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Integral Method Enabling the Determination of the Parameters of the Mayr and Generalised Mayr Models of Electric Arc Excited in the Circuit Using the Sinusoidal Current Source

Abstract: The article presents the primary properties of the Mayr mathematical models, the generalised Mayr model and the Pentegov model of electric arc as well as indicates the limited possibilities of the Mayr model in the accurate representation of arc dynamic characteristics in areas where current passes through the zero. The above-named difficulties can be eliminated using the generalised Mayr model. The article describes an integral method enabling the experimental identification of parameters of the generalised Mayr model and of the Mayr model of arc powered by a source having a sinusoidal wave. The above-named method was verified numerically by simulating processes in a simple electric circuit with macromodels of undisturbed arc.

Keywords: electric arc, Mayr model, generalized Mayr model, Pentegov model, integral method

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Introduction

The computer implementations of the Pentegov mathematical model [1] of arc utilise any freely selected static voltage-current characteristic. Although the model is linear and one-dimensional, it only constitutes the generalisation of other popular simpler linear mathematical models of arc [2]. For this reason, the Pentegov model provides vast representation possibilities of processes in circuits with any electric arcs.

The freedom related to the selection of the static characteristic of arc in the Pentegov model (developed along with Sidorets) impedes the development of general principles regulating the determination of mathematical model parameters. Only in special cases of the selection of a static characteristic shape and the waveform of current generated by an excitation source it is possible to develop spectral and integral methods related to the experimental determination of parameters of selected arc submodels (special cases of the Pentegov model) belonging to a relatively small set of models [3-7]. Extending the above-named set by a new model with the physically justified shape of a static characteristic could significantly facilitate the modelling of equipment and the simulation of processes in their circuits, particularly with low-current arcs.

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Selected Properties of the Mayr Model

One of the oldest and most frequently used arc column mathematical models applied when simulating processes in low-current electric circuits is the Mayr model [8] belonging to the class of linear models described by the 1st order differential equation. Changes in excitation current *i* correspond to changes in the conductance of column *g* in accordance with the following equation

$$Q_0 \frac{dg}{dt} + P_M g = i^2 \tag{1}$$

which can be expressed by the most frequently used form

$$\theta_M \frac{dg}{dt} + g = \frac{i^2}{P_M} \tag{2}$$

where P_M – constant Mayr power, W; Q_0 – enthalpy being the measure of exponential changes in conductance during arc energy changes, J; θ_M – time constant of the Mayr model

$$\theta_M = \frac{Q_0}{P_M} \tag{3}$$

expressed in milliseconds. The above-presented model corresponds to the static voltage-current characteristic of arc excited by direct current *I*

$$U_{col} = \frac{P_M}{I} \tag{4}$$

which can be described in the form of the conductance-current characteristic

$$G = \frac{I}{U_{col}} = \frac{I^2}{P_M} \tag{5}$$

The shapes of the static characteristics of the above-named model are presented in Figure 1.

Although the Mayr model describes low-current processes relatively well, the value of electrode gap breakdown voltage remains indefinite in this model. In practice, the above-named value depends on many physical factors including the temperature, pressure and chemical composition of gas as well as the temperature and shape of electrodes etc. This value is particularly important as regards bipolar alternating current as it also depends on the frequency and waveform of the current. The value of electrode gap breakdown voltage can also be set using various external constant or pulsed effects ionising the gas in the interelectrode gap area (in the form of laser radiation, microwave radiation etc.).

Usually, a decrease in the value of current module is accompanied by a significant increase in the value of arc damping function (up to the order of milliseconds). As a result, on dynamic characteristics the value of breakdown voltage often remains strongly diffuse. As the damping function also depends on many physical factors [9], in many types of electric devices (e.g. in plasma torches stabilised by gas flows, switches utilising SF_6) value θ_M remains very low. This leads to a significant increase in the amplitude of voltage on arc and an increase in the content of high-number harmonics in the voltage spectrum.

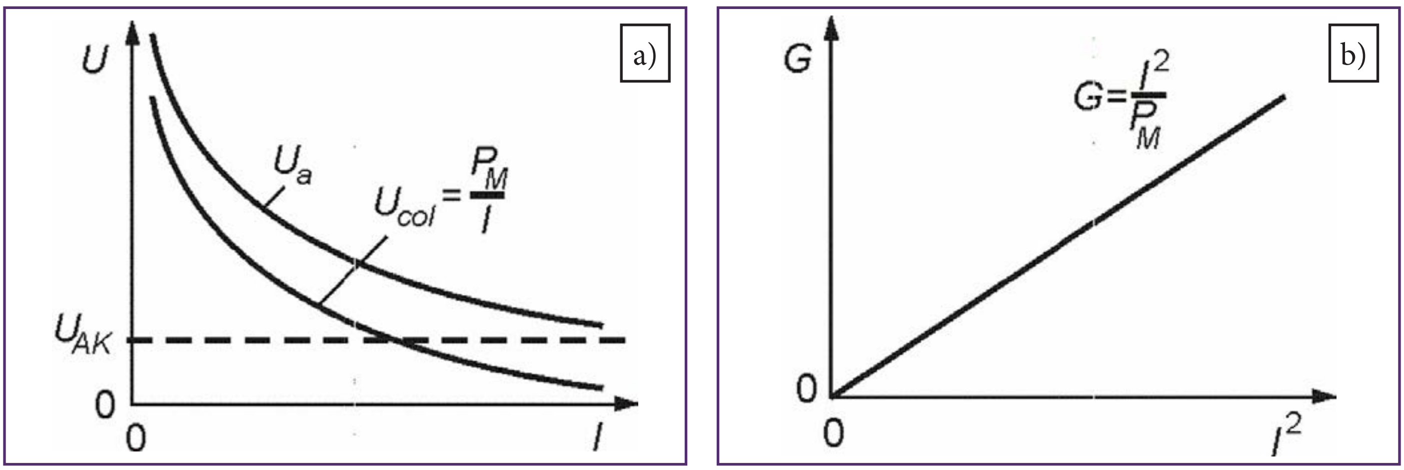

Fig. 1. Static characteristics of arc described by the Mayr model: characteristic $U(I)$ and b) characteristic $G(I^2)$

Mayr Model as a Special case of the Pentegov Model

The Pentegov model results from the equation of power balance in the column

$$\frac{dQ}{dt} = p_{el} - p_{dys} \tag{6}$$

where

– supplied electric power:

$$p_{el} = u_{col} i = \frac{i^2}{g} \tag{7}$$

– dissipated electric power:

$$p_{dys} = U_{col}(i_\theta) i_\theta = \frac{i_\theta^2}{g} \tag{8}$$

where i_θ - virtual state current; Q – enthalpy of gas in the column. Therefore, equation (6) can be expressed in another form

$$g\frac{dQ}{dt} = i^2 - i_\theta^2 \tag{9}$$

Based on transformations $gdQ = g\frac{dQ}{di_\theta^2} di_\theta^2$

and after adopting assumption

$$g\frac{dQ}{di_\theta^2} = \theta = const.$$

it is possible to identify the enthalpy of plasma $Q = 2\theta\int U_{col}(i_\theta) di_\theta$. Hence, the known linear equation of the Pentegov model [1] is obtained

$$\theta\frac{di_\theta^2}{dt} + i_\theta^2 = i^2 \tag{10}$$

The Mayr model is one of the special cases of the Pentegov model. In this model, the enthalpy amounts to

$$Q = 2\theta_M \int \frac{P_M}{i_\theta} di_\theta = \theta_M P_M \ln\left(\frac{i_\theta}{I_0}\right)^2 = Q_0 \ln\left(\frac{g}{g_0}\right) \tag{11}$$

where I_0 – integration constant; $g_0 = I_0^2 / P_M$; $\theta_M = \theta$ – model time constant. Quantity

$$Q_0 = \theta_M P_M \tag{12}$$

constitutes the measure of exponential changes in conductance during energy changes. This result is consistent with the Mayr assumption, where

$$\exp\left(\frac{Q}{Q_0}\right) = \frac{g}{g_0} \tag{13}$$

and the static voltage-current characteristic of the arc column has the form presented in (4).

Selected Properties of the Generalised Mayr Model (GMM)

The modification of the Mayr model makes it possible to allow for the finite (preset) value of voltage at the point of ignition discharge on the static characteristic of electric arc. The appropriate equation has the following form [10]

$$Q_0\frac{dg}{dt} + P_W g = i^2 + I_W^2 \tag{14}$$

which can be expressed in the following form

$$\theta_W\frac{dg}{dt} + g = \frac{i^2 + I_W^2}{P_W} = \frac{i^2}{P_W} + G_W \tag{15}$$

where $G_W = I_W^2 / P_W$ – characteristic conductance of the GMM, S; P_W – constant power of the GMM, W; I_W – constant component of the GMM current, A. Similar to previous cases, the time constant of the GMM is defined as

$$\theta_W = \frac{Q_0}{P_W} \tag{16}$$

and expressed in milliseconds. The model corresponds to the static characteristic of arc

$$U_{col} = \frac{P_W I}{I^2 + P_W G_W} = \frac{P_W I}{I^2 + I_W^2} \tag{17}$$

which can also be expressed in the following form

$$G = \frac{I}{U_{col}} = \frac{I^2}{P_W} + G_W \tag{18}$$

The shapes of the static characteristics of the above-presented model are demonstrated in Figure 2.

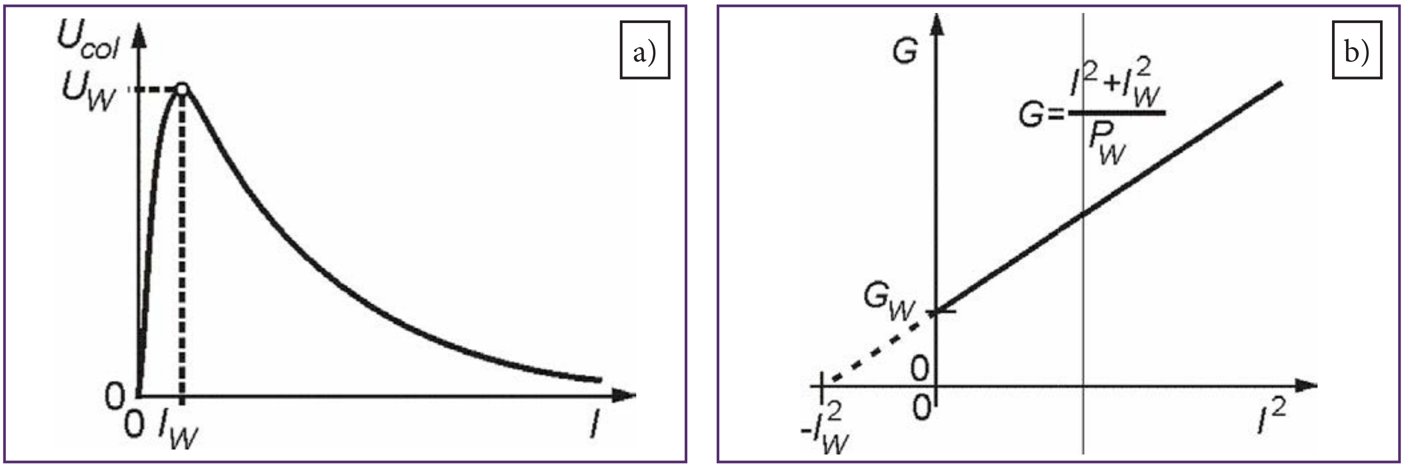

Fig. 2. Static characteristics of the column of arc described by the GMM: characteristic $U_{col}(I)$ and b) characteristic $G(I^2)$

Generalised Mayr Model as a Special case of the Pentegov Model

The input assumptions related to the GMM are similar to those of the Mayr model, i.e. (1), (2) and (6)-(9). The dependence resulting from these assumptions is the following

$$Q_0 \frac{dg}{dt} = i^2 - \left(\frac{Q_0}{\theta} g - I_W^2 \right) \tag{19}$$

The adoption of designation $P_w = Q_0/\theta_W$ is followed by the obtainment of equation (14) with the static characteristic determined by equation (17) or (18). The static characteristic of the model can also be presented in the system of other coordinates (Fig. 3).

The model corresponds to the static characteristic related to state current i_θ

$$U_{col}(i_\theta) = \frac{P_W i_\theta}{i_\theta^2 + P_W G_W} = \frac{P_W i_\theta}{i_\theta^2 + I_W^2} \tag{20}$$

When testing the shape of this function by equating its derivative to zero, the coordinates of the extreme point

$$S(I_W, U_W) = S\left(I_W, \frac{P_W}{2I_W} \right) \tag{21}$$

are obtained, there $U_W = P_W/(2\,I_W)$. Figure 4 presents the static characteristics of the column of arc $U_{col}(I)$. As can be seen, the curve of voltage U_{cW} passes through the zero point of the coordinate system and after reaching the maximum at point S nears the hyperbola constituting the static characteristic of the Mayr model U_{cM}. In the GMM, arc enthalpy amounts to

$$\begin{aligned} Q &= 2\theta_W \int \frac{P_W i_\theta}{i_\theta^2 + I_W^2} di_\theta = \\ &= \theta_W P_W \ln\left(\frac{i_\theta^2 + I_W^2}{I_0^2 + I_W^2} \right) = Q_0 \ln\left(\frac{g}{g_0} \right) \end{aligned} \tag{22}$$

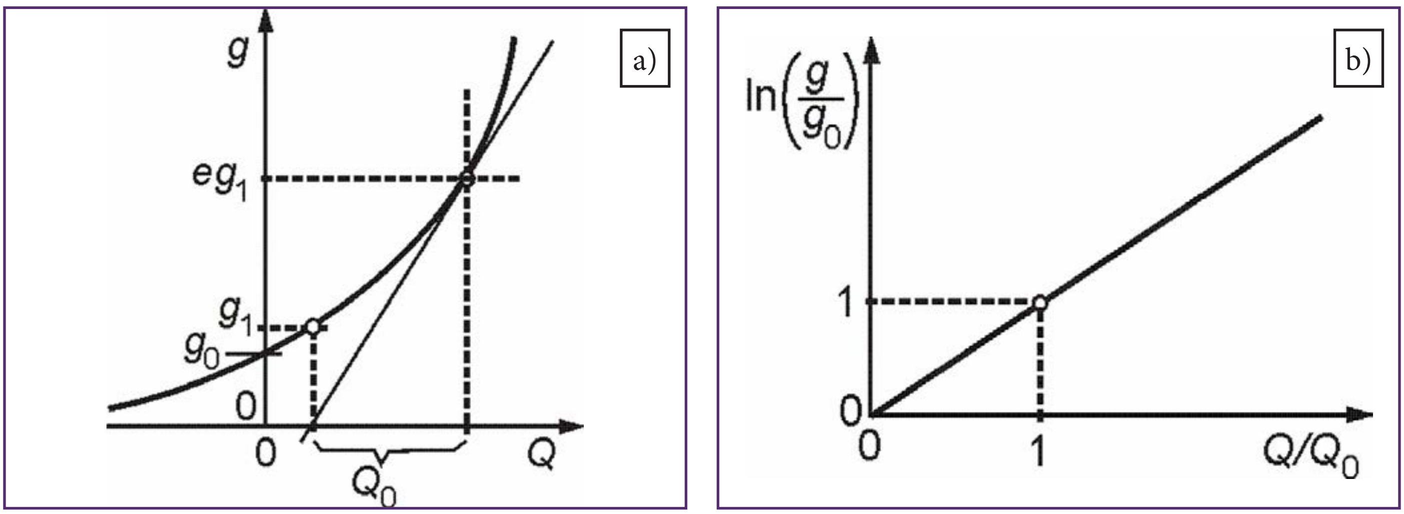

Fig. 3. Static characteristics of the GMM of the arc column: a) $g = f_1(Q)$; b) $\ln(g/g_0) = f_2(Q/Q_0)$

where I_0 – integration constant, $g_0 = \left(I_0^2 + I_W^2\right)/P_W$; $\theta_W = \theta$ – time constant of the model. Quantity

$$Q_0=\theta_W P_W \tag{23}$$

constitutes the measure of exponential conductance changes during energy. This result is consistent with the Mayr assumption (13).

Determination of the Parameters of the GMM and Mayr Mathematical Model of the Column of Arc Powered by an Ideal Power Source Generating Sinusoidal Waveform

The initial stage of investigation on electric arc involves the determination of near-electrode voltage drops (Fig. 1a) using various direct and indirect methods [11]. The knowledge of the above-named drops enables the identification of voltage on the arc column. In the symmetric case (nearly identical electrodes), the voltage on the arc column amounts to

$$u_{col}=u_a - U_{AK}\operatorname{sgn} i \tag{24},$$

where u_a – voltage on electrodes; U_K – near-cathode voltage drop; U_A – near-anode voltage drop; $U_{AK} = U_A + U_K$ – sum of near-cathode and near-anode voltage drops. If arc is asymmetric, ($U_{K1} \neq U_{K2}$, $U_{A1} \neq U_{A2}$) and then $U_{AK1} = U_{K1} + U_{A1} \neq \neq U_{AK2} = U_{K2} + U_{A2}$. Therefore, the voltage drop on the column of such arc amounts to

$$u_{col} = \begin{cases} u_a - U_{AK1}, \text{ if } i \geq 0 \\ u_a + U_{AK2}, \text{ if } i < 0 \end{cases} \tag{25}$$

It is assumed that arc is affected by excitation in the form of sinusoidal current

$$i = \sqrt{2} I_{rms} \cos \omega t \tag{26}$$

Base on equation (14), it is possible to write the differential equation of column conductance

$$Q_0 \frac{dg}{dt} + P_W g = I_{rms}^2 \left(1 + \cos 2\omega t\right) + I_W^2 \tag{27}$$

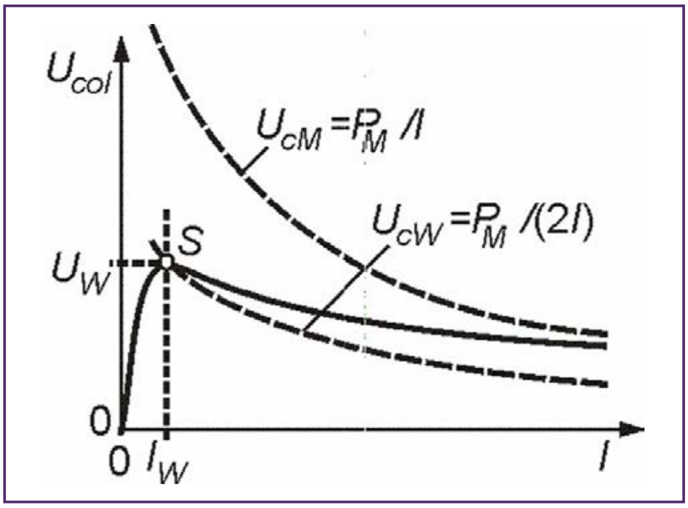

Fig. 4. Static characteristics of the Mayr models $U_{cM}(I)$ and GMM $U_{cW}(I)$

where I_{rms} – root-mean-square current; $\omega = 2\pi/T$ – pulsation; T – period of excitation current.

Current i_θ, corresponding to $\theta = \theta_W$ and excitation (26) fulfils equation (10) expressed as follows

$$\theta_W \frac{di_\theta^2}{dt} + i_\theta^2 = I_{rms}^2 \left(1 + \cos 2\omega t\right) \tag{28}$$

Its periodical solution is the following

$$i_\theta^2 = I_{rms}^2 \left[1 + \cos\varphi \cos\left(2\omega t - \varphi\right)\right] \tag{29}$$

where $\mathrm{tg}\varphi = 2\omega\theta_W$. Allowing for the relationship

$$P_W g = i_\theta^2 + I_W^2 \tag{30}$$

makes it possible to obtain the entire periodical solution

$$P_W g = I_W^2 + \\ + I_{rms}^2 \left(1 + \cos^2\varphi \cos 2\omega t + \sin\varphi \cos\varphi \sin 2\omega t\right) \tag{31}$$

The sought parameters of the GMM are Q_0, P_W and I_W. To identify them involvers the calculation of the definite integral of solution (31)

$$P_W \int_0^T g dt = \left(I_{rms}^2 + I_W^2\right)T \quad \omega T = n\pi, \qquad n \in N \tag{32}$$

Likewise, equation (15) multiplied by cos2ωT and integrated after time t gives

$$P_W \int_0^T g \cos 2\omega t dt = \frac{\cos^2\varphi}{2} I_{rms}^2 T \tag{33}$$

In turn, equation (31) multiplied by sin2ωT and integrated after time t leads to the obtainment of

$$P_W \int_0^T g \sin 2\omega t dt = \frac{1}{2} \sin\varphi \cos\varphi I_{rms}^2 T \tag{34}$$

After the division of equation (34) by (33), the following form is obtained

$$\mathrm{tg}\varphi = \frac{\int_0^T g \sin 2\omega t dt}{\int_0^T g \cos 2\omega t dt} \tag{35}$$

hence

$$\theta_W = \frac{1}{2\omega} \mathrm{tg}\varphi \tag{36}$$

Equation (33) taking into consideration

$\cos^2\varphi = \frac{1}{1+\mathrm{tg}^2\varphi}$ leads to the obtainment of

$$P_W = \frac{I_{rms}^2}{\frac{2}{T}\left(1+\mathrm{tg}^2\varphi\right)\int_0^T g \cos 2\omega t dt} \tag{37}$$

Alternatively, equation (34) taking into consideration

$\sin 2\varphi = \frac{2\mathrm{tg}\varphi}{1+\mathrm{tg}^2\varphi}$ leads to the obtainment of equivalent formula

$$P_W = \frac{I_{rms}^2 \mathrm{tg}\varphi}{\frac{2}{T}\left(1+\mathrm{tg}^2\varphi\right)\int_0^T g \sin 2\omega t dt} \tag{38}$$

The current of the GMM is identified using the following dependence

$$I_W^2 = P_W \frac{1}{T}\int_0^T g dt - I_{rms}^2 \tag{39}$$

Formulas (35)-(39) enable the relatively easy experimental determination of the parameters of the GMM using the integral method (involving the use of average and root-mean-square values). As the Mayr model constitutes a special case of the GMM (I_W = 0 A), the formulas enabling the determination of its parameters are simplified to the following form

$$P_M = \frac{I_{rms}^2}{\frac{1}{T}\int_0^T g dt} \tag{40}$$

$$\theta_M = \frac{1}{2\omega} \mathrm{tg}\varphi = \theta_W = \theta \tag{41}$$

Numerical Verification of the Integral Method Enabling the Determination of the Mayr Model and GMM Parameters

The investigation of the effectiveness of the integral method enabling the determination of the parameters of arc mathematical models involved the creation of its macromodel in the MATLAB-Simulink software programme. The macromodel was included in a simple circuit containing an ideal power source generating a sinusoidal waveform having frequency f = 50 Hz and an amplitude of 7 A. The investigation assumed nearly identical emissive properties of electrodes leading to the constant value of voltage U_{AK} drop and to the symmetry of arc electric characteristics. After the physical (using a special compensator) or numerical elimination of the above-named voltage, it is possible to identify momentary voltage on the arc column

$$u_{col}(i) = \frac{U_{col}(i_\theta)}{i_\theta} i = \frac{P_W i}{i_\theta^2 + P_W G_W} = \frac{P_W i}{i_\theta^2 + I_W^2} \tag{42}$$

In the preliminary simulation tests, the interim process in the circuit was eliminated and the appropriate value of arc initial conductance was set

$$G_0 = g(t = 0\mathrm{s}) = \frac{I_{rms}^2\left(1+\cos^2\varphi\right) + I_W^2}{P_W} \tag{43}$$

In the above-presented manner, the proper operation of data processing procedures was verified. Subsequent simulations involved the setting of various initial conditions. After a relatively long time enabling the lapse of the interim period, the system of data analysis was activated. The independent variables of the macromodel included power (set using the appropriate length of the plasma column) and the damping function ((time constant) set by selecting the appropriate chemical composition of the gas and adjusting the intensity of plasma column cooling).

The performed simulations resulted in the identification of the relative percentage errors related to the determination of the parameters of arc mathematical models. The demonstration of the effect of the preset parameters (power and damping) on the tendencies of changes in errors $\delta\theta$, δP_M, δP_W i $\delta I_W = f(P, \theta)$ required taking into consideration the signs of the above-named errors (preset values of the macromodel parameters were deducted from the values determined in the simulations).

Figure 5 presents correlations between the errors related to the determination of the parameters (time constant and power) of the Mayr mathematical model (2) and the preset macromodel parameters. The above-named errors are generated during numerical calculations. The computer-aided processing of measurement data constitutes the primary part of the measurement system. The low values of arc time constants correspond to the relatively high (exceeding 20%) positive values of the errors related to the determination of the model time constant, which means that measured values will be higher than actual ones. As can be seen, the measured values are almost independent of arc power. In turn, the errors related to the determination of the mathematical model power are relatively low (below 0.3%) and increase slightly along with increasing arc power. In cases of relatively high values of the arc damping factor, the above-named errors can be even negative.

Figure 6 presents the diagrams of percentage errors related to the determination of the parameters of the GMM (15) in the circuit with current excitation and an appropriate arc macromodel. Similar to the foregoing, the low values of arc damping factor correspond to the relatively high positive values of errors (above 20%) related to the determination of the model time constants. The values of the errors related to the determination of the mathematical model power are relatively low (below 1%). The relatively high values of the damping factor ($0.5 \cdot 10^{-3}$ s and $1 \cdot 10^{-3}$ s) correspond to the negative values of errors δP_W, δI_W,

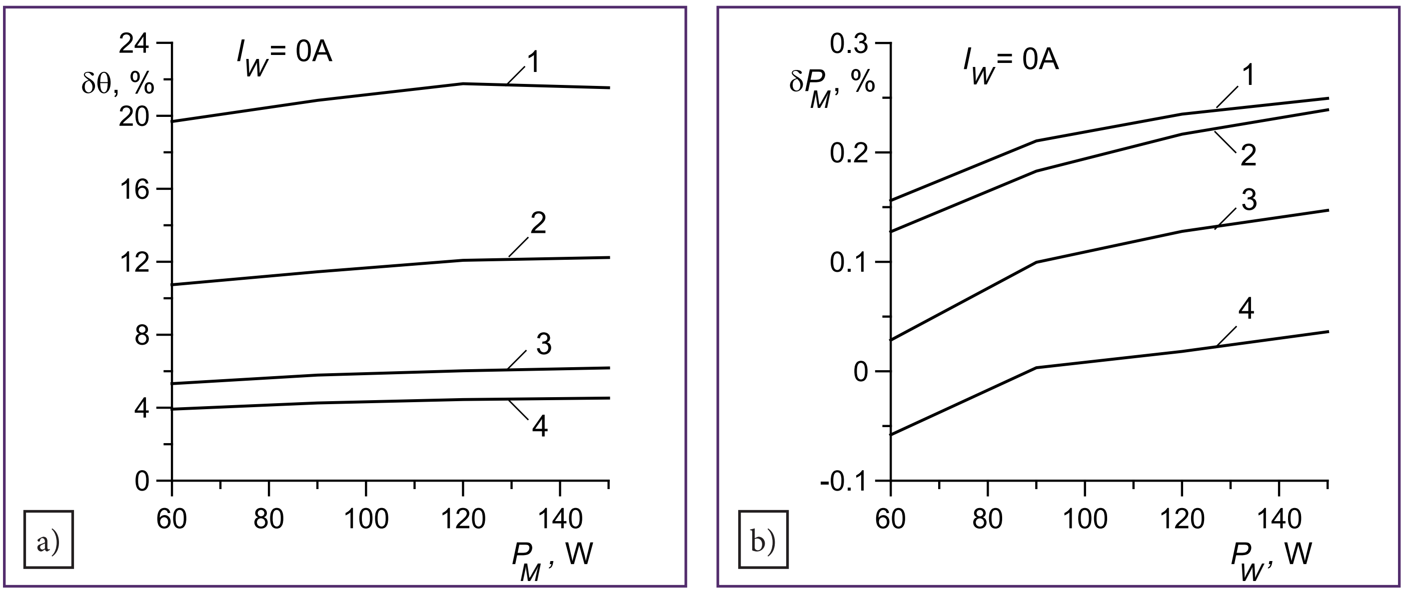

Fig. 5. Percentage errors related to the determination of the parameters of the Mayr model of arc (macromodel time constants: 1 - $\theta = 1 \cdot 10^{-4}$ s, 2 - $\theta = 2 \cdot 10^{-4}$ s, 3 - $\theta = 5 \cdot 10^{-4}$ s, 4 - $\theta = 1 \cdot 10^{-3}$ s): a) errors related to the determination of the mathematical model time constant $\delta\theta_M = \theta$; b) errors related to the determination of the Mayr power δP_M

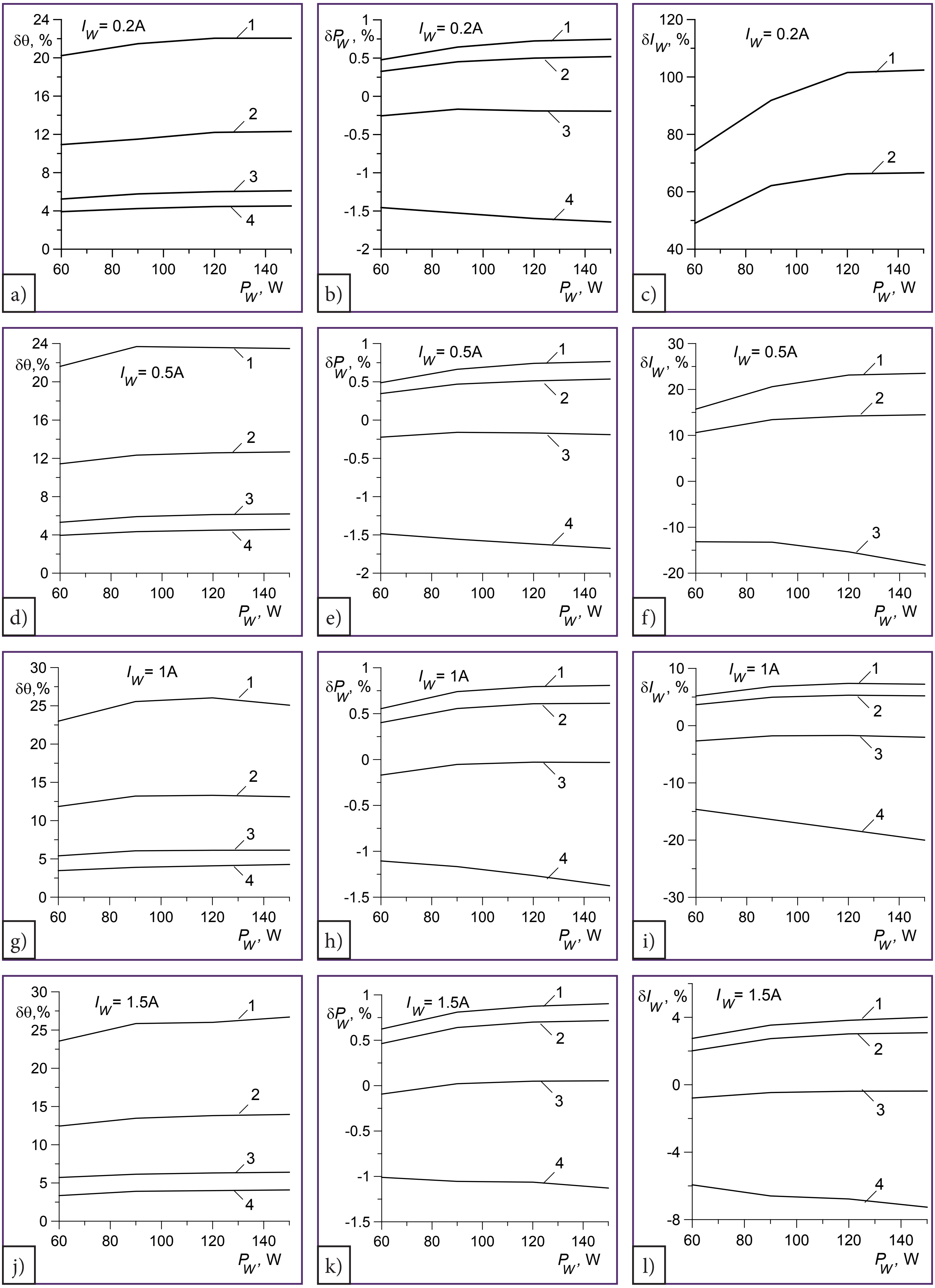

Fig. 6. Percentage errors related to the determination of the parameters of the GMM of arc (1 - $\theta = 1{\cdot}10^{-4}$ s, 2 - $\theta = 2{\cdot}10^{-4}$ s, 3 - $\theta = 5{\cdot}10^{-4}$ s, 4 - $\theta = 1{\cdot}10^{-3}$ s): a), d) g), j) errors related to the determination of time constant $\delta\theta$; b), e), h), k) errors related to the determination of power δP_W; c), f), i), l) errors related to the determination of current δI_W

which means that measured values will be lower than actual ones. If the value of current I_W of the macromodel is relatively low, the errors related to the determination of the values of current I_W of the mathematical model (15) are very high (even above 100%). The increase in I_W is accompanied by the decrease in error values, where measured values can be higher or lower than actual ones. The negative values of errors correspond to the relatively high values of the damping factor (above $5 \cdot 10^{-4}$ s).

The highest values concerning the errors related the determination of current IW of the GMM (39) correspond to the lowest values of the abscissa of the peak on the dynamic characteristics of the arc macromodel, where, in cases of high values of the damping function, the values of IW can be negative or even indefinite. The shift of the above-named abscissa towards higher current values is accompanied by the monotonic decrease in errors.

The research involved the simulation tests of the effect of current IW of the GMM on the value of the total harmonic distortion of voltage on the arc column [13]

$$THD_U = \sqrt{\sum_{i=2}^{n} U_i^2} / U_1 \tag{44}$$

where U_i – root-mean-square harmonic having number i. Selected test results are presented in Figure 7. If the time constant of arc θ model is

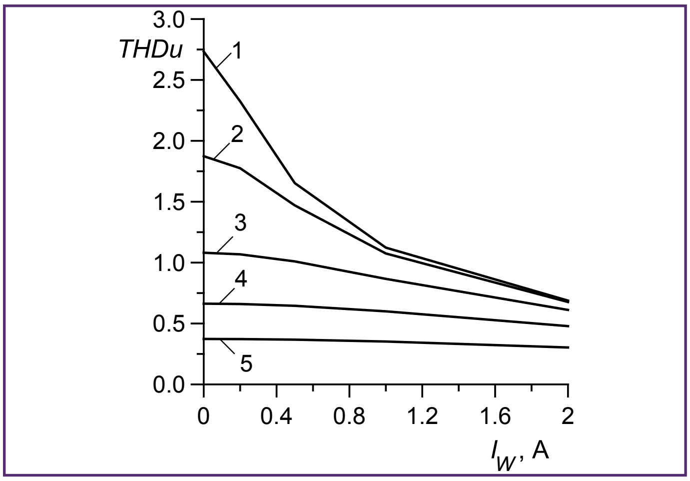

Fig. 7. Diagrams of THD_U related to voltage on the arc column (1 - $\theta = 1 \cdot 10^{-4}$ s, 2 - $\theta = 2 \cdot 10^{-4}$ s, 3 - $\theta = 5 \cdot 10^{-4}$ s, 4 - $\theta = 1 \cdot 10^{-3}$ s)

constant, an increase in current I_W leads to the steep drop in THD_U. The increasingly higher time constant is accompanied by the increasingly lower drop (until its almost entire decay). The value of P_W of the arc column macromodel does not affect THD_U in spite of the significant changes in the root-mean-square column voltage.

Conclusions

1. The use of sinusoidal current excitation in circuits with electric arc enables the effective identification of the parameters and characteristics of the Mayr mathematical model and of the GMM of arc by measuring current and voltage on the plasma column.

2. Based on the simulation test results it can be stated that in cases of external ionising factors (increasing the conductance of the electrode gap), the GMM (generalised Mayr model) reproduces the dynamic characteristics of electric arc better than the Mayr model. In particular, this statement concerns the area where current passes through the value of zero.

3. An increase in the time constant of electric arc reduces the GMM effectiveness in cases of high values of current I_W (high values of conductance G_W).

4. In comparison with the possibilities of the Pentegov model [12], the GMM has strictly correlated coordinates of the extreme point S (I_W, U_W) on the static characteristic. As a result, in some experimental tests it is possible to obtain lower accuracy of the representation of arc electric characteristics.

5. External factors disturbing the plasma column, present in physical conditions, can significantly increase errors related to the determination of mathematical model parameters, allowed for in this publication.

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