Antoni Sawicki

Diagnostics of Electric Arc versus the Development of Universal Mathematical Models

Abstract: The article presents universal mathematical static current-voltage characteristics-based models of electric arc and indicates primary issues concerned with arc diagnostics related to the determination of the above-named models. Particular attention was paid to the experimental determination of AC-powered arc voltage. Diagnostics-related purposes involved the use of bridge systems with one or two sources of current. Computer-aided simulations involving sinusoidal and trapezoidal current-based excitations made it possible to demonstrate the possibility of obtaining minimum values of bridge unbalance voltage. Such a condition indicated the proper determination of AC-powered arc ignition voltage.

Keywords: electric arc, universal mathematical models, arc diagnostics

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Introduction

The development of rational mathematical models of physical objects are often confronted with conflicting demands concerning accuracy, simplicity and versatility. The obtainment of the high accuracy of models is justified if a physical object subjected to examination has defined characteristics and parameters or if their variability range and manner can be identified precisely and described simply (e.g. statistically). In extreme cases, concerning the state of the matter, the selection of measurement equipment capable of continuous or repeated measurements proves extremely difficult. Because of the destructive impact of the environment it is often necessary to use slot methods, estimating the final diagnostic results on the basis of current indications of equipment. Having appropriate equipment and knowledge at disposal it is often possible to use indirect measurement-based methods. However, in such cases it is not always possible to obtain appropriately reliable results. One of the reasons for low measurement accuracy is diagnostics. In terms of electric arc, extreme states of the matter include very high temperature, very high rapidity of physical and chemical phenomena, very high current and its wide ranges of variability, high voltage, high values of magnetic field intensity, high gas flowrates, sudden changes of pressure etc.

Because of the low number of necessary parameters and simplified structures of created macromodels, the use of simple mathematical models makes measurements and simulations significantly simpler. In cases of electric arc, the aforesaid models include mathematical models expressed by (usually linear) first-order

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dr hab. inż. Antoni Sawicki – SEP – Association of Polish Electrical Engineers, (FSNT-SEP), Częstochowa Division

differential equations. The popular Mayr and Cassie models contain two parameters each. The more complex non-linear Zarudi equation contains three parameters [1]. Such simple equations could be recognised as useful when modelling electric effects in circuits with typical arc within relatively narrow ranges of changes concerning parameters of excitations and external effects. However, in many arc applications there are relatively wide changes of electric current, chemical composition, pressure and temperature of gases. There are also changes of electrode-related parameters and of various external factors affecting arc. In such cases, arc is characterised by very high sensitivity to changes of the distance between electrodes, magnetic field intensity, gas stream flowrates etc. Such situations often require modifications of simple mathematical models through the variation of parameters. The foregoing sometimes leads to the obtainment of models failing to satisfy the input energy balance equation. Although such models (because of the increased number of parameters) enable the obtainment of high approximation accuracy, they cannot be regarded as entirely reliable. Regrettably, some researchers unscrupulously use such simple arc models to model electric discharges which are not arc, such as spark or glow discharges.

One of the methods enabling the extension of the range of application of simple mathematical models is the series or the parallel connection of corresponding computer-generated macromodels. This is often the case of the Mayr and Casie submodels when creating the Habedank model or hybrid models [2]. Such an approach impedes the physical interpretation of parameters and the method of their experimental identification. However, it is then possible to model arc characteristics within wide ranges of parameter (e.g. electric current) changes.

A significantly more favourable solution involves the creation of mathematical macromodels containing appropriately many and clearly defined parameters explicitly related to static and dynamic characteristics of arc [1, 3–4] and being easy to interpret physically. If such parameters are used at the very beginning of the model creation process (in the balance of power in arc column), the proper modelling of physical phenomena is possible. In addition, such models can be used to create hybrid models, thus extending their approximation possibilities. The models characterised by the most extensive possibilities of approximating dynamic current-voltage characteristics of arc are universal mathematical models including simple Novikov-Schellhase model, Pentegov-Sidorec model [1, 5–6] and Mayr-Pentegov model [7–9]. The above-named models involve the use of the pre-set form of the static current-voltage characteristic. However, the range of its experimental determination is limited by arc burning stability and by external characteristics of the source. In addition, thermal, chemical, electromagnetic etc. phenomena corresponding to direct current may be different from those corresponding to alternating current. However, in many cases the use of such approximation leads to the obtainment of sufficiently good results.

A significantly simpler issue is the diagnostics of electronic simulators (imitators) of electric arc. Such diagnostics includes the verification of modelling accuracy concerning static and dynamic electric characteristics in relation to pre-set values. In such cases, the performance of tests is not affected by time limitations. The level of introduced deterministic or random interference is the experimenter's decision. An additional advantage is the elimination of the harmful effect of arc on personnel and environment.

Universal mathematical models of arc

After modifying the Mayr model of low-current arc [9] it is possible to obtain the equation in the conductance form

$$\frac{1}{g}\frac{dg}{dt}=\frac{1}{\theta_M}\left[\frac{P_{col}(t)}{P_{dis}(t,p)}-1\right]$$

where θ_M – corresponds to the time of relaxation of thermal processes, p – vector of parameters. Powers constituting this equation can be expressed using the following formulas:

- electric power supplied to arc:

$$P_{col}(t) = u_{col} i = \frac{i^2}{g}$$

- power dissipated from the column of arc:

$$P_{dis}(t) \cong U(|i|, p) \cdot |i| = \frac{i^2}{G(i, p)}$$

where $U(I)$ – static current-voltage characteristic, $G(I,p)$ – static column conductance characteristic. Based on the foregoing, the Novikov-Schellhase can be expressed in the following form [9]:

$$\frac{1}{g}\frac{dg}{dt} = \frac{1}{\theta_{Sh}}\left[\frac{|i|}{g \cdot U(|i|, p)} - 1\right] = \frac{1}{\theta_{Sh}}\left[\frac{|u|}{U(|i|, p)} - 1\right]$$

where p – pre-set parameter. Adopted assumption (3) is responsible for the fact that the model fails to satisfy the equation of energy balance.

The Pentegov-Sidorec model involves the consideration of hypothetical arc (instead of actual one), where the arc column conductance is defined as the function of fictional (virtual) state current $i_\theta(t)$, determined using the following differential equation:

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

with specific time constant $\theta = \text{const}$. In accordance with the adopted assumption, the current and the voltage of the model satisfy the following condition:

$$\frac{i}{u} = \frac{i_\theta}{U(i_\theta, p)} = g$$

where $U(I)$ – static current-voltage characteristic. The Pentegov assumption imposes restrictions on the mathematical model parameters:

$$Q(i_\theta, p) = 2\theta \int_0^{i_\theta} U(i_\theta, p) di_\theta$$

where Q – plasma enthalpy. In the general case, arc column voltage can be determined using the following proportion:

$$u = \frac{U(i_\theta, p)}{i_\theta} i$$

More general (in relation to (5)) is the equation of the Mayr-Pentegov model [7]:

$$\theta(i_\theta, p)\frac{di_\theta^2}{dt} + i_\theta^2 = i^2$$

involving the designation of the damping function:

$$\theta(i_\theta, p) = Q_p \frac{dg}{di_\theta^2}$$

dependent on coefficient Q_p in the enthalpy formula [7]. Similar to the previous case, p is the vector of parameters. In the macromodel of the arc column with the controlled voltage source it is possible to use the correlation analogous to (8):

$$u = \frac{i}{G(i_\theta, p)} = \frac{U(i_\theta, p)}{i_\theta} i$$

Determination of parameters of mathematical models of electric arc

Mathematical models of arc include, among other things, power, voltage, damping of conductance changes etc. However, the-above named parameters are not directly related to the actual parameters of arc. Because of adopted reduction assumptions, the latter (to some extent) differ from the former. In addition, the aforesaid parameters should not be considered separately from a specific model as they constitute closed sets of parameters directly connected with specific mathematical models. Because of the frequently high level of random disruption in arc and the lack of repeatability when obtaining experimental data, the above-named parameters should be determined simultaneously. Thermal processes in electrodes lead to the erosion of electrode materials, which results in changes of arc column length, changes of the fraction of the conical part in the column, etc. For this reason, the performance of measurements should be short.

However, experimental tests of electric arc are divided into stages. If arc is short (e.g. welding arc), it is characterised by low voltage drops. In such a case it is necessary to identify values of near-electrode voltage drops. This can be done directly [10] or indirectly [11], using direct or alternating current [12]. Near-electrode voltage drops depend on materials of electrodes and their thermal states. Because of the fact that near-electrode voltage drops only slightly depend on current, they are usually adopted as constant values, only depending on polarisation. In simplified tests, if chemical compositions of electrode materials are known, the values of near-electrode voltage drops can be obtained from physical tables. Long arc is usually characterised by relatively high voltage drops. As a result, low values of near-electrode voltage drops are treated as negligible.

The accurate determination of electric characteristics of the plasma column is affected by the conditions and states of electric arc burning. In the theory of electrotechnical devices, arcs are divided into stabilised and free. Electrical appliances are characterised by the presence of terminating arc. The burning of stabilised arc is accompanied by the relatively low level of external random disruptions. Stabilised arc burns in plasma equipment, where the position and geometrical dimensions of the column are determined by external factors such as the adjusted flow of gas (washing around the column), the narrow and intensively cooled metal channel and massive electrodes with the short plasma column. The level of disruptions in the arc plasma torches and high-pressure discharge lamps is low, whereas the repeatability of measurement results is high.

Free arc burning is accompanied by the significant level of disruptions resulting both from natural physical processes (e.g. strong turbulence of heated gases) and from the lack of natural shielding of arc against the effect of various external factors. If the level of disruptions is very high, the processing of experimental data requires the application of statistical methods and digital filtering. The more favourable DC arc burning stability is accompanied by the lower level of disruptions than that accompanying AC arc burning.

Arc burning states may change along with the course of technological processes. The foregoing is affected, among other things, by changes of the temperature and the chemical composition of the gas atmosphere. In some states the diagnostics of arc is easier, enabling the obtainment of more accurate results (e.g. at the final stage of charge melting in the steelmaking arc furnace), whereas in other cases it is more difficult, e.g. if accompanied by the high level of disruptions (e.g. the beginning of charge melting in the steelmaking furnace).

The notion of the static current-voltage characteristic of arc is treated slightly differently in theory and in practice. In practice, the static current-voltage characteristic of the arc column is treated as a set of point (diagram) determined experimentally during the quasi-DC-based powering of arc.

In theory, in cases of zero values of the state variable derivative (e.g. conductance), the static current-voltage characteristic of the arc column is treated as a set of points (diagram) of a function calculated using a mathematical model in the form of the first-order differential equation. Such a diagram of $U(I)$ can be called the model static current voltage characteristic. Obviously, reduction assumptions lead to certain differences in the shape of theoretical (model) and experimental static characteristics.

The experimental determination of static current-voltage characteristics of arc columns can be performed using various methods:

1. Usually, excitation is performed using quasi-direct current, the value of which is gradually changed from the maximum to the minimum value of current (corresponding to the

loss of arc burning stability and arc termination). The maximum value of current depends on the external characteristics of the power supply source as well as on the design parameters of the electric circuit of a given device. In turn, the minimum value of current depends on the distance between the electrodes, the thermal state of the electrodes and that of gas, etc. A decrease in the value of current is accompanied by an increase in arc voltage, which imposes requirements on the external characteristics of the power supply source.

2. Because of the dominant role of thermal processes in arc, it can be powered (without compromising its properties) by alternating current having a rectangular symmetric wave. Similar to the previous case, the amplitude of such current can be slowly reduced until the termination of arc. If both electrodes are the same, differences in results should not be significant (in comparison with the first method).

3. In arc powered by periodic current (sinusoidal, triangular or trapezoid), a significant role is played by processes connected with the inertia of plasma in the column. Because of this, each passage of current through the zero value is accompanied by the partial deionisation of plasma and arc termination followed by arc initiation. For this reason, current wavelengths should be characterised by the appropriate shape of the wave (steep passage of current through the zero value). Arc re-ignition voltage is usually significantly higher than arc termination voltage. Because of their lower stability, AC arcs are relatively short. Current-voltage characteristics are usually identified using measurements of root-mean-square current. In order to obtain the aforesaid characteristics it is necessary to slowly reduce root-mean-square current from its maximum value to its minimum value until the termination of arc.

Figure 1 presents an exemplary diagram of a static current-voltage characteristic obtained within a wide range of current changes. Taking into consideration an increase in current, it is possible to distinguish three areas:

a) glow discharge – high voltage drop, particularly near the cathode,
b) intermediate between glow and arc discharge – fast reduction of voltage drop,
c) arc discharge – low of slightly changing voltage.

The above-named diagram can be obtained for short and stabilised arc.

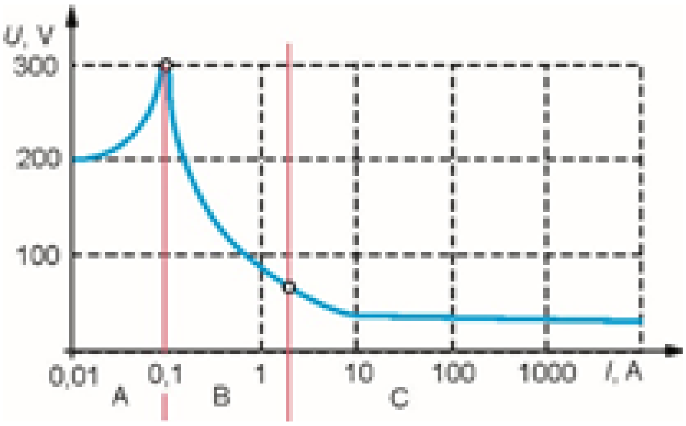

Fig. 1. Static current-voltage characteristic of an electric discharge in gas [13]

The voltage of arc discharge is higher than the voltage of arc termination (Fig. 2). After arc initiation, the quasi-static upslope of current is accompanied by a decrease in voltage from U_{ig} to U_C. In turn, the quasi-static reduction of current is accompanied by an increase in voltage from U_C up to U_{ex}. If current is overly low, arc is unstable. In such a situation, electrode spots perform wandering movements, thermionic emission decays, the plasma column undergoes deformation triggered by the convective movements of gases and arc is terminated.

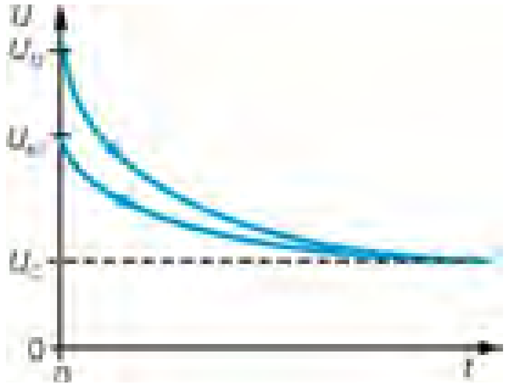

Fig. 2. Static current-voltage characteristics during the upslope and reduction of current

The above-presented descriptions reveal that the precise and explicit experimental determination of voltage on the static characteristic near the passage of current through zero is very difficult. In addition, such a situation provides sufficiently long time for (at least partial) gas deionisation and electrode cooling processes. For this reason, static experimental characteristics differ from those obtained without the above-named processes, i.e. during fast changes of current.

The dynamic current-voltage characteristics of decaying switching arc (presented in technical reference publications) cannot be recognised as equivalent to arc characteristics of electrotechnical devices with decaying current. In switching arc, current decay is triggered by the tension and intense cooling of the column by moving electrodes, intense gas flows, magnetic fields, etc.

The above-presented description leads to the following conclusions:

- It is not possible to experimentally obtain a static characteristic with very low current values. The reason for the above-named situation is the loss of arc burning stability. The value of the minimum current of arc depends on the distance between electrodes, the temperature of electrodes and gas environment, gas ionisation degree, etc. In turn, the classical mathematical Cassie model enables the approximation of a static characteristic with very low current values. In addition, it is possible to experimentally obtain a dynamic characteristic containing very low and zero values of current. If the passage of current through zero is sufficiently fast, plasma does not decay entirely, electrodes do not cool completely and remaining residual conductance is higher than 0 S.
- It is not possible to experimentally ignite arc having a pre-set length without applying high quasi-static voltage necessary for the breakdown of the electrode gap. The foregoing also results from the classical mathematical Mayr model. However, it is possible to experimentally obtain a dynamic characteristic containing very low and zero values of current and corresponding finite values of arc ignition voltage. Similar to the situation mentioned above, if the passage of current through zero is sufficiently fast, plasma does not decay entirely, electrodes do not cool completely and remaining residual conductance is higher than 0 S.

The generalised form of the model static current-voltage characteristic can be expressed as follows [6]:

$$U(I,p)=U_0\left(\frac{I_0 I}{I^2+I_M^2}\right)^n+U_C$$

Its particular case (if n=1), often used in practice is the following:

$$U(I,p)=\frac{P_M I}{I^2+I_M^2}+U_C$$

The coordinates of the extreme point are the following:

- in terms of function (12):

$$I=I_M, \qquad U=U_0\left(\frac{I_0}{2I_M}\right)^n+U_C$$

- in terms of function (13):

$$I=I_M \qquad U=\frac{P_M}{2I_M}+U_C$$

In some electrothermal and welding machines the value of ignition voltage is modified using ionisers and arc stabilisation oscillators [12]. To this end, pilot arc is sometimes used.

Publications [15, 16] discuss spectral and integral methods used to determine parameters of selected model static current-voltage characteristics used in the universal Pentegov-Sidorec model. The above-named methods can be applied using periodic excitations of sinusoidal or rectangular waveforms.

Figure 3 presents exemplary static current-voltage characteristics. In some electrotechnical devices and operating conditions [17]

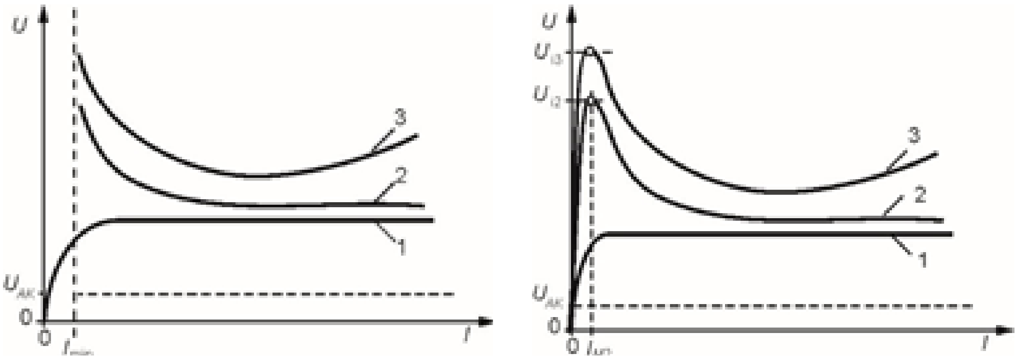

Fig. 3. Exemplary families of static current-voltage characteristics of arc: a) experimental and b) model (1 – arc in gas characterised by high temperature and high concentration of metal vapours, 2 – typical arc in electrotechnical devices and 3 – arc in high-pressure gas and with sharpened electrodes)

damping function values are so low that the area of the hysteresis of dynamic characteristics disappears. In such a range, dynamic characteristics are similar to static ones.

Phenomena occurring in the area of the current passage through zero may significantly affect dynamic characteristics of current and voltage in time. This is particularly noticeable using voltage to power low-current arc (Fig. 4).

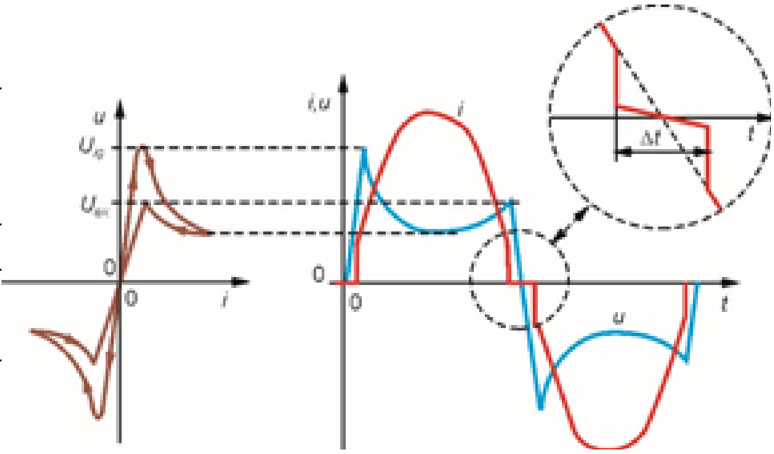

Fig. 4. Effect of the shape of time waveforms on the dynamic current-voltage characteristic of electric arc (Δt – currentless interval) [13]

The plasma of dynamic arc is characterised by the inertia of processes (particularly thermal ones), dependent on the proportion of column enthalpy to dissipated thermal power. For this reason, inertia is affected by the chemical composition and the temperature of the plasma-forming gas. Experimental tests of arc [18] revealed that inertia is strongly related to the non-linear damping characteristic (Fig. 5). Within the low-current range, the values of the above-named function are relatively high. In turn, within the high- current range, the values of the above-named function are very low. The determination of very low values of physical parameters usually entails significant measurement errors. One of the methods used to identify damping function values involves the introduction of sharp current disruption to DC arc. In turn, in another method, the value of the damping function is determined on the basis of the plasma column enthalpy [19].

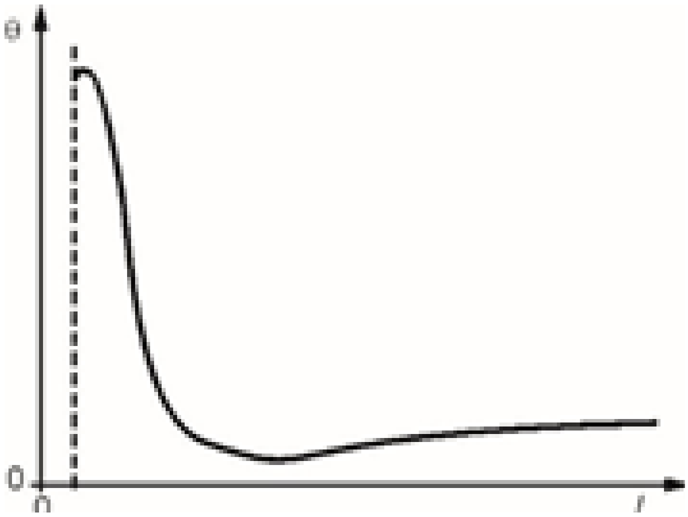

Fig. 5. Electric arc damping characteristic

Experimentally determined damping function values differ from damping functions of mathematical models. In simplified mathematical models, the aforesaid function is replaced by a time constant. Such a parameter is used in the universal Novikov-Schellhase (4) and Pentegov-Sidorec (5) models. Particular cases of static characteristics required the development of spectral and integral methods enabling the determination of the time constant of the Pentegov-Sidorec model with periodic sinusoidal excitation or non-commutative excitation [15, 16]. The Mayr-Pentegov model makes use of the damping function dependent on the static current-voltage characteristic. In such a case it is only necessary to determine one plasma enthalpy-related coefficient Q_p.

Diagnostics of electric arc using electronic and programme arc simulator

In terms of simulators (imitators), the electronic implementation of a specific mathematical model of electric arc is performed by a computer software programme controlling a set of semi-conductor high-current elements. For this reason, simulators can be regarded as universal systems limited by the range of allowed current values and responsiveness to implemented excitations. The making of low-current arc simulators results from the fact that the making of high-voltage electronic systems entails significant problems. The tendency to use welding arc simulators results from practical needs.

The diagnostics of electric arc simulators can be performed at stages. In such a case, in addition to energy saving, there are no limitations as regards the time and sequence of tests (which can be performed individually or as comparatively (i.e. involving two simulators)) [20–22].

The initial stage of experimental tests of electric arc within a given range of current excitations ($|i| > I_{min}$) can be followed by the making of an electronic simulator (imitator) of the mathematical model of arc (involving dominant fragments of static current-voltage characteristics and damping function characteristics).

The use of the universal model (5), (6) should involve the determination of the time constant and of the missing fragment of the static current-voltage characteristic within the range of low decaying current.

The use of the universal Mayr-Pentegov model (9)-(11) should involve the determination of enthalpy-related coefficient Q_p and of the missing fragment of the static characteristic.

The characteristics and parameters of universal mathematical models within ranges above arc termination current can be determined using the above-presented methods, discussed in more detail in publications [4, 11, 23]. The value of the time constant or of the damping function is usually extrapolated towards the y-axis (Fig. 5) [2]. It is necessary to determine model static current-voltage characteristics within the range of very low current. This can be done using, e.g. the comparative method. To this end it is possible to use a system consisting of burning physical arc and of the electronic arc simulator. At this stage of new tests the simulator simulates the mathematical model of arc obtained on the basis of experiments involving unipolar current excitation. The application of

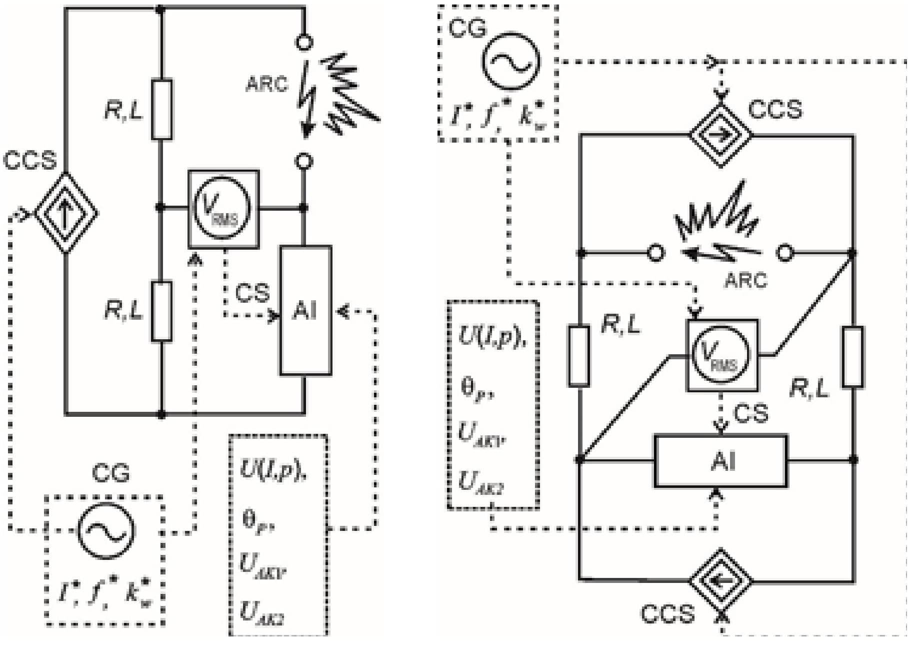

Fig. 6. Schematic diagram of the diagnostic system used in comparative tests of physical arc and the arc simulator: a) involving the use of one power supply source with a wide range of current and voltage changes, b) involving the use of two power supply sources with a wide range of current changes (ARC – physical arc, AI – arc simulator (imitator), CG – control generator, CCS – controlled current source, *R, L* – series components of bridge branch impedance, CS – corrective signal)

bipolar excitation follows the verification of the compatible operation of physical arc and of the simulator. In such a case it is possible to use sinusoidal current or symmetric trapezoid current and reduce the voltage of arc re-ignition from a high value to the obtainment of the conformity of voltage waveforms in both elements.

The shapes of electric arc characteristics enable their joining in series. The schematic diagram of such a diagnostic system with one current source is presented in Figure 6a. Another diagnostic variant, with two current sources, is presented in Figure 6b. It is possible to increase the accuracy of arc voltage identification by decreasing the measurement range to ranges close to the passage of current through the zero value.

In the proposed variant, the final stage of the diagnostic process can only be performed using a computer. Data collected in experimental tests can be used as model arc, whereas a selected universal macromodel of arc in a simulation programme can be used as the arc simulator. In such a situation there are no limitations concerning the power of arc (voltage and current). A similar programme of tests was performed by the Author.

The model macromodels (corresponding to actual arc) were created using the universal mathematical Pentegov-Sidorec or Mayr-Pentegov models. The aforesaid models involved the use of static current-voltage characteristics having the preset value of arc ignition voltage (defined by current I_M). In turn, the macromodels of tuned simulators involved the use of the same mathematical models, yet their static characteristics were characterised by the variable value of ignition voltage. The foregoing could be performed automatically using the corrective signal (CS). The process of diagnostics can be regarded as completed after the obtainment of the minimum values of bridge unbalance voltage.

Figures 7–11 present simulation results. The simplified variant involved tests concerning the possibility of only determining ignition voltage. For this reason, the characteristics of the model simulator and of the tuned simulator could only differ in values of current I_M. The assumed sum of near-electrode voltage drops amounted to 20 V. It was possible to clearly identify clear minimum values of bridge unbalance voltage, corresponding to the conformity of ignition voltage values related to both simulators.

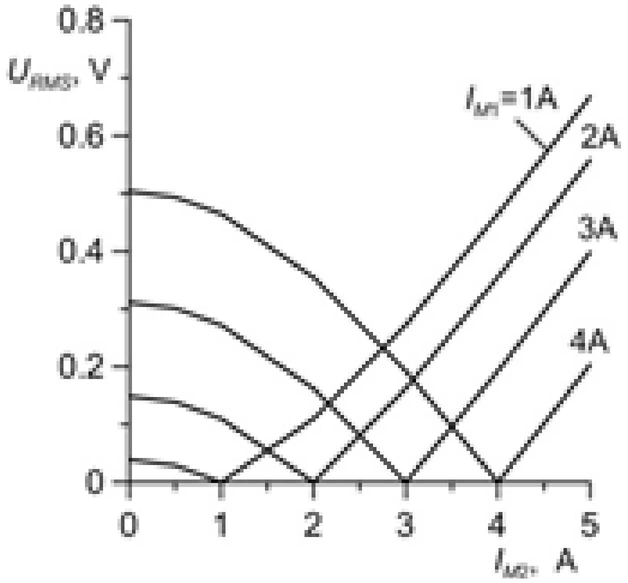

Fig. 7. Bridge unbalance voltage (Fig. 6a) in relation to the Pentegov-Sidorec arc models (4) with characteristic (13) (P_M = 200W, U_C = 30 V, θ =$2{\cdot}10^{-4}$ s); powering by sinusoidal current having an amplitude of 160 A and a frequency of 50 Hz

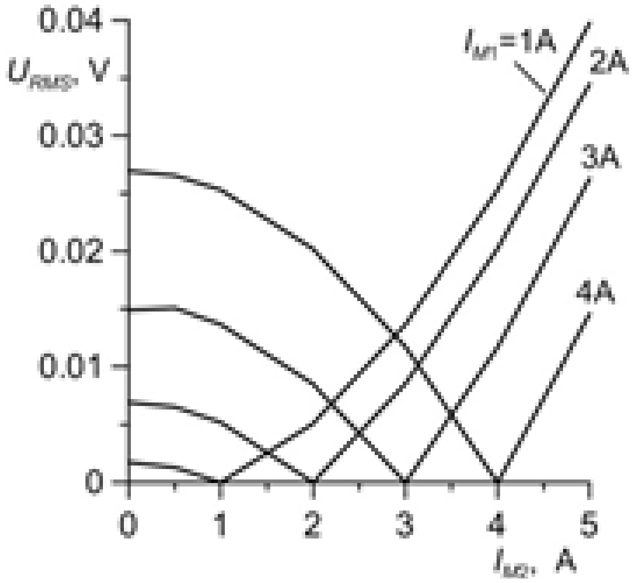

Fig. 8. Bridge unbalance voltage (Fig. 6a) in relation to the Mayr-Pentegov arc models (9) with characteristic (13) (P_M = 200W, U_C = 30 V, Q_p = 0.2 J); powering by trapezoid current having an amplitude of 200 A, slope inclination coefficient k_w = $250{\cdot}10^3$ A/s and a frequency of 50 Hz

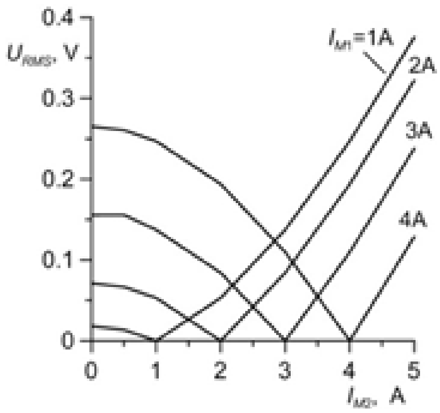

Fig. 9. Bridge unbalance voltage (Fig. 6b) in relation to the Pentegov-Sidorec arc models (4) with characteristic (13) (P_M = 300W, U_C = 40 V, θ =3·10^{-4} s); powering by sinusoidal current having an amplitude of 160 A and a frequency of 50 Hz

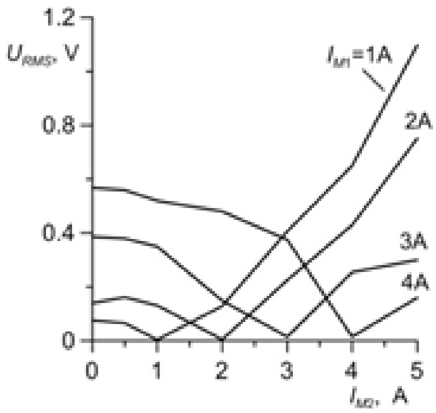

Fig. 10. Bridge unbalance voltage (Fig. 6b) in relation to the Pentegov-Sidorec arc models (4) with characteristic (12) (U_0 = 100 V, I_0 = 1 A, n = 0.8, U_C = 30 V, θ =2·10^{-4} s); powering by sinusoidal current having an amplitude of 200 A and a frequency of 50 Hz

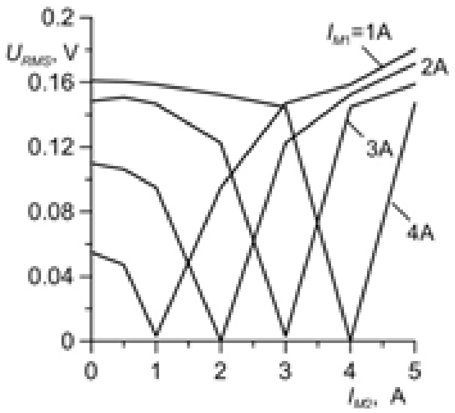

Fig. 11. Bridge unbalance voltage (Fig. 6b) in relation to the Mayr-Pentegov arc models (9) with characteristic (12) (P_M = 250W, U_C = 35 V, Q_p = 0.15 J); powering by trapezoid current having an amplitude of 200 A, slope inclination coefficient 250·10^3 A/s and a frequency of 50 Hz

Conclusions

1. The popularisation of universal mathematical models of arc necessitates the diagnostics of static current-voltage characteristics within wide ranges of current changes.
2. Previous methods used in the diagnostics of AC arc were focused on high-current ranges, which, because of power-related reasons, are of the greatest technological significance.
3. The precise simulation of low-current ranges can be useful in the assessment of arc voltage waveforms (used in systems enabling the automatic control of equipment).
4. The use of bridge systems with the macromodel of arc enabled the determination of arc ignition voltage in a circuit with alternating excitation.

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