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An electric arc information model

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ABSTRACT

The synthesis of mathematical models is an inalienable part of information technology. It allows for the analysis, prediction, and optimization of various systems and processes. A crucial component of this process is the selection of the correct mathematical approach and the validation of the model's adequacy. The proposed article is a component of the development of the visual-block modeling method, particularly for enhancing its library. As the library grows, the boundaries of applying the visual-block modeling method are expanded. The work's materials address the construction and use of a mathematical model of an electric arc using visual modeling tools. The proposed mathematical model has significantly higher efficiency compared to known models of the electric arc that adequately describes the electro-physical process in the electric arc. This allows for a reduction in modeling time for complex electro-technical systems, which include the processes of arc formation and reigniting. The presented model encompasses the description of two processes: electrodynamics and thermodynamic ones. The voltage and current for resignations are calculated automatically. The adequacy of the proposed model has been verified by comparing it with experimental data. Additionally, the adequacy of the proposed model is confirmed through the analysis of dynamic volt-ampere characteristics for various frequencies of the power source voltage. The developed mathematical model is formatted as an element of the visual-block modeling library. This allows for the direct use of the proposed model for synthesizing models of complex electro-technical systems, including the electric arc, thus expanding the boundaries of applying the visual-block modeling method.

Keywords: Arc discharge; visual-block modeling; arc parameter control; empirical coefficients: arc volt-ampere characteristics; mathematical arc model

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PROBLEM ANALYSIS AND TASK DEFINITION

Information technologies have long become an inalienable part of our lives. They are utilized in different areas: from medicine and science to business and everyday use. One of the key components of modern information technology is the synthesis of mathematical models [1]. Mathematical models of physical processes are widely used in information technology and assist in solving diverse tasks in various fields, from economics and science to technical disciplines and business. They allow saving time and resources by enabling virtual modeling and experiments, predictting system performance, and designing and testing various complex systems before their physical implementation [1].

One of the most crucial stages in the synthesis of mathematical models is the selection of a method for its synthesis. Presently, there is a concept of the visual-block modeling (VBM) proposed by several authors. The method allows standardizing the synthesis of models for complex electro-technical systems by creating a unified library and a standardized approach to model synthesis [2, 3], [4, 5], [6]. The developed VBM method significantly reduces the time required for synthesizing a control object model, speeding up the synthesis of the electro-technical system model by orders of magnitude [6].

The VBM concept involves the decomposition of the system in terms of the power train into a series of interconnected nodes. This decomposition is visualized as a power train system [3]. To further create the model, each node needs to be represented as a separate block. Each block appears in the form of a rectangle and contains inputs and outputs. Inputs are marked on the right, and outputs are marked on the left in terms of cause-and-effect relationship. Each input and output should be named at the discretion of the block's author, but it is mandatory to specify the direction of the power flow [4]. To indicate this, the following symbols are used after the name: “+” stands for incoming power flow; “-“– for outgoing power flow; “±” – for bidirectional power flow. Parameters of the system that are not physically related to the direction of the power flow are indicated without an index. Further organization of model synthesis occurs through the complementary connection of the created blocks according to the system of directions of power flows [6]. Each block is formed based on the mathematical model created for it in the form of a block diagram by connecting the corresponding inputs and outputs of standardized sketches [4].

Up to the present time, the VBM concept has not been applied to the modeling of electrotechnical and electrotechnological systems involving gas discharge. In the works [2, 3], [4, 5], [6], the concept has been used for synthesizing models of electromechanical systems. However, according to the authors, this approach can be effectively applied to analyze processes in other multiphysical systems.

Research in the field of describing the mathematical model of an arc started over a century ago, resulting in a considerable number of models describing the arc by now. These models can be divided into three groups: physical models, black-box models, and models based on graphical representations [7]. Black-box models solely outline the correlation between input and output signals, explaining the interaction between the arc and the electrical circuit.

The first widely known model of an electric arc is the Cassie arc model [8]. In this model, the arc temperature is assumed to be constant, cooling through forced convection. This implies that the cross-sectional area of the arc is proportional to the current, and the arc voltage remains constant. This model can be applied when the arc current is quite high; however, its adequacy diminishes at low currents.

Mayr introduced his arc model [9], in which the cross-sectional area of the arc was taken as a constant, and power losses were induced by heat conduction. Additionally, the conductivity of the arc was linked to temperature. Unlike the Mayr model, this model adequately describes the arc at low currents.

The Mayr and Cassie arc models are fundamental studies in the field of electric arc modeling, forming the basis of various arc models [10, 11], [12]. A more accurate model of the Cassie-Mayr electric arc with an increased number of parameters is presented in [10]. Generalized variations of the Cassie-Mayr models are proposed in [11] for modeling processes in an electric arc furnace. The arc model is compared with a large amount of experimental data, and additional parameters of the Cassie-Mayr model that change over time and are updated every half-cycle [11].

The Schavemaker and L.Van der Sluis arc model is a derivative of the Mayr arc model, where cooling power depends on the consumed electrical energy [12, 13]. The arc model presented in 2010 [14] demonstrates relatively high accuracy (the error does not exceed 5 %). It is based on the energy conservation law and is expressed through a differential equation derived by considering the energy balance coming from the power source and the internal energy of the object. The arc voltage is determined by conductivity, which depends on the arc temperature [14]. In 2013, Lin Yuan reviewed five popular arc models and investigated common models of arc discharges with fixed electrodes [7].

The mathematical model of the arc discussed in [9] is considered in the context of arc application in arc steelmaking furnaces. In contrast to previously known models, this model provides a clear representation of the relationship between arc voltage (current) in an arc steelmaking furnace and its length [15].

The mentioned arc models adhere to the black-box paradigm often referred to as common arc models. A notable model is the Van and Balogh model [16], which analyzes the arc in direct current microgrid systems based on wavelet transformation, combining the black-box approach with a causal model. An example of a causal model is the Leblond models [17], followed by their analysis by Litovski [18].

In the work [17], electrical circuits implementing existing arc models are presented, followed by an examination of arc models in terms of arc conductivity and a comparison of these models. As a development of the work [17], a new low-impedance arc model is introduced in the work

[18], which calculates time-variable "ablation" conductivity with a reduced number of parameters.

The arc models discussed in the above-mentioned works accurately describe the phase processes and volt-ampere characteristics of the arc. However, a drawback of these models is that they involve significant computational resource costs.

Such models encompass descriptions of processes with radically different intensities. A process of high intensity is the arc resignation process during the voltage application period, while a process of low intensity is associated with the thermodynamic parameters of the arc. When the model involves processes with different intensities, a problem arises due to a significant increase in computational costs. In other words, the model becomes slow; sometimes unacceptably slow to address tasks in Computer-Aided Design systems. In practical applications, it is often necessary to approximate the arc model using a finite number of points or linear segments. Existing approximation methods require additional research and optimization efforts to achieve better accuracy with minimal computational costs. This raises the challenge of creating a compromise model that provides a balance between model adequacy and computational speed. Therefore, the task was set to develop a model that would alleviate computational burdens and maintain reasonable adequacy.

Following the VBM methodology, the result of describing the model should be rationalized into the form of a VBM library element. In this case, it can be easily applied in standardized procedures for synthesizing models of complex electro-technical systems, including the arc burning and resignation process [3].

RESEARCH PURPOSE AND TASKS

The purpose of the research is to develop a component of the VBM library that describes an imitation model of an electric arc. In the future, this component may be utilized in the synthesis of multidisciplinary models of complex electrical systems, which include the process of arc ignition and resignation as a subprocess. This library component should provide a balance between sufficient adequacy and minimal computational costs.

The research tasks include describing and constructing a mathematical model, formalizing the model (describing the model in terms of visual modeling), and verifying the model's adequacy by comparing it with experimental data.

The object of the research is the model of an electric arc developed to simulate gas discharge in a circuit where an electric arc occurs.

The subject of the research is the processes that occur within the circuit where an electric arc occurs, from the perspective of electrical engineering parameters.

MATERIALS AND METHODS OF RESEARCH

In an arc discharge, electrons are emitted from the cathode due to thermionic emission, the repulsion of electrons from the heated cathode, and field emission – the release of electrons from the surface under the influence of an electric field [19]. The gas is ionized thermally when the high temperature of the discharge leads to the splitting of molecules into ions and electrons [20]. This flow can be concentrated at a hot spot on the cathode, reaching a density on the order of a million amperes per square centimeter. However, unlike a glow discharge, the arc has a less pronounced structure because the positive column is very bright and occupies almost the entire distance between the electrodes [21, 22]. Voltage drop at the cathode and anode occurs a few millimeters away from each electrode (Fig. 1). The voltage gradient in the positive column is less compared to other parts of the arc and may even be absent in very short arcs [23]. From the physics of the process, it is clear for arc lengths that the lengths and voltages in sections l_a and l_c (Fig. 1) do not depend on the length of the arc L [23].

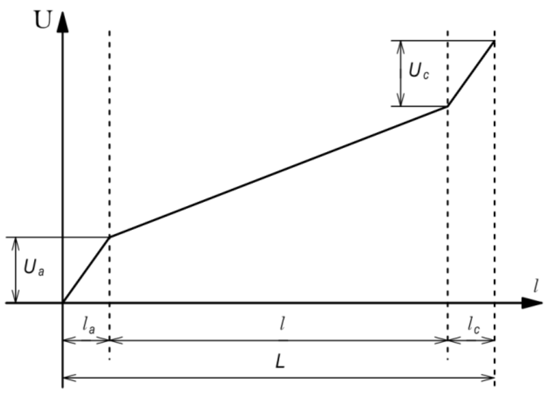

Fig. 1. **Potential diagram of the arc (potential distribution with respect to the cathode)**
***Source:* compiled by the authors**

So, the arc length in the l section primarily determines the voltage-ampere characteristic of the arc, where U_a and U_c are simply added to the voltage in the l section. The sum of these voltages fluctuates in the range of 15 to 25 V [24]. Considering that $l \gg (l_c + l_a)$, we further assume the total arc length to be $L = l$.

The circuit where the electric arc occurs (Fig. 2) consists of a power source, internal resistance, circuit inductance, and the immediate region where the electric arc occurs.

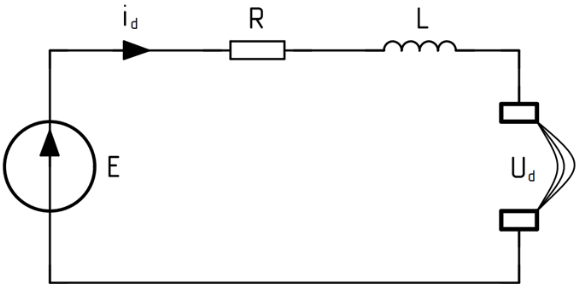

Fig. 2. **The scheme of the electric arc current circuit**
Source: **compiled by the authors**

The differential equation of the arc current circuit, with the corresponding equivalent circuit (Fig. 2), is determined by the following expression:

$$L_k \frac{di_d}{dt} = E - i_d R_k - U_d(i), \quad (1)$$

where L_k is the inductance of the circuit where the arc occurs; E is the electromotive force; i_d is the arc current; R_k is the internal resistance of the circuit where the arc occurs; U_d is the arc voltage.

Based on this circuit, taking into account that the main task is to study the processes of an electric arc under alternating current, in accordance with the requirements of the concept of visual-block modeling [5], it is possible to construct an energy path system (Fig. 3). The internal resistance of the circuit, R_k, is specified at the power source node.

An alternating current (AC) arc of low frequency (less than 100 Hz) is similar to a direct current (DC) arc. With each cycle of current oscillation, the arc is initiated by breakdown, and the roles of the anode and cathode change according to the change in the current direction [26]. This phenomenon is associated with the characteristics of AC, which changes its direction and maintains the arc in an excited state during each half cycle.

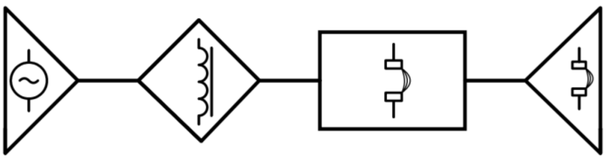

Fig. 3. **The energy path diagram of the electric arc**
Source: **compiled by the authors**

In further research, the Townsend and normal glow discharge can be approximated with an abnormal discharge. This allows for approximating the VAC of the electric arc into two segments (Fig. 4). The first segment can be described as a straight line with a specific slope, and the second describes the transition processes to the arc discharge and the arc discharge itself.

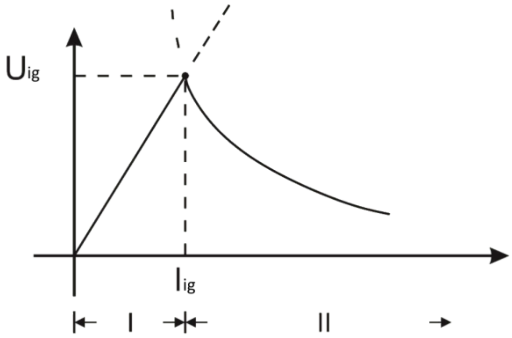

Fig. 4. **Static voltage-ampere characteristic of an electric arc**
Source: **compiled by the authors**

Model of the electric arc. The characteristic of the electric arc exhibits a nonlinear relationship between current and voltage. After the arc is established – this can occur by transitioning from a glow discharge or by instantaneous electrode short-circuit, followed by their separation – additional current increase is accompanied by a decrease in voltage across the arc terminals [25, 27].

This phenomenon is a result of the nonlinear nature of gas ionization in the arc due to the electron flow accelerated by the electric field. Considering this, we choose current as the argument for the current-voltage characteristic of the arc, as the current-voltage characteristic has a unique correspondence to the current and is ambiguous with respect to voltage.

The characteristic in the region I (Fig. 4) is described as a linear function:

$$u_I(i) = K_1 \cdot i_d, \quad (2)$$

where K_1 is the angular coefficient, which depends on the arc length l and its temperature t_c^o.

To simplify the model's parameterization, we determine K_1 through the breakdown specific voltage U_{ig}^*:

$$K_1 = f(a_1, +a_2, a_3, a_4, t_c^o, l) \Rightarrow$$
$$K_1 = f\left(U_{ig}^*, a_1, +a_2, a_3, a_4, l\right), \quad (3)$$

if $U_{ig}^* = U_{ig}/l$, where a_1, a_2, a_3, a_4, a_5 are approximation coefficients; t_c^o is the arc temperature; U_{ig} is the breakdown voltage of the gas gap.

The characteristic in the region II (Fig. 4) is described as an inversely proportional dependence with a pedestal:

$$u_{II}(i) = a_1 + a_2 \cdot l + \frac{a_3+a_4 \cdot l}{i_d}. \quad (4)$$

To determine the approximation a$_1$, a$_2$, a$_3$, a$_4$, a$_5$, a known dependence is used, which is approximated by Suits' expression [23]:

$$E_d = C_0 \cdot i_d^{-n} \cdot p^m, \quad (5)$$

where E_d is the electric field strength in the gap; p is the pressure; C_0, n, m are approximation coefficients. For the arc in atmospheric air, these coefficients have the following values: $C_0 = 80; n = 0{,}5$; $m = 0.31$ [19].

Using correlation analysis, we determine the approximation coefficients a$_1$, a$_2$, a$_3$, a$_4$, a$_5$, i.e., a$_1$=40; a$_2$ = 200; a$_3$ = 300; a$_4$=100; a$_5$ = $14{,}7 \cdot 10^{-6}$.

In the first approximation, the specific breakdown voltage U_{ig}^* can be determined as an inverse dependence on the temperature $U_{ig}^* = 1 \div (a_5 \cdot t_c^o)$, then considering (3):

$$U_{ig} = \frac{l}{a^5 \cdot t_c^o} \quad (6)$$

For the junction point of the characteristics of regions I and II, the following equation holds:

$$\frac{l}{a^5 \cdot t_c^o} = a_1 + a_2 \cdot l + \frac{a_3 + a_4 \cdot l}{I_{ig}}. \quad (7)$$

This allows determining the reignition current I_{ig}:

$$I_{ig} = \frac{a_3 + a_4 \cdot l}{l \div (a^5 \cdot t_c^o) - a_1 - a_2 \cdot l}. \quad (8)$$

By determining I_{ig} and considering (3) and (6), it is possible to find K_1:

$$K_1 = \frac{U_{ig}}{I_{ig}}. \quad (9)$$

Hence the expression for the arc VAC will be as follows:

$$u_d(i) = \begin{cases} K_1 \cdot i, if\ i_d \le I_{ig} \\ a_1 + a_2 \cdot l + \frac{a_3+a_4 \cdot l}{i_d}, if i_d > I_{ig} \end{cases} \quad (10)$$

The visual model of the electric arc is presented in Fig. 6, and its symbol as an element of the VBM library is shown in Fig. 5. The input parameters of the block are the arc current i_d (input energy flow), arc length l, and arc temperature T_d (output energy flow), with the output parameter being the arc voltage u_d (bidirectional energy flow).

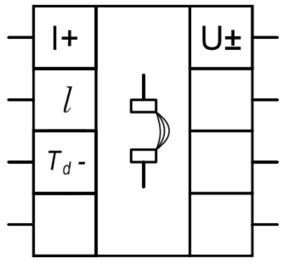

Fig. 5. **The symbol for the block modeling the electric arc voltage-ampere characteristic**
Source: **compiled by the authors**

According to the energy path system and energy flow directions (Fig. 3), a VBM has been synthesized using the arc model as an element from the library of elements [3]. In the synthesis process, the created block of the VAC of the electric arc (Fig. 6) was used, which is shown in Fig. 7. The VBM consists (from left to right) of a variable voltage power source block, an inductance block, an electric arc VAC block, and a thermodynamic block.

The visual block of inductance is well described in works [2, 3], [5], so its mathematical model and visual representation will not be described in the context of this article. The parameters of this block, according to [2], are the inductance L_k, the internal resistance of the inductance R_L, and the initial current *i(0)*.

These parameters are as follows:

$R_L = 0{,}1\ \Omega$, $L_k = 0{,}175$ *H*, *i(0) = 0,01 A.*

According to the visual-block modeling VBM (Fig. 7), the next block is the “AC Voltage Power Source” block.

The mathematical model [28] of the AC voltage source is described by the following expression:

$$u(i) = \sqrt{2} U_{eff} sin(2\pi f) - i \cdot R_{inf}, \quad (11)$$

where U_{eff} is the effective value of voltage, *f* is the frequency, R_{inf} is the internal resistance of the power source, which determines the slope of the current-voltage characteristic.

The visual model of the AC voltage power source is presented in Fig. 8. Based on the created visual model, taking into account the energy path system (Fig. 3), we create the symbol for the variable voltage power source block (Fig. 9). The input to this block is the current feedback *I*, and the output is the voltage *U*.

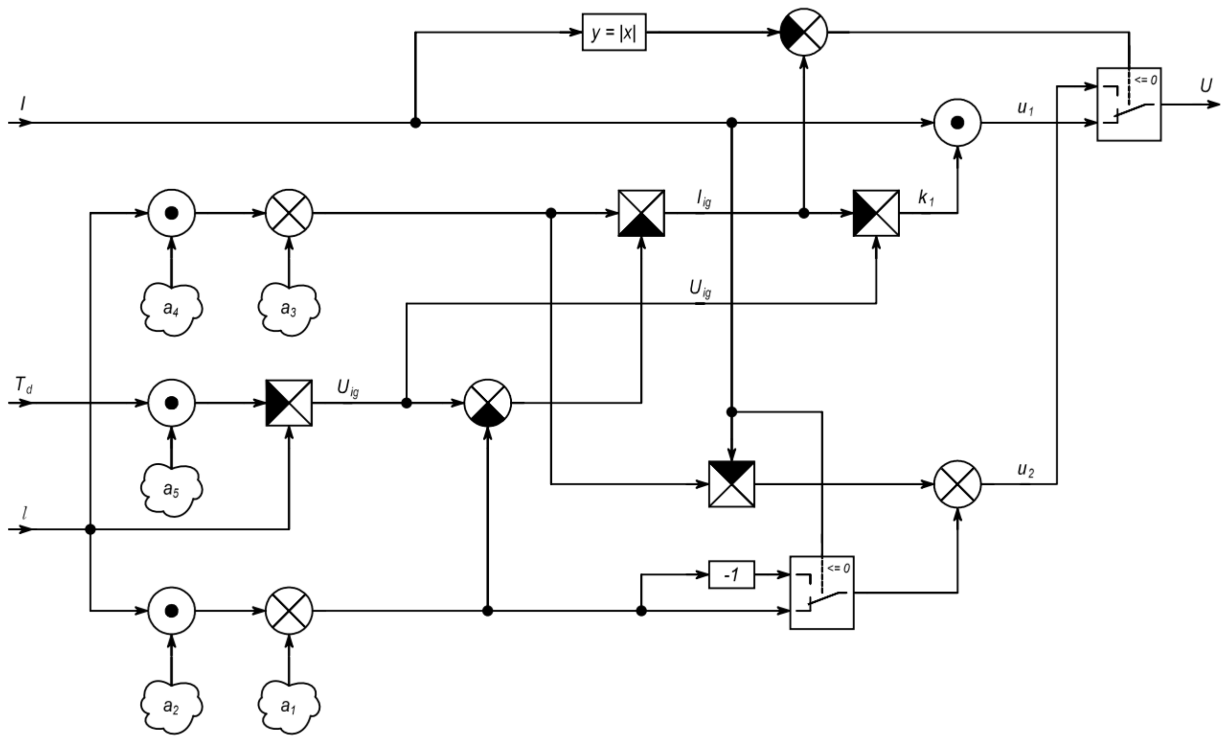

Fig. 6. **The visual-block modeling of the electric arc**
Source: **compiled by the authors**

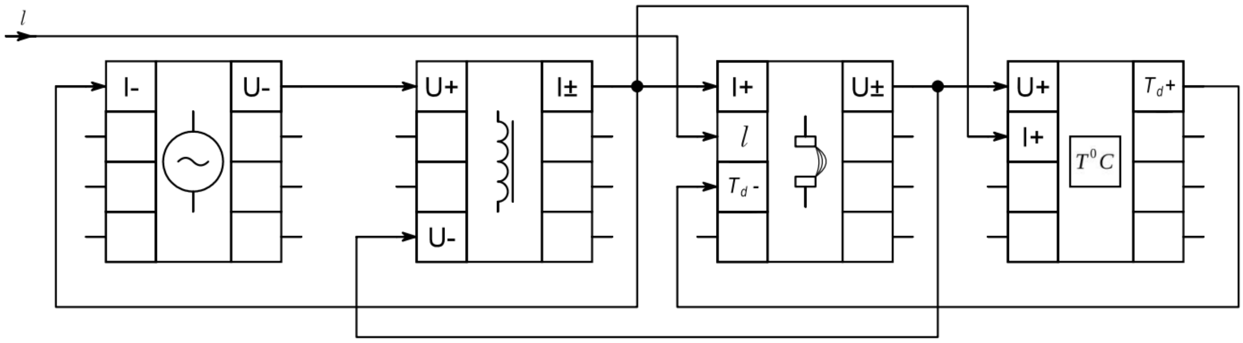

Fig. 7. **The visual-block model of the electrical engineering complex with an electric arc block**
Source: **compiled by the authors**

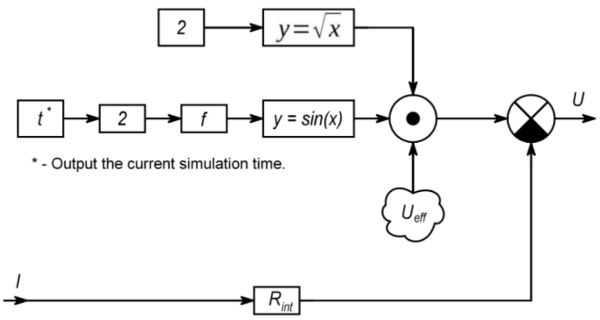

Fig. 8. **The visual model of the alternating current voltage power source**
Source: **compiled by the authors**

From the perspective of the energy flow direction, both of them are output energy flows.

The parameters of this block are: U_{eff} = 230 V; f = 50 Hz; R_{int} = 5 Ω.

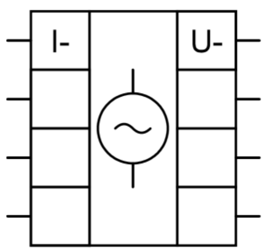

Fig. 9. **The symbol for the block modeling of the alternating current voltage power source**
Source: **compiled by the authors**

One of the inputs to the VAC block of the electric arc is the arc temperature. To model this parameter, a thermodynamic block has been created. The thermodynamic block is a key component in energy systems, and its operation is based on the principles of thermodynamics, where heat exchange and the conversion of the working medium into energy occur in a closed system. To describe the thermodynamic block, let's consider the thermodynamic cycle. It consists of interconnected sequences of thermodynamic processes that involve heat transfer and work within the system and from the system. At the same time, they change pressure, temperature, and other variables in the system, ultimately returning the system to its initial state [29].

To find the temperature, we will apply the following mathematical model:

$$T_d(t) = \frac{1}{m \cdot C} \int \big(p(t) - q(t)\big)\, dt + T(0), \quad (12)$$

where m is the mass; C is the specific heat capacity; $p(t)$ is the heating power; $q(t)$ is the cooling power; $T(0)$ is the initial temperature of the object (at the beginning of the modeling).

The inputs of this model are the voltage u_d and the arc current i_d ($p(t) = u_d(t) \cdot i_d(t)$) and the output is the arc temperature $T_d\,(t)$.

The cooling power $q(t)$ is calculated taking into account the heat transfer coefficient k_t and the ambient temperature T_0, according to the mathematical model:

$$q(t) = k_t \cdot (T_d - T_0)^2. \quad (13)$$

Considering equations (12) and (13), we construct a visual model of the thermodynamic block as shown in Fig. 10a. The notations for the thermodynamic block are provided in Fig. 10b.

RESEARCH RESULTS AND THEIR ANALYSIS

At industrial frequencies (50 or 60 Hz), electric arcs are relatively stable and predictable. The arc exhibits periodic oscillations in intensity and voltage, corresponding to the positive and negative half-periods of the AC signal. Arc reignition occurs at each zero-crossing point of the AC signal when the current falls to zero. The arc voltage follows the waveform of the AC voltage, typically resulting in a waveform with clear peaks and troughs [19, 25]. To validate the proposed model's effectiveness, a comparison was made between the voltage u_d (Fig. 11) and the current i_d (Fig. 12) dependencies over time from the proposed model and experimental data.

The visual block model (Fig. 7) was simulated using MATLAB Simulink with the corresponding block parameters mentioned above. These parameters correspond to the parameters of the experimental setup used for the experiment. Through a comparative analysis of the results obtained through simulation and experimentation, an error in the dynamic component in the transition zone from abnormal discharge to a stable arc was determined. Considering that the model is built based on the static characteristics of the electric arc, achieving an accuracy of over 80 % in dynamics is a satisfactory result.

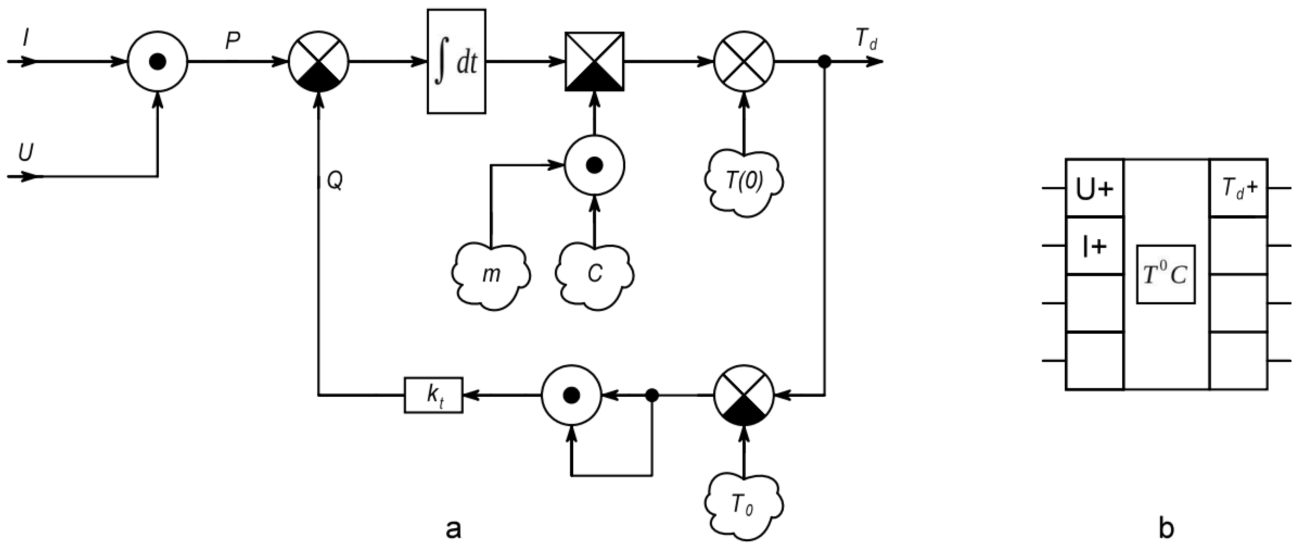

Fig. 10. **Thermodynamic block:**
a – visual model; b – block designation
Source: **compiled by the authors**

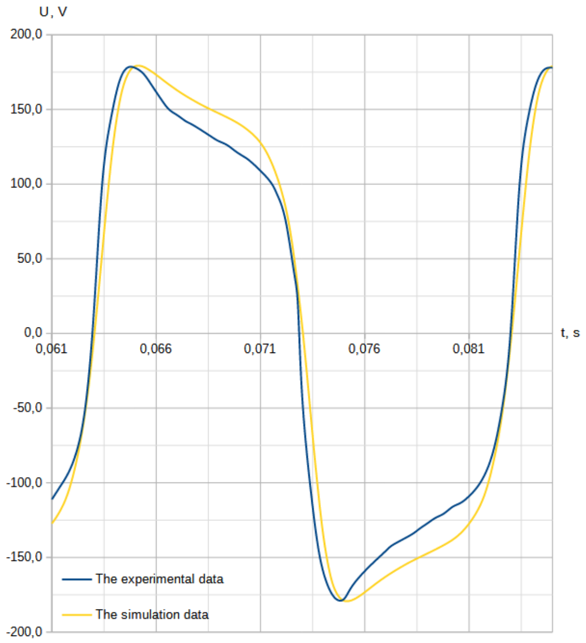

Fig. 11. **The voltage dependency u_d of the electric arc over time, f = 50 Hz**

Source: **compiled by the authors**

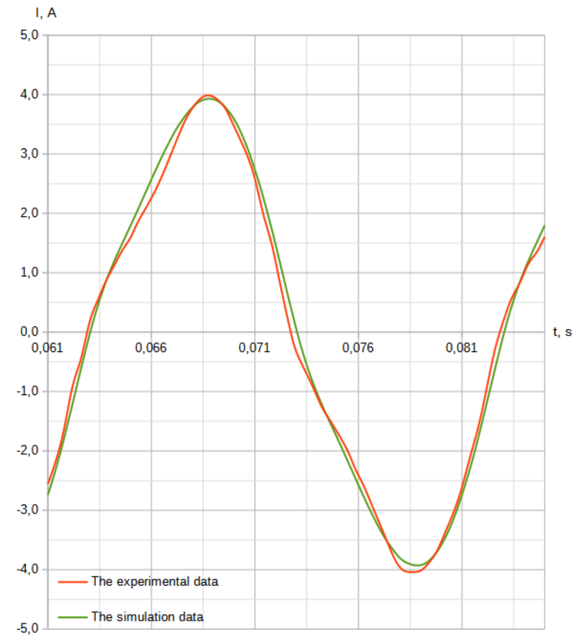

Fig. 12. **The current dependency i_d of the electric arc over time, f = 50 Hz**

Source: **compiled by the authors**

Fig. 13 depicts the VAC of the electric arc for both modeled and experimental data at a frequency of 50 Hz. The error does not exceed 20 %.

The main parameters and characteristics of the electric arc, such as the VAC, reignition voltage, and current, correspond to the experimental data, confirming the adequacy of the model. This allows for the application of this model in simulating electrical systems involving physical processes in the electric arc. A comparison of the simulation time between the proposed model and other black-box model variations revealed an order of magnitude reduction in computation time.

Analysis of the adequacy of the proposed electric arc at different power supply frequencies is essential. The specific behavior of the electric arc at different frequencies can have practical implications in various applications such as arc welding, plasma cutting, and electro-erosion machining. Researchers and engineers need to consider these frequency-dependent characteristics when designing systems or equipment involving electric arcs. The adequacy of the model was verified at the power supply frequency of 50 Hz compared to the experiment, confirming its adequacy at this frequency. For further analysis, we will extrapolate the proposed visual block model to operate at other frequencies.

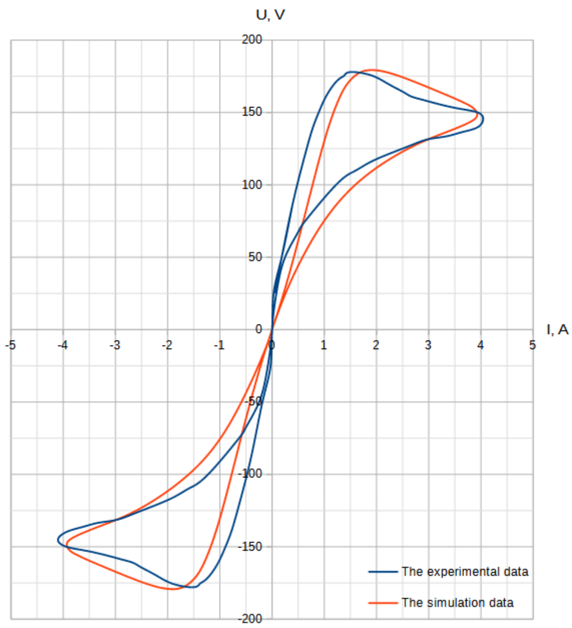

Fig. 13. **The dynamic current–voltage characteristic of the arc for f = 50 Hz**

Source: **compiled by the authors**

In a DC circuit, the electric arc is stable and continuous without cyclic interruptions observed AC arcs. The arc voltage remains relatively constant with minor fluctuations caused by the dynamics of the arc column [30]. Reigniting is not a concern in DC arcs as there are no zero crossings in the current waveform [31].

Fig. 14 illustrates the voltage u_d and current i_d dependencies of the electric arc over time with a constant voltage power supply. For this variation of modeling, the AC power supply, as presented in the paper, was replaced with a DC voltage power supply

from the visual block library described in [2, 7]. The block parameters are the following:
E = 230 V; R_{int} = 5 Ohms.

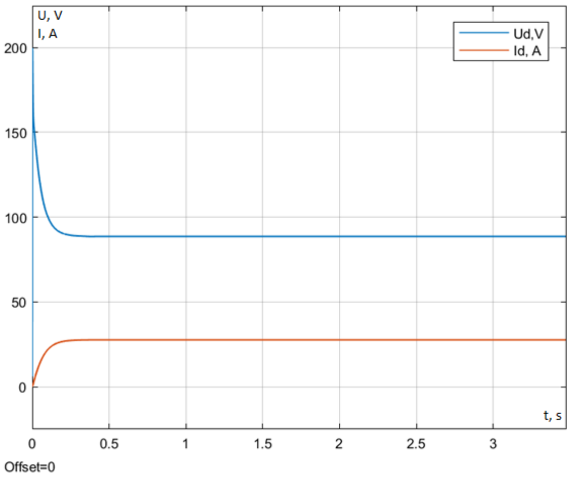

Fig. 14. **The dependency of voltage u_d and current i_d of the electric arc on time under direct current**
***Source:* compiled by the authors**

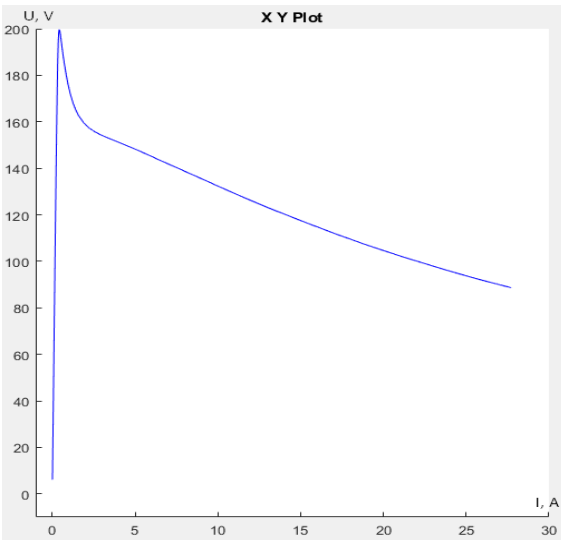

Fig. 15. **The dynamic voltage-ampere characteristic of the electric arc under direct current**
Source: compiled by the authors

The obtained VAC of the electric arc (Fig. 15) and the dependencies of voltage u_d and current i_d of the electric arc on time (Fig. 14) in a direct current circuit align with the general understanding [19, 31] of the arc under DC. After the breakdown of the gas gap, the voltage and current of the arc are limited by the circuit parameters and stabilize at a consistent level.

The simulation results at a frequency of 10 Hz are depicted in Fig. 16 (the dependency of voltage u_d and current i_d), and in Fig. 17 (the dynamic VAC of the arc). These dependencies combine the behavior of the arc under both DC and AC for the process stabilization with subsequent reignition upon polarity change.

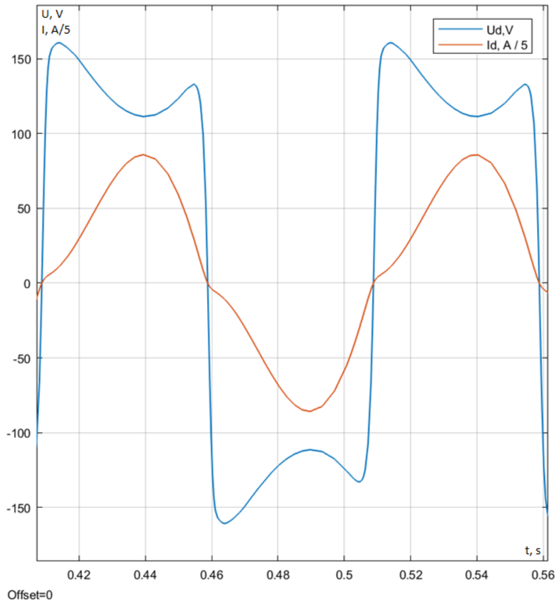

Fig. 16. **The dependency of voltage u_d and current i_d of the electric arc on time, f = 10 Hz**
***Source:* compiled by the authors**

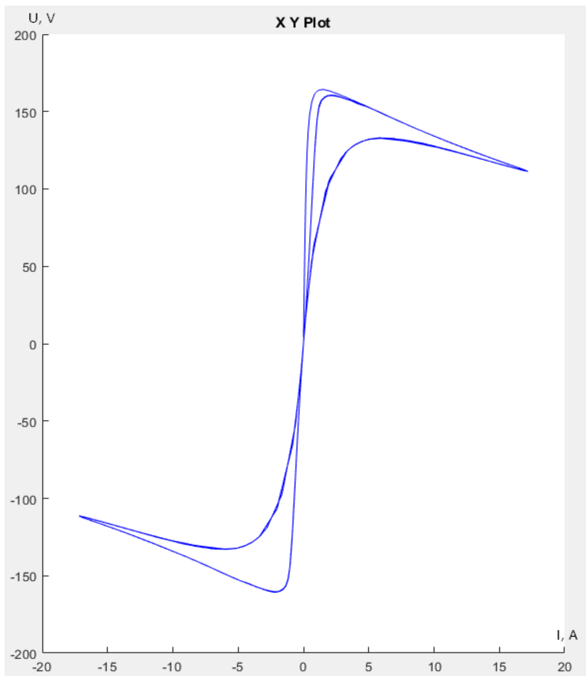

Fig. 17. **The dynamic voltage-ampere characteristic for the electric arc, f = 10 Hz**
***Source:* compiled by the authors**

The simulation results at a frequency of 25 Hz are shown in Fig. 18 (the dependency for voltage u_d

and current i_d), and in Fig. 19 (the dynamic VAC for the electric arc). In contrast to the VAC for the arc at a power supply frequency of 10 Hz, which combines the VAC for the arc under DC with reignition of the arc upon passing through zero, the VAC at a power supply frequency of 25 Hz approximates the behavior of the arc at industrial frequency.

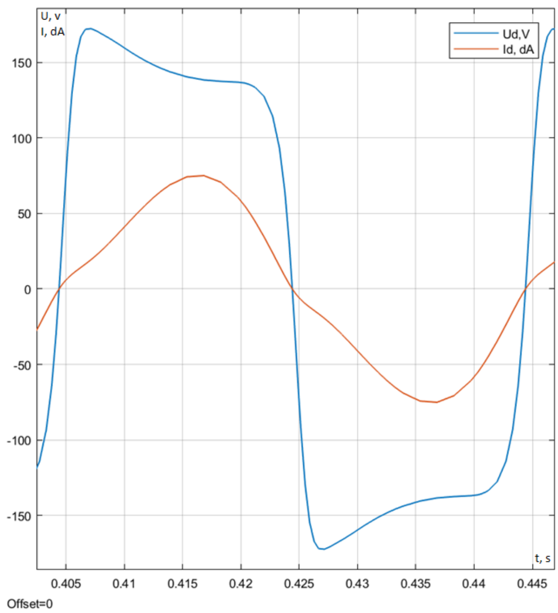

Fig. 18. **The dependency of voltage u_d and current i_d of the electric arc on time, f = 25 Hz**
***Source:* compiled by the authors**

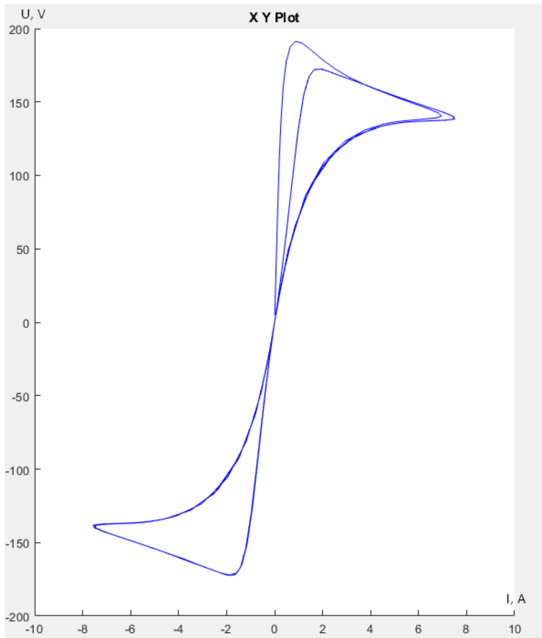

Fig. 19. **The dynamic voltage-ampere characteristic of the electric arc, f = 25 Hz**
***Source:* compiled by the authors**

At higher frequencies, the electric arc behaves differently. Reignition of the arc does not occur at every zero-crossing point of the AC signal, as it does at lower frequencies. Instead, the arc can be sustained for several cycles without extinguishing. The voltage wave at the arc becomes almost sinusoidal due to rapid changes in the current direction. The electric arc becomes similar to a resistive load. It can even be approximated by a linear VAC, where the voltage across the arc is proportional to the current flowing through it [26]. This characteristic distinguishes it from the nonlinear VAC that typically seen in arcs at lower frequencies.

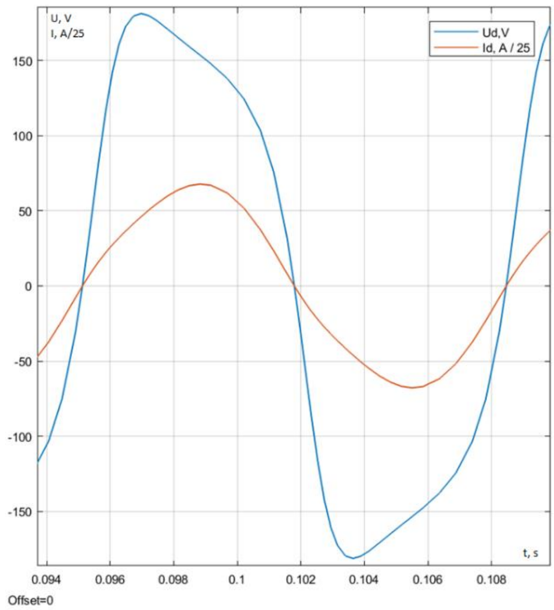

Fig. 20. **The dependency of voltage u_d and current i_d of the electric arc on time, f = 75 Hz**
***Source:* compiled by the authors**

The simulation results at a frequency of 75 Hz are shown in Fig. 20 (the dependency for voltage u_d and current i_d), and in Fig. 21 (the dynamic VAC of the arc). The simulation results at a frequency of 100 Hz are shown in Fig. 22 (the dependency f or voltage u_d and current i_d) and in Fig. 23 (the dynamic VAC for the arc). Although the voltage waveform is not sinusoidal at these frequencies, a smooth approximation of the voltage u_d to a sinusoidal form is still possible.

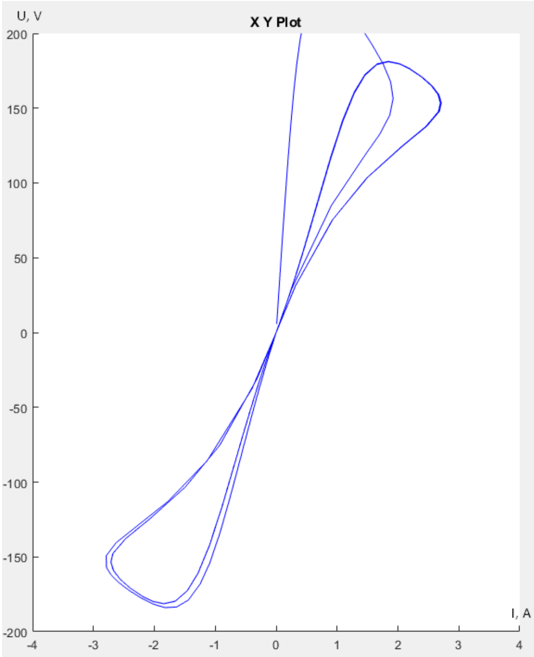

Fig. 21. **The dynamic voltage-ampere characteristic of the electric arc, f = 75 Hz**
Source: **compiled by the authors**

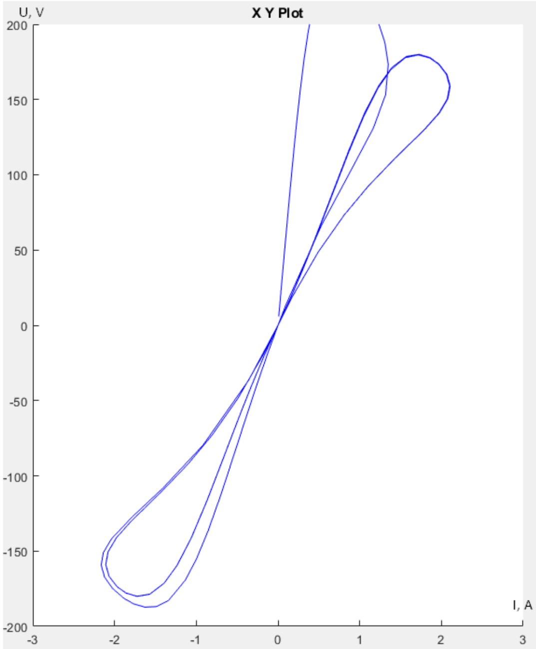

Fig. 23. **The dynamic current–voltage characteristic of the electric arc, f = 100 Hz**
Source: **compiled by the authors**

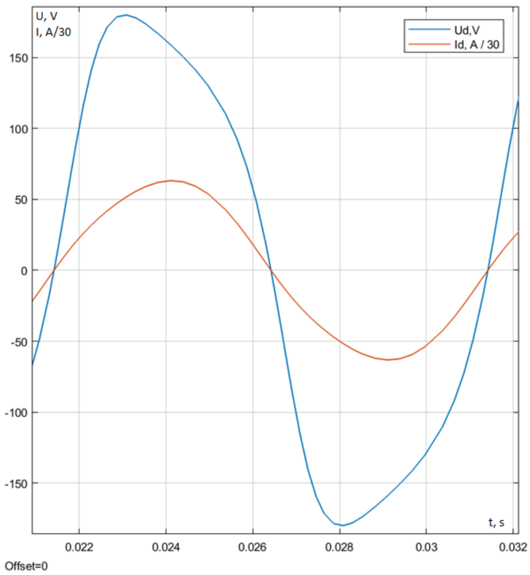

Fig. 22. **The dependency of voltage u_d and current i_d of the electric arc on time, f = 100 Hz**
Source: **compiled by the authors**

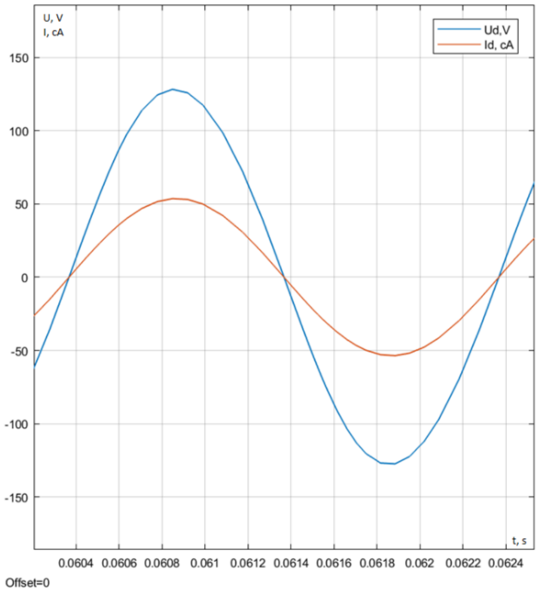

Fig. 24. **The dependency of voltage u_d and current i_d of the electric arc on time, f = 500 Hz**
Source: **compiled by the authors**

The simulation results at a frequency of 500 Hz are shown in Fig. 24 (the dependency for voltage u_d and current i_d), and in Fig. 25 (the dynamic VAC of the arc). The simulation results at a frequency of 2.5 kHz are shown in Fig. 26 (the dependency for voltage u_d and current i_d), and in Fig. 27 (the dynamic VAC for the arc). At such high frequencies, the voltage closely approximates a sinusoidal waveform, and the VAC for the arc is a straight line, resembling a resistive load.

The obtained results align entirely with the physical understanding of dynamic current–voltage characteristics of the arc at high frequencies, confirming the adequacy of the proposed model, which remains valid across a wide frequency range of the power supply.

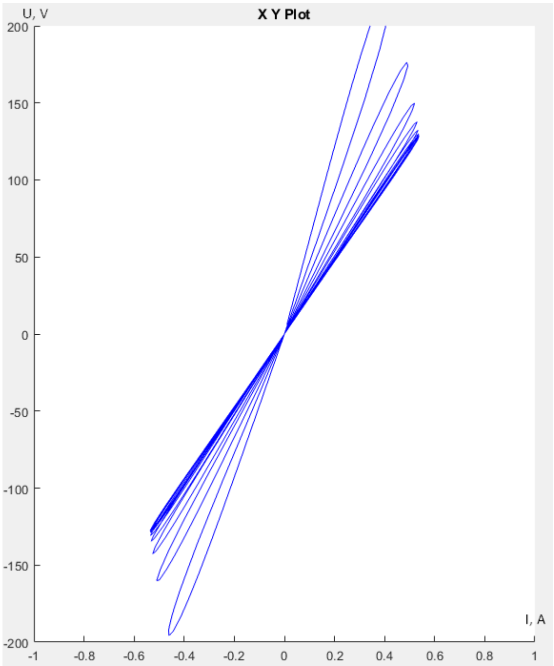

Fig. 25. **The dynamic voltage-ampere characteristic (VAC) for the electric arc, f = 500 Hz**
Source: **compiled by the authors**

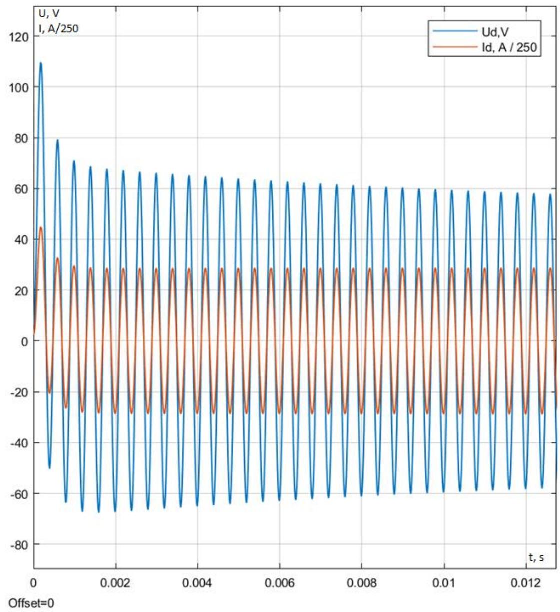

Fig. 26. **The dependency of voltage u_d and current i_d of the electric arc on time, f = 2.5 kHz**
Source: **compiled by the authors**

CONCLUSION

The proposed visual model of the volt-ampere characteristic (VAC) of the electric arc is presented in the form of an element of the visual block modeling (VBM) library. This not only expands the existing VBM library proposed in [2] but also allows for easy application of this model in unified procedures for synthesizing models of complex electrical systems that include the arc burning and reignition process. This extends the scope of the VBM methodology to the field of gas discharges. A comparison of the simulation time of the proposed model and other variations of models revealed an order of magnitude reduction in computation time.

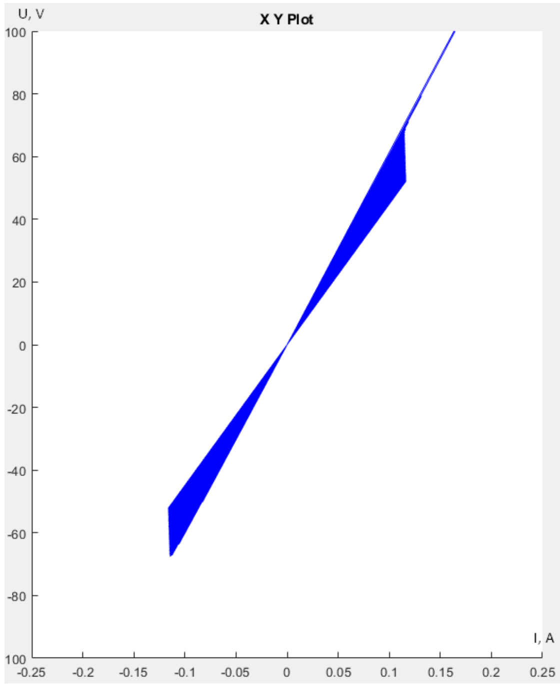

Fig. 27. **The dynamic voltage-ampere characteristic (VAC) for the electric arc, f = 2.5 kHz**
Source: **compiled by the authors**

A comparative analysis of the simulation results and experimental data demonstrated a high degree of adequacy of the proposed visual model. During the adequacy verification of the presented VAC model of the electric arc at the industrial frequency of 50 Hz, the dynamic error was determined not to exceed 20%. An adequacy analysis of the proposed model at different supply frequencies was conducted. The simulation results of the electric arc under constant current power supply confirmed the adequacy of the model and corresponded to the physical understanding of arc behavior under constant current. The obtained VAC completely align with the physical understanding of dynamic VAC of the arc at high frequencies, further confirming the adequacy of the proposed model, which remains applicable over a wide range of supply frequencies.

It is advisable to continue research using the proposed model as part of electrical complexes, such as modeling arc extinction processes, welding units, describing the operation of a collector in the dynamics of an electric drive, and more.

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Інформаційна модель дугових процесів

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АНОТАЦІЯ

Синтез математичних моделей є невід'ємною частиною інформаційних технологій. Він дозволяє аналізувати, прогнозувати та оптимізувати різноманітні системи та процеси. Важливою складовою цього процесу є вибір правильного математичного підходу та перевірка моделі на адекватність. Запропонована стаття є складовою частиною розвитку методу візуально-блочного моделювання в частині поповнення його бібліотеки. По мірі зростання бібліотеки збільшуються межі застосування методу візуально-блочного моделювання. В матеріалах роботи розглянуто питання побудови та використання математичної моделі електричної дуги засобами візуального моделювання. Запропонована математична модель має значно більш високу швидкодію, на відміну від відомих моделей електричної дуги, що адекватно описують електрофізичні процеси у електричній дузі. Це дає змогу скоротити час моделювання складних електротехнічних систем ~~комплексів~~, які включають в себе процеси утворення та перезапалювання дуги. Представлена модель включає опис двох процесів: електродинамічний та термодинамічний. Напруга та струм перезапалювання обраховуються автоматично. Перевірено адекватність запропонованої моделі шляхом порівняння її із експериментальними даними. Також адекватність запропонованої моделі підтверджується в ході аналізу динамічних вольт-амперних характеристик для різних частот напруги джерела живлення. Математична модель оформлена у вигляді елементу бібліотеки візуально-блочного моделювання. Це дозволяє використовувати запропоновану модель для моделювання складних електротехнічних комплексів, до складу яких входить електрична дуга, тобто розширює межі застосування методу візуально-блочного моделювання.

Ключові слова: дуга; візуально-блочне моделювання; математична модель; управління параметрами дуги; емпіричні коефіцієнти; вольт-амперна характеристика дуги

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