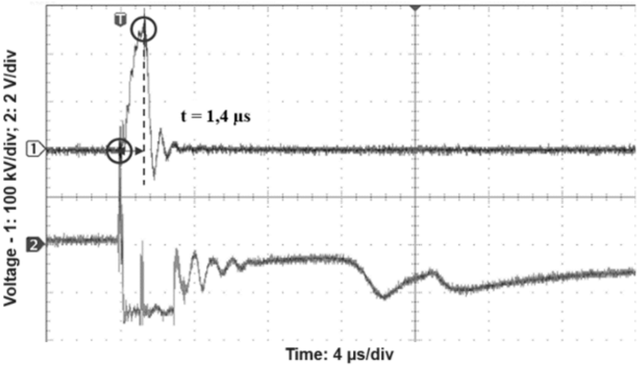

Fig. 3. Example of a fast discharge oscillogram for a positive polarity: U = 250 kV, oil type – GTL-I-BIO, 1 – voltage, 2 – light, time base: 4 µs/div, volts/div: 100 kV

After reading time to breakdown, the propagation velocity was calculated by dividing gap between electrodes by time to breakdown.

Measurement results

According to the standard [14], LIBV value is determined as the arithmetic mean of all measurements. However, the obtained results were additionally subjected to statistical processing using a two-parameter Weibull distribution. Probability plots of this distribution are presented in Figures 4 and 5 separately for a gap of 25 mm and 40 mm.

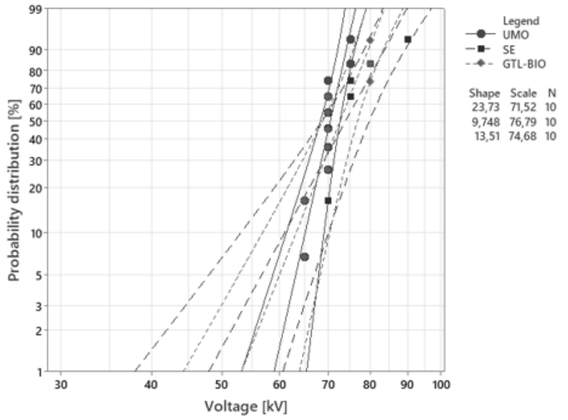

Fig. 4. Weibull plots of positive LIBV for 25 mm gap

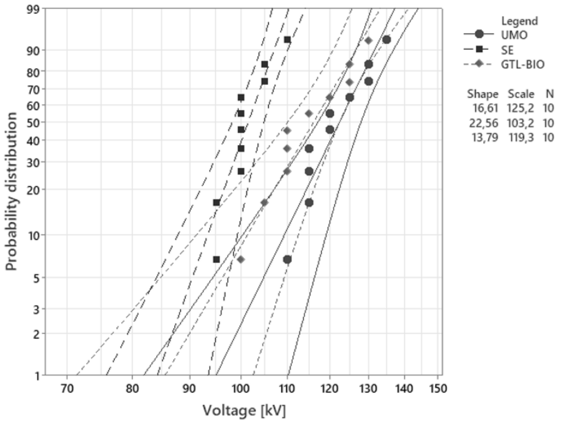

Fig. 5. Weibull plots of positive LIBV for 40 mm gap

From previous Figures, the breakdown probabilities of 5% ($V_{b5\%}$), 50% ($V_{b50\%}$) and arithmetic mean (V_{bav}) were determined. They are presented collectively in Table 1 and graphically in Figure 6.

Table 2. Summary of results for LIBV

Tested liquid	UMO	GTL-I-BIO	SE
Gap distance: 25 mm			
V_{bav} [kV]	70	72	73.5
$V_{b5\%}$ [kV]	63	60	56.5
$V_{b50\%}$ [kV]	70.5	72.5	74
Gap distance: 40 mm			
V_{bav} [kV]	121.5	115	101
$V_{b5\%}$ [kV]	104.7	96.2	90.4
$V_{b50\%}$ [kV]	122.5	116.2	101.5

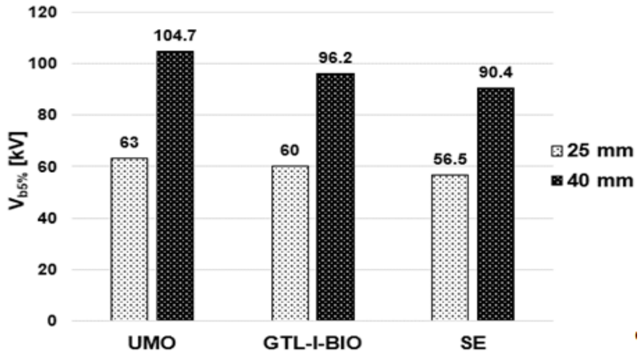

Fig. 6. 5% breakdown voltages

The next step was to determine acceleration voltages (V_a) for tested liquids. Measurements were therefore taken at voltage levels above LIBV. The testing voltage applied and the streamers' propagation velocity at a gap distance of 25 and 40 mm are shown in Figures 7 and 8, respectively. Because of the rapid shift in propagation order, determining acceleration voltage for positive polarity discharges is comparatively simpler than for negative discharges [8-9, 12-13]. Positive acceleration voltage (≈V_a), which is defined as the point at which streamer velocity reaches a minimum of 10 mm/μs, is roughly represented by the figure below. This value was chosen in accordance with the authors earlier research [8, 12-13].

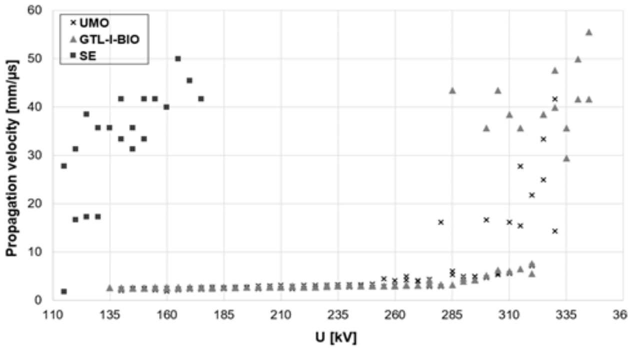

Fig. 7. Dependence of streamer propagation velocity in tested liquids on lightning impulse voltage - gap 25 mm, positive polarity

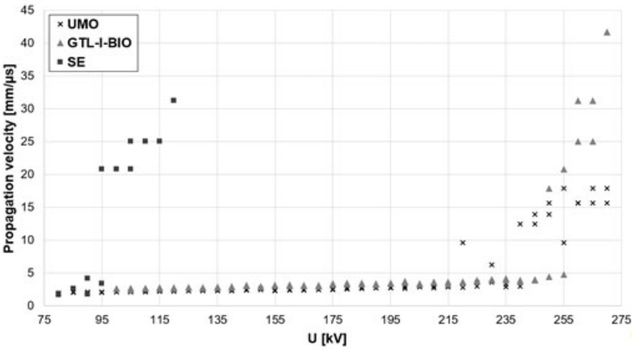

Fig. 8. Dependence of streamer propagation velocity in tested liquids on lightning impulse voltage - gap 40 mm, positive polarity

The results have been gathered in Table 3 and are also shown visually in Figure 9 for simpler understanding.

Table 3. Determined values of acceleration voltages

Tested liquid	UMO	GTL-I-BIO	SE
Gap distance: 25 mm			
≈V_a [kV]	240	250	95
Gap distance: 40 mm			
≈V_a [kV]	305	310	120

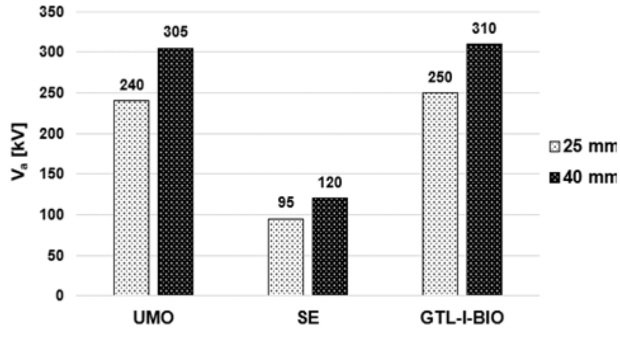

Fig. 9. Determined values of acceleration voltages

Discussion and conclusions

This article presents and compares lightning impulse breakdown voltages (LIBV) and acceleration voltages (V_a) for various insulating liquids, including naphthenic uninhibited mineral oil (UMO), inhibited biodegradable liquid produced by GTL technology (GTL-I-BIO) and synthetic ester (SE) The highest LIBV value was recorded for mineral oil UMO. However, the differences between tested liquids are not significant. Significant differences can be noticed by analysing results of acceleration voltages (V_a). The highest value was recorded for GTL-I-BIO. The lowest value was definitely achieved for synthetic ester (SE). Several conclusions can be drawn from the above considerations.

- Very similar results for LIBV prove that it is not a sufficient parameter determining the lightning properties of transformer liquids.
- Low values of the determined acceleration voltages for tested ester liquid are consistent with the theory and results of other studies [1, 8, 12, 17, 18]. Such behaviour of this type of fluids is often explained by the presence of polar molecules in their chemical structure (double oxygen bonds in the ester group). They have a reduced ionization potential, which may contribute to the acceleration of the development of discharges in esters.
- The similar LIVB and Va parameters of tested GTL-I-BIO fluid to the conventional naphthenic UMO prove that liquids produced in the GTL technology can be a good alternative to use of mineral oils without losing quality.
- Elevated V_a values signify a dielectric liquid increased resistance against the formation of more energetic and "fast" discharges. The V_a appears to be a helpful marker for comparing liquids, and it could provide insight into how different kinds of liquids ought to behave in large gaps with non-uniform field.
- As more and more alternative fluids for mineral oil reach the market, the measurement of acceleration voltage (V_a) at lightning impulse voltage ought to be part of the set of standard indicators of the dielectric qualities of dielectric liquids.

The authors intend to investigate accelerated temperature ageing of GTL type liquids in particular and how it affects their lightning properties in further stages of their work. When it comes to utilising these liquids in transformers, this appears to be significant.

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