DYNAMIC VOLT–AMPERE CHARACTERISTICS OF DIRECT CURRENT PLASMATRONS AT LARGE AND SMALL AMPLITUDES AND RATES OF CHANGE OF CURRENT

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The dynamic volt–ampere characteristics are obtained for a plasmatron with an interelectrode insertion at large amplitudes ($I_A > 50$ A) and small rates of change ($dI/dt \leq 5$ A/sec) of current. The results of an investigation by the method of small perturbations of a plasmatron with fixed arc length, in the frequency range 0.2-20 kHz, are given.

One of the most important problems in the practical use of plasmatrons is the establishment of the boundaries of stability of its operating conditions in U–I coordinates, i.e., the determination of the limits of variation of its parameters (I_A, U_A, G_g, etc.).

Existing methods of calculating the static U–I characteristics are notable for their low accuracy [3-6] or can be applied only to physically simplified models of plasmatrons [1, 2]. Hence the single and reliable method of determining the region of stability of a plasmatron is by experiment. Knowledge of the limits within which the current, voltage and gas flow rate vary is the starting point and the prerequisite for the investigation of the U–I characteristics in dynamic conditions.

The investigation of the dynamic U–I characteristics of plasmatrons for various rates of current change is necessary for the solution of problems in the automatic stabilization and programmed control of the stream parameters and allows the effect of the energy storage element of the electric arc on the nature of its resistance to be explained.

This paper is devoted to an investigation of the region of stability and the dynamic U–I characteristics of plasmatrons with an interelectrode insertion at large amplitudes ($I_A > 50$ A) and small rates of change of current ($dI/dt \leq 5$ A/sec), and also to an investigation of the static and dynamic U–I characteristics of a plasmatron with fixed arc length at small amplitudes ($\tilde{I}_A < 3$A) and large rates of change of current ($dI/dt > 10^2$ A/sec).

Experimental Apparatus. A block diagram of the electricity, water, and gas supply is shown in Fig. 1.

The direct current source ($U_A = 400$ V, $I_A = 200$ A) consists of a step-down power transformer T of type TMOA-63, a power rectifier 1, consisting of a three-phase bridge circuit using diodes of type VK-200 and thyristors of type VKDU-150, a commutator, and a protective apparatus. The supply voltage could be varied smoothly from 50 to 400 V.

To smooth fluctuations in the voltage rectifier, a square filter consisting of a battery of condensers C_1 (5120 μF, 450 V), C_2 (4500 μF, 600 V) and a choke coil L (40 MH) was provided.

The system 4 includes remote control, monitoring, signalling, and protection functions.

In the power circuit, in series with the plasmatron 5, were connected wire resistors $R_1 = 0.1$-$1.4\ \Omega$ and $R_2 = 0.05$-$0.4\ \Omega$ which could be varied smoothly and in steps.

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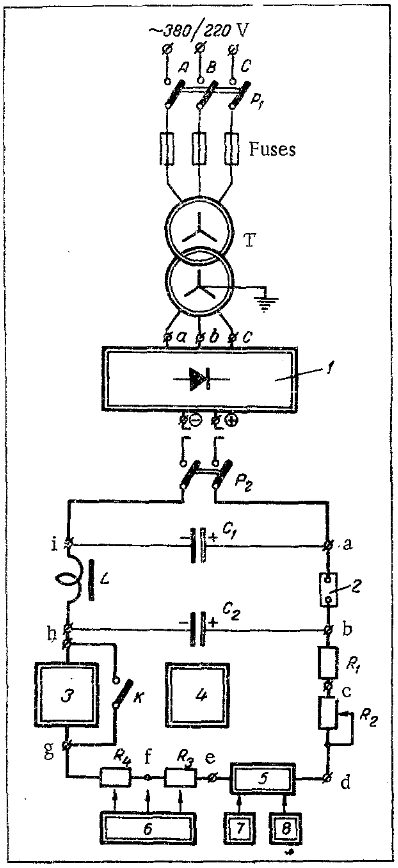

Fig. 1. Block diagram of the electric arc apparatus: 1) power rectifier; 2) shunt; 3) modulator; 4) control system; 5) plasmatron; 6) measuring system; 7) gas supply system; 8) water supply.

The modulator 3 was included in the power circuit to excite periodic oscillations of various shapes, frequencies (0.2-20 kHz), and amplitude (0-3.0 A).

The gas in the plasmatron 5 was supplied from the system 7 consisting of a high pressure tank, and reduction, control, and closing apparatus.

The gas flow rate was measured by a flow meter and a critical flow meter.

To cool the elements in the plasmatron discharge chamber the water supply system 8 was used.

The arc current and voltage in static and dynamic conditions for $dI/dt < 5$ A/sec were recorded by recording instruments of type N352 and by a loop oscillograph of type N700. The dynamic U–I characteristics were reproduced directly by a two-coordinate millivoltmeter of type N359.

The measuring system measures, observes, and records the dynamic U–I characteristics of a direct current arc, its variable components, and the phase shift between them for f = 20 Hz-20 kHz and the current in the power circuit up to 100 A and more. It includes selective measuring amplifiers of type U2-6, a lamp millivoltmeter of type V3-2A, single and double oscillographs of types ÉO-7 and S1-18, and a phase meter of type F2-1.

Current and voltage signals were taken from the wire resistors $R_3 = R_4 = 0.1\ \Omega$ and fed to the input of the measuring system 6. During adjustment at fixed frequency it was switched to the points s, f, g of the circuit. In this case the dynamic U–I characteristics can be observed on the ÉO-7 oscillograph screen as a straight line at a certain angle of slope to the coordinate axes. At the same time two components of these characteristics, coincident in phase, are observed on the S1-18 screen and the phase meter F2-1 shows the phase angle, which is zero.

To make measurements on the plasmatron the system 6 was switched to the points d, e, g.

A Plasmatron with an Interelectrode Insertion

The Static Volt–Ampere Characteristics. The investigation were made using a specially prepared plasmatron with an interelectrode insertion, a diagram of which is given in Fig. 2a.

The plasmatron discharge chamber is formed by water-cooled copper electrodes 1 and 5 and by sections of the interelectrode insertion 3, insulated from each other and from the electrodes.

The enclosed electrode 1 was the cathode and the electrode 5 at the other end was the anode. The cathode and anode dimensions were diameter and length, respectively, $d_c = 10$ mm, $l_c = 100$ mm, $d_a = 15$ mm, $l_a = 100$ mm. The interelectrode insertion 3 was made in three sections of diameter $d_s = 10$ mm and length $l_s = 10$ mm each so as to eliminate intersectional discharge which in a sufficiently large potential difference could lead to their breakdown [7-9].

Air at a flow rate of $G_g^1 = 1.0$ g/sec was applied tangentially in the gap between the cathode 1 and the interelectrode insertion 3. Air was also supplied tangentially in the remaining gaps at a flow rate G_g^2, which varied during the investigations. Because the gas supply was organized in this way it was possible not only to vary the electric field strength along the arc, but also to affect the breakdown potential between them.

The static U–I characteristics of a plasmatron with an interelectrode insertion working with air are shown in Fig. 2b.

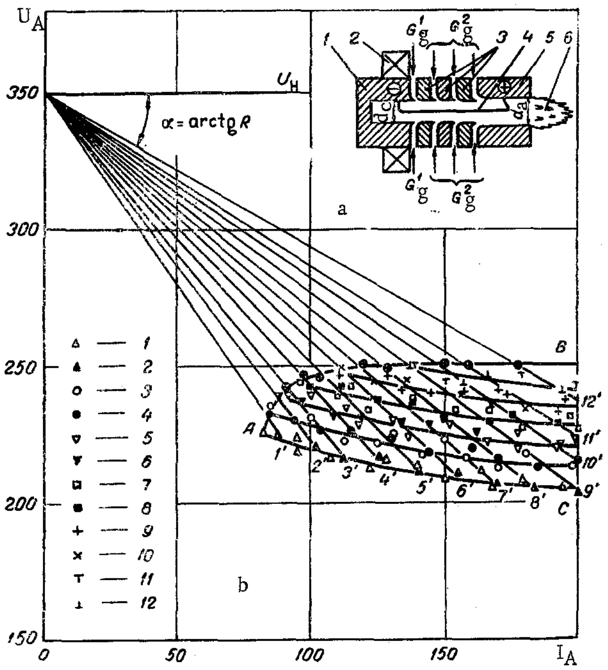

Fig. 2. Plasmatron with interelectrode insertion. a) Diagram of apparatus: 1) cathode; 2) magnetic field coil; 3) interelectrode insertion; 4) electric arc; 5) anode; 6) plasma stream. b) Static volt-ampere characteristics: air; $d_c = 10$ mm; $d_s = 10$ mm; $n_s = 3$; $d_a = 15$ mm. ABC) Region of stable operation; 1, 2) $G_g = 1.25$ g/sec; 3, 4) 1.5; 5, 6) 2.0; 7, 8) 2.5; 9, 10) 3.5; 11, 12) 4.5; 1') R = 1.4 Ω; 2') 1.25; 3') 1.2; 4') 1.1; 5') 1.0; 6') 0.9; 7') 0.85; 8') 0.8; 9') 0.75; 10') 0.65; 11') 0.6; 12') 0.55.

When G_g = const, R = var, these characteristics are falling curves which stratify and shift in the direction of high voltages as the gas flow rate increases.

In a plasmatron with a self-adjusting arc length the voltage increase is determined both by the increase in the arc length and by the increase in the field strength E of a unit column blown out in the longitudinal direction. In our case the arc length is scarcely affected by changes in the gas flow rate since it is necessarily elongated. Consequently, the increase in the intensity of combustion of the arc is primarily due to an increase in E. Since in a plasmatron with an interelectrode insertion the arc length is much greater than in a plasmatron with a self-adjusting arc, even a small increase in E leads to a significant change in the arc voltage. In addition, in a plasmatron without an interelectrode insertion, the bulk of the gas comes into no contact with the arc, since it is short. This explains why the arc voltage depends weakly on the gas flow rate. In a plasmatron with an interelectrode insertion a large part of G_g interacts with the arc since the latter occupies a significant part of the channel and this leads ultimately to an effective increase in U_A with increase in E [7-9].

When G_g = var, R = const, the static U–I characteristics are straight lines at an angle $\alpha = \arctan R$ to the abscissa.

The region of stable operation of the plasmatron (Fig. 2b) is bounded as follows:

1) above by the curve AB corresponding to $U_{A,max}$, $I_{A,min}$, G_g = const: the arc is quenched by the increase in its resistance $R_{A,max} = U_{A,max}/I_{A,min}$, the supply source being insufficient to maintain the arc process;

2) below by the curve AC beneath which the plasmatron operates in an unstable manner;

3) to the right by the straight line BC corresponding to maximum current ($I_{max} = 200$ A).

Investigations showed that a plasmatron with an interelectrode insertion is stable when the parameters vary within the following limits: 82 A $\le I_A \le$ 200 A; 204 V $\le U_A \le$ 250 V; 1.25 g/sec $\le G_g \le$ 4.5 g/sec; 0.55 Ω $\le R \le$ 1.4 Ω.

Dynamic Volt–Ampere Characteristics. These characteristics are formed by the ratio of the time-varying values of U and I.

The volt–ampere characteristics of a plasmatron with an interelectrode insertion in dynamic conditions are taken in the case when the current in the circuit varies as a result of a periodic change in the rheostat resistance (dR/dt = var, G_g = const). The dynamic U–I characteristics were recorded in the interval of variation of the parameters as used previously for the static characteristics ($G_g = 2$ g/sec, R = var).

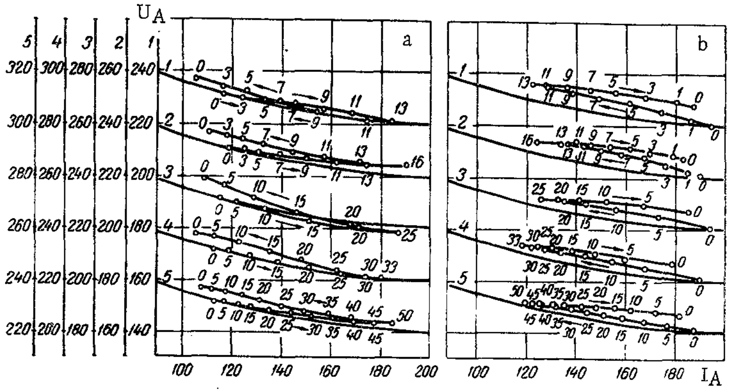

Fig. 3. Dynamic volt–ampere characteristics of a plasmatron with an interelectrode insertion (the gas is air, $d_c = 10$ mm, $d_s = 10$ mm, $n_s = 3$, $d_a = 15$ mm; the figures attached to the points show the time, sec): a) current larger then smaller; b) current smaller then greater; 1) $dI/dt = 5$ A/sec; 2) 4, 3) 3; 4) 2; 5) 1.5.

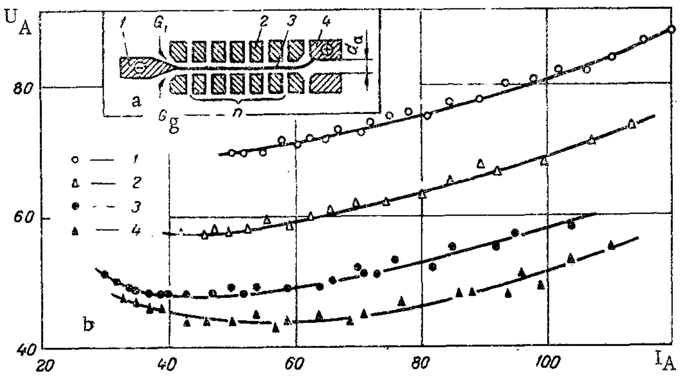

Fig. 4. A plasmatron with a fixed arc length. a) Diagram of apparatus: 1) cathode; 2) section of interelectrode insertion; 3) electric arc; 4) anode. b) Static volt–ampere characteristics: the gas is argon; $G_g = 0.03$ g/sec; $d_a = 4$ mm; 1) $d_s = 6$ mm; $n_s = 10$; 2) 6 and 8 respectively; 3) 6 and 6 respectively; 4) 8 and 6 respectively.

The current was made to change with time in two ways: a) increasing initially to some value and then decreasing (larger, then smaller; Fig. 3a); b) the converse behavior, decreasing to an appropriate value and then increasing (smaller, then greater; Fig. 3b). The dynamic characteristics were constructed from the values of U and I at the same moments of time.

The results showed that in both cases the dynamic U–I characteristics lay at a higher level on passing in the reverse direction than in the forward direction. After removing the perturbation the plasmatron does not return to its original state immediately but only after an interval of time (approximately 20 sec).

It follows from a comparison of the dynamic and static U–I characteristics that under the conditions a) and b) they differ slightly from each other, particularly in the second case.

These phenomena evidently are the result of the interaction of the arc with the gas flow as the current varies periodically. Then the average arc length and the field intensity vary slightly.

A Plasmatron with a Fixed Arc Length

Static Volt–Ampere Characteristics. The object of the investigation was a direct current plasmatron with a fixed arc length, a diagram of which appears in Fig. 4a. It consists of two electrodes 1, 4 and sections 2 of an interelectrode insertion. A tungsten column of diameter 10 mm was used as the electrode 1,

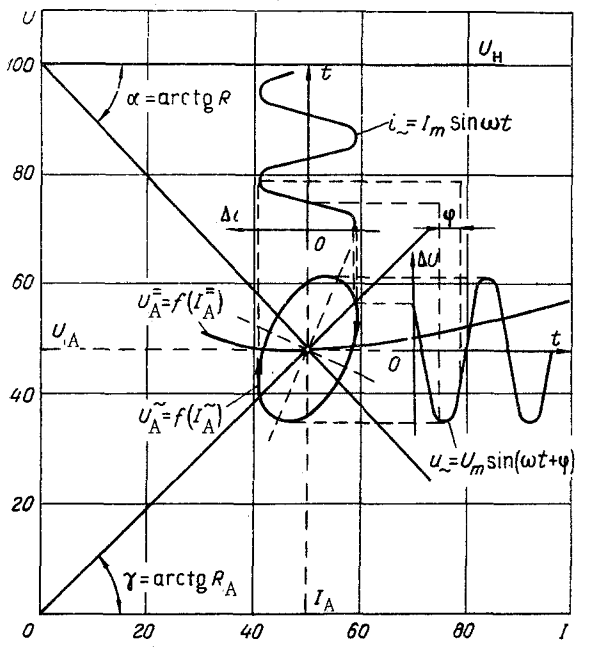

Fig. 5. Static and dynamic volt–ampere characteristics of a plasmatron with fixed arc length: the gas is argon; $G_g = 0.03$ g/sec; $d_a = 4$ mm; $d_s = 6$ mm; $n_s = 6$.

the working part being in the form of a cone. The electrode 4 was in the form of a tungsten sleeve of internal diameter 4 mm. Both electrodes were set in a water-cooled brass casing.

The interelectrode insertion consisted of water-cooled copper sections 2, insulated from each other and from the electrodes. Teflon rings were used for insulation and packing. The diameter and number of sections used in the experiments varied: d_s = 6-10 mm and n_s = 6-10. The thickness of each section was constant at 5 mm.

The gas forming the plasma was supplied at a flow rate G_g to the discharge chamber, through a neutral ring with two holes of diameter 1 mm.

Electrode 1 was the cathode, electrode 4 the anode.

The static U–I characteristics of a plasmatron with a fixed arc length are shown in Fig. 4b.

The experiments were made with argon at a constant flow rate ($G_g = 0.03$ g/sec). The equation $U_A^{=} = f(I_A^{=})$ was obtained for various ratios of the diameters and numbers of sections of the interelectrode insertion of the plasmatron. When the number of sections increased from 6 to 10 with $d_s = 6$ mm, the static U–I characteristics moved in the direction of higher intensities of combustion of the arc which was due both to the increase in the arc length and to the intensity of the electric field, E. When the number of sections was constant, $n_s = 6$, and their diameter increased from $d_s = 6$ mm to $d_s = 8$ mm, the characteristics were displaced downwards. Here the definite role is played by the nature of the change in the field intensity E of the arc as a function of the change in the current strength.

The static U–I characteristics of a plasmatron with 6 sections and ($dU/dI < 0$) d_s = 6 and 8 mm are U-shaped, i.e., have both decreasing and increasing parts ($dU/dI > 0$). The formation of characteristics of such a form is associated with the need to fix the arc length and restrict the increase in the effective diameter of the arc as the current increases.

Dynamic Volt–Ampere Characteristics. The dynamic U–I characteristics of the plasmatron were obtained by imposing a variable current component of sinusoidal form with amplitude $\tilde{I}_A = 0\text{-}3.0 \ll I_A^{=}$ on the plasmatron current.

The dynamic U–I characteristics were studied in three conditions: 1) $I_A = 30$ A; $U_A = 51$ V ($dU/dI < 0$); 2) $I_A = 50$ A; $U_A = 48$ V ($dU/dI^{\sim} = 0$); 3) $I_A = 70$ A; $U_A = 50$ V ($dU/dI > 0$), corresponding to the static U–I characteristics obtained with $d_s = 6$ mm, $n_s = 6$.

Figure 5 shows the equation $U_A^{=} = f(I_A^{=})$ in static conditions and $U_A^{\sim} = f(I_A^{\sim})$ in dynamic conditions. The dynamic U–I characteristics, as in [10-12], have the form of an ellipse with center at the point on the static U–I characteristics with parameters $I_A = 50$ A, $U_A = 48$ V. The variable components of the dynamic U–I characteristics are sinusoids, shifted in phase with respect to each other:

$$i_{\sim} = I_m \sin \omega t; \quad u_{\sim} = U_m \sin(\omega t + \varphi).$$

In Fig. 6 experimental dynamic U–I characteristics are shown $U_A = 51$ V, $I_A = 30$ A when the frequency of the imposed oscillations varied from 0.2 to 20 kHz. The amplitude of the variable current signal varied from 0 to 30 A.

The dynamic U–I characteristics of the variable components have the form of an ellipse which may degenerate into a straight line (Fig. 6a), depending on the frequency.

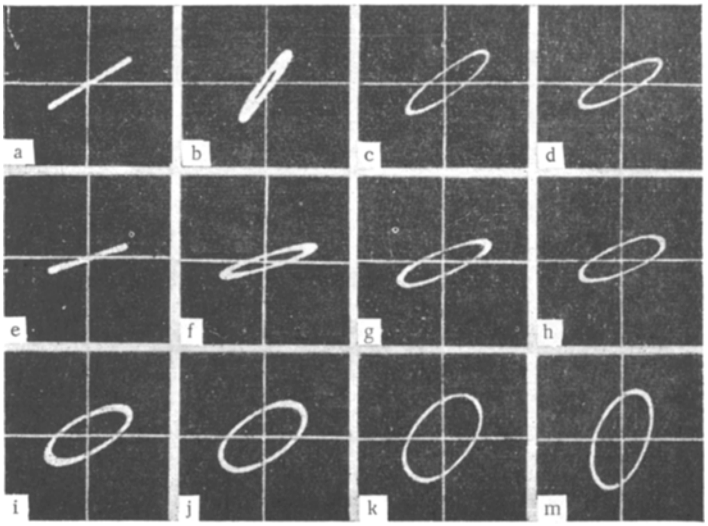

Fig. 6. Dynamic volt–ampere characteristics of a plasmatron with a fixed arc length: the gas is argon; $G_g = 0.03$ g/sec; $d_a = 4$ mm; $d_s = 6$ mm; $n_s = 6$; $U_D = 51$ V; $I_D = 30$ A. a) Tuning; b) f = 0.2 kHz, $\varphi = 5°$; a) tuning; b) f = 0.2 kHz, $\varphi = 5°$; c) 0.5 and 27°; d) 1.0 and 24; e) 2.0 and 0; f) 3.0 and 17; g) 4.0 and 27; h) 6.0 and 37; i) 8.0 and 42; j) 10.0 and 46; k) 15.0 and 51; m) 20.0 and 53.

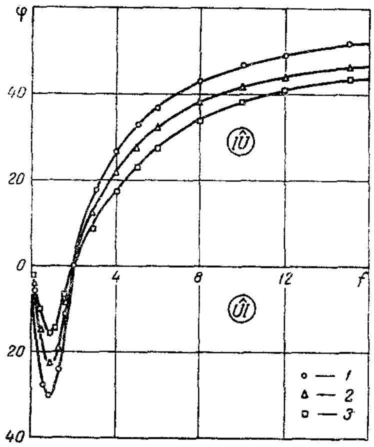

Fig. 7. The phase shift angle between the variable current and voltage components as a function of the frequency for a plasmatron with fixed arc length (φ, deg; f, kHz): the gas is argon; $G_g = 0.03$ g/sec; $d_a = 4$ mm; $d_s = 6$ mm; $n_s = 6$; $U_{mg} = 0.5$ V; $U_{mo} = 5$ V. 1) $I_A = 30$ A; $U_A = 51$ V; 2) 50 and 48, respectively; 3) 70 and 50, respectively.

The nature of the resistance of the arc as an element in the electric circuit was investigated in parallel. To do this the phase shift between the variable current and voltage components was measured.

In the above range of frequencies of the imposed oscillations, with $I_A = 50$ A, $I_A = 51$ V, the phase shift angle varied from 0 to 53°.

The equation $\varphi = f(f)$ is shown in Fig. 7. We see that the voltage leads the current in the frequency range 0.2-20 kHz, i.e., the arc resistance is inductive. As the frequency increases, conversely the current leads the voltage and the arc resistance is capacitive.

Analysis of the results obtained shows that the current in the circuit significantly affects the equation $\varphi = f(f)$, i.e., when the current increases from 30 to 70 A the phase shift decreases, but the qualitative form of the curve is preserved.

From the above investigations it was established that:

1. The dynamic U–I characteristics of a direct current plasmatron with an interelectrode insertion show electric hysteresis, differ from the static U–I characteristics in form, and are independent of the rate of change of the current within the limits 1.5-5 A/sec.

2. The dynamic U–I characteristics of a plasmatron with fixed arc length have the form of an ellipse, the shape and orientation of which vary with the frequency (f = 0.2-20 kHz) in U, I coordinates.

3. The arc resistance in the interval f = 0.2-2.0 kHz is inductive and in the interval 2.0-20 kHz it is capacitive.

NOTATION

U_A	is the voltage drop in the arc, V;
I_A	is the arc current, A;
$U^=$ and $U_A^\sim$	are the constant and variable components of arc voltage, V;
$I_A^=$ and $I_A^\sim$	are the constant and variable components of arc current, A;
U_{mg}	is the master generator voltage, V;
$U_{mo}^=$	is the modulator output voltage, V;
φ	is the phase shift angle between variable arc current and voltage components;
dI/dt	is the rate of change of current, A/sec.

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