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Dielectric performance of transformer liquids - Summary of a CIGRE study

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1. Introduction

Insulation systems of power transformers have been made of cellulose-based materials and mineral oils for more than a century. The main function of a transformer insulation system is to withstand electric stresses. When designed properly, the weakest part of this composite system is the insulating liquid.

Traditionally, mineral oils have dominated the market for use in electrical equipment. The composition of insulating mineral oils depends on the content of naphthenic, paraffinic, and aromatic hydrocarbons, as well as sulphur compounds, in the crude oil origin. The final product also heavily depends on the refining processes. The oils may also contain a range of additives, such as antioxidants, pour point depressants, and metal passivators.

During the last 20-30 years, new insulating liquids have arrived in the market. There are synthetic esters, essentially being a synthesis between an alcohol and a carboxylic acid, and natural esters being produced from seeds and plant oils. These esters are produced from a blend of unsaturated and saturated fatty acids, and the blend determines their physicochemical properties. There are also new liquid hydrocarbon liquids, produced either from natural gases (gas-to-liquid), or from bio-based feedstock, that are de-esterified and processed. All these liquids may contain additives.

Research has demonstrated that large differences in the dielectric performance can be observed among these liquids. The physical characteristics of a liquid (e.g. density, evaporation energy, and boiling point) and the quantum chemical properties (e.g. electronic excitation energies, ionisation potential) are dependent on its molecular composition, which varies with different liquids and additives. Even though the dielectric properties of a liquid clearly depend on physical properties, molecular composition, and quantum chemical properties, no currently known model can accurately predict the dielectric behaviour of an insulating liquid.

Traditional design rules for the insulation were mainly heuristic, based on statistics and experience. Research, emerging in the last few decades, has offered more insight into breakdown and pre-breakdown phenomena in insulating liquids, through investigating their behaviour in a wider range of conditions (e.g. larger gap distances, higher voltages). During the same time, new hydrocarbon-based liquids and also alternative liquids (e.g. esters) were introduced. It has now been observed that the standard test methods used for traditional mineral oils do not necessarily reflect the functional behaviour for all insulating fluids. With this as a background, CIGRE established a task force to review the dielectric performance of insulating liquids used in transformers. The work resulted in the publication of the CIGRE Technical Brochure TB 856, along with a tutorial that should be of interest for researchers, designers, and end users [1]. This paper gives a brief introduction and summary of the brochure.

2. Testing of transformer insulation systems

The maximum electric field in the liquid is one of the main parameters for a designer to consider. The insulation can withstand higher lightning impulse (LI) stress than ac stress, which is demonstrated by the well-known V-t curves. The required test stresses, normalised to the 1-minute ac test value are similar for the different voltage classes, seen in Figure 1. For shorter times, the stresses are standard switching impulse, standard lightning impulse, and chopped lightning impulse.

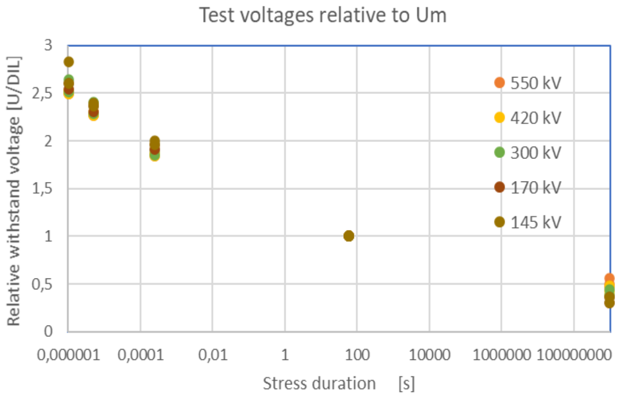

Figure 1: IEC test levels and in service voltages for different voltage classes relative to highest voltage for equipment U_m. DIL – The design Insulation level - is the phase-to-phase system voltage. Values taken from IEC 60076-3.

The test conditions for a transformer relate to its voltage class. The Design Insulation Level (DIL) is the one-minute phase-to-phase RMS withstand level, and the Basic Insulation Level (BIL) is the standard lightning impulse withstand level (approximately 2.3 times of the DIL). The current standards require testing BIL for negative impulse only. A transformer manufacturer will test the withstand capability of established insulation designs to find the ratios between BIL and DIL. This ratio is called the Test Conversion Factor (TCF). TCF has fixed values for given voltage classes and refers to testing voltages. Generally, conversion factors between DIL and BIL for design purposes (also called "Design Conversion Factors", DCF) do not have the same ratios as defined by the IEC/IEEE for test voltages. A transformer design is based on static ac 1 minute stress, and all transient stresses are converted to ac 1 minute stress with respective conversion factors. When the ac withstand voltage is known, then the use of DCF can reduce the amount of design work provided this ratio is valid. For design purposes, conversion factors are based on manufacture experience and experimental investigations of dielectric withstand of different insulation structures. While the BIL test level is a standardised test for the full insulation system, the DCF limits are used for specific design details and may vary from one manufacturer to the other. It should be emphasised that DCF limits have been developed mainly based on experiences from testing mineral oil impregnated insulation designs.

For transformer insulation, one differentiates between main (or major) insulation, being parts that see the full applied voltages, such as phase to ground or voltages between windings, and minor insulation, such as interturn or interdisc. The most economical use of materials is to stress the insulated gaps evenly. This is achieved when the average field is close to the maximum field. The utilisation factor η ($\eta = E_{avg}/E_{max}$) is 1 for an ideal uniform field (it is the inverse of the field enhancement factor). In the main gap between windings, the field is more or less uniform and utilisation factor is typically around 0.9, while typical values for interwinding edges can be around 0.5 and for lead exits around 0.4. For tap selectors, even lower utilisation values of approximately 0.2 can be found. These can all be referred to as semi-uniform fields. The CIGRE Technical Brochure TB 856 includes typical values for stresses, distances, and utilisation values that researchers should keep in mind when designing relevant discharge and breakdown experiments.

Scientists often use needle-to-plane bare electrode geometries with very divergent fields to study defect behaviour and breakdown phenomena, even if these geometries are not directly applicable in designs. Needle-to-plane and rod-to-plane electrodes will often have utilisation factors much lower than 0.1. Field geometry and paper/pressboard insulation have significant influence on breakdown events in liquid insulation that should be considered in practical transformer insulation designs.

3. Dielectric performance of insulating liquids/pre-breakdown phenomena/breakdown initiation and propagation

The dielectric performance of a liquid primarily describes its ability to withstand electric stresses. For a transformer, the stresses may vary in duration from fast lightning and switching impulses, to slow ac and dc voltages. When the withstand voltage of an insulating liquid is exceeded, it changes from being an insulator to becoming a “conductor” when an electric arc eventually occurs. Early studies were mainly concerned with finding the withstand voltage of design-relevant models with high utilisation factor [2]. The breakdown in mineral oils was found to be initiated by defects, like sharp protrusions and particles in high field regions. Such defects resulted in local field enhancement. When the electric field is close to uniform, insulation breakdown will follow once initiation takes place.

Research on breakdown processes using needle-to-plane gaps and high-speed imaging observations has revealed details in the pre-breakdown phenomena. Breakdown in the liquid is preceded by propagation of a *streamer* that short-circuits the insulation gap when reaching the other electrode. Streamers are composed of thin propagating gaseous channels. The streamer channel consists of a partially ionised gaseous phase [3], and is often considered as a nearly conducting object, acting as an extension of the electrode.

Figure 2 shows how the shape of the streamer channels in a mineral oil depends on the polarity of the impulse voltage. The widely used term *streamer* is somewhat confusing as it is borrowed from well-defined gas discharge physical models, whereas in liquids, it is used to describe a wide range of pre-breakdown processes that have little or no relation to the gas discharge physics.

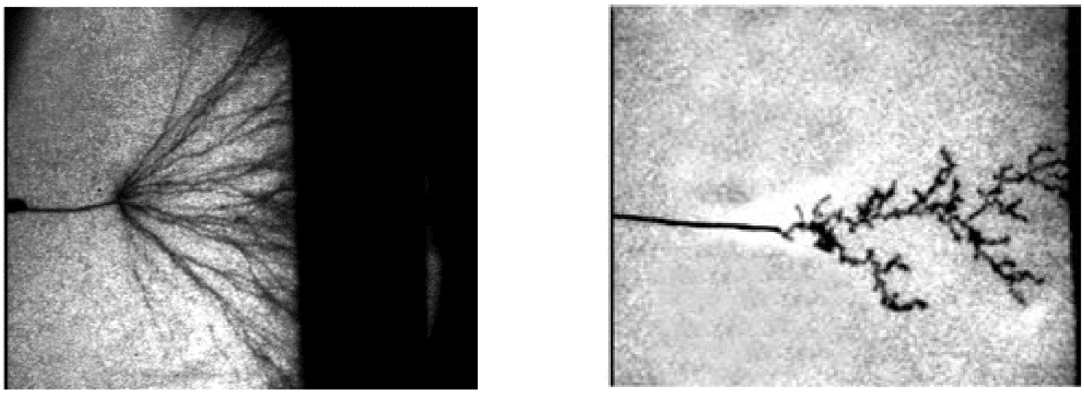

Figure 2: Streamers in mineral oil in a needle-to-plane geometry, initiated at the needle under step voltage. Left: Positive second mode type. Right: Negative second mode [4]. © 2001 IEEE.

Electrical breakdowns and pre-breakdown phenomena (streamers) in liquids are extremely complex and dependent on several factors. These factors include but are not limited to, the shape and polarity of the voltage, electrode geometry, external pressure, and the properties of the liquid. Knowledge of the mechanisms that govern initiation and propagation of the streamers is important in preventing electrical breakdown and equipment damage.

Studies in non-uniform, needle-to-plane geometries have shown that streamer velocities vary significantly, depending on the applied voltage level and the chemical composition of the liquid. At voltages where streamers start to develop, they typically propagate at millimetres per microsecond. Streamers may stop in the gap if the applied voltage is below the breakdown voltage, or if it is reduced below the breakdown voltage while the streamer propagates. When the applied voltage is high enough and applied during a time long enough to let the streamer bridge the gap, breakdown usually occurs. When the voltage is increased above the *acceleration voltage*, streamer propagation velocity quickly increases to hundreds of millimetres per microsecond. Such streamers may cross long gaps, even for the short duration of a lightning impulse. For example, if the acceleration voltage is exceeded for just 5 microseconds, then a streamer can cross a distance of more than half a metre during this time. Meanwhile, if the voltage stays below acceleration voltage, the propagation distancefor the same 5 microseconds will be approximately one centimetre.

Streamers can appear in insulating liquids when a very high local field in the range of MV/cm is present. This condition is easily met in a needle-to-plane geometry. However, for breakdown tests carried out with uniform fields, which are closer to operational designs, other phenomena must be considered to explain streamer initiation. Breakdown experiments carried out with uniform fields are "initiation-controlled", i.e. every streamer initiated propagates to breakdown, and the measured breakdown voltage represents the voltage required to initiate a streamer.

This has led to two different scenarios for liquid insulation breakdown:

- "*Initiation-controlled breakdown*" - a streamer, once initiated, systematically propagates to breakdown. This situation is found where the utilisation factor is high, e.g. in ac breakdown under semi-uniform fields. The measured breakdown voltage is interpreted as the voltage required to initiate a streamer. The initiation is largely governed by surface and volume defects.
- "*Propagation-controlled breakdown"* - a streamer, once initiated, does not necessarily propagate to breakdown. This situation is found where the utilisation factor is low, e.g. in needle-to-plane gaps, and when the time duration of the voltage is too short to allow a complete streamer propagation to breakdown. In this case, the measured breakdown voltage is calculated as the voltage required to obtain a complete propagation of the streamer. The time to breakdown is of the essence and studies have shown that the streamer velocities, and in particular the acceleration voltage, depend on physicochemical properties of the liquids.

Initiation-controlled breakdown

Understanding discharge initiation is complicated in real transformer insulation, where the utilisation factor η is high. As a first approximation, it can be assumed that streamer inception starts in the liquid where and when the field exceeds a threshold value.

High field regions are usually found at the high voltage side of a transformer, in areas where the conductor curvatures are small (such as at leads and edges of windings), or when distances to parts at different potential are small (interdisc and interturn gaps). Usually, a defect or contamination by a solid particle showing much higher permittivity and conductivity than oil (e.g. metallic particle, or hydrated cellulose) is needed to locally enhance the field above the inception threshold. A bare electrode is not the necessary requirement to initiate a streamer, as initiation can occur at surfaces of solid insulators, or at particles floating in the oil.

A large scatter in inception voltages is also usually observed – both for ac and impulse stresses. The scatter in inception voltages increases when going from low to high utilisation factors, as the influence of random defects to trigger streamers (contamination, surface protrusions, etc.). The presence of defects becomes increasingly important when the background field increases, and when the electrode surface and liquid volume subjected to high fields increase. In the 1970s, many studies were published on breakdown in mineral oil in uniform and semi-uniform geometries of different sizes to investigate the influence of stressed volumes and surfaces. Figure 3 shows an example where the insulation volumes were varied over a large scale. It is apparent that the breakdown voltages reduce with increasing volume. Similar studies were also performed showing correlations with stressed surface area. These all lead to volume or area theory where one, from knowledge of the breakdown for a small stressed "unit" volume, can derive breakdown probability for larger structures by "adding probabilities" [5].

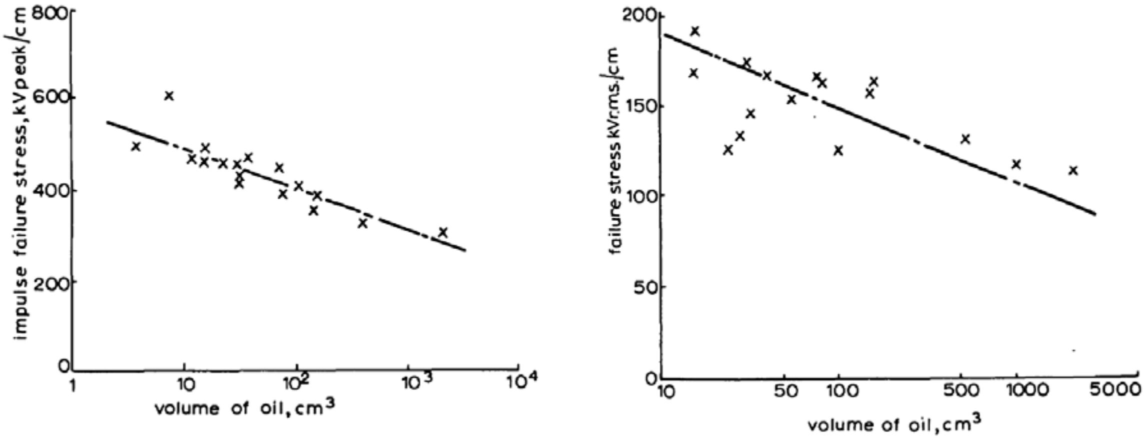

Figure 3: Correlation between lightning impulse breakdown strength (left) and ac breakdown strength (right) and stressed volume, each point representing the average of 10 tests. Voltages were gradually increased until breakdown [2].

It became evident that the breakdown voltage is dependent on the number of defects within a volume or at an area. For example, cellulose particles and their water content play an important role. Figure 4 shows that for different insulating liquids with varying water absorption properties, it is the relative water saturation of the liquid that plays a role in ac breakdown voltage, not the absolute concentration of the water measured in the liquid. The relative saturation of water in the liquid controls the water content of dust and cellulose particles and thus, their conductivity, and permittivity.

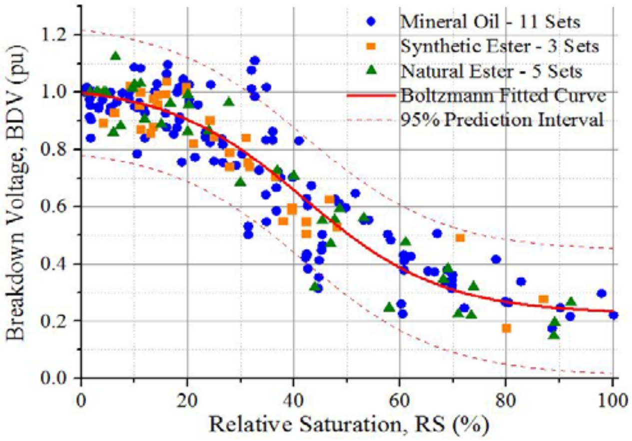

Figure 4: AC breakdown voltages according to IEC 60156 test of transformer liquids versus relative saturation of moisture for both mineral oil and ester liquids [6]. © 2012 IEEE.

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Propagation-controlled breakdown

As shown in Figure 2, the shape of the streamer varies with polarity. Generally, at equal voltage levels, a positive streamer will propagate faster and longer than a negative streamer. Hence, most studies have focused on positive streamers. In a non-uniform field, a streamer may start and then stop even though the voltage is still applied, if the applied voltage is lower than required for crossing the gap. A streamer may also stop if the voltage is rapidly decaying while it propagates: streamer initiated by a lightning impulse will be quenched if the voltage falls below some critical value required for further propagation.

Figure 5 presents the large variance in stopping lengths for positive streamers in a mineral oil for an applied step impulse voltage. The evolution of positive streamers is not even and progressive when the applied voltage is increased: steep transitions of velocity, shape, currents are observed. Positive streamers undergo different propagation “modes” as the voltage applied is increased, starting first with a slow and bubblelike mode. A second mode that develops has filamentary shaped channels and propagates at some 2-3 mm/µs from initiation up to breakdown voltage, or above. The third mode is faster with a nearly 10-fold increase before transitioning to the fastest mode (fourth mode), which has velocities greater than 100 mm/µs. During propagation, streamers may suddenly switch from one mode to another, making the complete description rather complex. Streamer branching typically increases with voltage up to the third mode, while transition to the fourth mode is characterised by a sudden reduction of branching—fourth mode streamers usually show only one channel. However, at increasing voltages, fourth mode streamers may also show more branches. Branching is considered an important feature of a streamer, but not well understood, and will vary from liquid to liquid and depends on additives [7, 8].

Figure 6 shows the average velocities of positive streamers observed in a needle-to-plane arrangement with an 80 mm gap under step impulse voltage, over a large voltage range, for three different insulating liquids. Since the streamer mode may change during propagation, the total propagation duration (from inception to breakdown) used to calculate the average velocity can include the contribution of different modes. *Average breakdown voltages* are also indicated in Figure 6. The velocities observed at the start are dominated by the second mode (about 2 mm/µs), observed over a wider voltage range in mineral oil, compared to other liquids (e.g. natural ester). The “acceleration voltage” is the voltage where a sudden increase in velocity is observed, above which the velocity again "stabilises" into the fourth mode propagation. While the average breakdown voltage is in the same range for the three liquids, the acceleration voltage varies significantly. One should be aware that properties like breakdown voltage and acceleration voltage do not necessarily scale with insulation distances. Extrapolation from small scale investigations to large scale design requires careful considerations. In a similar way, experiments carried out with short duration impulses, such as standard lightning impulse, which may induce streamer stopping due to insufficient duration, can lead to different results compared to Figure 6. This further complicates the interpretation of measurements, classification of liquids, and practical use of results [9].

It was observed that in similar conditions as in Figure 6, variations in hydrostatic pressure from 0.1 to 2.0 MPa reduced the propagation length and increased breakdown voltage, but showed little impact on velocities of the different modes [10].

As positive streamers are more critical, negative streamers have received less attention. However, negative streamers also change shape and accelerate with increasing voltage, but their modes are not as easily distinguishable as for the positive ones [11].

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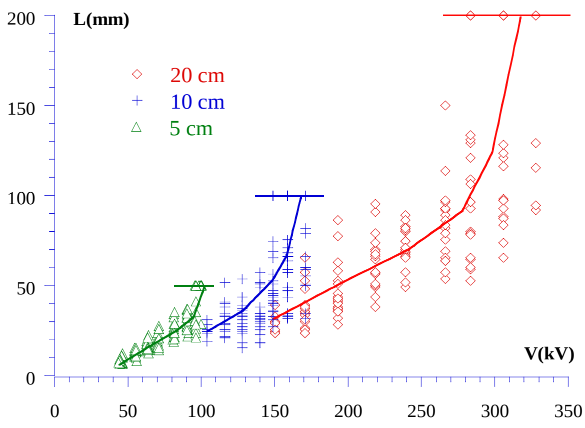

Figure 5: Stopping length for positive streamers in 5, 10 and 20 cm gaps under step voltage [12].   © 1994 IEEE.

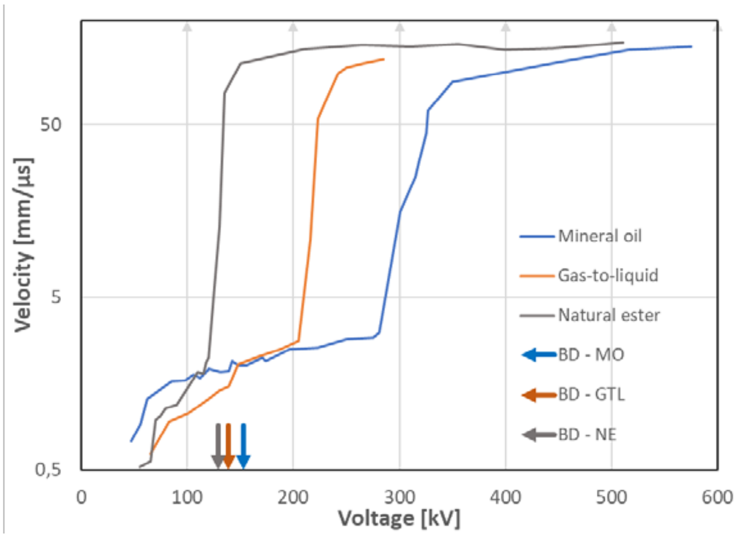

Figure 6: Breakdown voltages and streamer velocities for three different transformer insulating liquids. 80 mm needle-to-plane gap with applied positive step voltage. 50% breakdown probability voltages marked with arrows [1].

Within regions of high electric fields, spacers and barriers of solid dielectric material are present in a transformer. These materials impact the propagation of a streamer. A barrier can stop the propagation of a streamer [4, 13], while interfaces parallel to the field can accelerate a streamer creating a "creeping discharge" [11]. Figure 7 shows that restricting a streamer within an insulating tube reduces the acceleration voltage, and that reducing the diameter of the tube reduces the acceleration voltage further. To some degree, this is similar to a barrier surface along a transformer winding, which also restricts the spatial development of the streamer. The tangential electrical field along insulation surfaces defines the highest stress for streamer propagation. The influence of interfaces parallel to field on streamer propagation differs for different liquids. For lightning impulses, a surface parallel to the field will have little influence on the velocity of streamers in esters, while reducing the acceleration voltage for streamers in mineral oils [14].

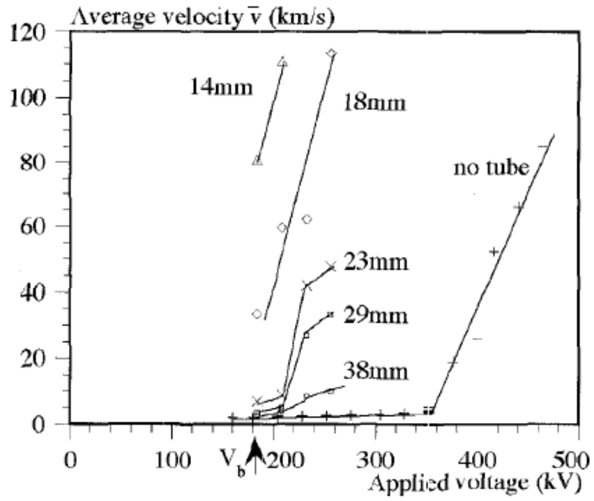

Figure 7: Average breakdown velocity for positive streamers in polypropylene tubes of given inner diameter using a 10 cm needle-to-plane gap in mineral oil [13]. © 1998 IEEE.

Theories and models for streamer propagation

Streamer propagation depends on many different and correlated physical processes in the gaseous channel, as well as in the liquid phase at its head [15]. Figure 8 illustrates such processes for the case of a second mode positive streamer. At the streamer head, the very high electric field E_h induces ionisation of the liquid, intense energy dissipation, and emission of a shock wave that later develops as a Mach cone. The resulting high temperature and pressure induce cavitation and evaporation of the liquid, producing the axial extension of the gaseous channel constituting the streamer body. Behind the propagating streamer head, the channel expands with a radial velocity v_r much lower than the axial velocity v_p, explaining the thin conical shape of the channel. Inside the channel a conduction current i_c occurs (motion of charge carriers), whereas only a displacement current i_d occurs in the insulating liquid surrounding the streamer.

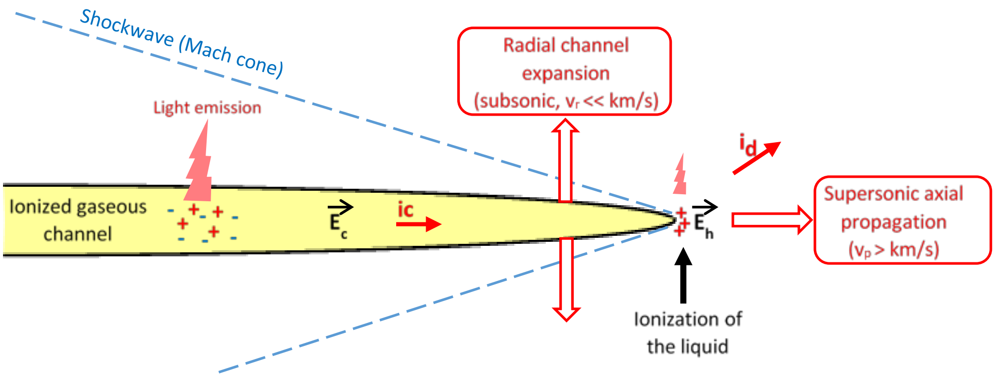

Figure 8: Illustration of phenomena involved during second mode positive streamer propagation.

For the second mode streamer channel, it has been observed and concluded that [1]:

- Current and light pulses are often seen from the channel during streamer propagation.
- Fields E_c within channel are moderate (~10 kV/cm at 0.1 MPa hydrostatic pressure), and strongly depend on the pressure and channel current.
- The channel radial expansion is primarily controlled by the surrounding liquid inertia.
- Following expansion, the gaseous channel will collapse, inducing a limited lifetime (e.g.10 µs)

- The channel lifetime and maximum diameter depend on hydrostatic pressure on the liquid.
- Internal power dissipation may increase channel volume and lifetime.
- The gas temperature and pressure are out of equilibrium and vary with position and time.
- Internal pressure can be much higher than the surrounding liquid hydrostatic pressure.
- Streamer stopping can be due to either voltage drop along the channel or channel collapse.

For the streamer head during second mode propagation one finds that:

- The electric field E_h is high enough (~10 MV/cm) to induce ionisation in the liquid phase.
- Even a large liquid hydrostatic pressure (e.g. 10 MPa) do not influence axial velocity v_p, supporting that ionisation processes actually take place in the liquid [10].
- Ionisation induces intense energy dissipation (10 W), high local transient temperature and pressure, leading to cavity nucleation, shockwave, and evaporation of liquid.
- The streamer axially extends due to this phase transition.
- Ionisation is favoured by low ionisation potential additives (e.g., polyaromatics), which also greatly increase branching [7, 8].
- Intense branching reduces the tip field E_h by mutual electrostatic shielding between branches, and induces some “self-regulation” of velocity when voltage is increased [8].

The observations from experimental studies indicate what should be included in a model for streamer propagation. No currently available model can predict streamer behaviour, polarity dependence, branching, mode shifts, and how these are linked to physicochemical characteristics of a liquid. However, there are models that can, to an extent, replicate some streamer properties.

A complete model should include both the processes taking place at the streamer tip in the liquid phase, and the processes in the streamer channel. The field needed to initiate a streamer discharge in a very small volume at a needle tip is on the order of 10 MV/cm. A reasonable assumption is that the field in front of a propagating streamer is similar to the initiation field. Additives with specific electronic properties influence streamer propagation, and their influences differ between positive and negative polarities [7]. However, the details of the evaporation and ionisation processes are not clear. Evidence of electron avalanches is observed for negative polarity [16], while it is still disputed for positive polarity.

4. Test methods

There are three IEC test methods for the determination of partial discharge and breakdown characteristics of insulation liquids:

- IEC 60156 - Determination of the breakdown voltage at power frequency, (similar to ASTM D1816).
- IEC 60897 - Determination of the lightning impulse breakdown voltage, (similar to ASTM D3300).
- IEC TR 61294 - Determination of the partial discharge inception voltage.

IEC 60156 has been widely used as a routine test to check liquid quality (e.g. contamination by water and particles), whereas IEC 60897 and IEC 61294 are used as a type test, with the intention to reveal the intrinsic dielectric properties of the insulating liquid.

In addition to the standard tests, the industry has developed various electrode configurations and insulation models. The aim of testing the insulation materials in more practical configurations and under more realistic conditions is to be more representative of operating transformers and tap-changers. Such configurations often involve electrodes with paper/pressboard covering and larger liquid volumes under enhanced stresses.

IEC 60156 – AC Breakdown Voltage

IEC 60156 defines a method for determining the mean ac breakdown voltage of insulating liquids in a short gap between spherically shaped bare electrodes. This test is one of the most widely used methods for testing insulating liquids. In addition to being used as an acceptance test for new or treated liquids, the method is classified as a routine test in IEC 60422 – Supervision and maintenance guidance of mineral insulating oils in electrical equipment. While the test method does not necessarily return an intrinsic liquid property required for design of transformer insulating systems, it provides a good representation of contaminations in the liquid, e.g. water and/or solid suspended matter [17] and is useful for the asset management of transformers.

IEC 60897 – Lightning Impulse Breakdown Voltage

The test in the IEC 60897 standard reveals the breakdown voltages of insulating liquids under standard lightning impulse for a needle-to-sphere bare electrodes gap. It was observed that the breakdown of an insulating liquid was largely independent of the contamination of the liquid (i.e. particles and water) [18]. A significant consideration for the introduction of IEC 60897 was that breakdown voltage under a negative lightning impulse, in a divergent field, was found to be related to the aromatic content of the mineral oils. This suggests that IEC 60897 can provide a measure of the liquid breakdown itself with almost no influence of the contamination by moisture or impurities.

Fundamentally, the test reflects the ability of a streamer to cross a gap during a specific impulse waveform. The voltage used during the test must be above the streamer initiation voltage. For slow mode streamers (e.g. the second mode streamers) a streamer might be quenched in a large gap during the short tail time of the LI stress. In contrast, fast mode streamers, like the third or fourth mode streamers, can cross a large gap under LI stress. The existing version of the IEC 60897 standard does not provide guidance on streamer velocity. The standard would be greatly improved if both the breakdown voltage and time from voltage application to breakdown, reflecting streamer velocities, were recorded for a wide range of voltages. This data would allow for generation of the V-t curve of a liquid for a specific gap and provide information on the acceleration voltage (as shown in Figure 9). The V-t curve indicates the capability of a liquid to withstand fast streamer events, which occur above acceleration voltage level. This information is helpful to characterise a liquid's functional properties and is useful to an insulation system designer.

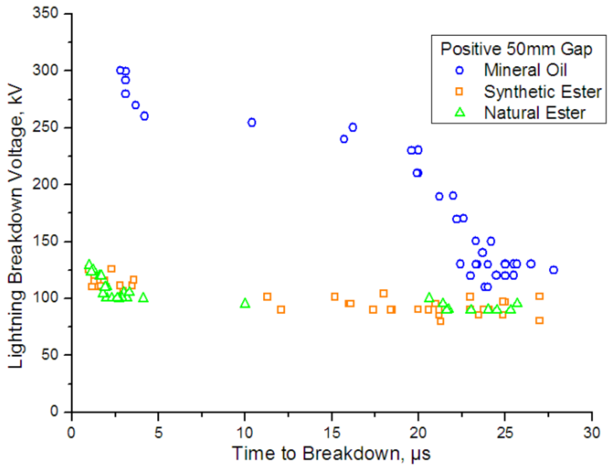

Figure 9 : V-t curve of various liquids at 50 mm gap under positive polarity lightning impulse [19].

IEC 61294 – Partial Discharge Inception Voltage

IEC 61294 was published as a technical report to define the procedure for determining Partial Discharge Inception Voltage (PDIV) of insulating liquids under a steadily increasing power frequency ac voltage. The PDIV is defined as "*the lowest voltage at which a partial discharge occurs of an apparent charge equal to or exceeding 100 pC when the sample is tested under the specified conditions*". The measured value is dependent on several factors, such as the criterion determined by increase of PD magnitude or PD number (pulse repetition rate), the way voltage is applied, and the PD detector and electrode configuration used. The technical report does not encompass modern versatile PD detectors. In the highly divergent electric field used in the described method, normally not present in a real transformer, PD inception is modified by the strong injection of charges by the needle electrode. Large charge injection very rarely exists at operating field in a transformer, and the practical relevance of liquid classification obtained with this method is questioned.

Industrial Tests

Modern test geometries vary widely, from needle-to-plane tests mainly focusing on propagation-controlled breakdown characteristics of liquids, to geometries with more uniform fields where initiation may govern breakdown. A number of in-house test geometries and procedures have been developed by equipment manufacturers. It would be advantageous if industry and academia could collaborate to "standardised" geometries with relevant utilisation factors. Additionally, electrode covering, and oil wedges should be considered, but are currently not always included. Documented test procedures and test conditions, such as the inclusion of water in oil, testing temperature, and particle content is also currently lacking.

5. Challenges for insulation design

Insulation designs have gradually been developed over many years based on benchmark testing of insulation models and data accumulated from both test labs and transformer service experience. Together, with studies of various theoretical models, the designs have been continuously modified in attempts of optimisation. As the current "design rules" and criteria for insulation design are predominantly based on experimental studies and experience, there is a need for future refinement for liquids other than mineral oils. Margins for effects from combined stresses such as LI occurring on energised transformers, and increased contaminations by water, particles, and gases should be considered during the acceptance tests.

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For the designer, the withstand voltage is regarded as the “safe” voltage. For all intents and purposes, “safe” indicate a sufficiently low breakdown probability, typically 1 %, which shall ensure a reliable long-term operation of the equipment for the stresses the insulation might experience during service. With this in mind, the 1 % value extracted from a 10-sample test have greater uncertainty than from a 100-sample test. As a result, it is preferable to derive the withstand voltage based on as large sample set as possible, to set a limit for failure probability. The test voltages that are required for a certain application define the withstand voltages which must be achieved by a suitable insulation construction.

Textbooks describe several design rules and practices [20, 21]:

- Volume and area theory
- Kappeler/Weidmann curves (Mean oil stress criteria)
- Cumulative stress/creep calculations
- Test conversion factors
- Streamer criterion

A commonality for all design rules and practices is that they have been heuristically derived for mineral oil insulation systems. However, there are still no comprehensive theories that could fully explain all processes which govern initiation and propagation of streamer breakdown in a liquid. As a result, theoretical fundaments are still not fully developed and validated for all liquids.

With the introduction of new liquids such as esters and synthetic / bio-based hydrocarbon oils, and continuous changes in the refining processes of mineral oils, there is a need to transpose the advances in knowledge of streamers in liquids to practical tools and rules for the transformer industry. It is already understood that present IEC standards do not fully reflect the functional dielectric performance of a transformer insulating liquid. The design criteria that have been developed for mineral oils cannot be directly applied on insulation systems impregnated with other liquids.

As discussed earlier, impulse voltage breakdown can either be initiation-controlled or propagation-controlled. Mineral oils are unique in regard to having a slow positive propagation second mode that is stable over a large range of voltages and gaps. Other liquids exhibit faster third and fourth modes that may occur at much lower voltages. These observations become critical for larger liquid gaps and higher impulse voltages (higher voltage classes). Investigations are needed to find how representative the established voltage vs time to breakdown curves are for other liquids than mineral oil. The propagation velocity of breakdown streamers, as well as typical voltage values at which different modes occur (e.g. acceleration voltage), constitute important and significant functional liquid parameters for power transformer applications.

The dielectric behaviour of liquids in uniform / semi-uniform fields remains more uncertain, with less basic knowledge accumulated compared to very divergent field. In a transformer, the utilisation factor is high in the main insulation gaps. The minor insulation areas, with smaller oil gaps, show insulating arrangements of lower utilisation factors. Extensive studies are required to better characterise and understand the behaviour of non-mineral oil liquids in insulation gaps with a varying, but moderate degree of inhomogeneity. For uncoated, bare electrodes, initiation-controlled breakdown will most probably be governed by the grade of contaminations (particles, moisture, etc.), and by the electrode surface roughness. Once initiated, the starting streamer will have unlimited access to charge from a bare electrode surface, while covered electrodes could restrain streamer initiation and propagation. Therefore, better insight into the effect of electrode covering on initiation-controlled breakdown is required for all types of liquids [22].

Studies on insulation breakdown in composite insulating arrangements with creepage interfaces and barriers are available for some insulation systems, but further investigations are required as current conclusions still diverge to some degree in particular when considering new liquids.

Conclusions

The introduction of new insulating liquids can be a challenge for the transformer industry when the behaviour and functional properties of the liquids are unknown and/or not fully documented. The performance of an insulating liquid is highly dependent on its chemistry. New and alternative insulating liquids, such as esters and gas-to-liquid oils, behave differently from the well-known, petroleum-based mineral oils. The term “mineral oil” is increasingly used as a general term for all kinds of naphthenic and paraffinic hydrocarbon-based liquids, independent of their origin, which also includes gas-to-liquid oils and bio-based hydrocarbons. Hence, the performance of mineral oils may change depending on their chemical composition, and changes in production process, refining and additives can all lead to different dielectric performance.

Insulating arrangements of electrical equipment filled with a new liquid do not necessarily behave in the same way as they do in petroleum-based mineral oil. As a result, the design rules currently used for traditional mineral oil will need to be verified. The present IEC standards, however, do not sufficiently reflect all relevant functional dielectric properties of insulating liquids, and hence revisions to the standards are required.

One predominant obstacle for improved understanding is the lack of a unified theory for liquid breakdown. Uncertainties regarding the driving mechanism behind streamer initiation and propagation is a barrier to developing functional, liquid specific, physics-based design tools. Consequently, further work on discharge and breakdown in insulating liquids and liquid impregnated insulation systems is required. Many more details on characteristics of different insulating fluids and methodologies of breakdown tests can be found in the extensive reference list in the CIGRE Technical Brochure 856.

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