DYNAMIC ELECTRIC STRENGTH OF LIQUID PERFLUORODIBUTYL ETHER

D. I. Karpov, A. L. Kupershtokh, E. I. Palchikov

Lavrentyev Institute of Hydrodynamics, SB RAS, Novosibirsk, 630090, RUSSIA
E-mail: karpov@hydro.nsc.ru

Abstract

An electric strength of perfluorodibutyl ether in small gaps between the hemispherical electrodes was investigated experimentally under AC voltage of linearly increasing amplitude. The influence of radius of hemispherical electrodes, gap lengths and also rate of voltage increase on probability of breakdown initiation was investigated experimentally and theoretically. In the macroscopic stochastic approach proposed in [1-4], breakdown initiation is described by macroscopic function of probability density of a streamer initiation $\mu(E)$. The fixed probability method was developed to reconstruct the function $\mu(E)$ using experimental data on series of breakdown voltages. The values of function $\mu(E)$ for perfluorodibutyl ether were determined in the range of electric field 0.4 to 0.9 MV/cm. Stochastic computer simulations of breakdown inception were carried out.

Keywords: dielectric liquids, electrical strength, breakdown, stochastic modeling.

Introduction

The ability of a dielectric to maintain its insulating properties under the action of strong electric fields is usually characterized by its electric strength. However, average value of electric field, at which breakdown of a dielectric occurs, also depends on specific experimental conditions such as the form and the sizes of electrodes, distance between them, magnitude and the form of applied voltage, etc [5-7]. Therefore, the classical concept about fixed "electric strength" fails. Instead of this, the concept of "dynamic electric strength" of dielectric that depends on the specific conditions listed above has to be used.

Moreover, numerous experimental data point to the principal role of stochastic processes at a breakdown. Thus, an adequate description of stochastic regularities of dielectric breakdown has to include probability distribution functions for such processes. One of the stochastic processes is the initiation of breakdown. The duration of this stage is a random variable for which the probability density depends on the electric field and its distribution along the surface of the electrodes [5, 6].

Many authors made efforts to describe stochastic regularities of breakdown using various statistical distributions [5-7]. Unfortunately, these approaches do not allow one to describe in a simple way how the complete set of specific experimental conditions influences the breakdown. In [1-2] it was proposed to describe the basic stochastic processes of streamer inception at the electrode by macroscopic function $\mu(E)$. This function is the probability density of breakdown initiation in a short time interval at a small element of an electrode surface near which the electric-field equals to E.

This macroscopic approach allows one to obtain the dependences of the breakdown initiation probability in time on the applied voltage, its waveform, electrode area, and gap length, etc and to simulate stochastic features of breakdown. And vice versa, it is possible to reconstruct the function $\mu(E)$ from experimental data. The conception of dynamic electric strength directly follows from stochastic approach by averaging the breakdown voltages over the probability distributions for every specific experimental condition.

Experiments

The experiments on breakdown in the perfluorodibutyl ether were carried out. The liquid was previously boiled for degassing with a backflow condenser to prevent boiling out of liquid

0-7803-7427-4/02/$17.00© 2002 IEEE

and then was filtered. The effective value of AC voltage of frequency 50 Hz increased with a constant rate k_e = 2 kV/s. Hemispherical stainless steel electrodes with surface radius R = 30 mm and brass electrodes with R = 40 mm were used. The surfaces of the electrodes were polished before each series of experiments. In experiments, the current effective value of voltage V_{EFF} at which breakdown of a dielectric occurred was registered (Fig. 1).

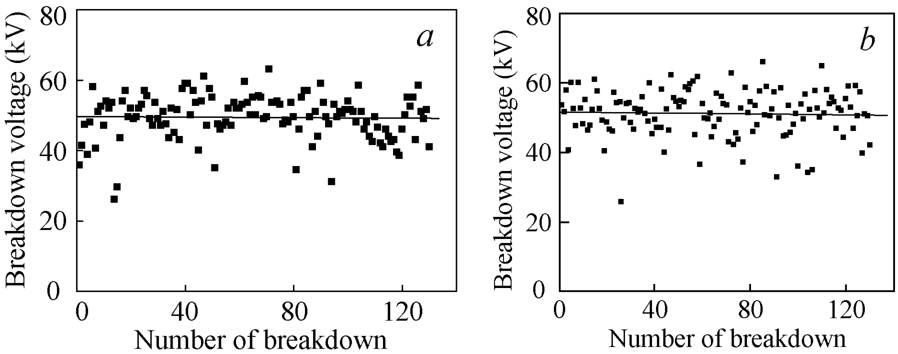

Fig. 1. Breakdown in perfluorodibutyl ether. (*a*) experiment, (*b*) simulation. R = 4 cm, d = 1.7 mm.

Distribution of the electric field

A good approximation for electric field strength on the surface of hemispherical electrodes was obtained by solving the Laplace equation in the gap between two metallic spheres:

$$E(\xi,\eta) = \frac{E_0\, d\, \sqrt{2(\mathrm{ch}\xi - \cos\eta)}}{2R\,\mathrm{sh}\,\xi_1} \sum_{l=0}^{\infty} \frac{e^{-(l+1/2)\xi_1}\, \mathrm{P}_l(\cos\eta)}{\mathrm{sh}((2l+1)\xi_1)} \times$$
$$\left\{ \mathrm{sh}\left(\left(l+\frac{1}{2}\right)(\xi+\xi_1)\right)\mathrm{sh}\,\xi + 2(\mathrm{ch}\,\xi - \cos\eta)\left(l+\frac{1}{2}\right)\mathrm{ch}\left(\left(l+\frac{1}{2}\right)(\xi+\xi_1)\right)\right\}. \quad (1)$$

Here $E_0 = V/d$ is the average electric field strength along an axis between electrodes, V is the applied voltage, R is the radius of spherical electrodes, d is the gap length between them, ξ and η are bispherical coordinates ($-\xi_1 < \xi < \xi_1$, $0 < \eta < \pi$), P_l is the Legendre polynomial of index l, $\xi_1 = \ln(1+\beta+\sqrt{\beta(2+\beta)})$, $\beta = d/2R$ is the reduced length of the gap. The relation between coordinate η and polar angle θ on the sphere is given by $\cos\eta = (1-(1+\beta)\cos\theta)/(1+\beta-\cos\theta)$.

In a narrow gap between hemispheres simple approximation of formula (1) is valid [2]

$$E \approx E_0 /(1+(1-\cos\theta)/\beta)\ . \quad (2)$$

Only a small part of the electrode area near the symmetry axis makes a major contribution to breakdown inception because of the sharp dependence of $\mu(E)$ on the electric field. For this region, the approximation (2) practically coincides with the exact solution (1) up to $\beta = 0.02$ [2].

The maximum value of electric field on the electrode surface is somewhat higher than the average value E_0 (Fig. 2). The coordinate z along symmetry axis is expressed through bispherical coordinate ξ as $z = R\,\mathrm{sh}\,\xi_1\,\mathrm{sh}\,\xi/(\mathrm{ch}\,\xi+1)$. Correction factor $a(\beta) = E_{max}/E_0 = 1+0.66\,\beta$ allows one to extend the range of the applicability of (2) to the values $\beta \approx 0.1$, using $a(\beta)\,E_0$ instead of E_0.

Macroscopic approach

Macroscopic function $\mu(E)$ used in stochastic approach [1-4] depends on only local electric field. The function $\mu(E)$ has physical sense of probability density of breakdown initiation on a small element of electrode surface in a short interval of time. The function $\mu(E)$ is rapidly increasing. The values of $\mu(E)$ depend on the properties of a specific dielectric and on the properties of the electrodes. Let us suppose that probability of breakdown inception near small element of surface of electrode at time t does not depend on previous moments of time and on events near other elements of electrode. In this case, the probability of breakdown inception in time t is equal to

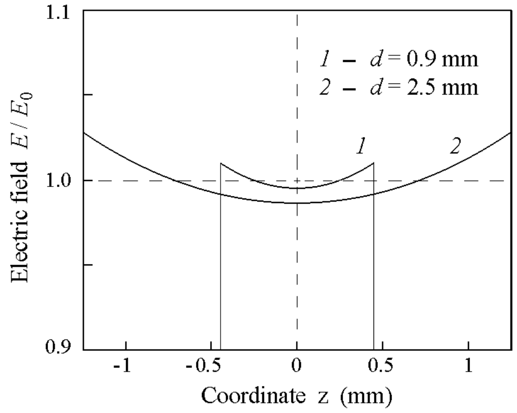

Fig. 2. Electric field strength along the symmetry axis of two spherical electrodes obtained from (1). at β = 0.028 (curve *1*) and β = 0.042 (curve *2*). R = 30 mm.

$$P_+(t) = 1 - \exp(-H) \tag{3}$$

where the value of integral of electric field action $H(t)$ changes in time as

$$H(t) = \int_0^t \left(\int_S \mu(E)\, ds \right) dt\,. \tag{4}$$

Using (2), it is possible to turn the integration in (4) from integral over the surface of electrode to the integral over electric field [1, 2]

$$\int_S \mu(E)\, ds \approx d\pi R E_0 \int_0^{E_0} \frac{\mu(E)}{E^2} dE\ . \tag{5}$$

On the right hand side of (5), we used zero as lower limit of integration, bearing in mind the extremely sharp dependence μ(E). For arbitrary form of function μ(E) for hemispherical electrodes

$$P_+ = 1 - \exp\left(- d\pi R \int_0^t \left(E_0(t) \int_0^{E_0(t)} \frac{\mu(E)}{E^2} dE \right) dt \right) \tag{6}$$

If it is possible to approximate μ(E) for dielectric by the power-law dependence

$$\mu(E) = A\left(E/E_1\right)^n, \tag{7}$$

the analytical expressions for integral of electric field action $H(t)$ can be derived for AC voltage of slowly increasing amplitude $V = \sqrt{2} k_e t \sin(\omega t)$ for hemispherical electrodes [3, 4].

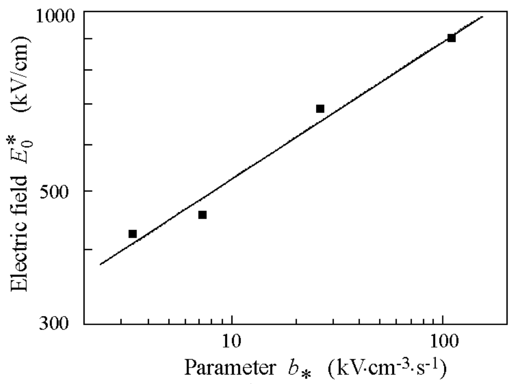

Fig. 3. Dependence E^*_0 on parameter b_*. Perfluorodibutyl ether. d = 0.44, 0.9, 1.7, 2.5 mm.

The dependences of the probability of breakdown on the radius of the electrode surface, gap distance, rate of increase in voltage, etc were derived in [2-4]. For hemispherical electrodes and AC voltage of linearly increased amplitude the parameter $b_* = k_e/(\pi R d^2)$ is convenient for preliminary comparing of the experimental data obtained at different values of k_e, d and R. It is convenient to use the values of electric field E^*_0 for which $P_+ = 0.63$. The results of the experiments were plotted as the dependences of E^*_0 on the parameter b_* (Fig. 3). The values E^*_0 correspond to H = 1 in (3) that allowed us to determine the function μ(E) from experiments (the method of fixed probability).

However, power-law approximation (7) gives too weak dependence of μ(E) on an electric field (Fig. 4, curve 1) that results in too wide scattering of breakdown voltages in simulations in comparison with the experiments. The approximation in the form

$$\mu = AE^2 \exp(E/g) \tag{8}$$

is sharper than approximation (7) and describes the histograms of breakdown voltages better. Integration over time in (6) was carried out numerically right up to the moment corresponding to amplitude value of electric field E^*_0. Then, A and g were obtained using the condition $H = 1$ for each series of breakdowns. The values of $\mu(E)$ obtained using (8) are shown in Fig. 4 (curve *2*).

Stochastic simulation

Using the reconstructed function $\mu(E)$, one can plot any dependences of the breakdown initiation probability for various geometry of electrodes and for various magnitude, duration, and waveform of the applied voltage. Stochastic computer simulation of series of breakdowns was carried out using (6) and (8). Statistical time lag before breakdown t_S was determined from

$$\int_0^{\omega t_S} \tau|\sin\tau| \left[e^{B\tau|\sin\tau|} - 1 \right] d\tau = -\frac{\omega^2 \ln(\zeta)}{\sqrt{2\pi}\, A g k_e R}, \quad (9)$$

where $B = \sqrt{2} k_e / (\omega d\, g)$, ζ is a random number that is uniformly distributed in the interval from 0 to 1. The integration on the left hand of (9) was carried out numerically until the value of the integral was equal to the random value of expression on the right hand side of (9). Typical series of breakdowns in transformer oil obtained in computer simulations is shown in Fig. 1,*b*. The results are in good agreement with the experimental ones.

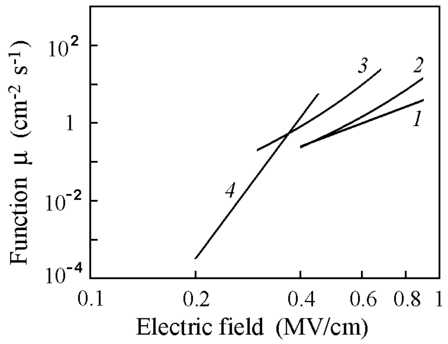

Fig. 4. Functions $\mu(E)$ reconstructed from experiment. The approximation (7) for perfluorodibutyl ether (*1*). The approximation (8) for perfluorodibutyl ether (*2*) and transformer oil (*3*) [4]. Straight line *4* is the function $\mu(E)$ reconstructed in [4] for transformer oil from the data of [5].

Conclusions

Probability distributions of breakdown initiation were analytically obtained hemispherical electrodes under AC voltage of linearly increasing amplitude. The direct computer simulations of experiments on breakdown in dielectric liquids describe essentially stochastic nature of breakdown that is necessary to take into account at designing high power electrical apparatus. This work was supported by the grant No. 47–2000 of the Siberian Branch of the Russian Academy of Science.

References

1. Klimkin V. F., Kupershtokh A. L., Statistical Lag Time in Fluctuation Model of Liquid Dielectric Breakdown and Experimental Results, *Proc. 11th Int. Conf. on Conduction and Breakdown in Dielectric Liquids*, Baden-Dättwil, Switzerland, 1993, pp. 395–399.

2. Kupershtokh A. L., Karpov D. I., Stochastic Features of Initiation of Liquid Dielectric Breakdown at Small Area of Positive Electrode, *Proc. 13th Int. Conf. on Dielectric Liquids*, Nara, Japan, 1999, pp. 203–206.

3. Kupershtokh A. L., Palchikov E. I., Karpov D. I., Ershov A. P., Probability Density Function of Electrical Breakdown Initiation in Dielectric Liquids under AC and DC Voltage, *Proc. 2nd Int. Workshop on Electrical Conduction, Convection, and Breakdown in Fluids*, Grenoble, France, 2000, pp. 91–94.

4. Kupershtokh A. L., Vitellas I., Agoris D. P., Karpov D. I., Charalambakos V. P., Stochastic Regularities of Electrical Breakdown Initiation in Transformer Oil, *Proc. of the Int. 2001 IEEE Industry Applications Conference*, 36th Int. IAS Annual Meeting, Chicago, Illinois, USA, 2001, Vol. 4, pp. 2729–2736.

5. Weber K. H., Endicott H. S., Area Effect and Its Extremal Basis for the Electric Breakdown of Transformer Oil, *Trans. Amer. Institute of Electrical Engineers*, 1956, Vol. 75, pp. 371–381.

6. Lewis T. J. and Ward B. W., A Statistical Interpretation of the Electrical Breakdown of Liquid Dielectrics, *Proc. Roy. Soc. A: Mathematical and Physical Sciences*, 1962, Vol. 269, No. 1337, pp. 109–124.

7. Gerhold J., Hubmann M., Telser E., Gap Size Effect on Liquid Helium Breakdown, *Cryogenics*, 1994, Vol. 34, pp. 579–586.