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INVESTIGATION OF DYNAMIC CHARACTERISTICS OF A GLOW DISCHARGE IN GAS FLOWS

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Stability of the gas-discharge-supply circuit system relative to current fluctuations is examined. The estimates are in agreement with investigations of a glow discharge in an air flow.

1. The stability of stationary flow discharge (GD) combustion must be assured for technological applications since current and voltage fluctuations result in reduction in the efficiency of the GD installation [1]. The fluctuations are due to voltage oscillations in the supply source, in parasitic capacitances and inductances of the loop, and also in the development of plasma instabilities in the discharge itself [1-3]. Hence, the stability of GD combustion or the damping of current fluctuations are governed by the whole discharge-supply loop system.

To produce optimally efficient and stable gas-discharge installations the dependence of the nature of the fluctuation on the GD maintenance circuit must be established theoretically and from experiments.

The simplest loop contains an emf source ε and a ballast resistance R_b connected in series with the GD (Fig. 1). A "static" current—voltage characteristic (CVC) obtained experimentally by varying ε and recording the discharge voltage U and current i is used in the stability analysis. It follows from a classical examination [4-7] that the GD should combust stably if

$$R_b > |r|, \tag{1}$$

$$L > R_b |r| C, \tag{2}$$

where L is the inductance connected in series with the GD, C is the capacitance in parallel with the GD, r is the GD differential resistance (DR) equal to the slope of the tangent to the CVC at the working point under consideration $r = dU/di$.

The necessary condition (1) denotes that as the CVC ($r > 0$) grows the GD is always stable and the oscillations in the GD-supply loop system are quenched while for a dropping CVC ($r < 0$) the load line corresponding to the equation $\varepsilon = IR_b + U$ should pass more steeply than the tangent to the CVC at the working point. Satisfaction of conditions (1) and (2) is sufficient for damping the fluctuations.

Condition (1) and (2) correctly describe the excitation and quenching of oscillation within the framework of the circuit taken, however, their application in this form to estimate the specific gas discharge system is made difficult since dynamic fluctuations always

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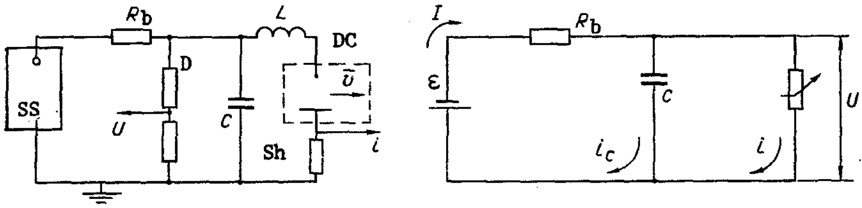

Fig. 1. Installation diagram and computation scheme: DC) discharge chamber; SS) supply source; C) capacitor (capacitance); L) choke (inductance); D) voltage divider; and Sh) current shunt.

exist in a GD, the discharge inductance depends on the time and it is not clear how (2) can be utilized to estimate the stability by means of a static CVC. It is more constructive to characterize a discharge by one, albeit time-dependent, DR instead of ascribing an inductance, capacitance, and a constant DR to it as occurs in (2).

The purpose of this paper is to study the voltage dependence in the discharge on the current in the presence of fluctuations relative to the mean values, to obtain "dynamic" CVC and DR of the GD-supply loop system, to investigate their relation to the nature and GD combustion and to the external supply loop parameters, and to determine the conditions for raising the stability of GD combustion. The necessity of involving the dynamic characteristics to examine the stability problem is also mentioned in [4].

2. The model of GD-supply loop system behavior should take account of the properties of both the discharge and the loop. We will express the GD properties by the magnitude r(t) of the dynamic DR. According to the physical meaning r displays the change in the voltage U in the discharge relative to the change in the current i at a definite time and a conclusion on the nature of the change in r can yield essential information for analysis of the system behavior.

The loop properties are governed by the parameters R_b, L, C, ε. The magnitude ε of the emf must be given in the general case as varying in an oscillatory manner: ε ∿ exp(jωt) since installation supply comes from a grid in typical circuits. We limit ourselves to the case of a constant emf ε = const which is equivalent to the case of a linearly varying output voltage of the source $v = IR_s + U$ since the source resistance R_s can be added to the ballast resistance R_b. Such an approximation correctly describes the process in a system for frequencies higher than the grid frequency when the current and voltage change due to grid voltage fluctuations is small during a period.

The inductance L enters implicitly into the DR since it is connected in series with the GD in the loop. The system behavior is described by the equations

$$v = \varepsilon - IR_s,\quad v = IR_b + U,\quad I = i + i_C,\quad i_C = C\frac{dU}{dt},\quad U = U_C,\quad r = \frac{dU}{di}, \tag{3}$$

which reduces to the differential equation

$$\frac{dI}{dt} + \frac{I}{(R_b + R_s)C} = \frac{i(t)}{(R_b + R_s)C}. \tag{4}$$

Let us analyze the cases of linear, exponential, and fluctuating changes in the discharge current i(t). According to the superposition principle, the currents can be combined for the analysis

$$i(t) = i_0 + \tilde{i}\,|t| + \tilde{i}\,[\exp(\alpha t) - 1] + \tilde{i}\exp j(\omega t - \pi/2),\ i = i_0 \text{ for } t = 0. \tag{5}$$

Using the notation $(R_b + R_s) = R$ we obtain in real form after substitution and manipulation

$$r(t) = -R\frac{1 - \exp(-t/RC)}{1 + RC} - R\frac{1 - \exp[-(\alpha + 1/RC)]}{1 + \alpha RC} - R\frac{\cos\omega t + \omega RC\sin\omega t - \exp(-t/RC)}{\cos\omega t\,(1 + \omega^2R^2C^2)}. \tag{6}$$

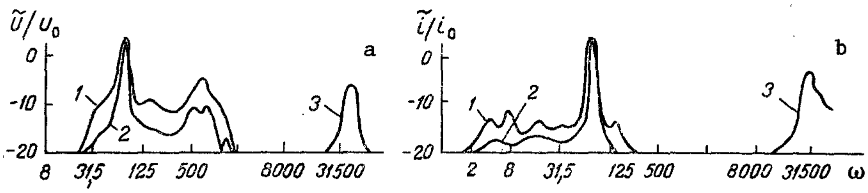

Fig. 2. Relative voltage fluctuation amplitude (a) and glow discharge current (b) over the frequency spectrum for different GD maintenance modes: 1) normal GD (U_0 = 2400 V, i_0 = 150 mA, R_b = 3kΩ), 2) normal GD (2400 V, 150 mA, 13 kΩ), 3) GD in the strata formation (2600 V, 390 mA, 3 kΩ), $\tilde{U}/U$, $\tilde{I}/i_0$, eV; ω, Hz.

The components in (6) correspond independently to the linear, exponential, and fluctuating cases; r(t) has the meaning of an ideal GD-supply loop system DR, i.e., if the discharge were to have such relative changes in U and i in time as would satisfy (6), then the current through the discharge in this system would vary (grow) in conformity with i(t) according to (5). However, the GD has the intrinsic DR r_d that is measured in the experiment and for $r_d \neq r$ would seemingly possess a stability margin that would not permit the current to grow. For large R the discharge is known to be stable, consequently, the following condition should be satisfied

$$r_d > r, \tag{7}$$

i.e., if the real DR r_d exceeds r than the linear or exponential change in current should clamp on according to (5). Stabilities with large increments α are most dangerous. The relatively elevated stability of a discharge to extinction (α < 0) whose reason is GD voltage stabilization by the capacitance C is interesting. It follows from (6) and (7) that the magnitude of the ballast resistance F_b must be increased to raise the stability, the mode of "negative" R_s must be used (a source with steeply descending characteristic), C must be diminished (disconnect the electrodes from the ground), and the loop constant RC must be diminished.

In a typical supply loop $R_b \sim 10^4$ and $R_s \sim 10^3$ Ω, the parasitic C ∿ 10^{-9}-10^{-11} F and the fluctuation frequency spectrum in the GD is $\omega \lesssim 10^6$ Hz. We have $r \approx -R$ from (6) for the linear and exponential current change modes (first and second components) for $t > R \approx 10^{-6}$ sec, consequently, the condition

$$r_d > -(R_b + R_s) \tag{8}$$

can be used for the estimate instead of (7). In the oscillation mode the third DR component r(t) varies in proportion to tan ωt with respect to the mean. The real $r_d(t)$ should vary the same in experiment. For the oscillatory disturbance in current $\tilde{I}$ exp jωt and voltage $\tilde{U}$ exp (jωt + jϕ) it is easy to obtain from a comparison with (6)

$$\cos\varphi = -\frac{R\tilde{i}}{\tilde{U}(1+\omega^2R^2C^2)}. \tag{9}$$

The active nature of the GD resistance of $\cos\phi \approx 1$ will be the damping condition. The stability estimate is performed correctly by filtering the "dangerous" frequency signal, determining $\tilde{U}$, $\tilde{I}$ (or the phase shift directly) and computing cos ϕ by means of (9). Physically, the GD stability or instability means that the parasitic capacitance C either hinders the change in GD current because of self-charging and energy absorption, or conversely, delivers energy to the loop and magnifies the instabiity, depending on the nature of the DR.

3. The experimental installation (Fig. 1) consisted of a gas discharge chamber, a gas (air) delivery line, and a pumping system with a vacuum pump. Air was pumped into the chamber channel at 10-80 m/sec velocities at the static pressure $1.3\cdot10^3$-$1.3\cdot10^4$ Pa. The discharge chamber cathode had the shape of a 2 mm cylinder and was mounted at a 45° angle to the flat anode. The interelectrode gap was 30 mm. The discharge was supplied from a high-voltage transformer through a full wave rectifier with a capacitive filter. The ballast resistance should be varied by steps between 2 and 64 kΩ limits. The source resistance equal 2 kΩ in the current band to 1 A. The parasitic capacitance was estimated by a computation to be within the limits 10^{-9}-10^{-11} F.

The current and voltage were measured with calibrated shunts and dividers. The "static" discharge CVC was recorded by a X–Y-plotter, the current and voltage fluctuations by an S8-14 oscilloscope, and the fluctuation amplitude-frequency spectrum by a TOA-111 spectrum analyzer.

The static CVC have a growing section for a diffuse GD combustion volume and a dropping section upon going over into the contracted state.

A number of experiments was performed for comparison at identical velocities (20 m/sec) and pressures ($5.3 \cdot 10^3$ Pa). The current and voltage fluctuations are not large ($\sim$5%) for small currents ($\leq$80 mA). As the current through the discharge increases the fluctuations as a whole grow, and the nature of the fluctuations is chaotic. As the current increases at the anodes, flow domains are formed rising to the cathode. The amplitude of the chaotic fluctuations here continues to grow in the discharge and the passage over to the developed contracted mode with current fluctuations up to 40% occurs at the critical current $\sim$550 mA. For currents $\geq$350 mA regular oscillatory current ($\sim$8%) and voltage ($\sim$6%) fluctuations are recorded and the zone between the electrodes glows brightly.

For small currents ($\leq$80 mA) the fluctuation spectrum is low-voltage: the frequency of the current fluctuations does not exceed 500 Hz, and of the voltage 2000 Hz. A peak at the 100 Hz grid frequency is extracted sharply in its background (Fig. 2). The peak at 1300 Hz is due to gasdynamic fluctuations during the flow around the cylindrical cathode at the Strouhal number Sh = 0.2 [7]. However, for currents greater than 350 mA high-frequency pulsations predominate in the 60-120 kHz range for the current and 10 and 100 kHz ranges for the voltage. This mode corresponds to development of a sticking instability in the GD or to the formation of strata [2, 3].

The nature of GD combustion depends on the external loop parameters R_b, C, L, RC. As R_b diminishes, the fluctuation amplitude increases (Fig. 2). The influence of the quantity C was confined by direct connection of an additional capacitance in parallel to the discharge. The fluctuations here grew as C increased until the relaxation oscillations mode. Connection of a choke of 36 H in the supply loop did not alter the nature of the GD combustion in a substantial manner.

Dynamic CVC and DR were constructed from results of oscilloscope patterns for several GR combustion modes (Fig. 3). For low currents ($\leq$80 mA) the fluctuations are not large, and the CVC is localized around the means u_0 and i_0 (Fig. 3a).

In the contraction mode (Fig. 3b) the dynamic CVC has a quite definite correlation with the load line, i.e., the mean DR value is close to the magnitude of the ballast resistance with opposite sign.

The strata formation mose is a good model for comparison with a computation since it contains oscillations at practically one frequency (Fig. 3c). It is seen that the nature of the DC change r_d agrees with r according to (6), therefore, the computation truly reflects the process in the system under the assumptions taken.

The characteristic sections of the quasilinear current change can be extracted on the oscillograms and, consequently, the estimation r of the DR can be performed in a linear approximation inconformity with (8). By calculating the value $r_p = \Delta U/\Delta i$ from the oscillograms and the CVC, we obtain the stability margin $K = r_d/(R_b + R_s)$ from whose values the possibility of diminishing R_b and raising the installation efficiency can be judged. Thus for the case (Fig. 3a) $K \approx -0.8$, that indicates a certain stability "margin" and in the contraction case $K \approx -0.95$ there is no stability margin for this mode and R_b must be increased to diminish the fluctuation level.

For the oscillatory fluctuations, cos ϕ can be estimated from Fig. 3c according to (9) for the 100 kHz frequency; we have $\cos\phi \approx -0.66$ for $\tilde{U} = 50$ V, $\tilde{I} = 30$ mA, $R_b = 500\ \Omega$, and $R_s = 2000\ \Omega$, and the phase shift between the current and voltage is $\phi = 0.8\pi$. Such a combustion mode is far from the damping condition $\cos\phi = 1$, i.e., the GD in the strata mode has the DR r_d close to the ideal according to (6). Almost matched oscilaltions in the GD occur even in the parasitic capacitance, and their amplitude is large.

4. Real GD properties are taken into account in the paper when the voltage in the discharge varies in a complex manner as the current changes. In the general case, the experimental dynamic CVC is not a section of a line but a curve with closed loops and intersections.

The cases of linear and exponential change in the current in a GD are analyzed. To quench such fluctuations the ballast resistance R_b should be increased, the parasitic

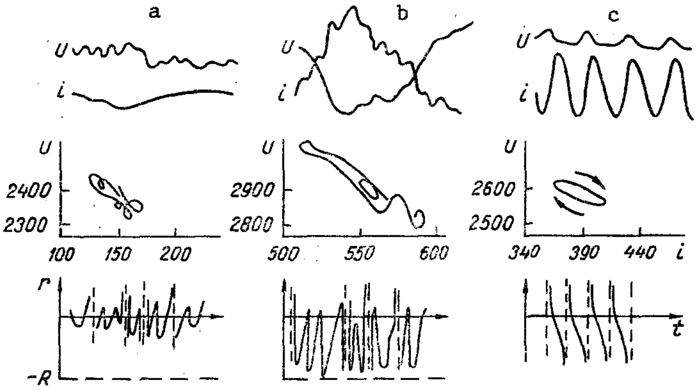

Fig. 3. Voltage (75 V/div) and current (10 mA/div) fluctuation oscillograms of a glow discharge in an air flow and graphs of the dynamic current—voltage characteristics and differential resistances: a) normal GD, b) contracted, c) GD in the strata formation mode. U, V; i, mA.

capacitance C decreases, a source with steeply dropping characteristic should be used, the loop constant RC should be diminished, as corresponds to experiment and agrees with the criteria (1) and (2). For typical GD maintenance conditions, the deduced criteria reduce to comparing the DR r_d with the quantity (R_b). The relatively large stability of the GD-supply loop system to extinction as compared with the transition into an arc is interesting.

Also analyzed is the oscillatory current variation mode. In the case of oscillations at one frequency, the dynamic CVC has the form of a closed figure, i.e., a phase shift ϕ exists between the discharge current and voltage. Favorable conditions for maintaining the oscillations in the GD-supply loop system are realized for $\cos \phi = -1$ which corresponds to oscillations along the load line. The remaining fluctuation spectrum is quenched. This is also observed in experiment, say, during strata formation in the GD. The damping condition reduces to the requirement $\cos \phi = 1$ meaning that the GD has an active resistance and is consequently always stable. This holds, say, in an alternating current discharge [1].

The dependences obtained permit estimation of the stability and comparison of different schemes to maintain the GD.

NOTATION

U, discharge voltage; i, discharge current; R_b, ballistic resistance, C, capacitance; L, inductance; ε, emf source; I, source current; i_C, current through the capacitance; U_C, voltage at the capacitance; ω, oscillation frequency; α, current variation index; ϕ, phase shift between the voltage and current; $\tilde{U}$, $\tilde{I}$, voltage and current amplitudes; r, computed differential resistance; r_d, measured differential resistance; t, time; v, output supply source voltage; U_0, i_0, mean stationary discharge voltage and current; j, imaginary unit.

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