

Antoni Sawicki

Modelling the Effect of External Disturbances in Static Characteristics of Unspecified and Determined Ignition Voltages on Dynamic Characteristics of Arc in a Circuit with Current Excitation. Part. 2. Simulation Test Result

Abstract: The mapping of nonlinear current-voltage characteristics of static arc with unspecified and determined ignition voltage involved the use of approximation functions (various modifications of the Ayrton and Nottingham equations). In addition, parameters of the above-named functions (power, voltage, resistance) depended on one selected disturbing parameter (length, gas mass stream, gas pressure). To this end, approximations based on power functions were used. The simulation of processes in circuits with forced sinusoidal current and electric arc involved the use of the Pentegov mathematical model. Selected parameters of created models were disturbed using specific rates of change. The study demonstrates the effectiveness of applied approximations in the form of voltage-current characteristics of dynamic arc.

Keywords: electric arc, Pentegov model, ignition voltage

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Introduction

Disturbances of the electric arc column may be triggered by the desirable control-related operations or undesired interference. The extension and the reduction of arc belong to the most common methods used to control the power of electric discharge, triggered by mechanical factors (movements of electrodes or barriers in ducts or the transverse flow of gas) or electrodynamic factors (activity of external magnetic fields). Changes in the gas mass stream may result from the necessity of obtaining appropriate temperature, gas enthalpy or the rate or pressure of a gas stream on the surface of a workpiece. The burning of electric arc

in environments characterised by various pressure results from the use of this “tool” for the performance of various metallurgical processes in furnaces and chemical processes in reactor chambers. Light technique utilises arc characterised by higher light (radiation) in gases of appropriate pressure.

By undertaking some protective measures it is possible to significantly reduce the effect of factors disturbing the burning of arc. The above-named measures include the stabilisation of the column position through the longitudinal flow of gas or by means of constrictor walls, the thermal insulation of the discharge area, the interaction of arc with laser radiation etc.

dr hab. inż. Antoni Sawicki(PhD (DSc) Habilitated Eng.), Professor at Częstochowa University of Technology, Faculty of Electric Engineering

The knowledge of static and dynamic arc characteristics is needed for the optimum (in terms of energy) control of the power of electrotechnical equipment, the maintaining of the adequate margin of discharge ignition, the reduction of investment and operating costs of equipment and the extension of its service life.

The first part of article [1] presents approximations of disturbed static current-voltage characteristics of arc by non-linear (power) functions. Sometimes, in cases of slight values of percentage deviations of external disturbances of arc from specified values, also linear approximations are used [2–4]. The above-named approximations may refer to changes in length, gas flow or gas pressure. As regards numerical calculations, the usability of the above-named linearisations is not high. However, they can facilitate the building of control systems and the performance of analysis concerning the operational stability of certain electrotechnical devices.

Disturbed static characteristics of arc

Experimental tests of arcs [5-8] reveal that the extension of column l_c leads to an increase in the value of voltage between electrodes. A similar effect can be obtained by increasing mass stream \dot{m} (volume) of gas washing around the column [2]. An increase in gas pressure p above the value of atmospheric pressure leads to an increase in arc voltage [9-11]. Parameters used in approximation equations (Tables 3 and 4 [1]) strongly depend on the chemical composition of the plasma-forming gas. As regards the use of technological gases only, the lowest value of voltage can be observed in relation to arc burning in argon. In cases of the same values of electric current, the voltage of arc burning in nitrogen or air is higher by twice. Slightly higher is the voltage of arc burning in helium. Nearly five times higher (in relation to argon) is the voltage of arc burning in hydrogen. The presence of metal vapours in the discharge area reduces arc voltage. Various technological

purposes involve the use of various gas mixtures. The suggested use of relative parameters (l_c/l_0) , (\dot{m}/\dot{m}_0) and $((p-p_0)/p_0)$ in approximation equations [1] improves their versatility. The primary values, i.e. $l_0 = 0.001$ m, $\dot{m}_0 = 0.001$ kg/s and $p_0 = 1 \cdot 10^3$ Pa, were adopted as constant values in all ranges of changes in current excitation. However, it is possible to use various values of primary parameters in individual ranges of current values, which could improve the accuracy of applied approximations yet, at the same time, it would increase the number of experimentally determined parameters.

The presentation of generalised results of simulations involved the use of the most complex current-voltage characteristics of arc. In Part 1 of article [1] and [12] the above-named characteristics were designated as (A7) and (A8) as well as (N7) and (N8). Because of the article length-related limitations, only special cases of characteristics were taken into consideration.

Figure 1 presents families of static current-voltage characteristics of arc characterised by the unspecified and determined values of ignition voltage corresponding to gradual column length changes.

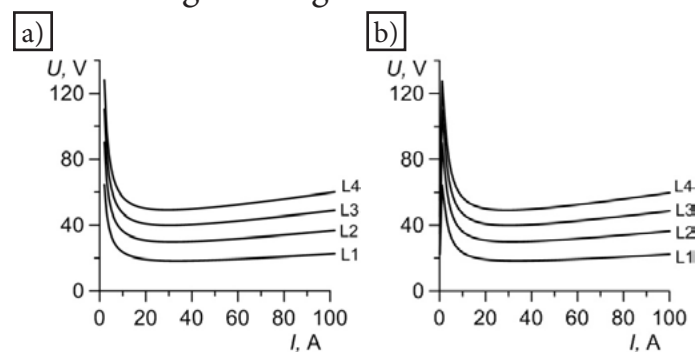


Fig. 1. Families of static characteristics of arc during gradual changes of column length l_c

$$(l_0 = 0.001 \text{ m}, n_{pl} = 0.4, P_1 = 60 \text{ W},$$

$$U_1 = 4 \text{ V}, n_{ul} = 0.8, n_{hl} = 0.6, R_1 = 0.04 \Omega, L_1 - l_c = 4 \cdot 10^{-3} \text{ m},$$

$$L_2 - l_c = 8 \cdot 10^{-3} \text{ m}, L_3 - l_c = 12 \cdot 10^{-3} \text{ m}, L_4 - l_c = 16 \cdot 10^{-3} \text{ m});$$

(a) unspecified ignition voltage (A7);

b) determined discharge ignition voltage (A8) ($I_M = 1$ A)

Figure 2 presents families of static current-voltage characteristics of arc characterised by the unspecified and determined values of ignition voltage corresponding to gradual changes in gas mass stream \dot{m} washing around

the column. Scientific reference publications sometimes present results of tests including gas flow rate \dot{v} . The correlation between the above-named parameters is the following:

$$\dot{m} = \dot{v}\rho \quad (1)$$

where ρ – gas mass density, kg/m^3 .

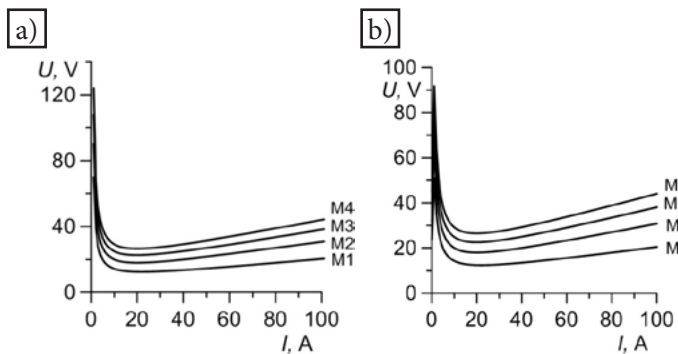


Fig. 2. Families of static characteristics of arc during gradual changes of gas mass stream

($\dot{m}_0 = 0.001 \text{ kg/s}$, $n_{pm} = 0.8$, $P_{m1} = 20 \text{ W}$, $P_{m0} = 60 \text{ W}$, $n_{um} = 0.8$, $U_{m1} = 4 \text{ V}$, $U_{m0} = 6 \text{ V}$, $n_{rm} = 0.5$, $R_{m1} = 0.1 \Omega$, $R_{m0} = 0.1 \Omega$, M1 – $\dot{m} = 1 \cdot 10^{-4} \text{ kg/s}$, M2 – $\dot{m} = 1 \cdot 10^{-3} \text{ kg/s}$, M3 – $\dot{m} = 2 \cdot 10^{-3} \text{ kg/s}$, M4 – $\dot{m} = 3 \cdot 10^{-3} \text{ kg/s}$):

a) unspecified ignition voltage (N7); b) determined discharge ignition voltage (N8) ($I_M = 0.6 \text{ A}$)

Figure 3 presents families of current-voltage characteristics of arc of unspecified and determined values of ignition voltage obtained during gradual changes in the pressure of gas washing around the column. Scientific reference publications frequently present results of experimental tests expressing the absolute value of pressure in various units, e.g. in bars ($1 \text{ bar} = 10^5 \text{ Pa}$).

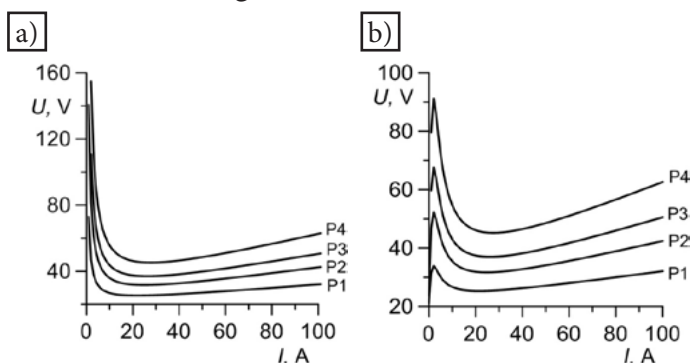


Fig. 3. Families of static characteristics of arc during gradual changes of gas pressure p ($p_0 = 1 \cdot 10^3 \text{ Pa}$,

$n_{pp} = 0.6$, $P_{p1} = 10 \text{ W}$, $P_{p0} = 15 \text{ W}$, $n_{up} = 0.8$, $U_{p1} = 0.1 \text{ V}$, $U_{p0} = 20 \text{ V}$, $n_{rp} = 0.5$, $R_{p1} = 0.02 \Omega$, $R_{p0} = 0.05 \Omega$, P1 – $p = 1 \cdot 10^4 \text{ Pa}$, P2 – $p = 5 \cdot 10^4 \text{ Pa}$, P3 – $p = 1 \cdot 10^5 \text{ Pa}$, P4 – $p = 2 \cdot 10^5 \text{ Pa}$):

a) unspecified ignition voltage (A7);

b) determined discharge ignition voltage (A8) ($I_M = 2 \text{ A}$)

Results of the simulation of mathematical models of arc subjected to stepped disturbances and sinusoidal current excitation

The operation of electrotechnical arc and plasma devices depends on performed technological operations and external disturbances. Depending on external conditions and applied control programmes, changes of several parameters of electric arc can take place at various rates at the same time or in a specific sequence. The effect of simultaneous fast two-parameter disturbances on the dynamic characteristics of arc of a selected static characteristic are presented in publication [13]. In similar calculations it is possible to use two-parameter approximations referred to in scientific reference publications, by, for instance, Drecker and Goldman [14] as well as Curtis and Decker [7].

The performance of simulation tests involved the preparation of an electric circuit macromodel containing the macromodel of electric arc representing the Pentegov mathematical model (developed in conjunction with Sidoretz) [15] of predefined static characteristics and external disturbances affecting them. Arc was powered by the power source of sinusoidal current having an amplitude of 100 A and a frequency of 50 Hz.

Figures 4, 5 and 6 presents dynamic characteristics of arc subjected to various types of disturbances. Parameters approximating the static characteristics of these arcs were selected in accordance with the data specified in descriptions of Figures 1-3. It was assumed that the time constant of arc was $\theta = 2 \cdot 10^{-4} \text{ s}$ and that the sum of near-electrode voltage drops amounted to 18 V. In Figure 4, arc was extended starting from 4 mm at a rate of 8 mm/s for 1 s. During the aforesaid operation, after 0.5 s there was an additional stepped increase in length of 10 mm. In turn, in Figure 5 arc was washed around by gas, the initial flow of which amounted to $1 \cdot 10^{-4} \text{ kg/s}$, which afterwards, increased at a rate of $3 \cdot 10^{-3} \text{ kg/s}^2$ for 1 s. During the above-presented

operation, after 0.5 s there was a stepped increase in the gas stream of $4 \cdot 10^{-3}$ kg/s. In addition, in terms of Figure 6, arc was in a chamber filled with gas under an initial pressure of $1 \cdot 10^4$ Pa, where pressure grew at a rate of $2 \cdot 10^5$ Pa/s for 1 s. During the above-named operation, after 0.5 s there was a stepped increase in the gas stream of $8 \cdot 10^4$ Pa. The above-presented diagrams of arc of static characteristics with unspecified

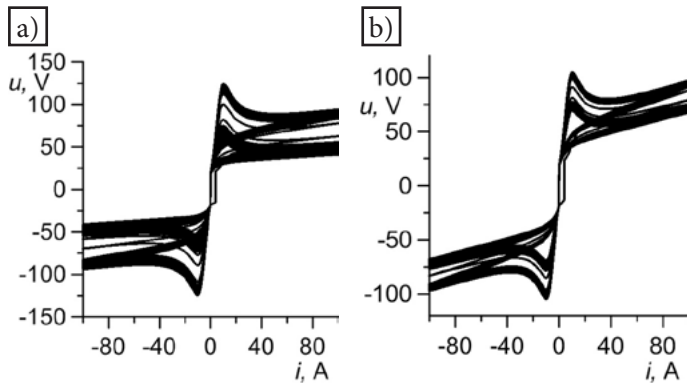


Fig. 4. Dynamic characteristics of arc subjected to length disturbances of: a) unspecified ignition voltage; b) determined ignition voltage ($I_M = 2A$)

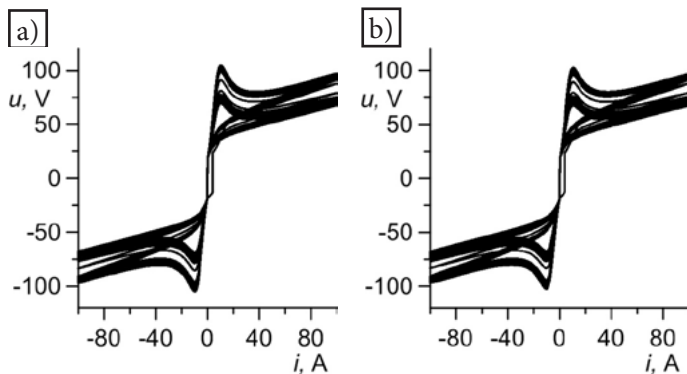


Fig. 5. Dynamic characteristics of arc subjected to disturbances of gas mass stream washing around the column of: a) unspecified ignition voltage; b) determined ignition voltage ($I_M = 3A$)

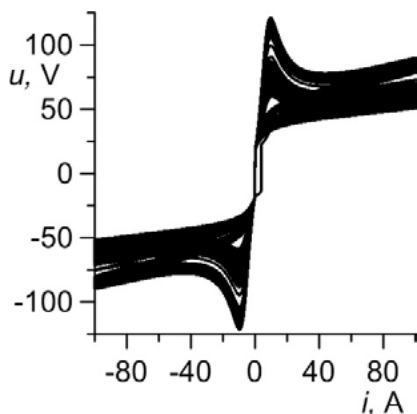


Fig. 6. Dynamic characteristic of arc characterised by unspecified ignition voltage subjected to gas pressure disturbances in the chamber with arc

and determined ignition voltage are characterised by very high similarity. Because of the fact that arc is a dissipative element in the electric circuit, dynamic current-voltage characteristics pass through the origin of coordinates (0, 0). Slight divergence of the figures from theory result from the numerical integration step adopted by the programme and the low precision of the graphic programme.

Concluding remarks

1. The activity of external disturbances of various physical nature enables the obtainment of very similar current-voltage characteristics of arc.
2. The mathematical model of arc subjected to external disturbances, discussed in the article, utilises the derivative of the column voltage in relation to the parameter. The applied approximations of data with power function $U_{col}(\dot{m})$ may impose the lower restriction of gas mass stream $\dot{m} > 0$. However, very low values of the stream have their physical justification, for instance, in the form of natural convective flows.
3. In the mathematical modelling of electric arc characterised by a very low damping function value, the application of current $I_M > 0$ A enables the more precise description of dynamic characteristics and, as a result, the limitation of values of voltage higher harmonics.

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