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SOME CHARACTERISTICS OF A PLASMATRON WITH AN INTERELECTRODE INSERT

A. S. Sergienko

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A critical analysis of the criterion $R_a^* + R_b > 0$ is made for a dc electric arc in the region of stable burning. The numerical values of the dynamic factor are determined and the dynamic current–voltage characteristic is investigated.

In [1, 2] the method of static current–voltage characteristics (SCVC) was used to establish the range of variation of the parameters of a dc electric arc centered by a distributed air vortex along a discharge chamber with a sectioned ($d_s = 1 \cdot 10^{-2}$ m, $n_s = 3$) interelectrode insert.

Devices of this type give a U-shaped SCVC ($R_a^* = dU_a/dI_a \gtrless 0$). This indicates [3] that current amplification in the arc is due both to the dominant increase in free-electron concentration in comparison with the reduction of their directional velocity (part with $R_a^* < 0$) and to the opposite relation of these characteristics (part with $R_a^* > 0$). In particular, in the considered plasma generator only the falling part ($R_a < 0$) of the SCVC could be obtained owing to the limitations of the power supply (U_L = 0–400 V; I_L = 200 A).

In this case, in accordance with the Kaufmann stability criterion [4]

$$K = R_a^* + R_b > 0 \tag{1}$$

a freely burning arc can exist for a long time only if the electrical circuit contains a series-connected ballast rheostat. We will analyze the validity of condition (1) for an arc operating in conditions of forced spatial stabilization. Criterion (1) is graphically illustrated in Fig. 1.

All points with coordinates belonging to the plane situated on the right of the bent line R^*–M–N will correspond to stable regimes. Since $R_a^* < 0$, the region ABC of existence of the arc lies below the R_b axis and well to the right of the interface MN($R_b = -R_a^*$). Hence, although condition (1) is satisfied on the boundaries AB and AC (the boundary BC identifies the maximum permissible prolonged current I_{max} = 200 A of the experimental device) the arc is extinguished. This fact leads to the following conclusion: In the case of an electric arc spatially stabilized by a gas vortex criterion (1) is a necessary, but not sufficient, condition for its existence. It is probably the unsteady mechanism of interaction of the positive column of the arc and its electrode regions with the surrounding medium that is responsible for the observed anomaly at the boundaries of the region ABC and for its limited size. In the discharge chamber of a plasma generator there occur numerous intense thermal, electric, and magnetohydrodynamic processes of a complex nature. In addition, the considered picture is greatly complicated by their pronounced unsteadiness.

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk.
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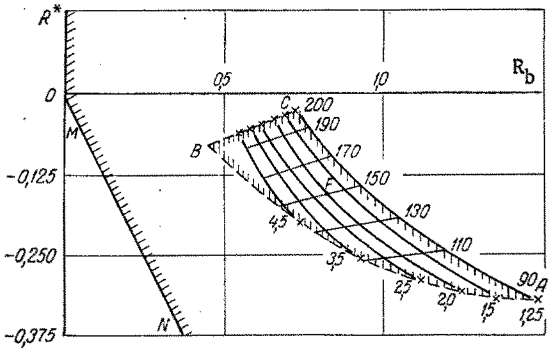

Fig. 1. Differential resistances of arc as function of resistance of ballast rheostat. ABC) stable arc region; MN) boundary. The figures on the line AB give the gas flow rate in $g \cdot sec^{-1}$; those on the line AC give the current in A. R^* and R_b are in Ω.

The spatial and temporal distortions of the contracted conducting arc channel are responsible for the fluctuations of the parameters over a broad spectrum in the general case and for small-scale fluctuations in particular [1, 2]. The correctness of representation of the arc parameter fluctuations by a Gaussian distribution function [5] confirms the stochastic nature of these fluctuations.

The amplitude–frequency characteristic (AFC) of the arc voltage fluctuations depends significantly on the selected working conditions (near the boundary AB or AC of the stability region). In other words, the AFC is largely determined by the absolute values of the arc voltage, arc current, and gas flow rate. An increase in arc current with G_g constant entails a reduction in amplitude and increase in frequency of the variable component of U_a, whereas an increase in gas flow rate has the opposite effect. Other conditions being equal, the shape, amplitude, and frequency of fluctuations of the integral parameters (U_a, I_a) of the arc depend on the degree of constriction of the arc or limitation of its mobility.

Regular fluctuations of arc voltage are found in a region bounded by a circle of diameter $d = \Delta R_a^* = -0.1$ Ω ($\Delta R_b = 0.15$ Ω), with center at point F with coordinates $R_a^* = -0.15$ Ω, $R_b = 0.83$ Ω. The guaranteed reserve of arc stability within the region ABC is $K = (0.37–1.18)$ Ω. The optimal value of K from the practical viewpoint is 0.68 Ω ($R_a^* = -0.15$ Ω, $R_b = 0.83$ Ω).

In view of this it is important from the scientific and practical viewpoints not only to determine experimentally the quantitative relation between the main quantities characterizing the process, but also to obtain an empirical or analytical relation.

In [2] experimental data were used to obtain an empirical expression which approximates with satisfactory accuracy the relation between the differential arc resistance and some of the parameters on which it depends

$$R_a^* = -AI^{-a}d^{-b}G_g^c G_{g1}^g G_{g2}^{-g}, \tag{2}$$

where $A = 392.6$, $a = 1.148$, $b = 0.426$, $c = 0.574$, and $g = 0.287$. In the range of variation of the main parameters within the region ABC ($82.5\ A \le I_a \le 200\ A$; $205\ V \le U_a \le 250\ V$; $1.25\ g \cdot sec^{-1} \le G_g \le 4.5\ g \cdot sec^{-1}$) the differential arc resistance is $R_a^* = -(0.027–0.32)$ Ω.

The static and differential resistance of an arc, as of any other heat-dependent resistor, depends on the temperature and, hence, on the power supplied to the discharge. If a set of SCVC is available the energy response of thermistors (including an electric arc) can be estimated from the sign and magnitude of the so-called dynamic factor [6]

$$D = \frac{U/I - dU/dI}{U/I + dU/dI} = \frac{R - R^*}{R + R^*}. \tag{3}$$

The functional relation between the dynamic factor and the ratio of the instantaneous power to the maximum power for a semiconducting thermistor, metal conductor, and electric arc is illustrated in Fig. 2. Semiconducting thermistors [6] with different boundary conditions, since the temperature coefficient of resistance is negative ($\beta = -dR_T/R_T dT$), have in the general case a variable positive dynamic factor ($D_T = 0–4$). In particular, for a KMT-1 thermistor ($R_{20} = 102.8$ kΩ, $B = 4225K$, $N_{max} = 64 \cdot 10^{-2}$ W) $D_T = 0–3$ (Fig. 2a, curve 1).

Metal resistors [6] have a positive temperature coefficient of resistance ($\beta_W > 0$) and, hence, $D_W < 0$. For instance, a platinum wire ($\beta_W = 3.95 \cdot 10^{-3}\ deg^{-1}$, $T_m = 20°C$, $N_{max} = 64 \cdot 10^{-2}$ W) has a dynamic factor $D_W = -0.35–0$ (Fig. 2a, curve 2). When the dissipated power varies in a wide range ($0 < N_{max} < \infty$) the dynamic factor D_W can take values ranging from 0 to −1.

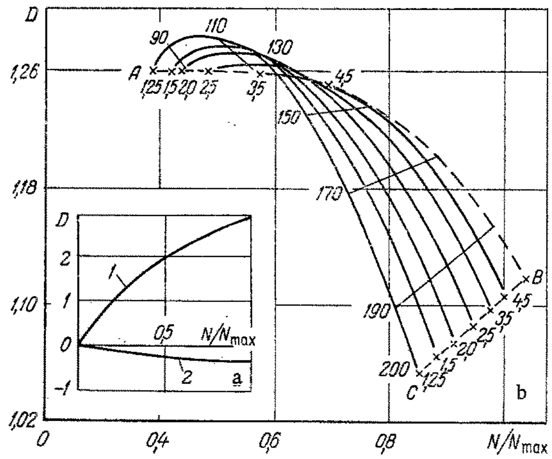

Fig. 2. Dynamic factor of some thermistors as function of relative value of dissipated power. a: 1) KMT-1 thermistor (R_{20} = 102.8 kΩ, B = 4225K, $N_{max} = 64 \cdot 10^{-2}$ W); 2) platinum wire ($\beta_w = 3.95 \cdot 10^{-3}$ deg^{-1}, T_m = 20°C, $N_{max} = 64 \cdot 10^{-2}$ W); b) electric arc of fixed length ($d_a = 1.5 \cdot 10^{-2}$ m, $d_c = 1 \cdot 10^{-2}$ m, $d_s = 1 \cdot 10^{-2}$ m, n_s = 3). ABC is the region of stable burning of the arc (N_{max} = 48.3 kW). The figures on line AC give the current in A; those on line BC give the gas flow rate in g·sec^{-1}.

For an electric arc burning in a sectioned channel with distributed gas injection [1, 2] the relation $D_a = \varphi(N)$ is a family of curves (G_g = const) of complex shape (Fig. 2b). In the power range 18.6 kW $\leq N_a \leq$ 48.3 kW the dynamic factor of the arc is D_a = 1.05–1.28.

An analysis of the stability of an electric arc on the basis of SCVC is not always admissible and can lead to erroneous results. For a rigorous treatment of stability the dynamic current–voltage characteristic (DCVC) must be used.

It is known [3] that any variation of the strength of the self-sustained current in the gas at a finite rate cannot in principle be derived from the SCVC owing to processes that inevitably lie outside the scope of this characteristic. There are several methods of producing a transient regime in an electric circuit and, hence, of measuring the DCVC. A periodic or aperiodic unsteady process can be obtained by supplying the arc with alternating [7, 8] or modulated [1] current, stepwise [9] or smooth [1] variation of the voltage drop on the discharge gap, exposure of the electric discharge to laser emission [10], etc.

In [1] quasisteady operation was obtained by smooth variation of the current in the circuit (U_L = const) at a prescribed rate ($\Delta I_a/\Delta\tau$ = 1.5–5 A·sec^{-1}) by reversible movement of the slider of the ballast rheostat (R_b = 0–0.4 Ω). The DCVC were plotted from the data of synchronous time scans of the arc voltage U_a and current I_a recorded on graph tapes of N340 recorders. The DCVC were also recorded simultaneously by means of a N359 two-coordinate recording millivoltmeter.

Below we compare the SCVC (G_g = 2.0 g·sec^{-1}) with a typical DCVC (Fig. 3 quadrant 1) obtained for G_g = 2.0 g·sec^{-1} and fixed rate of change of current in the circuit ($\Delta I_w/\Delta\tau$ = 1.5 A·sec^{-1}). In the initial state (point 1) the arc burns with U_a = 221.5 V and I_a = 188 A. An increase in the resistance of the ballast rheostat to R_b = 0.4 Ω shifts the arc to a new, lower, energy level (U_a = 232 V, I_a = 120 A). The presented CVC, as distinct from [11], differ significantly in shape (they bend in different directions). We can postulate that in unsteady conditions a higher arc burning voltage is required to maintain the equilibrium state. In the reverse course of the DCVC curves 2–3 lie a little higher and the coordinates lag slightly in time behind those of curves 1–2. The observed electrical hysteresis and the different shape of the DCVC are probably due to alteration of the temperature field of the electrode in the region of motion of the arc anchor spots. When the disturbance is removed the arc usually burns with a higher voltage ($\Delta U_a \simeq$ 7 V) and a lower current ($\Delta I_a \simeq$ 6 A). The arc returns to the initial state in time τ = 20–30 sec.

The relations $U_a = \varphi_1(\tau)$ and $I_a = \varphi_2(\tau)$ are shown in quadrants II and IV, respectively. Externally they recall a disturbance of exponential type. The rate of change of the arc current $w_i = dI_a/d\tau$ (quadrant III) is almost directly proportional to the rate of change of the arc voltage $w_u = dU_a/d\tau$. An appreciable deviation ($w_i > w_u$) from this rule is observed in the first 20–30 sec of the reverse course.

From the above account we can draw the following conclusions:

1. The condition for stable existence of an electric arc of controlled length requires substantial correction. For adequate generality it must include terms that take the "shunting" mechanism into account.

2. An electric arc burning in conditions of containment by distributed gas injection in a sectioned channel has a dynamic factor which is positive ($D_a > 0$) and variable (D_a = 1.05–1.28).

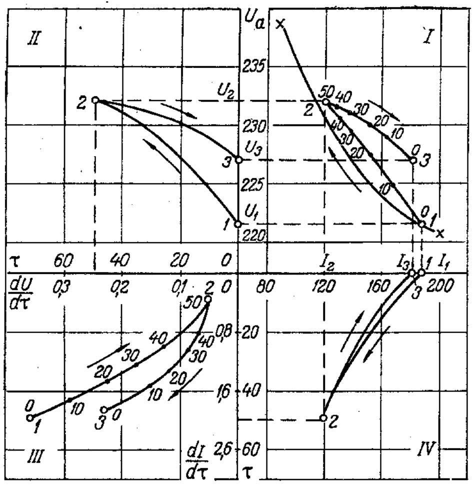

Fig. 3. Static and dynamic CVC of plasmatron with interelectrode insert and distributed gas injection. The gas was air; $G_g = 2.0\ g \cdot sec^{-1}$, $d_a = 1.5 \cdot 10^{-2}$ m, $d_c = 1 \cdot 10^{-2}$ m, $d_s = 1 \cdot 10^{-2}$ m, $n_s = 3$. The solid line in quadrant 1 is the SCVC. The figures on the graph are the time in sec, τ in sec, U_a in V, $dU/d\tau$ in V/sec, and $dI/d\tau$ in A/sec.

3. In conditions of slow ($f < 0.1$ Hz) transient processes the DCVC of an arc of fixed length differs significantly in shape and position from the SCVC. Hence, in the investigation of stability in these conditions the DCVC cannot be ignored.

NOTATION

U, voltage drop, V: I, current, A; N, power, W; R, static resistance, Ω; R^*, dynamic resistance, Ω; d, electrode diameter, m; n, number of sections in interelectrode insert; G_g, gas flow rate, $g \cdot sec^{-1}$; B, constant depending on properties of thermistor material, K; β, temperature coefficient, deg^{-1}; T, temperature; D, dynamic factor; τ, time, sec; w_i, rate of change of current, $A \cdot sec^{-1}$; w_u, rate of change of voltage, $V \cdot sec^{-1}$; f, frequency, Hz. Subscripts: *a*, arc; s, section; m, surrounding medium; T, thermistor; b, ballast; g, gas; w, wire.

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