Antoni SAWICKI, Maciej HALTOF

Czestochowa University of Technology, Faculty of Electrical Engineering

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Modeling the gliding discharge in GA plasma generators

Abstract. *The paper describes a method of modeling the electric arc discharge generating non-thermal plasma in a GA reactor. For this purpose the Pentegov mathematical model of the electric arc with a modified Ayrton static characteristics has been used. Simulations of processes occurring in the GA reactor with two variants of voltage source have been carried out.*

Streszczenie. *W artykule opisano sposób modelowania wyładowania łukowego, generującego plazmę nietermiczną w reaktorze typu gliding arc. W tym celu wykorzystano model matematyczny łuku elektrycznego Pentegowa, w którym zmodyfikowano charakterystykę statyczną Ayrtony. Przeprowadzono badania symulacyjne procesów zachodzących w reaktorze gliding arc z dwoma wariantami wymuszeń ze źródła napięciowego.* ***(Modelowanie wyładowań ślizgowych w plazmotronach "gliding arc"****).*

Keywords: gliding arc, arc model, Pentegov model.
Słowa kluczowe: gliding arc, model łuku, model Pentegowa.

Introduction

In the majority of technological devices, an arc is stabilised, which typically makes it possible to maintain constant arc length and stable spatial location. The heat dissipating conditions should remain fairly stable, too, due to the application of special shields, chambers or nozzles. The values of the parameters in thermal plasma so obtained should remain constant across time. Applying AC however, hinders stabilisation and maintaining thermal equilibrium of plasma. There are also devices, such as switching apparatuses, in which plasma is unstable, and ones in which the opposite is even required – plasma must be thermally and chemically active. This implies a necessity of large, almost periodical alternations of the parameters, which would be unacceptable or even detrimental in other types of plasma devices. These effects are partly neutralised in plasma generators combining a number of gliding discharges, such as three-phase ones.

The number and variety of physical phenomena occurring in the electric arc, as well as strong nonlinearity of electrical and thermal characteristics of gas make it difficult to account for the processes in GA plasma generators in a simple yet accurate way. The majority of mathematical models developed so far [2, 3] does not take into account the changes in the arc length, the quenching and igniting of the discharge, or the extreme changes in the thermal equilibrium conditions of plasma. What needs to be considered at the same time is the need to match the very unquiet load of the GA to the power supply systems. There have been attempts to approximate electromagnetic processes occurring in plasma generators by modifying the existing mathematical models [4-6]. The differential and integral formulas should guarantee sufficient accuracy of approximation within the prescribed intervals of the parameters. Physical interpretation of the results so obtained is however extremely difficult.

A mathematical model of a variable-length electric arc can be constructed on the basis of Pentegov's postulates [7]. They employ the static voltage-current characteristics. Typically it is formulated as a function dependent on the current and on the arc length, there are therefore no limitations with respect to developing various models of the gliding discharge.

The Pentegov model of the variable-length electric arc

The majority of mathematical models of the arc, including the Pentegov model, are based on the energy balance equation [7, 8]. Unlike some other models, the Pentegov model does not analyse in detail the physical processes affecting the geometrical dimensions of the arc or the distribution of such quantities as temperature, pressure, plasma conductivity, etc. Instead of a physical model of the arc, a virtual one is used, which is electrically inertia-free, since as is stipulated, its resistance is not subject to step changes. Because of this, the resistance is defined not by means of the real current but by means of some other current $i_\theta(t)$, alternating with a definite time constant θ and being a representation of the real current $i(t)$, and delayed with respect to it. In the steady state, the state current $i_\theta(t)$ coincides with the real current $i(t)$. When the current source has a high frequency ($f >> 1/\theta$), the thermal condition of the arc is defined by the RMS of the current. The arc state current $i_\theta(t)$ applies to all the isoenergetic states and can be also used for determining the parameters and dynamic characteristics of the arc (Table 1).

Table 1. Definitions of the physical quantities in a real arc and in the Pentegov model (U_a – arc voltage; ΔU_{AK} - sum of voltage drops near the electrodes)

Physical size	Actual arc	Pentegov model
Electric current	$i(t)$	$i(t); \quad i_\theta(t) \geq 0$
Dynamical voltage $U_{dyn}(t) =$ $= U_a(t) - \Delta U_{AK} =$	$U_{dyn}(i)$	$U_{dyn}(i_\theta) = \frac{U_{st}(i_\theta)}{i_\theta} i$
Power dissipation $P_{dys}(t) =$	$P_{dys}(i) = U_{dyn}(i) \cdot i =$ $= R_{dyn}(i) \cdot i^2$	$P_{dys}(i_\theta) = U_{st}(i_\theta) \cdot i_\theta =$ $= \frac{U_{st}(i_\theta)}{i_\theta} i^2 = R_{st}(i_\theta) \cdot i_\theta^2$
Dynamic resistance $R_{dyn}(t) =$	$R_{dyn}(i) = \frac{U_{dyn}(i)}{i}$	$R_{dyn}(i_\theta) = \frac{U_{st}(i_\theta)}{i_\theta} =$ $= R_{dyn}(i)$

The square of the state current and the square of real current are tied by the first-order linear equation

$$\theta \frac{di_\theta^2}{dt} + i_\theta^2 = i^2 \tag{1}$$

It is an advantage of this model that it can rely on any approximation of the static voltage-current characteristics and at the same time has a constant value of the damping factor function θ. Compared to other models [3, 9], it can employ more accurate approximations of static arc characteristics. One of the most often applied approximations is the one stated by Ayrton

$$U_{st}\left(I,l\right) = a + bl + \frac{c + dl}{I} \tag{2}$$

where a – sum of the voltage drops near the electrodes; b – voltage gradient, c; d – constant approximation factors, l – arc length. The quantity a can be obtained experimentally [2]. When the arc is long, the relatively low value of *a* can be disregarded.

A variant of the Pentegov model applied to the gliding arc discharge

GA plasma generators operate in a cyclic way with a time period between consecutive arc initiations of up to a few hundred miliseconds, with each of the cycles started by an auxiliary ignition [10]. After striking the arc, it moves in the form of thermal plasma along the curvature of the electrode edges, along the gas flow. The arc gliding causes increase in arc voltage until the discharge becomes unstable and plasma becomes non-thermal. Then, the arc goes off and the cycle is repeated. To represent the operation of the plasma generator, it is necessary to modify the static characteristics (2) of the model (1) by introducing a function of arc length variation in time in a form analogous to that presented in [6]

$$l\left(t\right) = l_0 + k \cdot \alpha \cdot v_g \cdot t \tag{3}$$

where: l_0 – gap between the electrodes at the spot where the arc is struck; k – correction factor; α - divergence angle between the electrodes; v_g – speed of the gas forcing the discharge motion. Besides, it is necessary to take into account the source representing the ignition in the expression defining the dynamic waveform of the arc voltage $U_{dyn}(i_\theta)$, presented in Table 1. The modified voltage function is

$$U_{dyn}\left(i_\theta\right) = \frac{U_{st}\left(i_\theta\right)}{i_\theta} i + \zeta(t)\frac{U_z}{i_\theta} i \tag{4}$$

where

$$\zeta\left(t\right) = \begin{cases} 1, & \text{if} \quad t_z < t \le t_1 \\ 0, & \text{if} \quad t_1 < t < t_2 \end{cases} \tag{5}$$

where: t – local time of a single discharge cycle; t_z – moment of ignition, t_z=0s; t_1 – duration of the ignition pulse; t_2 – conditional time of a cycle duration ($t_2 = t \leftrightarrow g(t) = g_{\min}$); $g_{\min}$ – minimal prescribed value of conductance just before the arc quenching; U_z – RMS voltage value of the auxiliary ignition source.

Simulations of processes in a circuit with gliding arc plasmatron

On the basis of the assumptions presented above and the universal arc model (1) with a predefined static characteristics, a circuit with a macromodel of a two-electrode GA plasma generator was constructed by means of MATLAB-Simulink. Two variants of supply were used: a real alternating sinusoidal source $u(t) = U_m sin(\omega t)$ and an alternating rectangular $u(t) = U_m(-1)^n$ (with the fill factor k_w = 0,5; where n – number of half-wave) of frequency 50 Hz. To strike an arc, the supply sources were correlated with an appropriate voltage source, described by analogous expressions. Fig. 1 presents results of a simulation in a circuit with discharges initiated by unipolar pulses and with the following prescribed parameters: U_m=1000V; U_{zm}=2000V; L=32mH; R=70Ω; $g_{\min}$=5·10^{-6}S; θ=2.4·10^{-4}s; k=0.01; l_0=3mm; α=25°; a=0V; b=1482V/m; c=2.9VA; d=14VA/m. Fig. 2 presents results of a simulation in a circuit with discharges initiated by bipolar pulses and with the following prescribed parameters: U_m=1000V; U_{zm}=2000V; L=32mH; R=70Ω; $g_{\min}$=5·10^{-6}S; θ=1.7·10^{-4}s; k=0.01; l_0=3mm; α=25°; a=0V; b=1100V/m; c=3.35VA; d=19VA/m. The shapes of the waveforms obtained are close to the experimental ones [1, 5] and meet the assumptions of the discharge under scrutiny. By comparing these two cases it can be stated that supplying the plasma generator from a source with a rectangular forcing (Figs 1b, 2b) enables either gain a higher temperature of output gas, or, with a higher gas flow v_g – greater production efficiency. This phenomenon can be explained by higher stability of the discharge.

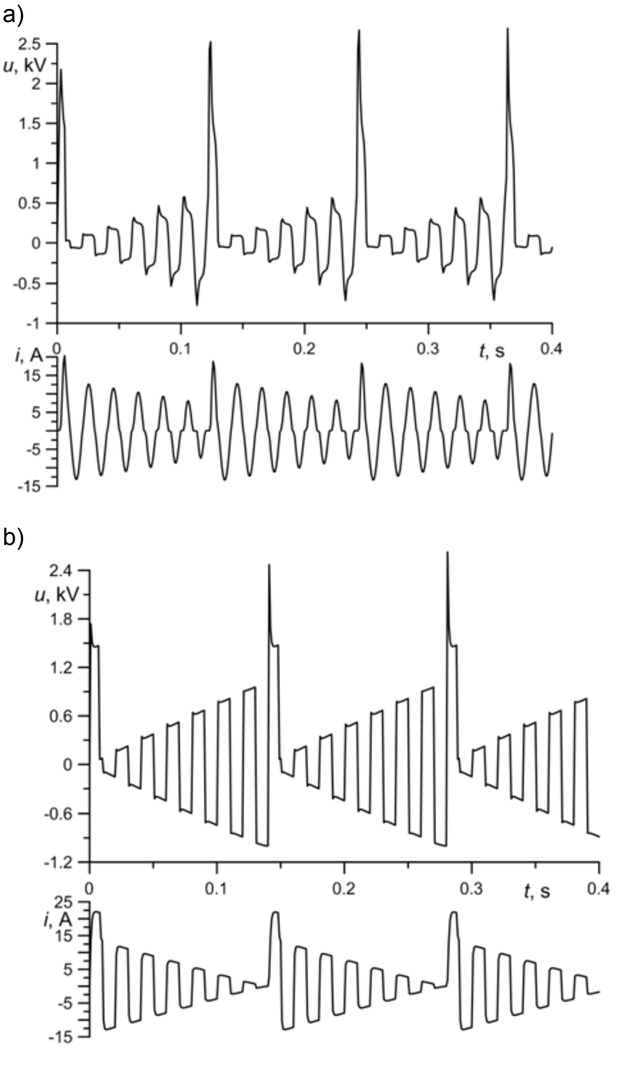

Fig. 1. Current and voltage waveforms in a simulated gliding arc plasma generator supplied from: a) sinusoidal source (v_g=10m/s; t_z=6.7ms); b) rectangular source (v_g=20m/s; t_z=8ms)

Conclusions

1. The majority of mathematical models of the electric arc developed so far assume constant arc length. Because of this, using such models for simulating processes in GA plasma generators requires an artificial modification of differential equations or of their solutions.
2. It is possible to solve the inverse problem, consisting in determining the approximation parameters of the static arc characteristics on the basis of similarity between the voltage and current waveforms in the model and those in the physical object.

3. The universality of the Pentegov models of the electric arc makes it fairly easy to represent the electric processes in a GA circuit in a broad range of parameters.
4. Applying a rectangular voltage source instead of a sinusoidal one for supplying a GA plasma generator provides a possibility of obtaining either higher temperature of the output gas, or a greater amount of the output gas maintaining the same gas temperature with higher gas flow applied on the input.

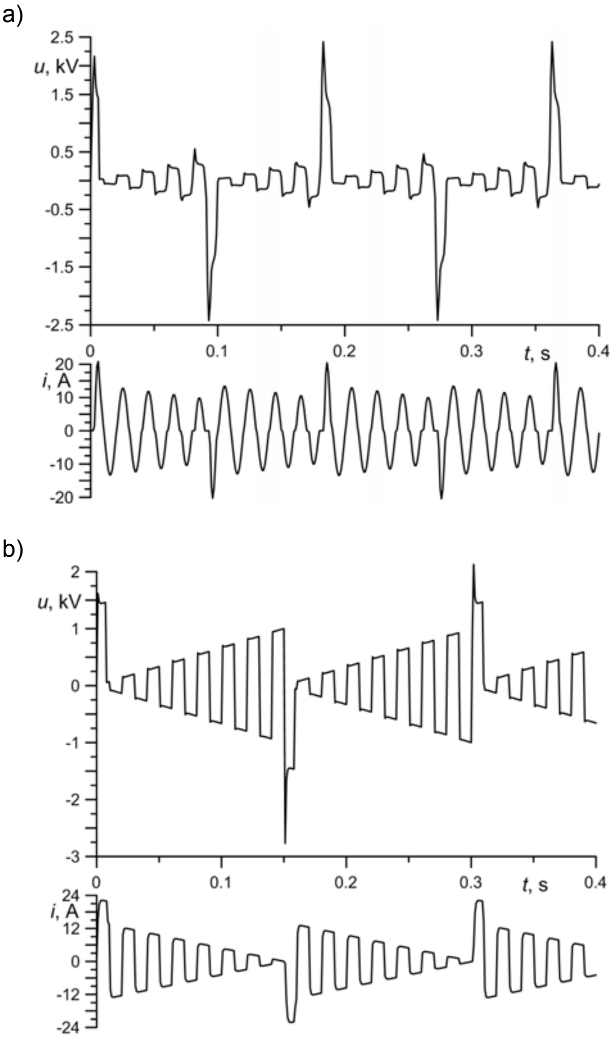

Fig. 2. Current and voltage waveforms in a simulated gliding arc plasma generator supplied from: a) sinusoidal source (v_g=12m/s; t_z=6.7ms) b) rectangular source (v_g=24m/s; t_z=8ms)

***Authors**: Ph.D. D.Sc. E.E. Antoni Sawicki, 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] Diatczyk J., Modeling discharge length for GA plasma reactor, Przegląd Elektrotechniczny, ISSN 0033-2097, R. 88 NR 6/2012, s. 89-91.
[2] Kruczinin A.M., Sawicki A., Urządzenia elektrotechnologiczne z nagrzewaniem łukowym i plazmowym, cz.1. Teoria nagrzewania łukowego i plazmowego, Skrypt 17, Wydawnictwo Politechniki Częstochowskiej, Częstochowa 1997.
[3] Sawicki A., Modele dynamiczne łuku elektrycznego wykorzystujące charakterystyki statyczne, Śląskie Wiadomości Elektryczne 2012, nr 6, s. 13-17.
[4] Jaroszyński L., H. D. Stryczewska H.D., The numerical model of the gliding arc discharge. II International Symposium: New Electrical and Electronic Technologies and Their Industrial Implementation NEET'2001, 2001, s. 114-117.
[5] Jaroszyński L., H. D. Stryczewska H.D., Computer simulation of the electric discharge in glidarc plasma reactor, 3rd International Conference: Electromagnetic devices and processes in environment protection ELMECO-3, 200, s. 31-36.
[6] Stryczewska H.D., Janowski T., Jaroszyński L., Mathematical model of the non-thermal plasma reactor, IV International Workshop on Advanced Plasma Tools and Process Engineering 1998, s. 175-180.
[7] Пентегов И.В., Математическая модель столба динамической электрической дуги, Автоматическая сварка, № 6 (279), 1976, с. 8-12.
[8] Пентегов И.В., Сидорец В.Н., Сравнительный анализ моделей динамической сварочной дуги, Автомат. Сварка, 1989, № 2 (431), с. 33-36.
[9] Marciniak L., Implementacja modeli łuku ziemnozwarciowego w programach PSCAD i Matlab/Simulink, Przegląd Elektrotechniczny 2012, R. 88, Nr 9a, s. 126-129.
[10] Czernichowski A., Gliding arc. Applications to engineering and environment control, Pure &Appl. Chern. 1994., Vol. 66, No. 6, pp. 1301-1310.