Antoni SAWICKI, Maciej HALTOF

Czestochowa University of Technology, Faculty of Electrical Engineering

doi:10.15199/48.2016.07.35

An integral method for determining the parameters of the universal electric arc model describing an arc with a hyperbolic-linear static characteristic

Abstract. *The article presents the limitations in usage of voltage-current static characteristics in mathematical modeling of an electric arc. On the basis of the experimental data approximations of static characteristics the Pentegov electric arc model for simulating processes in a simple electric arc circuit is proposed. The parameters of static characteristics and electric arc model were obtained by the integral method. A satisfactory agreement between experimental data and simulation results has been obtained for air and argon under different gas pressures.*

Streszczenie. *W publikacji wskazano na ograniczenia w wykorzystaniu charakterystyk statycznych napięciowo-prądowych do modelowania matematycznego łuku elektrycznego. Na podstawie przyjętej aproksymacji charakterystyk statycznych eksperymentalnych łuku, zaproponowano wykorzystanie uniwersalnego modelu Pentegowa do symulowania procesów w prostym obwodzie elektrycznym. Parametry charakterystyki statycznej i modelu matematycznego obliczono za pomocą metody całkowej. Uzyskano zadowalającą zgodność wyników symulacji i wybranych badań eksperymentalnych łuku swobodnego w powietrzu i argonie o różnym ciśnieniu. (**Metoda całkowa wyznaczania parametrów uniwersalnego modelu łuku elektrycznego o charakterystyce statycznej hiperboliczno-liniowej**).*

Keywords: electric arc, Pentegov model, static characteristics.
Słowa kluczowe: łuk elektryczny, model Pentegowa, charakterystyki statyczne.

Introduction

Among the specialists in electrotechnological devices (including welders), taking them into account and research, power systems, electrical equipment, mathematical models of the electric arc using complex static characteristics (U-I dependencies) (Kopplin-Schmidt, Novikov-Shellhase, Kulakov) are very popular [1-4]. This may be explained by the easy way to obtain those nonlinear functions in a wide range of current excitations through experiments. Much more difficulties have to be overcome if the damping function has to be determined experimentally [5]. Those models use a constant value of a damping factor, for this reason the damping factor as the nonphysical quantity has to be determined in combination with a particular voltage-current static characteristic. Whereas a required accuracy of dynamic characteristic approximations is to be achieved by a proper choice of the mathematical model. Due to assumed simplifications those models are able to approximate dynamic characteristics of the electrical arc and time series of electrical quantities in circuits with an arc with different accuracy. The fundamental assumption for creation of new models is the energy balance equation which should be met in the final form of the mathematical model. The condition is fulfilled by the Pentegov arc model (developed together with V.N. Sidorec) which however has not received enough attention of the scientific community [6]. On the other hand, more popular model by Novikov-Shellhase does not fulfill the energy balance equation what leads to difficulties in physical interpretation of the obtained results and causes an increase in prediction errors.

Among the measurement methods of determination the parameters of electric arc mathematical models [7] a particular role is played by the spectral and integral method described in [8, 9]. The reason is the possibility of carrying on-line or even in-situ diagnostic tests, what could be applied in diagnostic and automation systems of welding devices. However, the efficiency of those methods are dependent of a noise level in the surrounding area of the electric arc itself as well as in power circuit of the electric arc.

In the paper the usage of integral method for obtaining the parameters and characteristics of the electric arc mathematical model that approximates the properties of a free burning arc in chosen gases between graphite electrodes of different diameters via experimental measurements has been presented.

The universal model of an electric arc with defined static characteristic

Mayr and Cassie mathematical models of an electric arc are special cases of the Pentegov arc model [6]. They have given upfront static characteristics described by simple analytical functions (hyperbolic or ray-horizontal). For this reason their range of application is strongly limited to the particular electric arc characteristics. Much more possibilities of approximation of electric arc properties has Pentegov arc model, which as the two previously mentioned ones is also described by a linear differential equation and moreover fulfills the energy balance equation. Further generalizations of the electric arc are represented by non-linear models, for example such as equations by Schwarz-Avdonin [7, 10]. Although the analysis of non-linear models is much more difficult. In the publication [11] a method of determining four parameters of generalized non-linear model of an electric arc in electric apparatus was described.

According to the Pentegov approach, physical processes affecting geometrical dimensions of the plasma column and distributions of quantities such as: temperature, pressure, conductivity, etc. are not taken under consideration in detail. The electric arc resistance is not given by the real measured current, but by some virtual (state) current $i_\theta(t)$ delayed with respect to $i(t)$, which respectively changes with a specified time constant θ and reflects to some extent the real current $i(t)$.

The relation between the state current square and the real arc current square is described by a first-order linear equation

$$\theta \frac{di_\theta^2}{dt} + i_\theta^2 = i^2 \quad (1)$$

The advantages of this model are numerous, for example the modeling of an electric arc can be done with any approximation of voltage-current static characteristics and at the same time with constant value of damping factor (the so-called time constant). The model can be easily applied for simulating processes in welding devices with arc burning in different gases under various pressures between electrodes of different distance l_a and shape, made from any kind of materials. The examples of electric arc characteristics burning in selected gases and their approximations are shown in Figure 1.

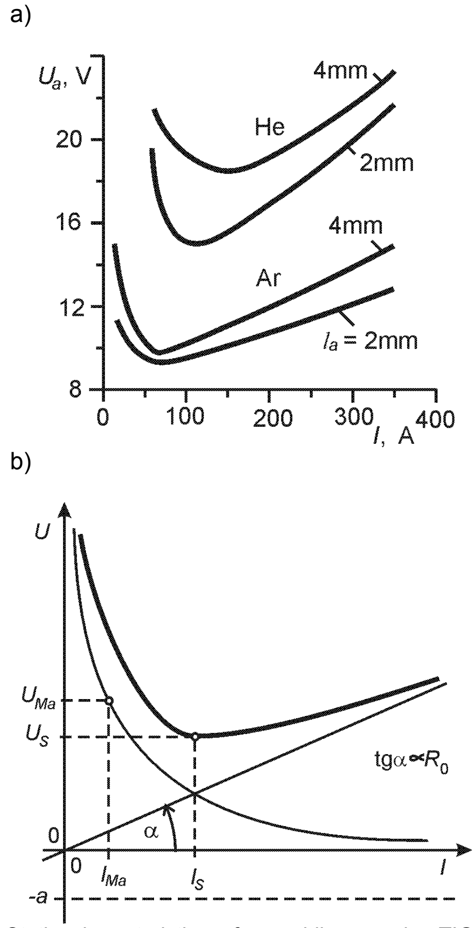


Fig. 1. Static characteristics of a welding arc by TIG devices: a) physical characteristics; b) examples of approximations by the hyperbolic-linear function

The equation defining the instantaneous value of an electric arc voltage $u(t)$ has the form of

(2) $$u(t) = a\,\mathrm{sgn}(i) + \frac{U_{stc}\left(i_\theta(t)\right)}{i_\theta(t)}\,i(t)$$

where: a – the sum of near-electrode voltage drops; U_{stc} - any form of function approximating the static characteristic of the arc column. The value of parameter a may be relatively easy determined experimentally [12]. In case of the short arc the value of the voltage drop on the arc plasma column is calculated by a subtraction between the total arc voltage and the parameter a, whereas in the case of the long arc, the low value of a near-electrode voltage drop can be neglected.

As shown in Figure 1 in strong current regime the families of static characteristics rise. They can be approximated by a simple function

(3) $$U_{st}\left(I, L_a\right) = bL_a I + \frac{c + dL_a}{I}$$

Equation (3) can be presented in a different form as

(4) $$U_{st}\left(I, L_a\right) = R_0\left(L_a\right)I + \frac{P_M\left(L_a\right)}{I}$$

In case of the arc with a constant length (L_0 = const.) where a static characteristic of the plasma column can be described by equation

(5) $$U_{stc}\left(I\right) = R_0 I + \frac{P_M}{I}$$

where: $R_0 = bL_0$, $P_M = c + dL_0$ – constant approximation factors. If the factor b = 0 Ω/m the Pentegov arc model with a hyperbolic static characteristic is obtained, which is equivalent to the Mayr model.

Method for determining the parameters of the Pentegov arc model with the hyperbolic-linear static characteristic

Consider a circuit with an electric arc described by the static characteristic given by equation (5) is powered by a variable sinusoidal current excitation of pulsation ω

(6) $$i = I_m \cos\left(\omega t + \frac{\varphi}{2}\right)$$

The state current can be described using the following dependence

(7) $$i_\theta^2 = I_{rms}^2\left(1 + \cos\varphi \cos 2\omega t\right)$$

where $I_{rms} = I_m/\sqrt{2}$ - RMS current value. The value of phase shift is related to the time constant of the arc

(8) $$tg\varphi = 2\omega\theta$$

Taking into account the Pentegov model assumptions the following expressions are obtained

(9) $$U_{rms}^2 = \frac{P_M^2}{I_{rms}^2 \sin\varphi} + 2P_M R_0 + R_0^2 I_{rms}^2$$

(10) $$P = P_M + R_0 I_{rms}^2$$

(11) $$R = \frac{P_M}{I_{rms}^2 \sin\varphi} + R_0$$

After solving the above given system of equations the following expressions for model parameters are obtained [9]:

(12) $$P_M = \frac{\left(U_{rms} I_{rms}\right)^2 - P^2}{RI_{rms}^2 - P}$$

(13) $$R_0 = \frac{RP - U_{rms}^2}{RI_{rms}^2 - P}$$

where: R - the mean arc column resistance, P - the mean arc column power. The model time constant is given by the formula

(14) $$\theta = \frac{1}{2\omega\sqrt{\left[\frac{(R - R_0)I_{rms}^2}{P_M}\right]^2 - 1}}$$

Experimental studies and computer simulations of electric quantities in a circuit with the electric arc

The authors conducted experimental studies of free burning arcs between graphite electrodes of different diameter placed in closed chamber filled with selected gases:

a) in air atmosphere at specified pressure of 1000 mbar with cylindrical electrodes diameter d = 6.5 mm and the electric arc powered by single transformer source STB-250;
b) in argon atmosphere at specified pressure of 250 mbar with cylindrical electrodes diameter d = 12.85 mm and the electric arc powered by two transformer sources STB-250 connected in series.

The data acquisition was performed with a NI PXI 6259 measurement card with 20 kHz sampling frequency. The measurement card was combined with a low-pass anti-aliasing filter with frequency set at 10 kHz.

In the first stage of the research the static characteristics (U-I dependencies) of the electric arc sourced by DC welding device ESAB OrigoTM 3000i AC/DC were determined. The gradient characteristics of $U = f(L)$ (Fig. 2) were obtained what resulted in a successful determination of near-electrodes voltage drops (obtained by extrapolation of U-I dependencies to the axis of ordinates OY).

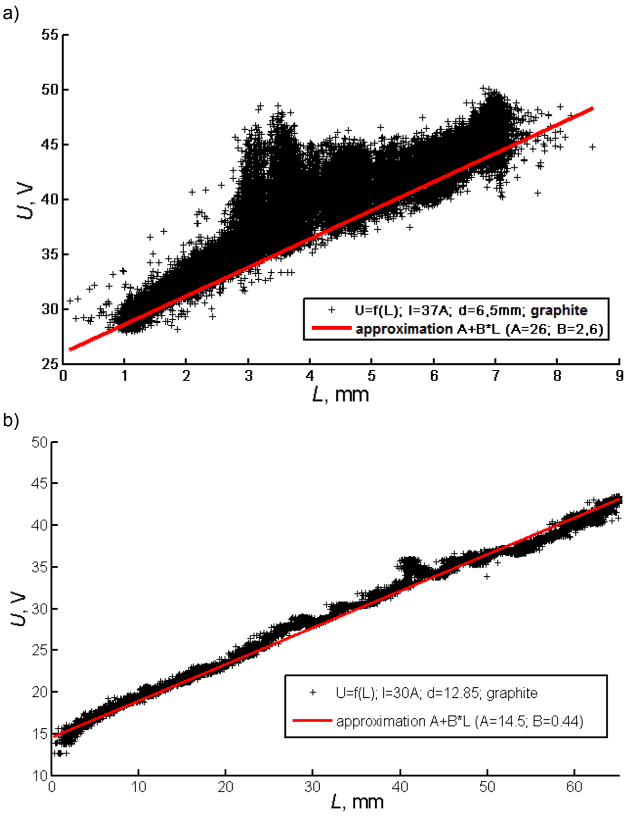


Fig. 2 Gradient characteristic of the electric arc a) in air at pressure p = 1000 mbar; b) in argon at pressure p = 250 mbar

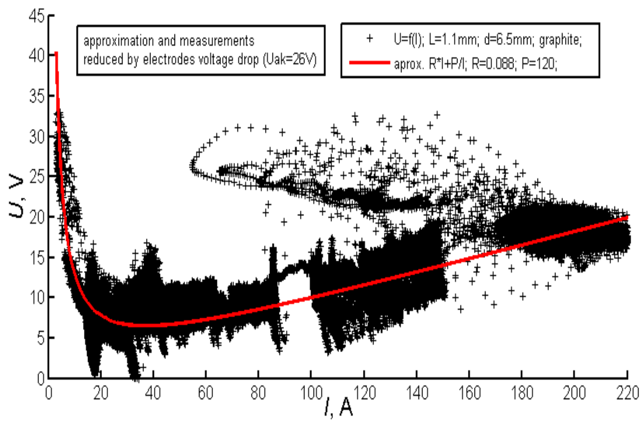


Fig. 3. Static characteristic of the arc column burning in air at pressure of 1000mbar and approximation by function (5) (R = 0.088 Ω; P = 120 W; L = 1.1 mm)

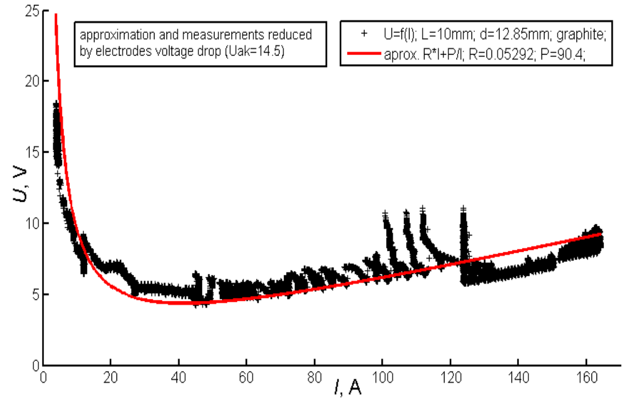


Fig. 4. Static characteristic of the arc column burning in argon at pressure of 250mbar and approximation by function (5) (R = 0.05292 Ω; P = 90.4 W; L = 10 mm)

In accordance with the assumptions of the Pentegov arc model defined by expression (4), the static characteristics U-I of the electric arc were calculated (practically the characteristics of the plasma column). The measurement data and their approximations were adjusted by subtraction of near-electrodes voltage drops obtained from the data, as shown in Figure 2. In the case of testing a stabilized arc and usage of electrotechnological devices where it is not possible to obtain static characteristics easily, the authors recommend to apply the expressions (12)-(13). The static characteristics and their approximations are presented in Figures 3 and 4.

The obtained parameters of approximating functions (Fig. 3 and 4) allowed for determining the static characteristics (5) and time constants (14) ($\theta = 1{,}677 \cdot 10^{-5}$ s in air, $\theta = 1{,}574 \cdot 10^{-5}$ s in argon, respectively). Those values were the fundamental data to create the electric arc model (1) and subsequent computer simulations in a simple electric circuit.

Comparing the time series shown in Figures 5 and 6 it is noticeable that the universal Pentegov arc model in a relatively accurate way simulates the discharges in both air and argon with different distances between electrodes. The accuracy is higher if the electric arc burns in the argon atmosphere due to more efficient arc stability. The electric arc burning in the air atmosphere is more unstable what causes a fall in accuracy of the considered expressions. To compare the experimental data and numerical simulations hysteresis loops are depicted in the Figure 7.

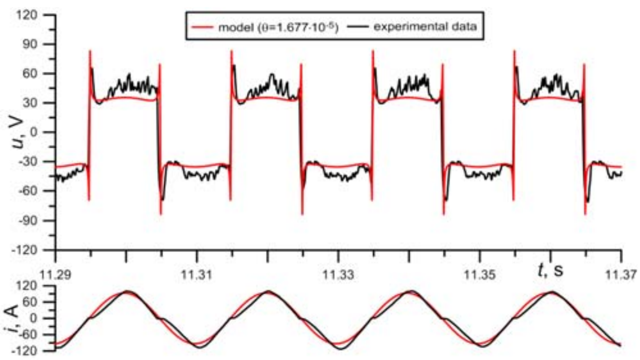


Fig. 5. Experimental time series of current and voltage of the arc and their approximations (L = 1,1 mm, p = 1000 mbar, gas - air)

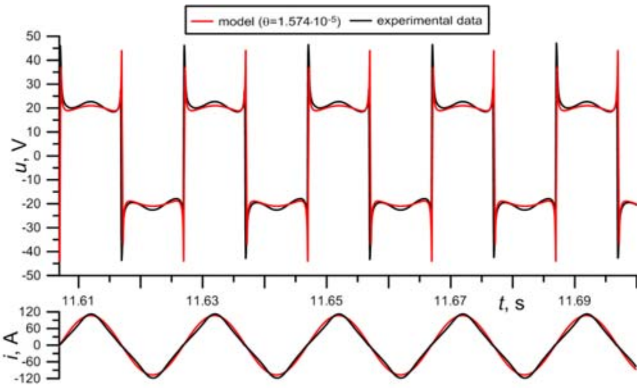
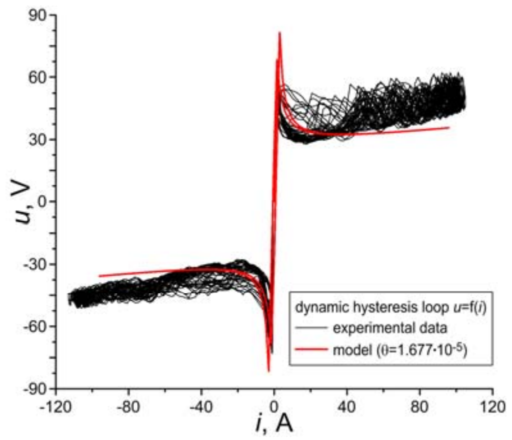


Fig. 6. Experimental time series of current and voltage of the arc and their approximations (L = 10 mm, p = 250 mbar, gas - argon)

a)



b)

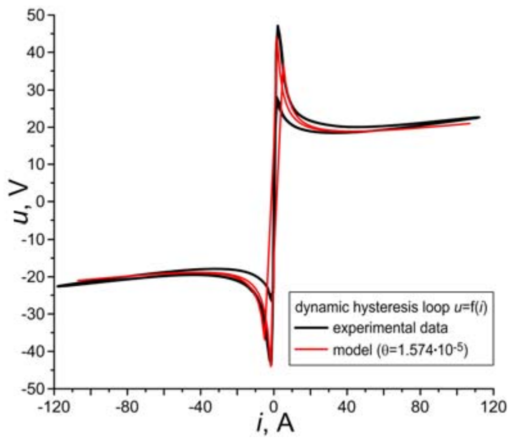


Fig. 7. Dynamic hysteresis loops a) arc burning in air (p = 1000 mbar, L = 1.1 mm) b) arc burning in argon (p = 250 mbar, L = 10 mm)

Conclusions

1. The described integral method allows for an easy and efficient determination of the Pentegov arc model parameters under weakly disturbed conditions on the basis of experimental measured data in a welding circuit powered by a sine-waveform source.
2. High efficiency of the presented integral method and the Pentegov arc model, that describes the arc with the hyperbolic-linear static characteristic, results from a relatively frequent use of electric arc with such properties and is due to the wide use of alternating current sources in welding processes.
3. The errors in determining the model parameters of an electric arc rise with increase of level of random disturbances. The fact makes the presented method more preferred for modeling stabilized welding arcs powered by stabilized current sources.
4. The experimental research of the free burning arc in chosen conditions (in argon, which is a gas with reduced pressure) has revealed that satisfactory results of approximations by the described method may be obtained.

Authors: *Ph.D. D.Sc. E.E. Antoni Sawicki, Professor at Czestochowa University of Technology, Faculty of Electrical Engineering, Al. Armii Krajowej 17, 42-200 Częstochowa, E-mail: sawicki.a7@gmail.com; M.Sc. E.E. Maciej Haltof, Czestochowa University of Technology, Faculty of Electrical Engineering, Al. Armii Krajowej 17, 42-200 Częstochowa, E-mail: maciej@haltof.pl.*

REFERENCES

[1] Kopplin H., Schmidt E., Beitrag zum dynamischen Verhalten des Lichtbogens in Olarmen Hochspannungs-Leistungsschaltem, *ETZ*, Bd. 80, Heft 23, Dezember (1959), pp. 805-811
[2] Новиков О.Я., Устойчивость электрической дуги, *Энергия*, Ленинградское отделение, Ленинград (1978)
[3] Шельгазе М., Математическая модель переходных процессов в сварочной дуге и ее исследования, *Автоматическая сварка* (1971), № 7, с.13-16
[4] Schőtzau H. J., Kneubühl F. K., A New Approach to High-Power Arc Dynamics, *ETEP* (1994), vol. 4, no. 2, p. 89-99
[5] Kalasek V., Measurements of time constants on cascade d.c. arc in nitrogen, TH-Report 71 - E - 18 ISBN 90 6144 018 1, Eindhoven University of Technology (1971)
[6] Пентегов И.В., Сидорец В.Н., Сравнительный анализ моделей динамической сварочной дуги, *Автомат. Сварка*, (1989), № 2, с. 33-36
[7] Gimenez W., Hevia O., Metodología para la modelización del arco eléctrico a partir de oscilogramas de ensayos. *III Seminario Argentino de usuarios del EMTP*, 26 y 27 de Noviembre (1998), Buenos Aires, Argentina
[8] Sawicki A., Haltof M., Testing the effect of column length disturbance on the method used for determining the Pentegov model describing the electric arc of the Ayrton type static characteristics, *Biuletyn Instytutu Spawalnictwa* (2014), no 6, s. p. 39-44
[9] Sawicki A., Haltof M., Method for Determining the Parameters of the Pentegov Model Describing an Electric Arc with Hyperbolic-Linear Static Characteristic, *Biuletyn Instytutu Spawalnictwa* (2015), no 3, p. 55-60
[10] Sawicki A., Zmodyfikowane modele Schwarza-Avdonina łuku asymetrycznego, *Półrocznik AGH Elektrotechnikia i Elektronika* (2010), t. 29, z. 1-2, s.20-25
[11] Белкин Г.С., О постоянных величинах в обобщенном уравнении Касси–Майра для динамической вольт-амперной характеристики дуги, *Электричество* (2012), №3, 19-22
[12] Filkenburg W., Maecker H., Elektrische Bogen und thermisches Plasma, in: Handbuch der Physik. S. Flugge (ed.), *Springer*, Berlin (1956)