Dealing with the Size Effect in Insulating Liquids. A Volume Effect, an Area Effect or even a Particle Effect?

A Concise Review

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Abstract-Insulating liquids play an important role as insulating media in various high voltage applications and infrastructure installations. The dielectric strength of an insulating liquid depends on the experimental conditions (in case of laboratory testing) and/or the service conditions (in case of apparatuses in service). One of the main factors affecting the dielectric strength of insulating liquids is the so-called size effect, i.e. the effect of the size of the electrodes, of the size of the liquid volume under stress and of the gap spacing between the electrodes. All the aforementioned parameters are investigated in the context of the present short review.

Keywords-insulating liquids; liquid dielectrics; transformer oil; dielectric strength; volume effect; gap effect; area effect

I. INTRODUCTION

For several decades the mechanism of electric breakdown in insulating liquids has been a subject of great interest [1-3]. Although a considerable amount of data has been obtained and promising hypotheses on the mechanism of breakdown have been published, results often indicate serious inconsistencies and this fact has prevented the adoption of a universally accepted theory capable of explaining the workings of electric breakdown in these liquids [1-2]. Comprehensive reviews on breakdown of insulating liquids were published some years ago [4, 5]. It is generally agreed that electrical breakdown in liquids is statistical in nature and the dielectric strength depends on pressure, temperature, field geometry, electrode area, liquid volume, gap spacing, voltage waveform, electrode material and finish, additives and impurities, past history, time and magnitude of pre-stress.

It is the purpose of this short review to investigate the dielectric strength of insulating liquids with reference to the so-called size effects, i.e. the effects the gap spacing, the electrode area and the oil volume under stress. It is understandable that the terms "dielectric strength" and "breakdown strength" in the context of the present paper are used interchangeably. It is also understandable that since transformer oil played a predominant role in high voltage engineering applications in the past several decades, a particular emphasis is given on this specific liquid.

II. SIZE EFFECTS

The existence of a size effect for insulating liquids is accepted by the researchers although there is no agreement whether this should be a volume effect or an area effect. Either can occur depending on the test conditions. The weak links presumably have a statistical distribution of magnitude and number, as noted in [6]. According to the weak link theory, an increase in the size of the specimen results in increased probability of a large weak link being present in the test gap and a corresponding reduction in dielectric strength. The weak links are in the liquid bulk or on the surface of the electrodes; which particular link causes breakdown will depend on its magnitude and the experimental conditions. If a weak link present in the liquid bulk initiates breakdown a volume effect should result. If a weak link present on the electrode surface initiates breakdown, an area effect should result. As was pointed out in [6], whether the size effect is area or volume dependent is determined by the relative quality of the insulating liquid compared with that of the electrode surfaces and the time of application of stress.

III. GAP EFFECT

Many researchers reported a decrease in breakdown strength as the electrode separation increases [1]. A definite tendency for the dielectric strength to increase for smaller gap

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spacings using spherical electrodes was reported in [7]. The authors of [7], however, did not find a similar phenomenon for larger gaps. They suggested that electrons are supplied to the liquid by emission from the cathode but breakdown will occur only if the number of electrons is adequately multiplied by an ionization process in the bulk of the liquid.

Spherical electrodes were also used in [8], where it was suggested that a surprisingly large increase in dielectric strength was noted as the gap was reduced. The author of [8] suggested that the small gaps restrict cumulative ionization. A dependence of the dielectric strength on gap spacing was reported in [9]. Furthermore, it was reported a dependence of the breakdown strength on gap for various electrode configurations using n-hexane [10]. In yet another research paper, the dependence of dielectric strength and breakdown voltage on gap was investigated [11]. Similar to [9], a relationship was found to exist between the dielectric strength and the gap spacing in [11]. It was suggested that the dependence of dielectric strength on gap length arises from a collision ionization process [11].

Another approach was proposed in [12], where the authors, investigating the electrical breakdown for long gaps and non-uniform geometries, concluded that electrical breakdown initiation using AC and DC voltages is governed to a large extent by impurities in the oil or on the electrode surfaces. In [13], a strong dependence of the breakdown voltage on gap spacing was indicated and it was remarked that for small gap lengths the electrode surface pretreatment is of additional importance [13]. In [14], an effort was made to explain the relationship between the breakdown conduction current and the gap length suggesting that longer gaps would be capable of providing more positive ions. These ions would drift to the cathode thereby forming a positive space charge thus enhancing electron emission and they would also increase the probability of liquid dissociation by energetic electrons and the subsequent bubbler formation.

Authors of [15] and of [6], working independently, proposed that the breakdown voltages versus oil gaps between electrodes, line up on a straight line in a log scale paper and they postulated that the relation between breakdown voltage and gap can be expressed by a simple equation,

$$V = K \cdot d^n \qquad (1)$$

where V is the breakdown voltage, K a constant, d the gap length and n takes values between 0 and 1. Moreover, it was reported that for AC ramp voltages, the gap effect is stronger than the area effect suggesting that a simple volume effect should not be expected.

IV. AREA EFFECT

An older study indicated a considerable increase in dielectric strength when used electrodes of smaller diameter were used [16]. Before that, the importance and influence of the electrode area effect was recognized in [17]. In [18], the idea that the area effect is due to the inherent variability in dielectric strength was proposed. A formula was established in [19-20], in which the modal dielectric strength was related to the electrode area, based on extreme value statistics,

$$V_1 - V_2 = [s \cdot \log_e(A_2/A_1)]/\sigma_N \qquad (2)$$

where V is the modal dielectric strength, A the area, s the standard deviation of N measured breakdowns and σ_N the function of the number of N breakdowns only (it is true that, conventionally, voltages are symbolized by V and dielectric strengths by E. In (2), however, we strictly followed the symbols of [19, 20]). Equation (2) was verified by the authors for impulse and 60 Hz voltages under carefully controlled conditions. In [19, 20] it was indicated that any difference, which may exist in the breakdown mechanism between impulse and 60 Hz tests, does not change the predicted area effect. The above proposed model was influenced by the "weak link" theory developed in [21], where it was pointed out that the "weakest link" concept, when applicable, may be the key to the occurrence of certain observed relationships between the strength of specimens and their size. In yet another publication [22], it was shown that from a statistical point of view, the effect of selecting the lowest breakdown from two tests on a given specimen is equivalent to a hypothetical test on twice the specimen, providing that enough measurements are taken for the full statistical meaning of the test.

In [6], it was shown that a certain decrease in breakdown strength was observed when the electrode area was increased for both impulse and AC testing. However, the data of [6] show a reduction in standard deviation with increasing area, which is in disagreement with what is predicted by the extreme value theory (the latter requires that the standard deviation remains constant). In [23], 12 pairs of spheres in parallel under oil were used, in order to investigate the statistical nature of the area effect. The authors of [23] showed that the distribution of the breakdown voltages of a random sample arbitrarily chosen from the parent population, is a Gaussian distribution, which is in contrast to the findings of [19, 20]. Both research groups established, however, the existence of the "minima of groups area effect," which states that if from a total of N breakdowns (the stressed area of the test object being Q), only the p lowest breakdown voltages from p groups, each of q breakdown values, are considered, where N=p·q, the effect is the same as that of p readings taken on another test object with a stressed area of q·Q. In general agreement with the above, publication [4] remarked that if there is a distribution in the sizes of the asperities on the electrode surface and the most prominent of these initiates breakdown, then an increase in the area of the electrodes will lead to a greater probability of breakdown. The consequence of the area effect is that the modal values of breakdown strength as observed with flat electrodes having different areas, but at a constant gap, would decrease approximately with the logarithm of the area. As was remarked in the same publication, the electrode pretreatment affects the breakdown strength of a given oil sample. Roughening of either the cathode or the anode or both affects the strength and also the area effect, because it increases the number of preferential sites from which breakdown can be initiated by electron emission.

V. VOLUME EFFECT

A volume effect results if the weak links exist in the liquid itself. It was reported that the primary factor determining the unit dielectric strength of commercial oil of controlled quality

for electrodes of different geometries is the volume of that oil under stress [8]. In the same publication, the stressed volume was defined as the volume enclosed by the 90% equigradient surface. Another researcher [24], testing a range of electrode areas and gaps in pure oil found that the 50 Hz AC strength was a function of the stressed volume. For a gap range of 1 to 4 mm and electrode areas 10^{-1} to 10^3 cm^2, the mean breakdown strength associated with 'V' ccs of oil could be expressed as

$$E(V) = E_1 - K \cdot \log_{10}(V) \tag{3}$$

where $E(V)$ is the mean breakdown strength, E_1 is the value for 1 cc and $K = 25$ kV/cm (rms).

It was reported [25], that a volume effect for both AC and impulse voltages is possible. It the aforementioned publication, the stressed volume was defined as in [8]. The distribution function was shown to be Gaussian although the data could be plotted equally well on extreme value probability paper. The AC breakdown strength of the oil was also found to be affected by the level of particle contamination. In [15], it was reported that the oil breakdown could be described by its stressed oil volume in a wide range from 10^{-2} to 10^5 cm^3. It was also pointed out that oil breakdown probability, Gaussian or extreme value distribution, might be affected by the test conditions. According to [15], larger volumes of oil give larger standard deviation and their distribution function approaches more closely the extreme value distribution.

In [26], it was shown that the experimental results were more consistent with a volume theory rather than with a simple area effect for both impulse and AC voltages. In the same publication, however, it was pointed out that the adoption of the stressed volume as the dominant factor affecting the breakdown does not imply that breakdown is uninfluenced by the nature of the electrode surface. In [6], although it was indicated that for impulse voltages a simple volume effect exists since the area and gap effects were approximately equal, for AC voltages the dielectric strength dependence on gap spacing was much greater than on area. Therefore, a simple volume effect was not observed.

VI. SOME FURTHER REMARKS ON THE SIZE EFFECTS

Researching further the question of size effects on transformer oil, it was reported that for rather small areas (up to 20 cm^2), the breakdown strength decrease with increasing electrode area was at first 70 kV/cm/decade, while it falls at about 35 kV/cm/decade for areas in the range of 30 to 1000 cm^2 and it almost disappears for electrode areas larger than 1000 cm^2 [27]. A non-linear relationship exists between the breakdown strength and the logarithm of the electrode area. This is due to the fact that transformer oil breakdown strength has a minimum value and a leveling off the line relating the strength with the area should be expected. A similar downward trend was observed in [15]. The average change of approximately 35 kV/cm/decade noted in [27] was also in agreement with data reported earlier in [6]. In [27] it was also pointed out that the breakdown strength reduces with increasing the gap spacing. It was further remarked that, up to an electrode area of 1240 cm^2, the gap effect was approximately 80 kV/cm/decade. The gap spacing effect is a complex phenomenon. The breakdown voltage increase is somewhat less proportional to the gap length for uniform electrode arrangements [27]. This is in agreement with earlier research data [13].

An increase of the gap can also increase the population of impurities entering the gap, which might act as nucleation sites and subsequently reduce the breakdown strength, as was suggested in [14, 28]. In [29], it was reported that the charge of a particle in contact with an electrode is proportional to gap voltage and not to the local electric field, a conclusion not unjustified in the light of the work done in [27]. The effect of gap spacing on breakdown strength is complicated since there are many influencing factors, such as physical size factors (for example, flushing action is better for larger gaps but the higher voltage level produces more decomposition products at breakdown) and weak links existing in the oil volume and/or on the electrode surfaces.

If a simple volume effect exists (i.e. a volume effect which can be fully traced to the gap effect and the area effect), area and gap effects should be equal. However, it is realized that the gap effect seems to be stronger than the area effect, suggesting thus that a simple volume effect should not be expected [27]. An increase of specimen size leads inevitably to the introduction of imperfections which may vary from those of molecular dimensions up to gross defects arising from inclusions [30]. The question, however, as to whether a size effect can be attributed to a volume effect or to an area effect seems to be open since in [31] it was reported that dielectric degradation can be attributed to either the electrode area or the stressed oil volume.

VII. LATER RESEARCH ON SIZE EFFECTS

The cleanliness of electrodes is of paramount importance since clean electrodes restrict the sites from which streamers can emanate [32]. Besides the cleanliness of the electrodes, other factors such as the rate of voltage rise play a role in determining the variance in the time to breakdown, when impulse voltages are applied [32]. Initiation sites from the electrodes, in quasi-uniform arrangements, play a dominant role in determining discharge initiation in mineral oil of technical purity [33]. However, as the electrode radius becomes larger, the volume effect gains in importance [33]. This is somehow contradicted in [34], where particular attention was paid to the electrode surface since the probability density function of streamer inception on a small element of electrode area depends on local electric field. Such a function, described as $\mu(E)$, depends on the electrode radius for hemispherical electrodes. It is to be noted, however, that in the same publication [34], it is also remarked that in the case of narrow gaps, the effective area of hemispherical electrodes is proportional to the product of the radius of electrode to the gap length, leaving thus some room for further discussion as to the possibility of a volume effect.

In [35], it is implied tacitly that a volume effect is at work since the effect of the shape of the electrodes is not considered stronger than the effect of gap length. It must be pointed out that in [35] different electrode geometries were used, such as sphere-sphere, plane-plane, mushroom-mushroom and sphere-plane. The conclusions of [35] are not fundamentally at

variance with those of [29]. In [36], an emphasis was put on the electrode configuration, remarking that when the flux lines are more uniformly distributed higher breakdown voltages are expected. It was reported that electrode arrangements such as Rogowski-plane or sphere-plane should be preferred to arrangements such as rod-plane [36]. No indication was given however, as to a clear area or volume effect with the tested arrangements. Although [37] did not tackle the problems of either area or volume effect, it pointed out that the type of the statistical distribution of breakdown voltage values in transformer oil testing depends on whether the oil is of poor quality (in this case a positively skewed distribution results), of relatively good quality (when we are likely to have a negatively skewed distribution) or of moderate quality (when it is expected a more or less normal distribution). It is tacitly implied that such quality variations may also have an effect on whether an area effect or a volume effect will appear. Reference [37] is in agreement with an earlier publication [38], where it was remarked that larger volumes and larger areas increase the probability to find larger elongated particles in the vicinity of the electrodes and thus to facilitate streamer initiation. Reference [38] tends to support the view that a particle effect seems to be more probable than a pure area or volume effect. The views expressed in [38] were already expressed in earlier publications [39], where the possibility that the observed decrease in breakdown voltage with an increase in particle count may be related more to the presence of large particles at the higher particle concentrations than to the higher concentration itself. It must, however, be remarked that the approach of [38] was more elaborate than the one in [39]. Emphasis on the role of foreign particles was also given in [40] and it was remarked that the measured AC breakdown voltage of an insulating liquid mostly represents its quality rather than its characteristics. Relatively recently, there was a report on size effects [41], where the authors used an old idea proposed in [8], by using the notion of the 90% equigradient surface (which in [41] is named effective electrode area A_{eff}). The conclusions of [41] were that the breakdown strength E can be expressed both as a function of the effective electrode area A_{eff} as well as a function of the gap length. Although no clear proposal as to a pure area effect or a volume effect was formulated, one of the points made was that the effective electrode area is equivalent to the pit area, i.e. the electrode area affected by the activity of discharges.

VIII. SOME FURTHER COMMENTS

It is true that most of the research on area effect and volume effect was carried out not in the most recent decades. Testing larger and smaller electrode areas as well as larger and smaller oil volumes was of interest more in earlier times than it is nowadays. The advent of modern techniques, such as the Schlieren technique, shifted the interest of the researchers from the macroscopic investigations to the microscopic level and more to the mechanism and the dynamics of breakdown in insulating liquids [5, 42-46]. The size effects were investigated thereafter in conjunction with these or similar techniques [34]. As the years passed by, there were also other ways to approach the questions concerning the transformer oil insulation [47]. There was, so to speak, a shift in research interests to the more fundamentals of insulating liquid breakdown.

It is also true that, from the experience of past decades with various insulating liquids and, in particular, with transformer oil, evidently the electrode surface quality as well as the liquid quality determine to a significant extent whether there may be an area or a volume effect. This is not, however, to imply that the questions regarding the size effects in insulting liquids have all been answered. New insulating liquids require further work w.r.t. the size effects, such as liquids in very low temperatures [48-50] as well as the nanofluids [51-53], not to forget challenging alternatives to transformer oil, such as silicone fluids [54] and vegetable oils [55]. Publications [56, 57] refer to a variety of possibilities regarding new promising insulating liquids and one can easily draw the conclusion that there is a lot more research to be done w.r.t. the size effects. Furthermore, such size effects must also be investigated in conjunction with the new proposed insulating liquids with solid insulation [30, 58]. Furthermore, since transformer oil is subjected to repetitive pulse stresses in some applications, it would be interesting to investigate the size effects also in relation to such pulse stresses [59]. In the aforementioned case, it is of interest to see whether foreign particles may play a role as suggested before [38] with other kinds of stresses.

IX. CONCLUSIONS

This short review presented aspects of older and more recent work on the size effects in insulating liquids. It seems that sometimes it is difficult to separate the area effect from the volume effect since the two intermingle and depend on the state of the liquid itself. The gap effect also plays a role affecting to a great extent the volume effect. The purity of the insulating liquid seems to play a determining role since it strongly influences the distribution of the breakdown voltage values.

REFERENCES

[1] S. Whitehead, "Electrical discharges in liquids," in *Dielectric Phenomena*, Eds. Benn, London, 1928

[2] D. F. Binns, "Breakdown in liquids," in *Electrical Insulation*, edited by A. Bradwell, Eds. Peter Peregrinus Ltd., London, UK, 1983, pp. 15-32

[3] R. Badent, "Modell der elektronendominanten Streamerentladung in Isolieroel," Ph. D. Thesis, Universitaet Karlsruhe, Institut fuer Elektroenergiesysteme und Hochspannungstechnik (IEH), 1996

[4] A. H. Sharbough, J. C. Devins, and S. J. Rzad, "Progress in the field of electric breakdown in dielectric liquids," *IEEE Transactions on Electrical Insulation*, vol. 13, pp. 249-276, 1978

[5] A. Beroual, M. Zahn, R. Badent, K. Kist, A. J. Schwab, H. Yamashita, K. Yamazawa, M. Danikas, W. G. Chadband and Y. Torshin, "Propagation and structure of streamers in liquid dielectrics," *IEEE Electrical Insulation Magazine*, vol. 14, no. 2, pp. 6-17, 1998

[6] W. R. Bell, "Influence of specimen size on the dielectric strength of transformer oil," *IEEE Transactions on Electrical Insulation*, vol. 12, no. 4, pp. 281-292, 1977

[7] J. L. Maksiejewski and H. Tropper, "Some factors affecting the measurement of the electric strength of organic liquids," *Proceedings of the IEE, Part II: Power Engineering*, vol. 101, no. 80, pp. 183-190, 1954

[8] W. R. Wilson, "A fundamental factor controlling the unit dielectric strength of oil," *Transactions of the AIEE, Part III: Power Apparatus and Systems*, pp. 68-74, 1953

[9] D. W. Swan and T. J. Lewis, "Influence of electrode surface conditions on the electrical strength of liquefied gases," *Journal of Electrochemical Society*, vol. 107, no. 3, pp. 180-185, 1960

[10] T. J. Lewis, "Molecular structure and the electrical strength of liquid hydrocarbons," *Journal of Electrochemical Society*, vol. 107, no. 3, pp. 185-191, 1960

[11] K. C. Kao and J. B. Higham, "The effects of hydrostatic pressure, temperature and voltage duration on the electric strengths of hydrocarbon liquids," *Journal of Electrochemical Society*, vol. 108, no. 6, pp. 522-528, 1961.

[12] A. M. Sletten and T. W. Dakin, "Electric breakdown of long gaps in transformer oil," *IEEE Transactions on Power, Apparatus and Systems*, vol. 83, no. 5, pp. 457-459, 1964.

[13] B. Gaenger, "The breakdown voltage of oil gaps with high DC voltage," *IEEE Transactions on Power, Apparatus and Systems*, vol. 87, no. 10, pp. 1840-1843, 1968.

[14] A. R. Nosseir, "Effect of dissolved gases, stress and gap spacing on high-field conductivity in liquid insulants," *IEEE Transactions on Electrical Insulation*, vol. 10, no. 2, pp. 58-62, 1975.

[15] Y. Kawaguchi, H. Murata and M. Ikeda, "Breakdown of transformer oil," *IEEE Transactions on Power, Apparatus and Systems*, vol. 91, no. 1, pp. 9-23, 1972.

[16] R. Hancox and H. Tropper, "The breakdown of transformer oil under impulse voltages," *Proceedings of the IEE, Part A: Power Engineering*, vol. 105, no. 21, pp. 250-262, 1958 .

[17] M. C. Holmes, "Breakdown voltage as a function of electrode area and dielectric homogeneity," *Journal of the Franklin Institute*, vol. 211, pp. 777-779, 1931.

[18] L. R. Hill and P. L. Schmidt, "Insulation breakdown as a function of area," *Transactions of AIEE*, vol. 67, pp. 442-444, 1948.

[19] K. S. Weber and H. S. Endicott, "Area effect and its external basis for the electric breakdown of transformer oil," *Transactions of AIEE*, vol. 75, no. III, pp. 371- 381, 1956.

[20] K. S. Weber and H. S. Endicott, "External area effect for large area electrodes for the electric breakdown of transformer oil," *Transactions of AIEE*, vol. 76, pp. 1091- 1098, 1957.

[21] B. Epstein, "Statistical aspects of fracture problems," *Journal of Applied Physics*, vol. 19, pp. 140-147, 1948.

[22] B. Epstein and H. Brooks, "The theory of extreme values and its implications in the study of the dielectric strength of capacitors," *Journal of Applied Physics*, vol. 19, pp. 544-550, 1948.

[23] T. H. Sie and O. Wohlfahrt, "Transference of test results from experiments on small models to n times larger test objects with insulation under oil," *AIEE Transactions on Power Apparatus and Systems*, vol. 81, pp. 601-607, 1962.

[24] H. Kappeler, "Recent forms of execution of 380 kV transformer bushings," *CIGRE Report*, No. 126, 1958.

[25] S. Palmer and W. A. Sharpley, "Electric strength of transformer insulation," *Proceedings of the IEE*, vol. 116, no. 12, pp. 2029-2037, 1969.

[26] J. K. Nelson, B. Salvage, and W. A. Sharpley, "Electric strength of transformer oil for large electrode areas," *Proceedings of the IEE*, vol. 118, no. 2, pp. 388-393, 1971.

[27] M. G. Danikas, "Factors affecting the breakdown strength of transformer oil," M. Sc. Thesis, University of Newcastle-upon-Tyne, Faculty of Engineering, Department of Electrical and Electronic Engineering, 1982.

[28] J. D. Morgan, M. A. Abdellah, and F. Ferracane, "Statistical analysis of breakdown in transformer oil," *Conference Record of the 1984 IEEE International Symposium on Electrical Insulation*, Montreal, Canada, June 11-13, 1984, pp. 288-290.

[29] P. Felsenthal and B. Vonnegut, "Enhanced charge transfer in dielectric fluids containing conducting particles," *British Journal of Applied Physics*, vol. 18, pp. 1801-1806, 1967.

[30] N. Parkman, "Breakdown in composites," in *Electrical Insulation*, edited by A. Bradwell, Peter Peregrinus Ltd., London, UK, 1983, pp. 52-69.

[31] N. Giao Trinh, C. Vincent, and J. Regis, "Electriode area and stressed volume: Two apparent effects of large-volume oil insulation," *Conference Record of 1982 IEEE International Symposium on Electrical Insulation*, Philadelphia. Pa. USA, June 7-9, 1982, pp. 115-118.

[32] K. L. Stricklett, D. M. Weidenheimer, N. R. Pereira, and D. C. Judy, "Electrcal breakdown in transformer oil in large gaps," *1992 Annual Report on Conference on Electrical Insulation and Dielectric Phenomena (CEIDP)*, Victoria, B.C. Canada, October 18-21, 1992, pp. 248-254.

[33] P. Rozga and D. Hantsz, "Influence of volume effect on electrical discharge initiation in mineral oil in the setup of insulated electrodes," *Electrical Engineering*, vol. 99, pp. 179-186, 2017.

[34] A. L. Kupershtokh, E. I. Palchikov, D. I. Karpov, I. Vitellas, D. P. Agoris, and V. P. Charalambakos, "Stochastic model of breakdown initiation in dielectric liquids," *Journal of Physics D: Applied Physics*, vol. 35, pp. 3106-3121, 2002.

[35] M. V. Patil, R. S. Pote, and R. S. Kankale, "Dielectric behavior of insulating material under transformer oil," *International Journal of Emerging Engineering Research and Technology*, vol. 2, no. 3, pp. 213-219, 2014.

[36] K. L. Ratnakar and B. Rajesh Kamath, "Influence of electrode configuration on AC breakdown voltages," *International Journal of Research and Scientific Innovation*, vol. IV, no. VI, pp. 60-63, 2017.

[37] S. I. Spartalis, M. G. Danikas, G. P. Andreou, and G. Vekris, "Statistical study of the oil dielectric strength in power distribution transformers," *Journal of Electrical Engineering*, vol. 59, no. 2, pp. 68-74, 2008.

[38] R. Tobazeon, "Breakdown in liquids: area effect, volume effect or … particle effect?," *Journal of Electrostatics*, vol. 40-41, pp. 389-394, 1997.

[39] K. N. Mathes and J. M. Atkins, "Influence of particles on partial discharges and breakdown in oil," *Conference Record of the 1978 IEEE International Conferenc on Electrical Insulation, Philadelphia*, PA, USA, 12-14 June, 1978.

[40] M. Rycroft, "Vegetable oil as insulating fluid for transformers," *Energize*, vol. April, pp. 37-40, 2014.

[41] W. Yuan, T. Wang, H. Ni, M. Gao, Y. Ding, Y. Li, Y. Zhao, and Q. Zhang, "Weibull statistical analysis of size effects on the impulse breakdown strength in transformer oil," *Proceedings of the 19th IEEE International Conference on Dielectric Liquids*, Manchester, UK, 25-29 June 2017.

[42] W. G. Chadband and J. H. Calderwood, "The propagation of discharges in dielectric liquids," *Journal of Electrostatics*, vol. 7, pp. 75-91, 1979.

[43] P. O. Wong and E. O. Forster, "The dynamics of electrical breakdown in liquid hydrocarbons," *IEEE Transactions on Electrical Insulation*, vol. 17, no. 3, pp. 203-220, 1982.

[44] E. O. Forster, "The search for universal features of electrical breakdown in solids, liquids and gases," *IEEE Transactions on Electrical Insulation*, vol. 17, no. 6, pp. 517-521, 1982.

[45] W. F. Schmidt, "Elementary processes in the development of the electrical breakdown of liquids," *IEEE Transactions on Electrical Insulation*, vol. 17, no. 6, pp. 478-483, 1982.

[46] E. O. Forster, "Partial discharges and streamers in liquid dielectrics – The significance of the inception voltage," IEEE Transactions on Electrical Insulation, vol. 28, no. 6, pp. 941-946, 1993.

[47] R. Sarathi, P. D. Singh, and M. G. Danikas, "Characterization of partial discharges in transformer oil insulation under AC and DC voltage using acoustic emission technique," *Journal of Electrical Engineering*, vol. 58, no. 2, pp. 91-97, 2007.

[48] H. Fujino, "Electrical insulation technology for superconducting devices in Japan," *IEEE Electrical Insulation Magazine*, vol. 6, no. 2, pp. 7-15, 1990.

[49] N. Hayakawa, S. Nishimachi, T. Matsuoka, H. Kojima, M. Hanai, and H. Okubo, "Breakdown characteristics and size effect in sub-cooled liquid nitrogen," *Proceedings of the 2014 IEEE International Conference on Liquid Dielectrics*, Bled, Slovenia, June 30–July 3, 2014.

[50] P. Malelis and M. G. Danikas, "Insulating materials at very low temperatures: a short review," *Engineering, Technology & Applied Science Research*, vol. 10, no. 3, pp. 5590-5595, 2020.

[51] Q. Wang, M. Rafiq, Y. Lv, C. Li, and K. Yi, "Preparation of three types of transformer oil-based nanofluids and comparative study on the effect of nanoparticle concentrations on insulating property of transformer oil," *Journal of Nanotechnology*, Article ID 5802753, 2016.

[52] M. Rafiq, Y. Lv, and C. Li, "A review of properties, opportunities and challenges of transformer oil-based nanofluids," *Journal of Nanomaterials*, Article ID 8371560, 2016.

[53] M. G. Danikas, "Breakdown in nanofluids: a short review on experimental results and related mechanisms," *Engineering, Technology & Applied Science Research*, vol. 8, no. 5, pp. 3300-3309, 2018.

[54] C. C. Claiborne and H. A. Pearce, "Transformer fluids," *IEEE Electrical Insulation Magazine*, vol. 5, no. 4, pp. 16-19, 1989.

[55] J. Carcedo, I. Fernandez, A. Ortiz, F. Delgado, C. J. Renedo, and C. Pesquera, "Aging assessment of dielectric vegetable oils," *IEEE Electrical Insulation Magazine*, vol. 31, no. 6, pp. 13-21, 2015.

[56] I. Fofana, V. Wasserberg, H. Borsi, and E. Gockenbach, "Challenge of mixed insulating liquids for use in high-voltage transformers, Part 1: Investigation of mixed liquids," *IEEE Electrical Insulation Magazine*, vol. 18, no. 3, pp. 18-31, 2002.

[57] I. Fofana, "50 years in the development of insulating liquids," *IEEE Electrical Insulation Magazine*, vol. 29, no. 5, pp. 13-25, 2013.

[58] J. Staight, "Properties and applications of solid/liquid composites," in *Electrical Insulation*, edited by A. Bradwell, Eds. Peter Peregrinus Ltd., London, UK, 1983, pp. 147-163.

[59] A. Pokryvailo and C. Carp, "Comparison of the dielectric strength of transformer oil under DC and repetitive multimillisecond pulses," *IEEE Electrical Insulation Magazine*, vol. 28, no. 3. pp. 40-49, 2012.