Zeitschrift: Helvetica Physica Acta
Band: 45 (1972)
Heft: 5

Artikel: On the breakdown mechanism of recurring discharges in a liquid dielectric

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DOI: https://doi.org/10.5169/seals-114415

Helvetica Physica Acta
Vol. 45, 1972.
Birkhäuser Verlag Basel

On the Breakdown Mechanism of Recurring Discharges in a Liquid Dielectric

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Abstract. The breakdown strength of recurring discharges has been investigated with an apparatus which permits the application of high-voltage and high-current pulses at a variable rate to an electrode system with programmable electrode separation and with paraffin as dielectric. The experimental results for the breakdown strength are given as a function of several discharge parameters. The dependence on the time interval between successive discharges has been studied with particular emphasis. The breakdown strength was shown to decrease systematically with diminishing time interval. A quantitative explanation of these observations is presented on the assumption of an avalanche process originating in the liquid. Supposedly the electrons which are emitted from the previous discharges and whose number depends on the time interval between the discharges are multiplied until a critical charge density is reached giving rise to a streamer and eventually leading to breakdown.

Introduction

The mechanism of electric breakdown in dielectric liquids has for a long time been the subject of various investigations. Progress has however been slower than in the fields of gaseous discharges or of solid dielectrics. Judging by the number of published papers (see bibliography of the review articles of Ref. [1]) considerable work has, nevertheless, been done. We must, therefore, conclude that the processes involved are complicated and that many mechanisms may be at work.

The theories dealing with breakdown in liquid dielectrics can be divided into two main groups: the first assumes that an avalanche process of ionization takes place as it is known to occur in gases and solids; the second group claims that the preponderant role is played by the presence or the creation of agents of another phase (bubbles, suspended solid particles). Both sets of theories have strong arguments in their favour and are still vigorously advocated by their respective partisans (see recent review articles, Ref. [2]). In fact the two points of view do not differ as fundamentally as it may seem. The theories based on multiplication of charge carriers have to allow for a transition from the liquid to the gas phase at a given stage of the discharge, since an arc is eventually formed; whereas in the cavitation theories, an avalanche process is supposed to develop in the gas bubble. The difference between the two theories is therefore only a question of the succession of the events. Nevertheless, it must be understood that the criterion for breakdown will depend strongly on the order of events.

We have decided to study the breakdown phenomena by applying repetitive discharges to a pair of electrodes which are separated by a small gap. Therefore, we have adapted for our measurements a commercial electro-discharge machine by

providing it with the necessary equipment for generating the discharge power and for transducing and processing the measurement data.

The main result of this study to be presented here is a relation between the time interval Δt_I between successive discharges and the breakdown strength E_B. The latter is obtained by measuring the average breakdown voltage $\bar{U}_B$ and the mean value d of the gap.

$$n_{\text{crit}} = \frac{\text{const}}{(\Delta t_I)^x} \exp\left(\delta a \exp - \frac{b}{E_B}\right). \tag{1}$$

This expression is interpreted in the following way. n_{crit} is the electron concentration needed for the formation of a streamer which leads to breakdown. It is built up from an initial density n of charge carriers by a multiplication process. The high speed of breakdown, making necessary a very fast electronic detector for measuring the peak height of the electrode voltage, limits the choice of the charge carriers to free or almost free electrons. The initial density n of electrons which are available after the time interval Δt_I since the previous discharge is responsible for the memory effect between successive sparks. It decays proportional to $(\Delta t_I)^{-x}$. This law corresponds to a diffusion or recombination process as expected if x is of the order of unity. The multiplication process appears in the second factor of our expression and has the form $\exp \alpha\delta$. The ionization coefficient α depends on the electric field E according to $\alpha = a \exp(-b/E)$, where the length a^{-1} is related to the path of the carriers between ionizing collisions and where b is given by the ionization potential divided by the mean free path for inelastic collisions. δ is the width of the cathode region in which the electric field is supposedly enhanced and where, therefore, the avalanche builds up.

Fitting the measured data to the equation (1) yields numerical values for $\delta a/x$ and b. With an upper limit for δ of a few μm and with $x = 1$ a lower limit for a and b is deduced of $a = 10^5$ cm^{-1} and $b = 1.2 \cdot 10^6$ volts/cm. These values are compatible with those estimated from the molecular data.

Since no simple explanation of the observed data can be given if breakdown were controlled by the presence of gaseous cavities we believe that our measurements tend to support the breakdown hypothesis based on electron multiplication processes in the liquid phase.

Experimental Technique

The experimental arrangement purports to control, as precisely as possible, the relevant parameters which influence the discharges in a liquid. The task is not easy, firstly because the dimensions within which these phenomena occur are exceedingly small and secondly because they are extremely rapid and follow each other at a high repetition rate. In addition to this comes the complication caused by the stochastic nature of the processes.

The experimental set-up for measuring the breakdown strength consists of three main parts. The central part is composed of the electrode pair, together with a servo system for controlling the distances between the two electrodes, and of a hydraulic circuit. The latter supplies the dielectric liquid to the gap between the electrodes. The second part consists of a power and control device which furnishes the electric discharge current pulsed according to given pulse lengths and interval instructions. A control signal is provided for the servo system which drives the mobile electrodes

according to a cyclic program governing the variation of the size of the gap. The measuring instruments form the third part. They comprise transducers, electronic analogue equipment, data acquisition apparatus and recorders. The block diagram of Figure 1 shows these elements and their interconnections.

The electrodes were given the form of two identical tubes. They are mounted on a common axis as shown in Figure 2. As a consequence, the discharge takes place between the two opposing end faces. The walls of these ring-shaped faces are 5 mm wide and have an outer diameter of 40 mm. The dielectric fluid is introduced under slight pressure into the tubes and flows outwards through the gap. These are ideal conditions from the point of view of electro-discharge machining, in so far as the velocity of the dielectric fluid is almost uniform over the whole working area. The electrode materials investigated are electrolytic copper and steel (Ac 37-2N).

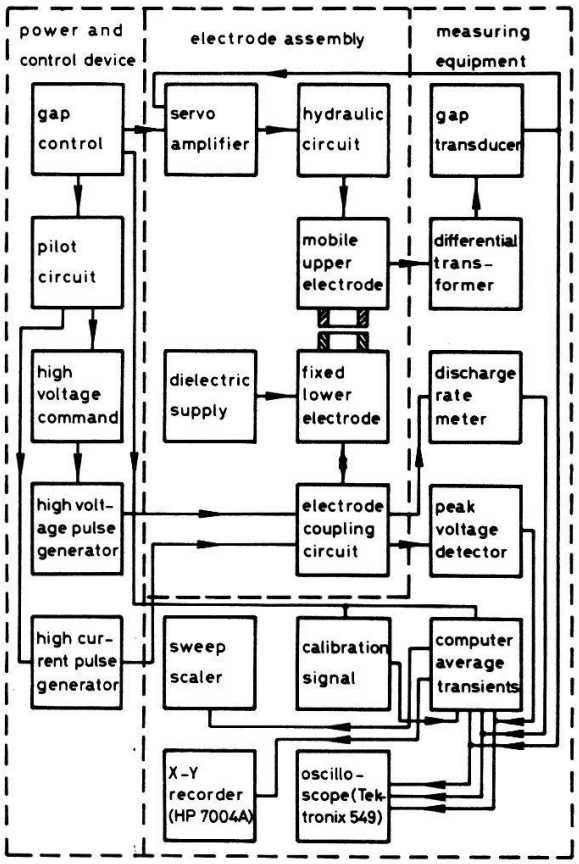

Figure 1
Block diagram of experimental set-up.

The electrodes are mounted on a machine for electro-discharge machining (Eleroda D1-S[1])) which incorporates a hydraulic servo system. Normally, the servo controls the gap between the electrodes with a view of maintaining optimal working conditions. In our case, we were obliged to have the gap varying linearily in order to be able to record the breakdown data as a linear function of the gap. We therefore had to equip the machine with a transducer for measuring the size of the gap. The error signal for the servo control corresponds to the difference of the sawtooth command signal and the measured gap size. Figure 3 illustrates schematically the servo system. A second servo, incorporated in the gap transducer, is interlaced with it and will be referred to

[1]) Obtained through the courtesy of the Ateliers des Charmilles S.A. Geneva.

later. A complete cycle of the command signal contains, besides the sawtooth during which the discharges are applied, a phase where the gap is flushed with clean paraffin oil and where the transducer is readjusted by bringing the electrodes into contact with each other. The minimum and maximum gap can be chosen within a limit of 100 μm. The length of one cycle can be varied from approximately 1 to 4 sec.

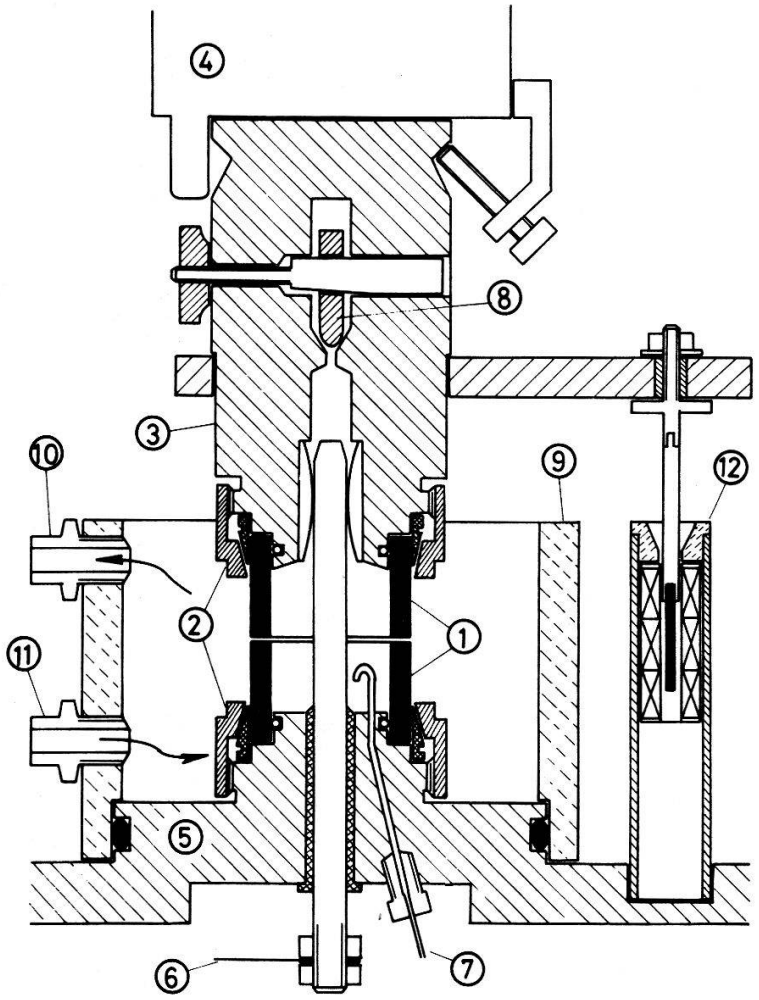

Figure 2
Mechanical set-up of electrode assembly:

1. Pair of electrodes
2. Tightening nuts
3. Holder of mobile upper electrode
4. Servo piston for vertical displacement of the upper electrode
5. Holder of fixed lower electrode (at ground potential)
6. Electrical connector for upper electrode
7. Dielectric fluid supply
8. Air vent
9. Dielectric liquid container
10. Dielectric liquid outlet
11. Dielectric liquid inlet (for continual flushing of containiner)
12. Displacement transducer (differential transformer).

The frequency response of the servo system has been pushed upwards by means of electronic phase advance so that the resonance frequency lies at 40 hertz.

The dielectric liquid is a well-defined fraction of paraffin (Mentor 28 from Esso). It is injected into the electrode tubes and flows through the gap outward as a laminar current. If it were injected at constant pressure, the mean flow velocity would vary

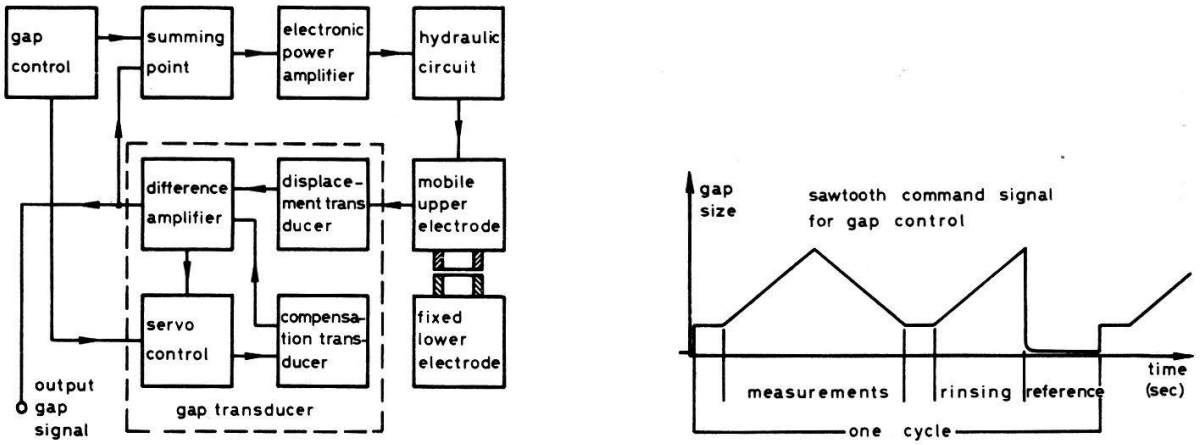

Figure 3
Block diagram of the servo system for the gap control, with diagram of sawtooth command signal.

according to the square of the gap. In order to reduce a velocity variation by as much as 100 times, under constant pressure the oil is injected through a capillary tube of such dimensions that the flow rate becomes almost constant. In this way the flow velocity is governed, when the gap is very small, by the gap resistance and as soon as the gap reaches normal operating values, by the resistance of the capillary tube. As can be seen from the broken line curve in Figure 4, the velocity changes in this case by approximately a factor of 5 whilst the gap varies from 10 μm to 100 μm. Since contamination of the dielectric is known to be a decisive factor in breakdown behaviour, its concentration has to be controlled carefully. The incoming fluid ought to be fresh; the contamination built up by the discharges should be maintained constant, irrespective of the size of the gap. This is the case for a constant flow rate of the dielectric liquid. According to the full line curve in Figure 4, this was achieved down to the smallest useful electrode distances. Prior to the injection into the capillary tube at a pressure of 6 atm. the paraffin oil is cleaned by passing it through a millipore filter type AA, the size of the pores being 0.8 μm.

The task of generating the discharge high-voltage and high-current pulses had to be divided among two different instruments. The high-voltage generator is capable of charging the electrodes to more than 2000 volts within 20 to 200 nsec. This implies currents of up to 50 amperes and more since the electrode capacity (plus stray capacities) varies from 300 to 1000 pF according to the size of the gap. The circuit employs three stages equipped altogether with six vacuum tubes, Philips PL 509.

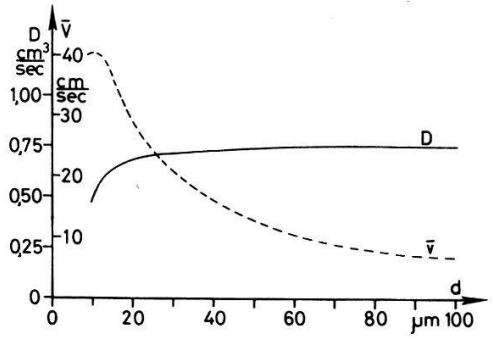

Figure 4
Flow rate D and verage flow velocity v of the dielectric liquid traversing the electrode gap.

After the discharge has been ignited by the high-voltage pulse, a second generator takes over the task of furnishing the current. Rapidly after the breakdown, the discharge channel becomes highly conducting and forms an arc, the arc voltage being comprised between 20 and 40 volts. The Isopulse ELP S-1 generator provided with the Eleroda D1-S machine delivers, for any length of time, the necessary arc current up to 40 amperes. It is fitted with transistors for a maximum of 80 volts.

The two generators are branched to the electrodes through a chain of diodes which isolate the generators from each other. In keeping with the fast pulse risetime, they have to switch fast, stand high voltages and high current. In order to avoid current loops, the connection to the upper electrode—the lower electrode is at ground potential—is made inside the tube by means of a bar which is mounted on the axis of the two tubes (see Figure 2). It extends through the bottom of the lower electrode into a box-like support where the diodes are located. The box also houses a grounding resistor and the attenuators which, for measuring purposes, divide the electrode voltage. The electrical components in the box are cooled by the same dielectric liquid which circulates in the container surrounding the electrodes.

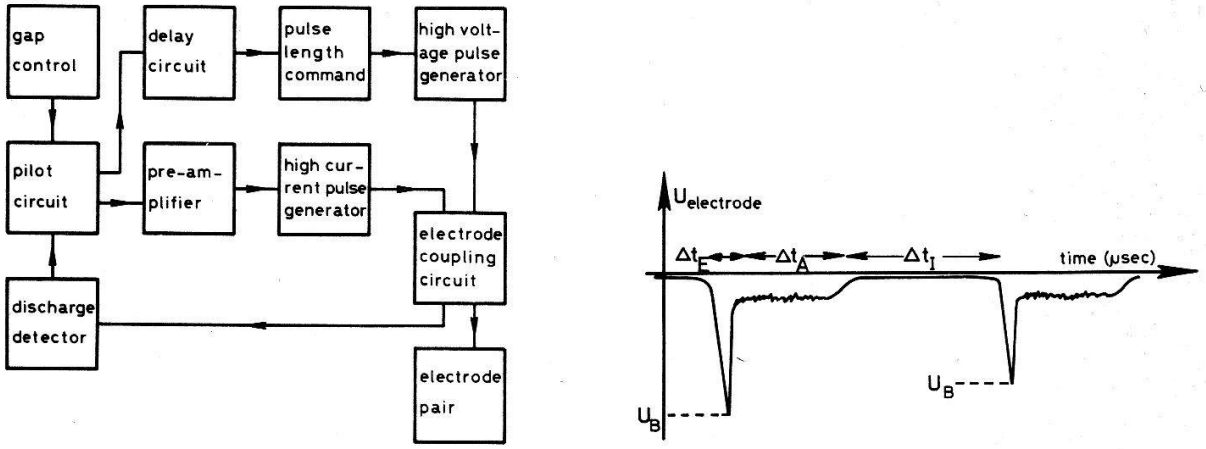

Figure 5
Block diagram of the discharge command and pulse generator circuit, with diagram of the pulse form.

The generators are connected and synchronized by the pilot circuit shown in Figure 5. This circuit generates a short pulse, variable in length from 20 to 200 nsec, which is applied to the high-voltage generator. It generates also a long pulse, the duration of which can be chosen in powers of 2, starting at 1.5 μsec. This pulse is applied to the Isopulse generator. The delay between the two signals takes account of the rise and transit time of the pulses in the generators so that the current is ready to flow from the Isopulse generator when breakdown occurs. The repetition fequency of the pulses is controlled by the selection of the time interval between the current pulses, the increments being the same as for the pulse duration.

What follows describes the measuring equipment, beginning with the gap transducer. As was already mentioned in connection with the servo control for the electrode gap, the gap transducer forms part of the feedback loop. The measurement of the size of the gap has to be effected with great care because the breakdown characteristic depends so strongly on this quantity. In order to determine the size of the gap, it does not suffice to measure the relative position of the two electrodes—this is done by means of the differential transformer—but it is also necessary to take into account the wear of the electrodes resulting from the erosive action of the discharges. Although

this effect changes continuously the value indicated by the displacement transducer the variation is slow enough to tolerate a correction in intervals of a few seconds. The correction is applied by having the core of a second differential transformer, called compensation transducer, servo controlled, so that the difference signal of the two transformers indicates zero when the electrodes are brought into contact with each other. It will be recalled that this is done once every cycle of the electrode movements. The sensitivity of the transducer is 18 mvolts/μm $\pm$ 5%. It is constant within these error limits over a region of 3 mm. The reproductibility of the output signal for a given position is better than 1 μm.

For the measurement of the breakdown voltage, a peak voltage detector has been developed. The probe connected to the electrode divides the potential of the electrode step by step, offering different attenuation ratios. For the best high-frequency response, the cable transmitting the signal from the electrode assembly to the instrument rack is terminated and acts as the last resistor of the divider. The voltage peak height is

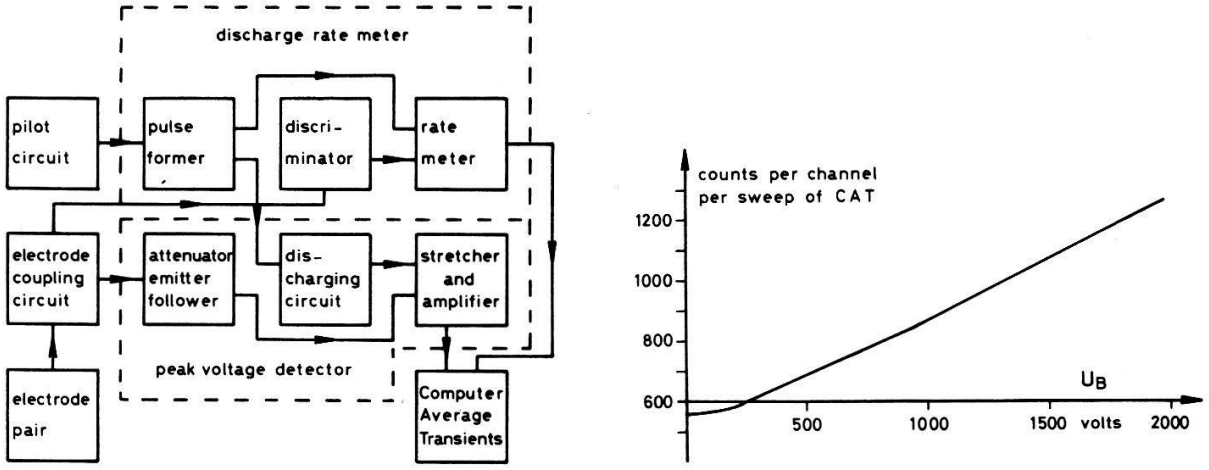

Figure 6
Block diagram of discharge rate meter and peak voltage detector for the measurement of the breakdown voltage, with calibration curve.

stored by charging a capacitor through a diode, followed by suitable amplification, in order to obtain a low impedance output. The time constant for charging the peak detecting capacitor is 14 $\pm$ 2 nsec; the output signal decays almost linearly within 20 $\pm$ 2 msec to zero. Prior to any measurement, the peak detector is discharged so that a peak of lower voltage than the preceding pulse can faithfully be recorded. The discharging takes place just $\frac{1}{2}$ μsec before the new voltage peak arrives, so that the mean output voltage recorded by the computer of average transient (CAT) is little affected.

When discharges occur over very small distances, it often happens that the gap is short-circuited (an explanation based on the formation of metallic bridges is given in Ref. [3]). In order to determine the mean breakdown voltage, the frequency of the pulses giving rise to true discharges had, therefore, to be known. A rate meter with a discrimination level adjusted to little below the arc voltage was added to the peak detector as illustrated by the block diagram of Figure 6.

The output of these measuring instruments, namely the gap transducer, the peak detector, the discharge rate meter and a calibration signal was fed to the computer of average transients which sweeps these four input voltages each over a hundred channels where they are successively added up. The sweep is synchronized with the

electrode movement. The recorded data correspond, therefore, to the mean breakdown voltage as a function of the gap. For small values of the gap where the electrodes are likely to become shorted, as already mentioned, the breakdown voltage has to be corrected according to the reduced discharge rate. Other corrections are necessary for the threshold of the peak detector and for its charge loss when the intervals between discharges become comparable to 20 msec. The non-linearity of the analogue-to-digital converter was quite appreciable (12%) and could only be partially eliminated. The overall calibration curve which connects the electrode voltage with the number of counts per sweep accumulated in a channel of the CAT is to be found in Figure 6. At given pulse parameters, a standard measurement run comprises hundred cycles of the electrode movement and lasts somewhat less than 10 min.

Simultaneously with the recording by the CAT, the breakdown behaviour was studied in a direct manner by means of a storage oscilloscope Tektronix 549. Whereas the CAT provided mean values, observations on the oscilloscope informed about the scattering of the breakdown strength.

Measurements

It is a well-known fact in the field of electro-erosion that the breakdown strength of a dielectric liquid diminishes when discharges are produced recurrently. This being granted, we feel that the analysis of the breakdown mechanism has to be based on these premises. Consequently, we measured the breakdown voltage U_B as a function of the size of the gap for different time intervals between discharges.

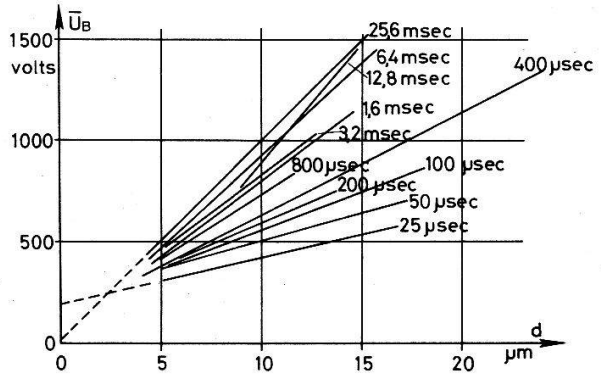

Figure 7
Average breakdown voltage $\bar{U}_B$ as a function of electrode gap d for short duration high-voltage pulses, $\Delta t_E + \Delta t_A = 200$ nsec. Positive electrode: electrolytic copper; negative electrode: steel Ac 37-2N; dielectric liquid: Mentor 28 Esso; pulse interval Δt_I as indicated.

Our conclusions are mainly based on the measurements effected on pulses of short duration (200 nsec) produced by the high-voltage generator. The results are shown in Figure 7.

We also investigated discharges of longer duration obtained by switching on the current generator after breakdown has been ignited by the high-voltage generator. Unfortunately, the data acquisition system as it then existed was unable to retrieve reliable averages of the breakdown voltages, except for the shortest pulse duration of the current generator which is 2.5 μsec. This pulse duration is somewhat longer than that indicated in the foregoing section. The reason is that the current continues to flow after the end of the command signal due to the induction of the cables. Figure 8

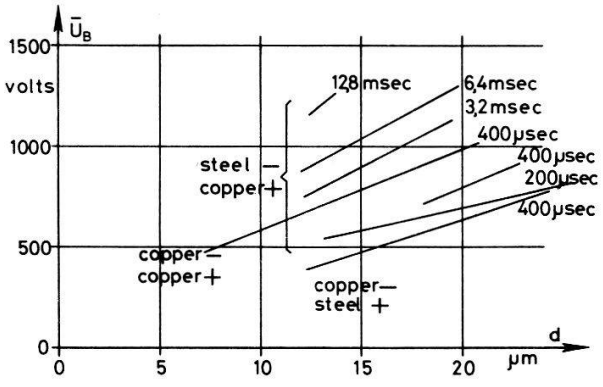

Figure 8
Average breakdown voltage $\bar{U}_B$ as a function of electrode gap d for high-voltage pulses followed by rectangular current pulses of $I = 18$ amp. and $\Delta t_A = 2.5$ μsec. Electrodes: copper and steel with polarity as indicated; dielectric liquid: Mentor 28 Esso; pulse interval Δt_I as indicated.

gives the results of the corresponding measurements. A comparison of the curves with those of Figure 7 having the same time interval, Δt_I, reveals that an increase in the discharge length Δt_A diminishes the breakdown voltage, the same way as a reduction of the time interval between discharges does. This effect is the more pronounced the longer the pulses are. Quantitative recording is hampered due to the occurrence of an overlap of the gap region of dominating short-circuits with the region of occasional lack of ignition. Under such conditions, the calculation of reasonably correct average breakdown voltages becomes impossible. Even the measurements of Figure 7 are subject to a certain margin of error due to the calibration of the peak detecting instrument as well as to other sources. The absolute error may amount to ±20%. However, the relative error is believed to be much smaller. Figure 9 illustrates, by way of example, the relevance of statistical and systematic deviations of the individual data of all the measurement runs which have been combined to establish the curve for $\Delta t_I = 1.6$ msec of Figure 7. The points of the graph in Figure 9 represent an average obtained by accumulating in the CAT the peak voltages of roughly 2000 discharges. The concluding section will revert to the problem of the scattering of the breakdown voltage and provide the opportunity for some particular observations.

The electrode pair of the measurements recorded in Figure 7 consist of a positive copper and a negative steel electrode. This combination, typical of electro-erosion work, does not seem to influence much the results obtained with the short high-voltage pulses. The reversal of the polarity of electrodes or the combination of two steel or two copper electrodes do not yield very different breakdown curves (Figure 10).

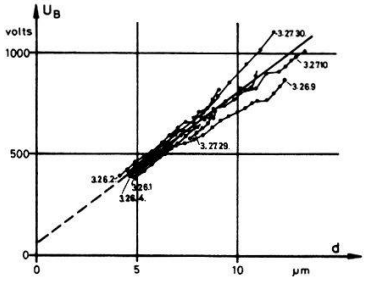

Figure 9
Examples of individual measurements of the breakdown voltage U_B as a function of the electrode gap d corresponding to the averaged curve for $\Delta t_I = 1.6$ msec of Figure 7. Number of measurement run indicated.

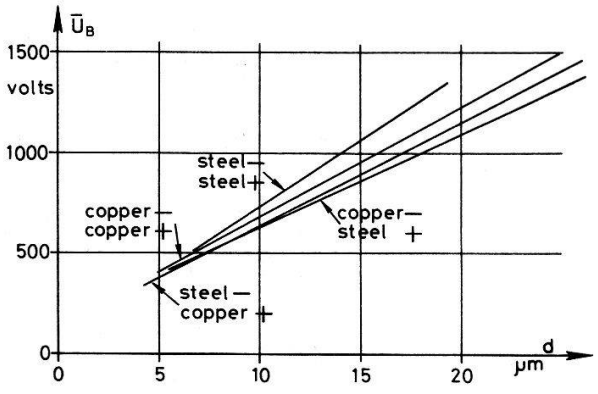

Figure 10
Average breakdown voltage $\bar{U}_B$ as a function of electrode gap d for short duration high-voltage pulses with different electrode materials, as indicated. Dielectric liquid: Mentor 28 Esso; pulse interval $\Delta t_I = 400$ μsec.

This does not hold true when discharges of longer duration are involved (Figure 8). With respect to those measurements, work in progress undertaken with more powerful data-handling equipment will be the object of a subsequent paper.

Discussion

Since a discharge in a liquid is accompanied by a large number of secondary effects, as for example loading of the dielectric liquid with impurity ions, injection of free electrons, creation of gas bubbles, alteration of the chemical composition of the liquid, local increase in the temperature of the liquid, initiation of shock waves, attack of the electrode surfaces, heating up of the metallic boundaries, ejection of metal particles, numerous hypotheses can be put forward to explain the decrease of the breakdown strength when the time interval between discharges diminishes. We will analyse the data in terms of electronic processes as we believe that the rapidity of the breakdown event necessarily involves the fastest acting charge carriers which are the electrons. Any other charged entity with lower mobility must seem inappropriate as they would not establish conduction within a few nanoseconds. The absence of any change of behaviour of the breakdown strength when passing with suitable substances from the liquid phase through the critical point to the gas phase is also considered as evidence against having electronic processes starting only after the formation of gas bubbles. Our conception of the breakdown mechanism in liquids coincides, therefore, with the electronic breakdown theory of solid dielectrics which was formulated by von Hippel [4]. The credit for introducing the concept to liquid dielectrics goes to Goodwin and Macfadyen and to Lewis [5].

According to the electronic theory, breakdown is thought of as proceeding through the following stages: emission of free electrons, their multiplication, formation of a plasma channel and transition to an arc discharge.

The presence of a free electron is always necessary to initiate a multiplication process. In order to explain the memory effect of breakdown strength when the discharges follow each other rapidly a certain abundance of free electrons varying as a function of the repetition frequency is postulated. This could be due to a static charge left over from the previous discharges which could be maintained on shallow traps and from which the electrons could easily be freed. Free electrons could also be thought of emanating from the electrodes as a permanent current. In this case the time variation

would come from a corresponding variation of the emission rate or a change of the drift velocity. Immediately after a discharge the potential distribution at the electrode–liquid interface or the scattering centres in the liquid might become distorted and would be restored through diffusion. A better knowledge of these processes is necessary to interpret correctly the dependence of breakdown strength on the electrode materials.

As an electric field is applied between the electrodes the free electrons accelerate and undergo collisions, some of them leading to ionization. The few initial electrons multiply and form an avalanche. As soon as a critical charge density is reached space charge effects and photo-ionization become important, leading, it is supposed, to the development of a streamer. The streamer bridges the gap. In doing so collisions with the molecules of the liquid occur at such a high rate that a plasma channel is created. The change of phase which it implies allows for a dependence of the breakdown strength on hydrostatic pressure, a fact which is sometimes improperly quoted as being a unique feature of cavitation theories. The transition from the plasma channel to an arc discharge proceeds in an analogous way to the development of a spark in air.

The critical phase after which the process of breakdown continues irrevocably is attained when the condition for streamer formation is fulfilled. According to L. B. Loeb, J. M. Meek and H. Raether, the originators of the theory of streamers in a gas, the criterion for their establishment requires a given electron multiplication. In a gas under normal conditions this number has been determined empirically and amounts approximately to e^{20}. However, the theory is not sufficiently elaborate to allow extrapolation to the liquid phase. If the phenomenon occurs there as well, we might conjecture that the electron multiplication factor required to trigger a streamer is much smaller than in a gas. The reason is that rather than the total charge, the decisive factors are the charge density and the density of the medium, a higher charge density being the consequence of a diffusion coefficient of electrons several order of magnitudes smaller in a liquid than in a gas.

A lower limit for the charge concentration in the streamer is imposed by the principle of energy conservation. In order to build up the plasma channel the necessary energy of evaporation must be furnished by the applied field. In agreement with Watson and Sharbaugh [6], who investigated particularly this aspect, the required power density amounts to

$$jE = en_{\text{crit}}\,\mu E^2 = \frac{\rho}{\tau}[c_p(T_b - T_0) + C_b], \tag{2}$$

where the current density j has been expressed by the electronic charge e, the electron concentration n and the mobility μ, and where τ is the delay for formation of the plasma channel and ρ the density, c_p the specific heat, T_b the boiling temperature, T_0 the ambient temperature and C_b the latent heat of vaporization of the dielectric liquid. This energy balance is far from being complete since neither the heating to plasma temperature, nor energy losses to the surroundings have been taken into consideration. The preceding formula, which yields a value for n_{crit}, for the type of paraffin used in our experiments, of between 10^{19} and 10^{20} cm^{-3}, represents therefore only the lower limit of the electron concentration for the initiation of breakdown.

We assume now that this critical electron concentration is the product of two factors: the first $n(\Delta t_I)$ being characteristic of the emission mechanism and depending on the time interval Δt_I which has elapsed between the end of the preceding discharge and the beginning of the next; the second representing the process of multiplication: $\exp \alpha\delta$. The $n(\Delta t_I)$ electrons which are available at the end of Δt_I are each the starting

point of an avalanche when the electric field is turned on, leading, after sufficient growth, to the critical electron density

$$n_{\text{crit}} = n(\Delta t_I) \exp \delta\alpha(E_B). \tag{3}$$

The observed decrease in the breakdown field E_B, as the repetition rate of the discharges is raised, is the result of an increasing availability of initial electrons which compensate for the need for multiplication.

Making this assumption, the dependence of $n(\Delta t_I)$ may be deduced from our measurements if the dependence of the ionization coefficient α on the electric field E is known. It is instructive to consider semiconductors, where for obvious reasons the questions related to breakdown have received much attention. Chynoweth [7] and many investigators after him have shown empirically that the field dependence of the ionization coefficient in semiconductors closely follows the formula

$$\alpha = a \exp -\frac{b}{E} \tag{4}$$

Such a relationship has equally been deduced from theoretical work by Shockley [8a], Baraff [8b] and others, who in doing so related the coefficients to atomic parameters. It should also be noticed that in gases the first coefficient of ionization shows a similar behaviour. Equation (4) is obtained for liquids as well when, in the low field case, the momentum of the electrons after an inelastic collision is supposed to become randomized The probability of an ionizing event is then calculated by evaluating the velocity distribution of the electrons in the direction of the field.

In what follows we extend the validity of the above relationship to liquid dielectrics. There remains an uncertainty in evaluating the coefficients a and b of Equation (4) in so far as the distribution of the electric field in the gap is only poorly known. We are informed from the semiconductors that the potential gradient deviates considerably at the metal–dielectric interface from the average value due to the work function, absorbed layers, surface states and impurities. Only a few potential barrier measurements have been attempted in liquids as the experimental difficulties are very large. The work undertaken by Bloor and Morant [9] supports the idea that a steep potential drop extending over a distance δ of a few μm into the liquid exists at the cathode followed by a linear increase to the potential of the anode. If this is the case, multiplication is essentially limited to the cathode region. Thus we are also in agreement with the observation that the breakdown strength is independent of the length d of the gap. When d becomes comparable to δ some divergence from this should be noticed in our measurements.

If we plot the recorded breakdown voltages $\bar{U}_B$ of Figure 7 as a function of the logarithm of the time interval Δt_I between discharges for given values of the gap distance d, we notice an approximately linear relationship over three decades of the time interval scale (Figure 11). We can use the field dependence of the ionization coefficient α according to Equation (4) and then obtain a fit to the data of Figure 11 with the expression

$$\log \Delta t_I = \text{const} + A \exp\left(-\frac{b}{\bar{U}_B/d}\right) \tag{5}$$

where the mean breakdown strength E_B is expressed by the ratio of the average breakdown voltage $\bar{U}_B$ and the gap d. Adjusting the coefficients in (5) to $A = 26$ and $b = 1.2 \cdot 10^6$ volts/cm leads to the curves drawn as solid lines in Figure 11.

We come to the conclusion that, by comparing expression (5) with equation (3), the electron concentration $n(\Delta t_I)$ behaves like $1/(\Delta t_I)^x$. The exponent x comes from equating $A = \delta a/x$; but since neither the thickness δ of the cathode region, where the avalanche process is supposed to take place, nor the coefficient a are known to any accuracy, x cannot be determined empirically. If it is taken to be 1, the proportionality of the electron concentration to $1/\Delta t_I$ is consistent with a process of diffusion in a plane as well as with a process of recombination, where the electrons recombine at the rate: $dn/dt = -\gamma n^2$, γ being the coefficient of volume recombination.

Since little can be inferred about the thickness of the supposed potential barrier region, except that it must be smaller than a few μm, all we can conclude about a is a lower limit of 10^5 cm^{-1}. This result may be compared with the corresponding value for

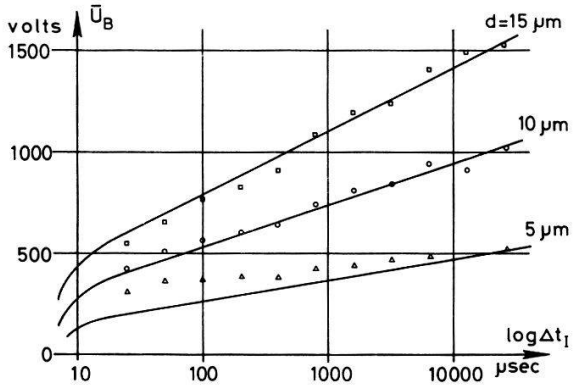

Figure 11

Average breakdown voltage $\bar{U}_B$ as a function of pulse interval Δt_I for short duration high-voltage pulses. Data of Figure 7 plotted for gap sizes $d = 5$, 10, 15 μm. Solid line curves correspond to

$$\log_{10} \Delta t_I = \log_{10} 6\ \mu\text{sec} + \frac{26}{2.3} \exp - \frac{1.2 \cdot 10^6\ \text{volts/cm}}{\bar{U}_B/d}$$

silicon of around 10^6 cm^{-1} (Ref. [10]). With respect to the coefficient b, our fit to the measurements gives $1.2 \cdot 10^6$ volts/cm. In Shockley's theory of the low-field form of the ionization coefficient of semiconductors, b signifies the ratio of the ionization potential U_i and the mean free path λ between inelastic collisions. In the literature on breakdown in silicon we find an average value of b of $1.7 \cdot 10^6$ volts/cm [10] which, with a band gap of 1.1 volts, gives a mean free path of 65 Å. The average ionization potential of paraffin is estimated to be several volts, so that with our b a λ of several hundred ångstrøms results. Such a mean free path is certainly too high for a liquid. However, since here, as in the case of the coefficient a, the value of b represents only a lower limit, a correction can be applied which reduces the mean free path. The true value of b is larger by the same factor as the field of the cathode drop is enhanced with respect to the average gradient in the gap. Thus with an amplification factor of 5 and with an ionization potential of 3 volts, for instance, we would get a mean free path for inelastic collisions of 50 Å, which is quite a realistic value. The contraction of the cathode potential drop region by the same factor results in an increase of the coefficient a and brings it close to 10^6 cm^{-1}.

The curves of the breakdown strength in Figure 11 must level off for large time intervals Δt_I when breakdown is no longer influenced by previous discharges. If this

levelling off happens just outside the range of the investigated time intervals we obtain a critical electron multiplication factor of e^{10} for our measurements.

It might be necessary to recall that the breakdown strength of a liquid dielectric would only have a relative meaning without specifying how the voltage is applied to the electrodes. In our experiments the electrode potential is increased approximately linearly at the rate of $12 \cdot 10^3$ volts/μsec.

Conclusion

Our interpretation of the breakdown strength measurements of recurring discharges has been based on an electron multiplication process. The measured decrease of the breakdown strength with increasing repetition rate of the discharges has been accounted for using the assumption that the charge multiplication needed to reach a critical electron concentration for the formation of a streamer is lessened by the occurrence of an electron emission process. The dependence of the number of initial electrons on the time interval between successive discharges has been deduced from the experimental data; it is found to be a simple power law. If its exponent is assumed such that the electron concentration is proportional to the inverse of time, it agrees with the time dependence of recombination or a diffusion process in a plane. It is of interest that the mentioned law is obeyed over a range of three decades of the time intervals.

In order to establish this relationship the electric field dependence of the ionization coefficient had to be known explicitly. Using a simple model of the electronic interactions with the molecules of the liquid we obtained the same field dependence of the ionization coefficient as for semiconducting dielectrics and introduced it into the exponential law of charge multiplication. This procedure is justified in so far as the coefficients in the expression for the ionization coefficient, which we obtained from fitting the experimental data, have been shown to be related in a compatible way to the molecular parameters of the dielectric liquid. In order to achieve full agreement and to explain the observed independence of the breakdown strength on the gap length we were obliged to suppose an enhancement of the electric field by space charges in the cathode region.

It is evident that the analysis of our measurements contains several hypothetical elements. They are difficult to check because the number of measurable physical quantities in this field is very limited. The study of breakdown strength as a function of the repetition rate of the discharges provides, therefore, useful additional information. Other interesting aspects of this technique are its ability to keep a uniform electrode distance and its insensitivity to impurities. The latter is evident from the high breakdown strength attained for long time intervals. This insensitivity can probably be explained by the large number of breakdown trials which are performed, whereby extreme values caused by the action of impurities disappear in the large mass of the other data.

The investigation of the scattering of the breakdown strength is a further important source of information. We observed [11] a very peculiar behaviour of the breakdown voltage when we studied the individual values of successive discharges on the screen of an oscilloscope. The photographic records (see Figure 12) taken during measurement runs show on the upper trace the evolution of the breakdown voltage. The scattering of the breakdown voltages deviates obviously from a purely statistical behaviour. Leaving out the statistical component, which is also present, the breakdown voltage

increases systematically to a certain value from which it falls back to a lower level and then repeats. Recent observations have shown that the discharges tend to be grouped at a site of the electrode pair from which they jump occasionally to a new site. If these observations are related, they suggest that, besides the reported effect which is proportional to the discharge rate, another emission mechanism exists which, acting over a longer time scale, modulates the breakdown strength in the described manner.

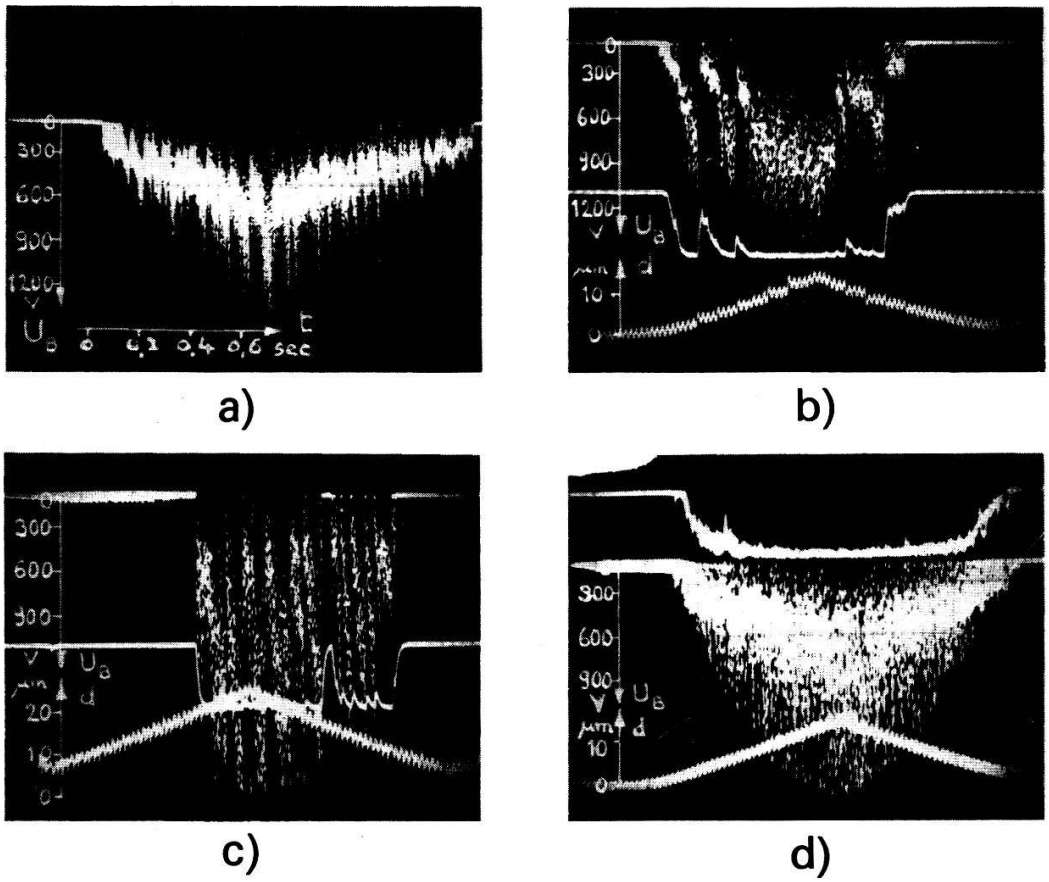

Figure 12
Oscilloscope recordings of breakdown voltage U_B (upper trace), discharge rate (middle trace) and electrode gap d (lower trace) as a function of time during one cycle of the sawtooth command signal of the electrode gap control. Each point of the trace of the breakdown voltages corresponds to a discharge. Dielectric liquid: Mentor 28 Esso. Electrode materials and pulse intervals: a) Copper pos. steel neg., $\Delta t_E + \Delta t_A = 0.2$ μsec, $\Delta t_I = 50$ μsec. b) Copper, copper, $\Delta t_E + \Delta t_A = 0.2$ μsec, $\Delta t_I = 400$ μsec. c) Steel, steel, $\Delta t_E + \Delta t_A = 2.5$ μsec, $\Delta t_I = 400$ μsec. d) Copper pos., steel neg., $\Delta t_E + \Delta t_A = 0.2$ μsec, $\Delta t_I = 400$ μsec. On this recording there are 3 sweeps superimposed showing a rapid smearing out of the patterns illustrated by the first three pictures.

The study of the breakdown time lags opens another of the few windows into the experimental field of electrical discharges in liquids. Though extensive work has already been performed by a research group in London [12] we think it necessary to extend it to the case of discharges where the erosive action on the electrodes is not suppressed in order to check our conclusions. It is quite obvious that considerable effort will be required in order to be able to explain in a satisfactory manner all the facets of the breakdown phenomena in liquid dielectrics.

Acknowledgements

It is a pleasure for us to thank J. Pfau, H. Rhyner and D. Dubi of the Ateliers des Charmilles S.A. for their interest and collaboration with this work. D. Dubi has

constructed some components of our measuring equipment and the Ateliers des Charmilles S.A. have in part financed this study.

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