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ELECTRICAL BREAKDOWN OF LIQUID DIELECTRICS (A REVIEW)

I. E. Balygin

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Wright-Patterson Air Force Base, Ohio

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by

I. Ye. Balygin

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13. ABSTRACT

This review is a comparison of different test data on liquid dielectric breakdown. It supports the assertion that only in certain particular cases is the liquid breakdown mechanism similar to the mechanism of gas. This mechanism is largely determined by the physical and chemical nature of the substance and by certain external factors, such as the form and material of the electrodes, the form of the applied voltage, and a few others. From this it follows that no unitary mechanism for the breakdown of liquid dielectrics exists, and therefore one can scarcely look for the creation of a breakdown theory which will be generally valid for all liquid dielectrics, regardless of their physical and chemical nature.

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* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

ELECTRICAL BREAKDOWN OF LIQUID DIELECTRICS (A REVIEW)

I. Ye. Balygin, Candidate of Technical Sciences

As the reader is well aware, insulting liquids are extensively employed in the manufacture of electrical equipment and capacitors. For this reason, problems relating to the electrical strength of these liquids are understandably the subject of keen interest. Very important research on this subject has been conducted by Soviet scientists working in Moscow, Leningrad, and Tomsk.

It was long ago noted that, given a certain voltage, gas bubbles will appear on the electrodes of a gap filled with a liquid which has not been purified and purged of gas with the requisite care. Such bubbles grow more numerous as the voltage increases. They rise to the surface of the liquid as their place is occupied by new bubbles. At the higher voltages so many of these bubbles appear that they form a gas channel along the entire length of the interelectrode gap. Based on these data it has been concluded that the breakdown in liquids is nothing more than a slightly disguised gas breakdown.

For the special case of a severely nonuniform field and retarded discharges, V. S. Komel'kov [2] has shown, using

oscillographic recordings of the breakdown occurrences and photographing them with a rotating camera, that breakdown occurs in the same fashion in transformer oil and distilled water as it does in a vacuum. During the predischarge period individual streamers are formed (leader process), which originate at the electrode having the greatest curvature. In the event of two pointed electrodes the leader process begins at both. As the leader moves more deeply into the gap, the rate of its development slows and in some cases may even stop altogether. Corresponding to each leader stage is a current pulse. The duration of the leader stage in transformer oil in the case of sparkgaps $l \approx 18$ cm is 20-100 microseconds, but in water when $l \approx 11.7$ cm only 9.5 microseconds.

Certain similar features may also be found in the particular case of transformer oil and air breakdown under a highly inhomogeneous electrical field. Fig. 1, for example, shows curves illustrating the dependence of the breakdown voltage valve E_{np}* for air (a) [3] and transformer oil (b) on sparkgap length [5] in the case of a pulsed voltage and needle-shaped and flat electrodes. From these curves it is evident that, in both cases, E_{np} is considerably smaller for a positive point than for a negative, with the exception of air gaps of less than 5 mm.

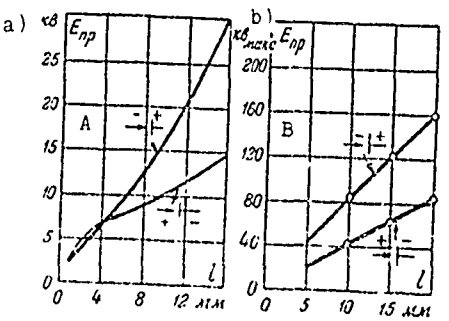

Fig. 1. Curves showing the dependence of breakdown voltages E_{np} for air (a) and transformer oil (b) on the length l of sparkgaps for points of different polarity.

KEY: a) kV; b) kV_{max}

*Translator's Note - The Russian letters "np" of the subscript signify "breakdown."

However, according to Panov [3], given the same point and plane but with a sparkgap of l = 6 cm, the E_{np} value for transformer oil is virtually independent of the point polarity in the case of an effective pulsed voltage time of 40-50 microseconds. On the other hand, the effect of polarity is again in evidence when l = 20 cm and the energizing is of the order of 10 microseconds. This indicates that to some degree the transformer-oil breakdown mechanism is determined by the length of the sparkgap and the effective time of the pulsed voltage.

Vorob'yev and Prikhod'ko [4] found a decrease in breakdown values for positive points, as compared with negative, in nine test liquids. There are indications, however, that the effect of polarity with shock voltages is negligible in the breakdown of purified and gas-purged transformer oil [5]. On the strength of this fact one may conclude that, given a sharply nonuniform electrical field, the breakdown mechanism of pure and degassed transformer oil differs from the breakdown mechanism of air.

Some similarity can be detected with respect to lowered breakdown voltages for transformer oil and air at high frequencies. According to Val'ter and Inge [5] the breakdown voltage of carefully purified mineral oils is about 30% lower at a freqency of 10^6 Hz than with a 50-Hz alternating voltage; for xylene, however, this decrease is only 5%. In the same frequency range the reduction equals some 20% for air.

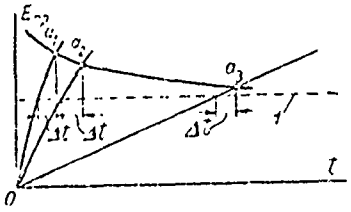

Fig. 2. Delay time in CCl_4 breakdown. Breakdowns at points a_1, a_2, and a_3.

For breakdowns of carbon tetrachloride CCl_4 (shock voltage), Attwood and Buxby [6] discovered that E_{np} falls off as the steepness of the pulse leading edge declines. It was also found that this is accompanied by only a very minor change in the breakdown delay time Δt (Fig. 2). On the average, Δt is equal approximately to several microseconds. Based on these observations the authors concluded that the CCl_4 breakdown mechanism is the same as that of air.

While acknowledging the inadequacy of the experimental data in support of such far-reaching analogies, the aforementioned authors nevertheless consider it probable that the CCl_4 breakdown delay is determined by the build-up time of a positive space charge at the anode in the form of a streamer. This streamer reaches the cathode by stages and the breakdown is completed.

An important point to be made here is that this explanation of the details of the breakdown mechanism of liquids based on gas discharge considerations cannot be entirely convincing for the reason that at the present time there is still no firm consensus regarding the details of the gas discharge mechanism itself. As the reader will recall, according to Townsend's theory the forming of a discharge in gases must occur at a comparatively slow rate. For example, given a uniform field, atmospheric pressure, and a 10 mm long sparkgap, discharge formation time in air should be about 18 milliseconds [7]. Experimental data, however, have indicated that this period is many times smaller [8]. It was this discrepancy, of course, that prompted the formulation of a new gas-breakdown theory - the streamer theory - according to which the brief delay time in breakdown formation when $p\delta > 200$ mm Hg × cm was explained by the effect of a positive volumetric charge and the processes of photoionization [9]. Subsequent testing, however, has demonstrated that this time is very largely dependent on the magnitude of the overvoltages

in the sparkgap [10]. In this way, the streamer theory has also been shown to be unsubstantiated.

Based on reasoning regarding the build-up of the positive volumetric charge and the corresponding deformation of the field, Attwood and Buxby have derived a formula which links the breakdown delay time Δt with the breakdown voltage values for pulsed E_u and constant E_n voltages:

$$\frac{1}{2}(E_u + E_n)\,\Delta t = C = \frac{D}{2},$$

where D is the length of the sparkgap, and C is a constant.

Analyzing test material on the breakdown of different liquids under the effect of squarewave pulsed voltage in a uniform field, Edwards [11] also concluded that the liquid breakdown mechanism resembles the gas. This writer conducted breakdown experiments for sparkgaps of very small length (a few hundredths of a millimeter). Pulse duration ranged from 0.2 to 20 microseconds. Fig. 3 shows the breakdown voltage curves obtained by Edwards for benzene and thrice-distilled water for different squarewave pulse durations. These curves indicate that at exposures of less than 3 microseconds the breakdown voltages of liquids begin to rise. Approximately the same thing was found for hexane, octane, carbon tetrachloride, and ethyl alcohol. In addition, it was discovered that by increasing the length of the sparkgap the E_{np} of the liquids is made to decrease (Fig. 4). Edwards explains this relationship by ionization processes associated with breakdown formation. Somewhat earlier [12] the same laws had been discovered in the breakdown of benzene and ethyl alcohol.

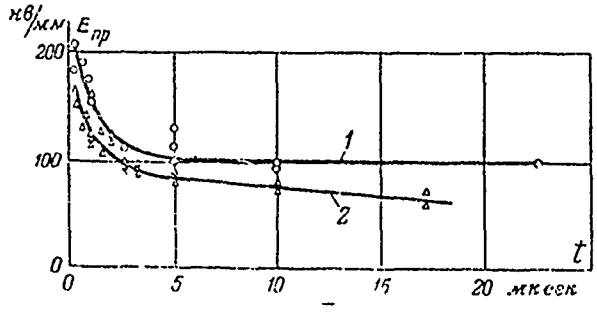

Fig. 3. Dependence of breakdown voltage on the duration of a squarewave pulse: 1 - benzene; 2 - water.

Designation: кв/мм = kV/min; мксек = μs.

In the two last-mentioned articles there are, among other things, indications that, once begun, breakdown may possibly complete itself within a time period of 10^{-9} s. This seems to be a purely gratuitous assertion, and it should be remembered in this connection that the whole question of the duration of breakdown formation and completion, not only in liquids but in solid dielectrics as well, is not completely clear at the present time, with different authors citing contradictory data. References can be cited to the effect that the time during which breakdown must be completed is 10^{-5}-10^{-6} s [8]. The justification here is that inasmuch as the increase of uniform-dielectric breakdown voltages begins at times less than 10^{-5}-10^{-6} s, thus about the same interval should be required for completion of the breakdown. There are also allusions to a probable duration of 10^{-7} and 10^{-8} s [13, 14, 15, 16]. For their substantiation of breakdown development duration in liquid and solid dielectrics authors frequently refer to the oscillographic recordings of air breakdown obtained by Rogowski and his colleagues a quarter-century ago [8]. On this count it is worth-while noting that there are as yet insufficient grounds for the drawing of analogies between the breakdown formation time in air and in dielectrics of different aggregate state having a different physical and chemical character.

Differences in the breakdown mechanism of gases and liquids can be seen in the dependence of $E_{пр}$ on the electrode material. For benzene, hexene, and xylene it has been found that, given a uniform field, the breakdown voltage of liquids decreases from

silver to iron electrodes [17] in the following order: silver (greatest E_{np}), zinc, gold, aluminum, copper, lead, brass, steel (least E_{np}). According to Edwards [11] there is a noticeable difference (~18%) in E_{np} for benzene and CCl_4 with electrodes of phosphor-bronze, silver, and steel, but the highest E_{np} are obtained with steel electrodes in a uniform field. Evidently, this obvious contradiction can be explained by differences in the size of the sparkgaps and voltage waveforms. One thing is certain, and that is there *is* a relationship between E_{np} and the electrode material in the breakdown of liquids. In air breakdown (uniform field), on the other hand, no such relationship has been discovered, save for gaps measuring hundredths of a millimeter [18].

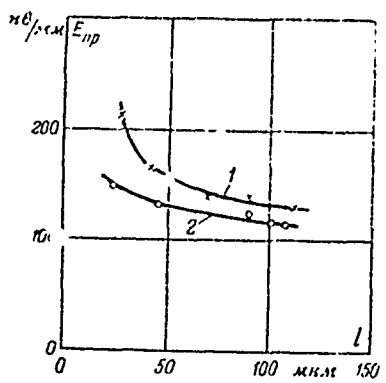

Fig. 4. Dependence of electric-field breakdown strength on sparkgap length. Uniform field and squarewave pulse: 1 - benzene; 2 - n - hexane; *l* - sparkgap length.

Designation: кв/мм = kV/mm мкм = μm.

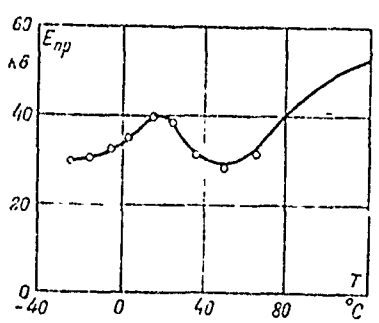

Fig. 5. Dependence of breakdown voltage of glycerine on temperature with a pulsed voltage and severely nonuniform electrical field. T - temperature.

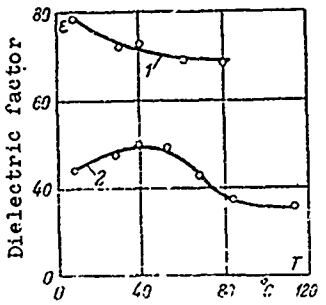

Fig. 6. Dependence of the electrical permeability of glycerine and water on temperature: 1 - water; 2 - glycerine; ε - dielectric factor; T - temperature.

For certain liquids there is a major difference in the temperature dependence of E_{np} with respect to the same dependence for gases. For example, following Vorob'yev and Prikhod'ko [4, 19], the E_{np} of glycerine in a nonuniform field (positive and negative point) varies with increasing temperature according to the curve in Fig. 5, while the temperature dependence of the electrical permeability of this substance follows the curve shown in Fig. 6 (for purposes of comparison this same figure also indicates a similar curve for water). It will be seen that ε is maximum at 35-40°C. Comparing Figs. 5 and 6 one concludes that E_{np} of glycerine depends on ε; as the latter decreases, E_{np} increases. The same relationship was also found for water (Figs. 6 and 7), the only difference being that E_{np} increases only to a temperature of 60-70°C.

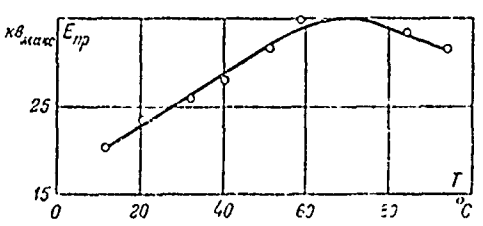

Fig. 7. Dependence of the breakdown voltage of water on the temperature for a pulsed voltage and severely nonuniform electrical field.

Designation: кв/макс = kV/max.

The reader will recall that according to Townsend's theory, which is considered valid today for $p\delta < 200$ mm Hg × cm, the expression for the current as a function of the ionization coefficients and sparkgap length contains the initial current value i_0:

$$i = i_0 \frac{(\alpha - \beta) e^{(\alpha-\beta)\delta}}{(1-\gamma)\alpha - (\alpha\gamma + \beta) e^{(\alpha-\beta)\delta}}.$$

When β and $\gamma = 0$, the avalanche build-up formula is simplified: $i = i_0 e^{\alpha\delta}$. It would appear that if the breakdown mechanism for liquids and gases is the same, then the initial conductivity of the former ought to have a significant effect on the breakdown voltage value; however, no appreciable difference in breakdown voltages has been discovered in testing with purified and unpurified xylyl despite the fact the conductivities of these liquids differ very markedly [20]. The same result was also forthcoming in breakdown experiments with water and certain aqueous solutions [21]. Using pulsed voltages, studies were run on distilled water with a conductivity of $1.43 \cdot 10^{-4}$ ohm^{-1} cm^{-1} and an NH_4OH aqueous solution with an approximately seven-times-greater conductivity. The following breakdown voltages for a 0.4-mm gap were found: 18 kV for the distilled water and 25 kV for the NH_4OH solution. Consequently, in this case too the breakdown voltage was found to be higher for the solution despite the fact that its conductivity was several times greater than that of the pure water. From this it is clear that, at least in certain cases, the breakdown mechanism for gases and liquids is not the same.

Thus, when comparing the laws governing the breakdown of liquid and gaseous dielectrics similar and dissimilar features can be found. What all this means is that there is no single mechanism to explain liquid breakdown. The material of the electrodes, the length of the sparkgap, the voltage waveform, the geometry of the electrical field, and certain other factors - all of these, evidently, to one degree or another, influence the discharge mechanism. For this reason, in isolated instances, a discharge similar to a gas discharge results. Other test data, as we have seen, provide a basis for diametrically opposite assertions. There is reason to believe that a major role is

played in the breakdown of insulating liquids by electron capture on the part of the molecules of the substance. If this formative process is considered from the point of view of the Townsend theory, then with electron capture by the liquid molecules a correction factor must be introduced into the avalanche expression, since as the probability of capture C increases, ionization intensity will decrease, but at the same time there will exist a certain probability of the release of the captured electrons r because of thermal oscillations [22]. Thus, the avalanche build-up must follow the law:

$$n = n_0 \exp\left[\int_0^x (\alpha - c + r)\, dx\right].$$

In addition to this correction for electron capture, there is general recognition of energy losses by moving electrons due to the excitation of oscillations in the neighboring molecules or atoms of liquid and solid dielectrics.

In gases the energy of electrons moving in an electrical field is expended mainly in the excitation of atoms and molecules, the dissociation of molecules, and second-order collisions. This loss mechanism protects the gas against easy breakdown. Losses of this kind also take place in liquids, but here energy consumption is directed in far larger measure to the excitation of oscillations in the electrons of the molecules and atoms [23]. The present view holds that when slow electrons collide with molecules the transfer of energy quanta does not take place mechanically, but is effected through an electrical interaction. Because of this, changes occur in the binding forces of the molecule atoms. Their equilibrium state is disrupted and oscillations are originated [24].

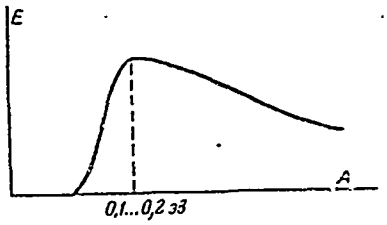

Fig. 8. Energy losses by electrons moving in an electrical field on interaction with the molecules of the substance: E - applied field strength; A - electron energy $\frac{eV^2}{2}$

It is easy to imagine that there must exist some maximum applied field strength at which the greatest electron energy loss will occur, inasmuch as the slow electrons have inadequate energy to excite vibrations, while the fast interact with molecules during a brief time interval, with the heavy molecules unable to move from their place (Fig. 8).

The electrons released in impact ionization enter the conductivity zone with low energy. Then, moving in the electrical field, they acquire sufficient energy for impact ionization. The applied electrical field compensates for the electron energy losses, and breakdown ensues provided that, on the average, the electrons receive more energy from the field than they lose in vibration excitation and for other causes of consumption. At the present time, this concept is regarded as the most accurate, although its accuracy has been demonstrated only in the breakdown of alkali-haloid crystals.

From this discussion of the contemporary view of the breakdown effect in liquid dielectrics one might conclude that during the formational period of the breakdown what happens is a kind of conversion of part of the energy of the applied electrical field into thermal energy through vibration excitation and radiant energy through disturbances of the electrons of the molecules and atoms of the dielectric. These processes may be of scientific

and practical interest from the standpoint of dielectric breakdown under limited-power pulses. If during the formation of the breakdown there is a conversion of the electrical energy of the applied field and if the store of this energy is limited, then its pre-breakdown consumption will lead to deformation in the form of the pulse, and the breakdown voltage may increase. A number of references can be found in the technical literature to energy losses in preparation of breakdown [25].

From the practical standpoint, questions of breakdown by pulses of severely limited power are important in the shielding of electrical machines, equipment, and explosion-hazard premises against induced overvoltages caused by lightning. Regrettably, the literature contains no information on this question.

Thus, collations and comparisons of different test data on liquid dielectric breakdown supports the assertion that only in certain particular cases is the liquid breakdown mechanism similar to the mechanism for gas. Generally speaking, evidently, this mechanism is largely determined by the physical and chemical nature of the substance and by certain external factors, such as the form and material of the electrodes, the form of the applied voltage, and a few others. From this it follows that no unitary mechanism for the breakdown of liquid dielectrics exists, and therefore one can scarcely look for the creation of a breakdown theory which will be generally valid for all liquid dielectrics, regardless of their physical and chemical nature.

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