LOWERING OF THE BREAKDOWN POTENTIAL OF A GAS UNDER STEADY IONIZING RADIATION

A. A. Dantser and V. A. Feoktistov

UDC 537.5

The problem of the lowering of the electric strength of a gas under steady external ionizing radiation is solved numerically. The right-hand branches of the Paschen curve for helium, argon, and xenon are calculated by the so-called ranging method using the standard Runge–Kutta program.

The development of various automatic control systems for nuclear power plants requires an estimate of the working lifetime of gas-discharge devices exposed to dose rates $P_\gamma \sim 10^2-10^5$ P/sec in the gamma radiation field of a reactor. Under these conditions one of the critical parameters is the electric strength.

The book [1] lists a long bibliography of papers devoted to the theoretical and experimental studies of the effect of radiation on the change in the breakdown potential of a gap. Calculations by Rogowski and his coworkers show that the relative lowering of the breakdown potential $\eta = (U_0 - U_*)/U_0$, where U_0 is the static breakdown potential neglecting space charge and U_* is the breakdown potential in the presence of a photoelectric cathode emission current I_0, is proportional to $\sqrt{I_0}$. This result is derived by applying perturbation theory and expanding the system of equations in series in terms of the small parameter $\Delta E = E(x) - E_0$, where E_0 is the initial homogeneous field for plane geometry of the electrodes and $E(x)$ is the field deformed by the space charge when the current is I_0. Therefore the range of applicability of the relation $\eta \sim \sqrt{I_0}$ is limited by the condition $\Delta E \ll E_0$, and $\eta \ll 1$.

In the case under consideration ionizing radiation leads to a severe deformation of the field and perturbation theory is not applicable. Since there is no exact analytical solution for the motion of particles in a self-consistent inhomogeneous field taking account of impact ionization, we calculate the dependence of the breakdown potential of a gap on the dose rate P_γ numerically by computer.

In plane geometry the system of equations describing the drift of particles in an inhomogeneous field taking account of impact ionization and the creation of particles by a uniform external source has the form

$$\frac{dj_e}{dx} = -\alpha(E)\, j_e + Q; \quad \frac{dE}{dx} = \frac{4\pi}{v_+(E)}\left\{j - j_e\left(1 + \frac{v_+(E)}{v_e(E)}\right)\right\}, \tag{1}$$

where j is the total current density, j_e is the electron current density, E is the electric field, v_+ and v_e are the drift velocities of positive ions and electrons, $\alpha(E)$ is the coefficient of impact ionization, and Q is the charge created by the external source per unit volume of gas per unit time; the origin of coordinates is at the anode. The parameters of the problem are j and Q.

For inert gases and an uncontaminated cathode secondary avalanches are produced mainly by ions [2], and therefore the boundary condition has the form

$$j_e(d) = \frac{\gamma_+ j}{1+\gamma_+}, \quad j_e(0) = j, \tag{2}$$

where γ_+ is the coefficient of secondary ionization by ions. In order to solve system (1) it is necessary to specify explicity the form of the functions $\alpha(E)$ and $v_{+e}(E)$. By interpolation of experimental data for the drift velocity of ions in inert gases Kagan and Perel' [3] obtained empirical expressions of the form

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Teknicheskoi Fiziki, No.3, pp. 26-31, May-June, 1975. Original article submitted October 4, 1974.

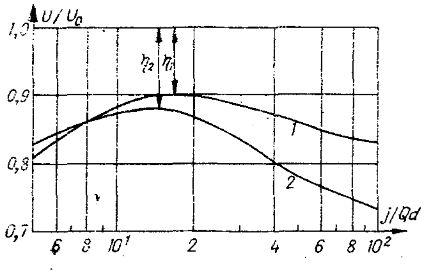

Fig. 1

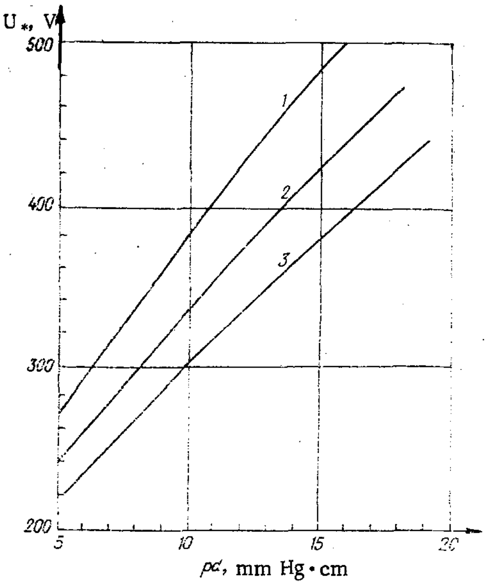

Fig. 2

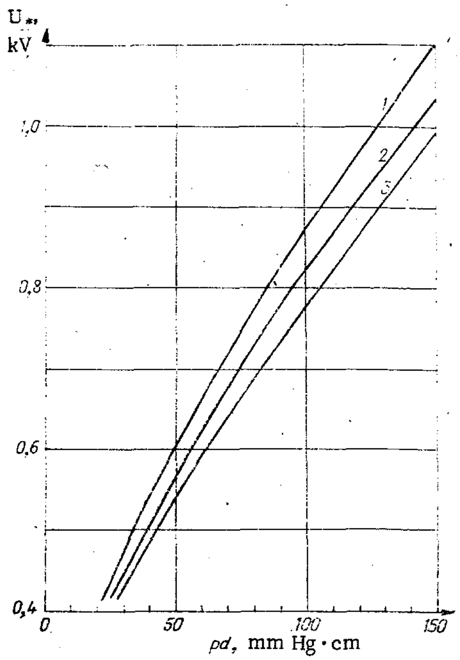

Fig. 3

$$v_+(E) = K_+\frac{E}{p}\left(1 - C\frac{E}{p}\right), \quad \frac{E}{p} < D; \tag{3}$$

$$v_+(E) = K'_+\left(\frac{E}{p}\right)^{1/2}\left(1 - C'\left(\frac{p}{E}\right)^{3/2}\right), \quad \frac{E}{p} > D,$$

where p is the pressure and K_+, K'_+, C, C', and D are constants for a given gas. The mobility of positive ions in inert gases has been found analytically also [4]. We used Eqs. (3) in our numerical solutions since they are in satisfactory agreement with the experimental data. In contrast with v_+ we can limit ourselves to the linear approximation $v_e = K_e(E/p)$ for the drift velocity of electrons since v_e enters system (1) as a small correction of the order $v_+(E)/v_e$. Ward [3] showed that the expression

$$\alpha\left(\frac{E}{p}\right) = Ap\exp\left\{-B\sqrt{\frac{p}{E}}\right\}, \quad \frac{E}{p} < W \tag{4}$$

for the coefficient $\alpha(E)$ is valid over a wide range of values of E/p for inert pases. The numerical values of the constants in Eqs. (3) and (4) are given by Ward [3]. Thus system (1), (2) together with Eqs. (3) and (4) completely determines the problem. The determination of the breakdown potential U_* reduces to the calculation of the volt–ampere characteristic U = U(j) for a given Q, where U_* is found from the condition dU/dj = 0 [5].

System (1) together with boundary condition (2) is a two-point boundary-value problem for a system of ordinary differential equations (of the two variables E and j_e only the boundary values for j_e are given at two points). One method for solving system (1), (2) numerically is to specify another variable E(x = 0) at x = 0 in a relatively arbitrary way. Since now two functions are specified at x = 0 the solution can be obtained by using any standard program. We used the Runge–Kutta program. The choice of the function E(x = 0) is continued until the solution obtained for $j_e(x = d)$ agrees with the boundary value $\gamma_+ j/(1 + \gamma_+)$ to an a priori specified accuracy. By integrating the distribution of the field over the interval (0, d) the value of the potential corresponding to the given j and Q can be obtained. By specifying other values of j and Q and repeating the calculation ab initio the volt–ampere characteristic U = U(j) can be computed for various values of Q. This calculational procedure as applied to gas-discharge problems was first used by

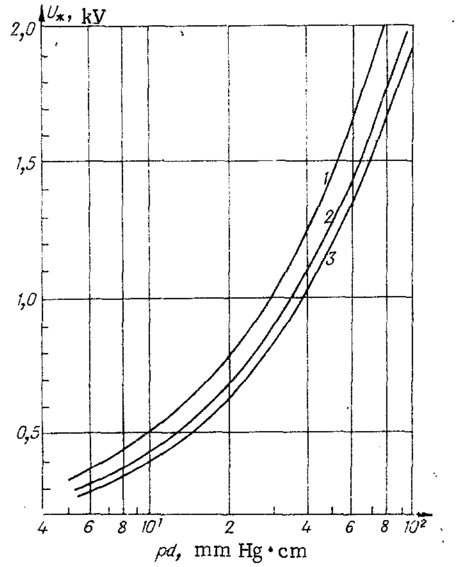

Fig. 4

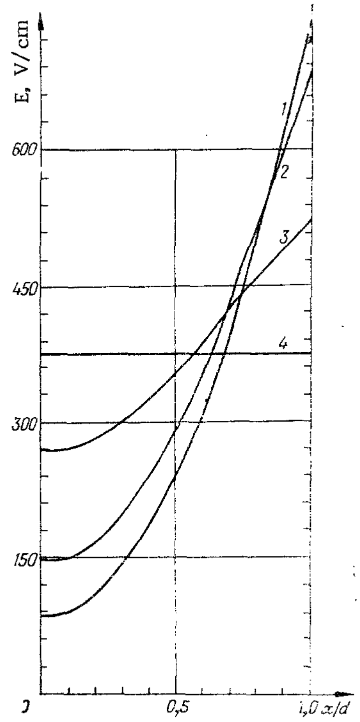

Fig. 5

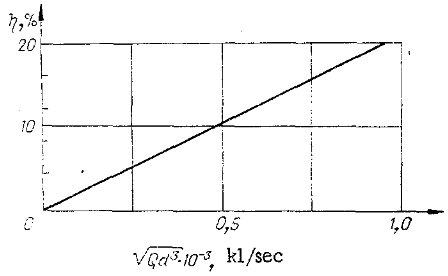

Fig. 6

Ward [6] to estimate the cathode fall in a glow discharge. Figure 1 shows the calculated volt–ampere characteristics for argon with $Q = (1/3) \cdot 10^{-6}$, $d = 1$, and $p = 5$ (curve 1), and for $p = 10$ (curve 2) (in the text and on the figures the units are: V, cm, mm of Hg, Kl, sec). The ordinate is the potential relative to the static breakdown potential U determined from the condition $\mu = \gamma_+ (\exp(\alpha_0 d) - 1) = 1$, where α_0 is the coefficient of impact ionization in the field E_0. Taking account of (4) the condition $\mu = 1$ has the form

$$U_0 = pdB^2\left[\ln(pdA) - \ln\ln\left(1 + \frac{1}{\gamma_+}\right)\right]^{-2} \quad (5)$$

In all the calculations the coefficient of secondary ionization γ_+ was taken as 0.02. The relative lowering of the breakdown potential η is determined from Fig. 1 as the difference $1 - (U/U_0)_{max}$. If the system (1), (2) is reduced to dimensionless form, dimensional arguments show that the breakdown potential U_* depends on the parameter $d^3 Q$ as well as on the dimensional combination pd; i.e., $U_* = U_*(pd, d^3 Q)$. By determining the maximum of the volt–ampere characteristic for various choices of the parameters pd and d^3Q the dependence of U_* on pd can be constructed for various d^3Q. Figure 2 shows the right-hand branch of the Paschen curve for argon [curve 1 neglects space charge, Eq. (5), curve 2 corresponds to $d^3Q = (1/3) \cdot 10^{-6}$; for curve 3 $d^3Q = 10^{-6}$]. Similar curves for xenon and helium are shown in Figs. 3 and 4 using the same notation as in Fig. 2. Calculations show that in the cases under consideration η can have values of tens of percent. The calculational method described permits the determination of η as a function of Q. If we neglect the contribution to Q from secondary processes in the sheath separating the gas gap from the surrounding space the relation between P_γ and Q has the form [7]

$$P_\gamma = aQ[a = 5.5 \cdot 10^{26}(\lambda_1 \omega/\lambda_1)],$$

where λ_1 and λ_2 are the average linear energy-transfer coefficients for air at standard pressure and the filling gas at the pressure P, which is of interest to us, in cm, ω is the energy of ion formation in the filling gas, J/ion, and Q is in kl/cm^3 • sec. For example, for $E_\gamma \sim 1$ MeV we find for argon $a = 1.2 \cdot 10^{12}/p$ so that curves 1 and 2 in Fig. 1 correspond to $P_\gamma = 8 \cdot 10^4$ R/sec and $P_\gamma = 4 \cdot 10^4$ R/sec.

The mechanism for lowering the breakdown potential is explained by the increase in the multiplication factor from the deformation of the field by the space charge. Figure 5 shows the field distribution for ignition currents j_* corresponding to various values of Q [argon d = 1, p = 10; curve 4 gives the initial homogeneous field; curve 3 corresponds to $d^3Q = (1/3) \cdot 10^{-7}$, curve 2, to $d^3 Q = (1/3) \cdot 10^{-6}$, and curve 1, to $d^3 Q = 10^{-6}$]. For such an inhomogeneity of the field a relation of the form $\eta \sim \sqrt{Q}$, which can be derived within the framework of perturbation theory when $E(x) - E_0 \ll E_0$ and $\eta \ll 1$, is not applicable. However, from Fig. 6 which shows η as a function of $\sqrt{d^3Q}$ (argon pd = 10) it is clear that the dependence is linear in the region of the values of Q which are of interest to us up to $\eta \simeq 22\%$. The generalization of the calculation to the case $\gamma_+ = \gamma_+ (E)$ is not difficult in principle and can be done as in [8].

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