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Oleh Bondar, Serhii Siversky, Yevgen Gurin, Oleksandr Koliadenko, Volodymyr Bashko, Vladyslav Kopysov, Viacheslav Pilipenko

MODELING OF ELECTROMAGNETIC PROCESSES IN A NONLINEAR CIRCUIT OF AN ELECTROLYZER FOR PULSE DEPOSITION OF METAL COATINGS

Abstract. *The primary objective of this study is to construct a comprehensive analytical model describing the electromagnetic processes in a nonlinear electrical circuit of an electrolyzer operating under pulsed electrodeposition conditions. Special attention is given to the influence of reversed rectangular voltage pulse parameters on the near-cathode voltage drop, deposition current, and the general electrochemical behavior of the system. The goal is to identify optimal operation modes of the pulse power supply that ensure high-quality metal coatings while minimizing energy consumption and structural defects.*

Methodology. The research employs the method of variable transformation to develop a set of differential equations describing the dynamic behavior of voltage and current in a nonlinear electrolyzer circuit during pulsed operation. The model accounts for critical circuit components: resistive, capacitive, and inductive elements of the electrolyte, as well as nonlinear conductances reflecting electrochemical properties. Analytical expressions for voltage drop and deposition current are derived for both the forward and reverse pulse intervals. The model includes the influence of electrolyte inductance–an often-neglected factor–which significantly alters the current front shape and ultimately affects deposition kinetics and coating characteristics. Numerical simulations are performed to validate the analytical solutions.

Results. Closed-form analytical expressions were obtained for the time-dependent near-cathode voltage drop and deposition current under pulsed conditions. It was shown that the electrolyte inductance leads to a rounding of the current front, influencing both the amplitude and stability of the electrochemical reactions. A parametric analysis identified that the optimal pulse duty cycle lies in the range of $\tau/T \approx 0.73$ to 0.78. Within this interval, the maximum near-cathode voltage drop does not exceed 0.6 V, while the peak *voltage and total current remain within safe technological limits (up to 13 V and 150 A, respectively). The average partial discharge current at the cathode remains stable at approximately 70 A, ensuring consistent deposition rates.*

Scientific novelty. This work introduces a novel analytical approach to modeling pulsed electrodeposition that, for the first time, includes the effect of electrolyte inductance. Unlike existing models relying heavily on numerical simulations, the proposed model allows for direct computation of key process parameters. It enables the derivation of precise criteria for determining the optimal ranges of input pulse parameters–both in amplitude and duration–necessary to avoid the formation of crystalline defects and to achieve uniform, high-quality coatings. These innovations significantly advance the theoretical understanding of pulsed electrochemical processes.

Practical significance. The developed model provides a valuable tool for industries that utilize electrochemical metal deposition, including microelectronics, galvanics, mechanical engineering, and power systems. It offers a foundation for designing advanced pulse power supplies with optimized operation modes and supports the development of automated control systems for deposition processes. Furthermore, the model can aid in adapting laboratory results for industrial implementation, improving coating quality, process efficiency, and operational reliability.

Keywords: *metal electrodeposition, pulsed electrolysis, reversed rectangular voltage, analytical modeling, near-cathode voltage drop, electrolyte inductance, deposition current, process optimization.*

Introduction

In the field of modern materials science and electrochemical technologies, the process of metal electrodeposition occupies an important place–one of the key methods for creating thin functional layers, coatings, and microstructures that find broad application in microelectronics, mechanical engineering, energy, medicine, and the aerospace industry. The development of this technology is driven by the constant need to improve deposition efficiency, enhance the physicochemical properties of the resulting coatings, and optimize the energy consumption of the process. In particular, there is growing interest in advanced electrodeposition modes that allow precise control over coating parameters–such as thickness, density, uniformity, surface morphology, crystalline structure, and adhesion to the substrate.

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Traditional electrodeposition systems widely use direct current (DC) sources. However, over time, it became evident that the constant energy supply mode has limitations in terms of controllability of the coating microstructure. Therefore, there arose a need to introduce alternative methods that would enable more effective control over the kinetics of electrochemical reactions and coating formation. One of these promising approaches is pulse electrochemistry–the use of periodically varying voltage or current to control metal deposition.

A special place among pulse modes is occupied by the use of rectangular pulses, which can be unipolar or reversed. Unipolar rectangular pulses have already found wide application in various industries, as they significantly reduce deposit graininess, increase its density and hardness, decrease porosity, and provide coatings with improved adhesion to the substrate. However, further improvement of the deposition process required even more precise control, especially when applying coatings to complex surfaces or working with microelectronic components.

In this context, the need arises to consider modified pulse deposition methods, particularly the use of reversed rectangular pulse voltage. This approach involves alternating cathodic (negative) and anodic (positive) pulses of specific duration and amplitude, allowing not only deposition but also partial modification of the already formed coating layer. Such a mode enables the implementation of complex electrochemical scenarios: surface cleaning, defect reduction, removal of loosely adhered particles, elimination of excessive crystal growth, as well as suppression of passivation processes or oxide film formation.

As noted in scientific sources [1, 2], the action of reverse pulses during the electrodeposition process has a dual nature, depending on the chemical composition of the electrolyte, the properties of the deposited metal, and the specific parameters of the pulse signal. In some cases, anodic (reverse) pulses can lead to partial dissolution of the deposit, especially if deposition occurred unevenly or with the formation of excessively large crystal structures. This dissolution contributes to surface "smoothing," removing peaks of micro-roughness, ultimately ensuring a more uniform metal distribution in subsequent deposition phases. Thus, the use of reverse voltage allows for optimization of coating morphology and ensures greater uniformity.

Another possible effect of anodic pulses is the passivation of the surface through the formation of salt or oxide films. Under such conditions, active centers on the deposit surface become blocked, and further metal deposition becomes possible only with a sufficiently high cathodic overpotential. This leads to the formation of new crystallization centers, which are distributed evenly across the entire surface, again ensuring uniform coverage and fine-grained structure. This approach is especially important when applying electroplated coatings for functional or decorative purposes, where a homogeneous microstructure with a high-quality surface is required.

The efficiency of pulsed reverse deposition also depends on the signal parameters: amplitude of the cathodic and anodic pulses, their duration, repetition frequency, and the ratio of active to passive phase durations. For example, an excessively long anodic phase can lead to excessive dissolution or oxidation, while short positive pulses have only a minor effect on the surface, providing gentle control over the coating structure. Thus, the development of effective control algorithms for pulsed modes requires a precise understanding of the electrochemical behavior of a specific system.

The influence of reversed pulses on the current distribution in the electrolyte should also be taken into account, as well as the related electromagnetic processes, which can significantly alter the dynamics of mass transfer in the interelectrode space. For example, studies [3, 4] numerically analyzed the features of electric field distribution, current density, and ion concentration in the presence of reversed rectangular pulses. It was shown that such modes can lead to the emergence of complex convective flows and local zones of increased or decreased metal concentration, which directly affects the quality of the deposition.

In this context, studying the mechanisms of action of reversed rectangular pulse voltage is relevant from both theoretical and practical perspectives. The combination of experimental approaches with numerical modeling opens new possibilities for optimizing electrodeposition processes, reducing the cost of coating production, and increasing the reliability of technologies used in high-tech industries. Moreover, such modes can also be applied in systems for electrolytic

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polishing, electroforming, nanostructure formation, and the creation of functional composite layers.

Problem Statement. The aim of this study is a detailed analysis of the impact of reversed rectangular pulse voltage on the features of the metal electrodeposition process.

Main Research Section. Pulse power sources with rectangular waveforms have been used in pulse electrolysis for a long time [2, 5]. The gradual improvement of these power supplies has expanded the range of possible electrodeposition modes by enabling adjustments in pulse frequency and duty cycle. In recent years, several studies have also focused on metal electrodeposition using periodic rectangular pulses, including [6]. That work examined the electromagnetic processes during iron deposition under various pulse shapes, including rectangular ones. However, due to the use of numerical methods for calculations, general patterns linking the key indicators of coating quality and growth rate with the electrical parameters of the equivalent circuit remained undetermined. Therefore, we now present an analytical solution to a similar problem using the method of variable transformation. The equivalent circuit of the electrodeposition process is shown in Fig. 1. Unlike the circuit considered in [6], this model includes the inductance of the electrolyte. The necessity of accounting for inductance arises from its role in the phenomenon of “current pulse front rounding,” which significantly affects both the rate and properties of metal deposition in pulse mode [2].

The equivalent circuit of the electrolyzer is shown in Fig. 1. The waveform of the input voltage is presented in Fig. 2.

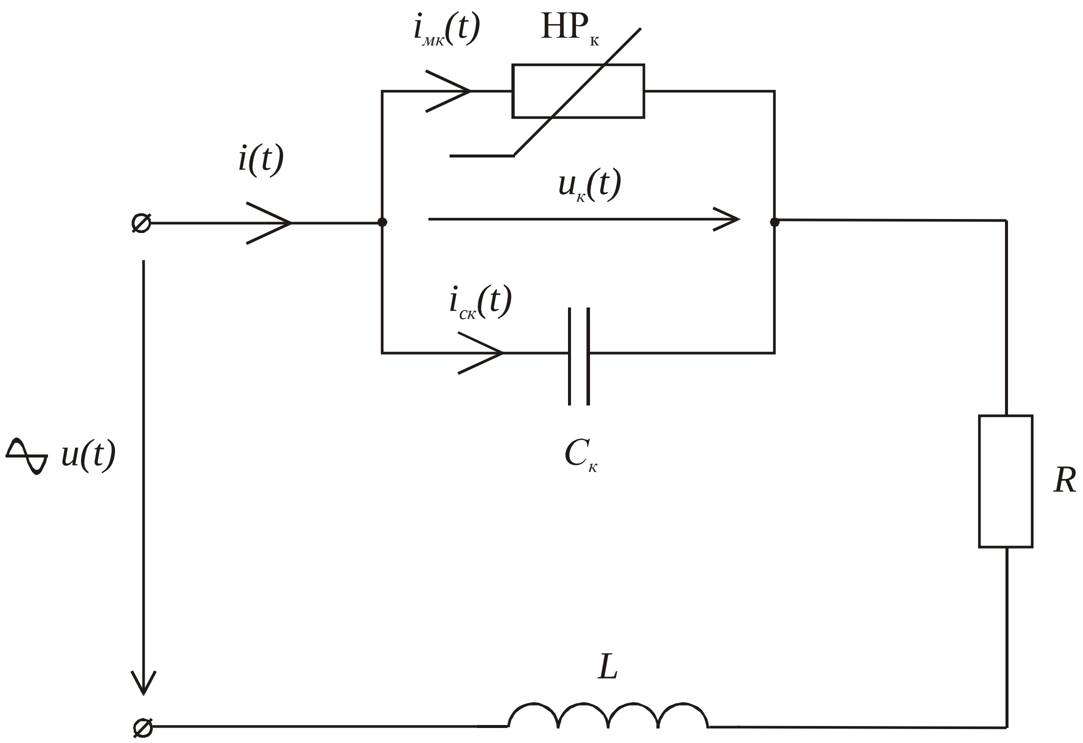

Figure 1 - Equivalent circuit of the electrodeposition process

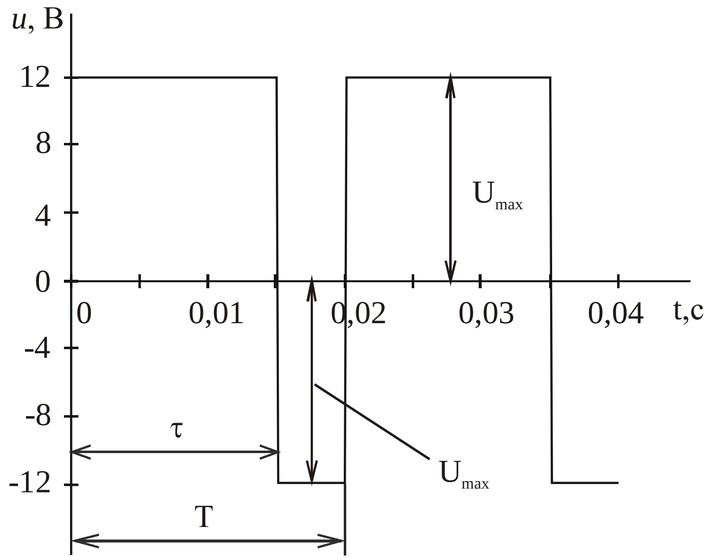

Figure 2 - Waveform of the reversed rectangular voltage *u(t)*

Analytical expression of the input voltage over one period

$$u(t) = \begin{cases} U_{\max,\,fwd} & \text{for } t \in [0, \tau] \\ -U_{\max,\,rev} & \text{for } t \in [\tau, T] \end{cases}, \quad (1)$$

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where $U_{\max\, fwd}$ – maximum value of the input voltage during the forward pulse;

$U_{\max\,\mathrm{rev}}$ – maximum value of the input voltage during the reverse pulse.

Then, in the interval of the forward pulse, the process in the circuit is described by the equation:

$$\ddot{u}_{\kappa}(t) + N(u_{\kappa}(t))\dot{u}_{\kappa}(t) + M(u_{\kappa}(t)) = \delta_1, \tag{2}$$

where
$$N(u_{\kappa}(t)) = n_0 + n_2 u_{\kappa}^2(t), \tag{3}$$

$$n_0 = \frac{R}{L} + \frac{z_1}{C_{\kappa}}, \tag{4}$$

$$n_2 = \frac{3z_3}{C_{\kappa}}, \tag{5}$$

$$M(u_{\kappa}(t)) = m_1 u_{\kappa}(t) + m_3 u_{\kappa}^3(t), \tag{6}$$

$$m_1 = \frac{1}{LC_{\kappa}} + \frac{Rz_1}{LC_{\kappa}}, \tag{7}$$

$$m_3 = \frac{Rz_3}{LC_{\kappa}}, \tag{8}$$

$$\delta_1 = \frac{U_{\max\,\text{пр}}}{LC_{\kappa}}. \tag{9}$$

According to the formula

$$N_{cp1} = 2 \cdot n_1 = \frac{\int_0^{U_{\kappa\max}} N(u_{\kappa})du_{\kappa}}{U_{\kappa\max}}, \tag{10}$$

where $U_{\kappa\max}$ – the maximum value of cathodic polarization during the forward pulse interval; we proceed to the equation

$$\ddot{u}_{\kappa}(t) + 2 \cdot n_1 \dot{u}_{\kappa}(t) + M(u_{\kappa}(t)) = \delta_1. \tag{11}$$

Let us write the solution of equation (2) in implicit form:

$$g(u_к)=e^{-n_1 t}\left[\overset{*}{G}_{m1}\cos\lambda t+\overset{*}{G}_{m2}\sin\lambda t\right]+\frac{\delta}{\theta}. \quad (12)$$

Let us choose an alternative form of the so-called amplitude function in the form:

$$g(u_к(t))=u_к(t)\sqrt{m_1+\frac{1}{2}m_1u_к^2(t)}. \quad (13)$$

Then the integration constants are equal to:

$$\overset{*}{G}_{m1}=-\frac{\delta}{\theta}, \quad (14)$$

$$\overset{*}{G}_{m2}=0. \quad (15)$$

Let us write equation (12) in explicit form:

$$u_к(t)=\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n_1 t}\left(-\frac{\delta_1}{\theta}\cos\lambda_1 t\right)+\frac{\delta_1}{\theta}\right]^2}}. \quad (16)$$

Accordingly, the deposition current is:

$$i_{мк}(t)=z_1\cdot\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n_1 t}\left(-\frac{\delta_1}{\theta}\cos\lambda_1 t\right)+\frac{\delta_1}{\theta}\right]^2}}+$$

$$+z_3\cdot\left(\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n_1 t}\left(-\frac{\delta_1}{\theta}\cos\lambda_1 t\right)+\frac{\delta_1}{\theta}\right]^2}}\right)^3. \quad (17)$$

В рівняннях (12), (17)

$$\lambda_1=\sqrt{\theta^2-n_1{}^2}. \quad (18)$$

In the interval of the reverse pulse, the electromagnetic process in the circuit is described by the equation:

$$\ddot{u}_к(t)+N(u_к(t))\dot{u}_к(t)+M(u_к(t))=\delta_2, \quad (19)$$

where

$$\delta_2=\frac{-U_{\max\,\mathrm{rev}}}{LC_к}. \quad (20)$$

Let us simplify equation (19) using the expression:

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$$N_{cp2}=2\cdot n_2=\frac{\int\limits_{U_{\kappa\min2}}^{U_{\kappa\max2}}N(u_\kappa)du_\kappa}{U_{\kappa\max 2}-U_{\kappa\min 2}}, \tag{21}$$

where $U_{\kappa\max 2}$, $U_{\kappa\min 2}$ – accordingly, the maximum and minimum values of the near-cathode voltage drop during the reverse pulse interval.

As a result, we obtain:

$$\ddot{u}_\kappa(t)+2\cdot n_2\,\dot{u}_\kappa(t)+M(u_\kappa(t))=\delta_2. \tag{22}$$

Proceeding similarly to the previous interval, we write the solution of equation (20) in implicit form:

$$g(u_\kappa(t))=e^{-n_2(t-\tau)}\left(G_{m3}^{*}\cos\lambda_2(t-\tau)+G_{m4}^{*}\sin\lambda_2(t-\tau)\right)+\frac{\delta_2}{\theta}, \tag{23}$$

where $$\lambda_2=\sqrt{\theta^2-n_2{}^2}\,. \tag{24}$$

To determine the integration constants G_{m3} and G_{m4}, we use the initial conditions for the reverse pulse interval. As these initial conditions, we take the value of the near-cathode voltage drop and its first derivative at the end of the forward pulse interval, i.e., at t=τ. For this purpose, we differentiate equation (12), substituting into it G_{m1} and G_{m2}. We obtain:

$$g'(u_\kappa(t))\cdot\dot{u}_\kappa(t)=\theta\cdot\dot{u}_\kappa(t)=-n_1e^{-n_1t}\left(\frac{-\delta_1}{\theta}\right)\cos\lambda_1t-$$

$$-\frac{e^{-n_1t}}{\lambda_1}\cdot\left(\frac{-\delta_1}{\theta}\right)\sin\lambda_1t=\frac{\delta_1}{\theta}e^{-n_1t}\left(n_1\cos\lambda_1t+\frac{1}{\lambda_1}\sin\lambda_1t\right), \tag{25}$$

$$\dot{u}_\kappa(\tau)=\frac{\delta_1}{\theta}e^{-n_1\tau}\left(n_1\cos\lambda_1\tau+\frac{1}{\lambda_1}\sin\lambda_1\tau\right), \tag{26}$$

Then

$$G_{m3}^{*}=g(u_\kappa(\tau))-\frac{\delta_2}{\theta}, \tag{27}$$

$$G_{m4}^{*}=\frac{1}{\lambda_2}\left(n_2\cdot u_\kappa(\tau)+\theta\dot{u}_\kappa(\tau)\right). \tag{28}$$

Thus, in the interval τ…T, the solution for the near-cathode voltage drop in explicit form can be written as:

$$u_\kappa(t)=\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n_2(t-\tau)}\left[\left(g(u_\kappa(\tau))-\frac{\delta_2}{\theta}\right)\cos\lambda_2(t-\tau)+\frac{1}{\lambda_2}\left(n_2\cdot u_\kappa(\tau)+\theta\dot{u}_\kappa(\tau)\right)\sin\lambda_2(t-\tau)\right]+\frac{\delta_2}{\theta}\right]^2}} \quad (29)$$

or, in a single-term form

$$u_\kappa(t)=\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n(t-\tau)}A_{2m}{}^{*}\sin\left(\lambda_2(t-\tau)+\xi_2{}^{*}\right)+\frac{\delta_2}{\theta}\right]^2}}, \quad (30)$$

$$A_{m2}{}^{*}=\sqrt{\left(g(u_\kappa(\tau))-\frac{\delta_2}{\theta}\right)^2+\left(\frac{1}{\lambda_2}\left(n_2\cdot u_\kappa(\tau)+\theta\dot{u}_\kappa(\tau)\right)\right)^2}, \quad (31)$$

$$\xi_2{}^{*}=\mathrm{arctg}\frac{n_2\cdot u_\kappa(\tau)+\theta\dot{u}_\kappa(\tau)}{\lambda_2\left(g(u_\kappa(\tau))-\frac{\delta_2}{\theta}\right)}. \quad (32)$$

Then, the deposition current is

$$i_{\text{мк}}(t)=z_1\cdot\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n_2(t-\tau)}A_{m2}{}^{*}\sin\left(\lambda_2(t-\tau)+\xi_2{}^{*}\right)+\frac{\delta_2}{\theta}\right]^2}}+$$
$$+z_3\cdot\left(\sqrt{-\frac{m_1}{m_3}+\sqrt{\left(\frac{m_1}{m_3}\right)^2+\frac{2}{m_3}\left[e^{-n_2(t-\tau)}A_{m2}{}^{*}\sin\left(\lambda_2(t-\tau)+\xi_2{}^{*}\right)+\frac{\delta_2}{\theta}\right]^2}}\right)^3. \quad (33)$$

By using fitting techniques, analytical expressions for the near-cathode voltage drop and deposition current during the second pulse can be obtained. As an example, let us perform calculations using the following parameters of the equivalent circuit for the nickel plating process: (T = 0.02 s, τ = 0.75T, $U_{\text{max,fwd}}$ = 12V, $U_{\text{max, rev}}$ = 12 V, R = 0.08 Om, C = 0.8 F, z_1 = 8.0 S, z_3 = 609.5 S/V^2, L = 5 ·10^{-5}H. The accuracy of such a calculation for cathodic polarization and deposition current can be evaluated based on Fig. 3 and Fig. 4.

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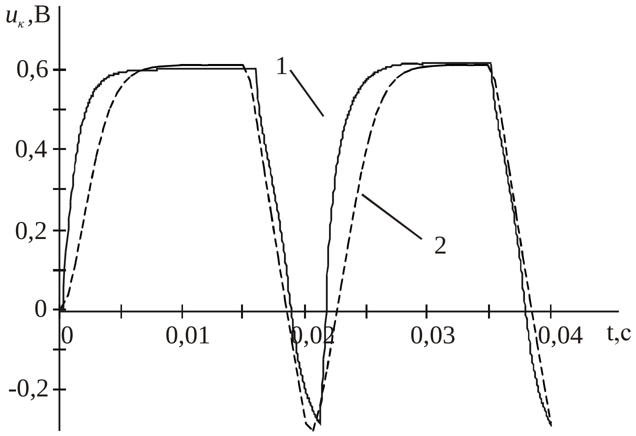

Figure 3 - Time dependence of the near-cathode voltage drop: 1 – analytical calculation; 2 – numerical calculation

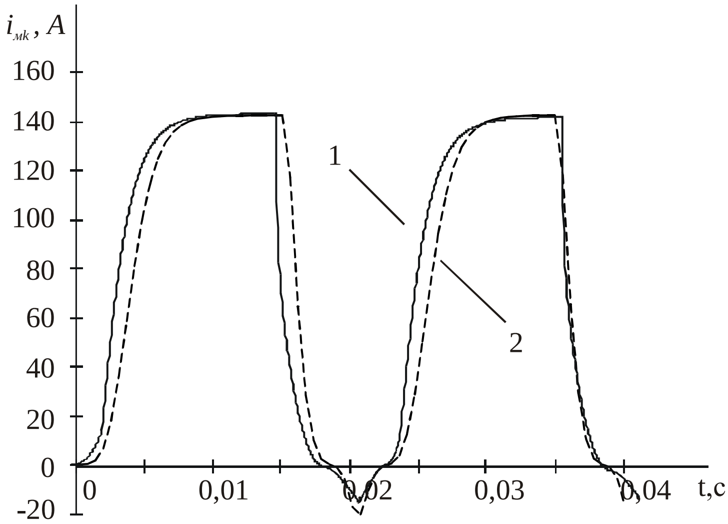

Figure 4 - Time dependence of the deposition current: 1 – analytical calculation; 2 – numerical calculation

Based on the obtained approximate analytical expressions (16), (17), (30), and (33), let us investigate the influence of one of the parameters of the input rectangular periodic pulse voltage (Fig. 2) on the key qualitative and quantitative indicators of coating growth–namely, the duration of the forward and reverse pulses, assuming equal maximum voltages in both pulses, $U_{fwd\,max}=U_{rev\,max}$. The maximum value of the input voltage will be varied in such a way that the average value remains constant and equal to 6 V. Then, the maximum value of the voltage during the forward pulse is:

$$U_{\text{fwd}\max} = \frac{U_{\text{cp}}}{\kappa_{\tau} - \kappa_{U_{пз}}\left(1-\kappa_{\tau}\right)}, \quad (34)$$

where
$$\kappa_{\tau} = \frac{\tau}{T}, \quad (35)$$

$$\kappa_{U_{пз}} = \frac{U_{fwd\max}}{U_{\text{rev}\max}}. \quad (36)$$

In analyzing the results, we will apply the same criteria used in the previous subsection to assess the influence of duty cycle on the considered indicators. As can be seen from Figs. 5 and 7, at low ratios $\tau/T<0.55$, the maximum values of the source voltage and the total circuit current are excessively high compared to other operating modes. More importantly, the peak values of the near-cathode voltage drop are also sufficiently high to reliably cause defects in the crystal lattice of the coating.

At the same time, for $\tau/T>0.81$, the minimum value of the near-cathode voltage drop becomes positive ($U_{kmin}>0$), which indicates the disappearance of the passivation effect of the deposited layer (Fig. 6).

Therefore, from the perspective of the analyzed factors, the most favorable operating modes of the pulse voltage source for this electrolyzer lie in the range of approximately $\tau/T\approx0.73...0.78$. In this range, the maximum value of U_k does not exceed 0.6 V, and the peak values of the input voltage and total circuit current are relatively low (Figs. 5 and 7), reaching up to 13.0 V and 150 A, respectively.

It should also be noted that the modes within the proposed range provide the same deposition rate, since the average partial discharge current of metal ions at the cathode remains constant (Fig. 8) and is approximately 70 A.

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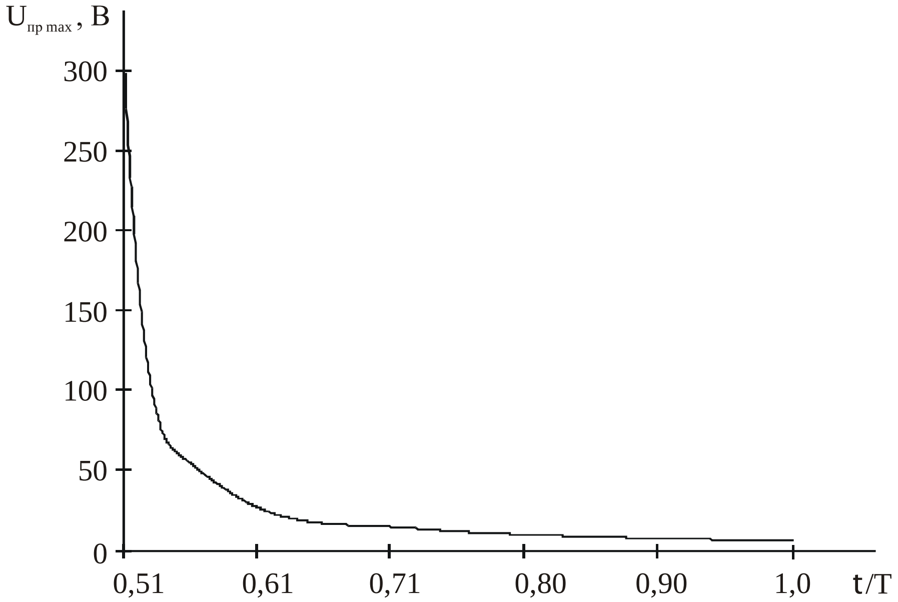

Figure 5 - Dependence of the maximum value of the reversed rectangular input voltage on τ/T at U_{avg}=const=6 V

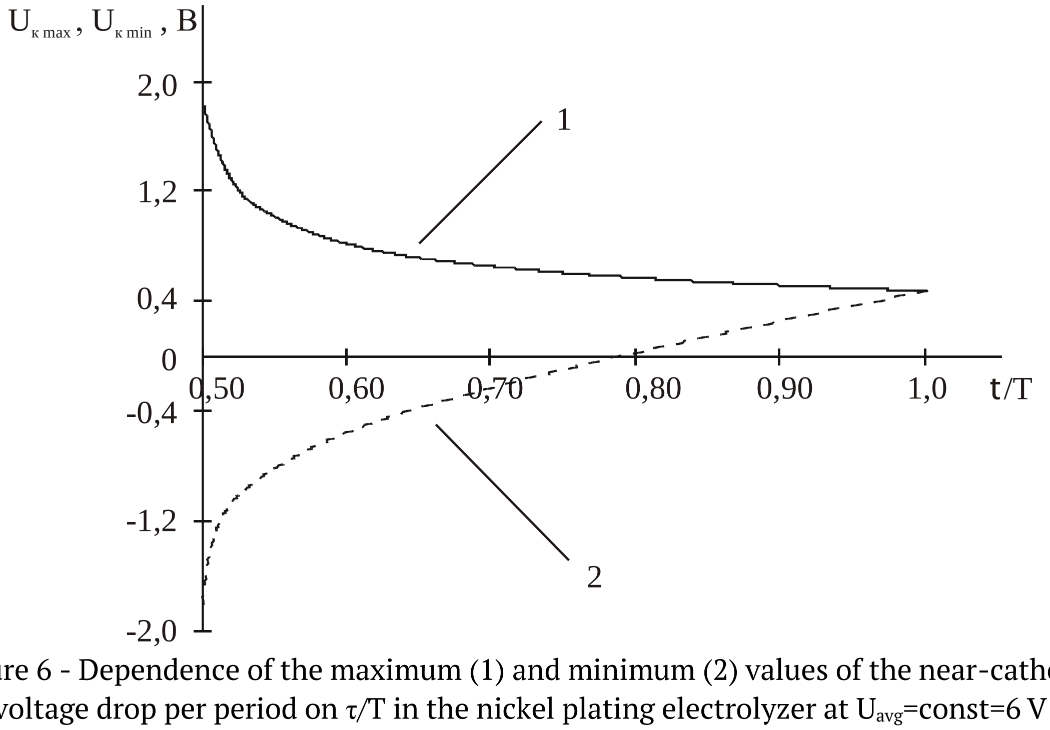

Figure 6 - Dependence of the maximum (1) and minimum (2) values of the near-cathode voltage drop per period on τ/T in the nickel plating electrolyzer at U_{avg}=const=6 V

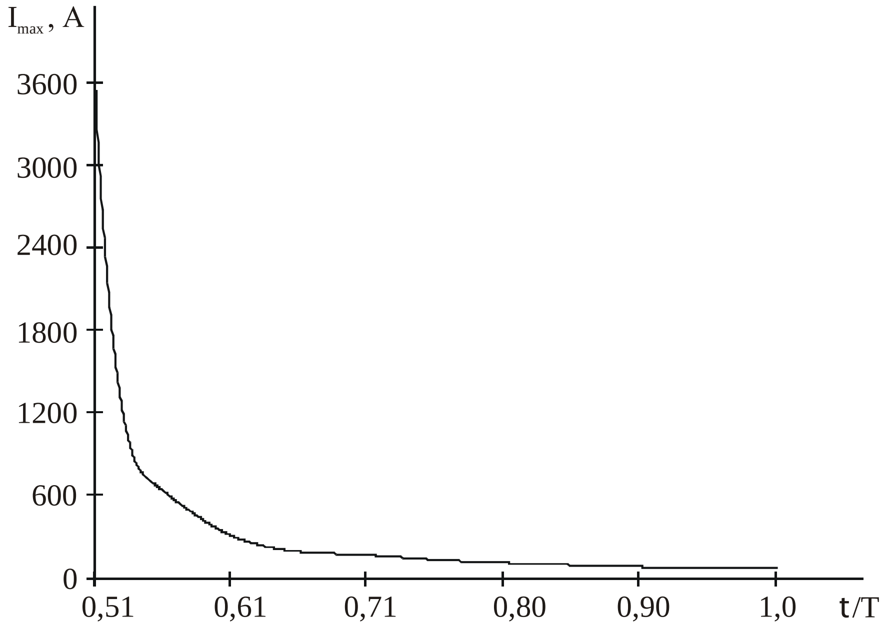

Figure 7 - Dependence of the maximum value of the total current per period in the nickel plating electrolyzer on τ/T at U_{avg}=const=6 V

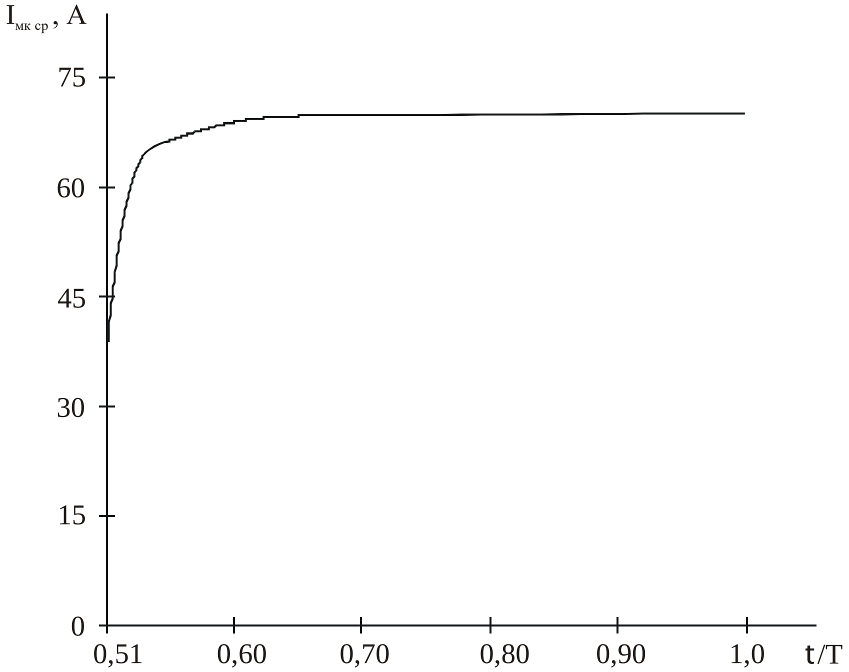

Figure 8 - Dependence of the average discharge current of metal ions per period in the nickel plating electrolyzer on τ/T at U_{avg}=const=6 V

The above recommendations were obtained purely through theoretical means using analytical calculations. Experimental data regarding the advantages of various deposition modes for iron and nickel, as presented in [2], do not contradict these

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findings. Further refinement of the obtained input voltage parameter intervals is possible through investigations using a laboratory model of the electrolyzer and final verification on industrial equipment.

Conclusions

A comprehensive analytical model was developed to describe electromagnetic processes in a nonlinear equivalent circuit of a pulse-mode electrolyzer. In contrast to previous models, this approach takes into account the inductance of the electrolyte, which plays a critical role in shaping the current pulse front and, consequently, in determining the quality and rate of metal deposition. This inclusion improves the accuracy of modeling and allows for better control of the electrochemical process.

General analytical solutions were obtained for the near-cathode voltage drop and the deposition current during both the forward and reverse intervals of rectangular pulse voltage. These solutions provide insight into the transient behavior of the system, making it possible to predict the evolution of key technological parameters, such as maximum and minimum polarization values, peak current levels, and the rate of ion discharge.

A parametric study was conducted to analyze the influence of the pulse duty cycle (expressed as $\frac{\tau}{T}$) on the efficiency and stability of the electrodeposition process. It was shown that for low values of $\frac{\tau}{T} < 0.55$, the peak current and voltage values become excessively high, increasing the risk of structural defects in the coating due to thermal and electrical overloads.

At high values of the duty cycle ($\frac{\tau}{T} > 0.81$), passivation of the cathodic surface is no longer observed, as indicated by the positive minimum polarization. This effect can compromise the uniformity and adhesion of the deposited layer, particularly for coatings requiring fine grain structures and high surface quality.

An optimal range for pulse duration was identified as $\frac{\tau}{T} \approx 0.73 \ldots 0.78$, where all evaluated parameters remain within acceptable technological limits. Specifically, the peak near-cathode voltage does not exceed 0.6 V, while the maximum source voltage and total current are limited to 13 V and 150 A, respectively. Furthermore, the average partial discharge current of metal ions remains stable at approximately 70 A, ensuring a consistent deposition rate across this range.

The validity of the analytical model is supported by comparison with numerical calculations and is qualitatively consistent with experimental results reported in the literature. This confirms the suitability of the model for practical applications and process optimization in pulse electroplating of nickel and iron.

The presented theoretical framework may serve as a foundation for the design of advanced pulse power supplies and control algorithms for electroplating systems. Further enhancement of this work is possible through experimental validation using laboratory-scale electrolyzers and eventual adaptation for industrial systems, enabling improved reliability, cost-efficiency, and coating performance in high-tech manufacturing environments.

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Олег Бондар, Сергій Сіверський, Євген Гурін, Олександр Коляденко,
Володимир Башко, Владислав Кописов, В'ячеслав Пиліпенко

МОДЕЛЮВАННЯ ЕЛЕКТРОМАГНІТНИХ ПРОЦЕСІВ У НЕЛІНІЙНОМУ КОЛІ ЕЛЕКТРОЛІЗЕРА ІМПУЛЬСНОГО ОСАДЖЕННЯ МЕТАЛЕВИХ ПОКРИТТІВ

Анотація. *Метою даного дослідження є побудова аналітичної моделі електромагнітних процесів у нелінійному електричному колі електролізера, який працює в режимі імпульсного осадження металевих покриттів. Особливу увагу приділено впливу параметрів реверсованої прямокутної напруги на прикатодний спад напруги, струм осадження та загальні електрофізичні характеристики процесу. Дослідження спрямовано на виявлення оптимальних режимів роботи джерела живлення, які забезпечують найвищу якість осадженого шару при мінімальних енергетичних затратах.*

Для опису процесів у колі було використано метод перетворення змінних та побудовано систему диференціальних рівнянь, що відображає динаміку напруги та струму в умовах імпульсного живлення. У моделі враховано ключові елементи кола: активний опір, ємність, індуктивність електроліту, а також нелінійні провідності, що характеризують електрохімічну поведінку системи. Для аналізу якості покриття здійснено моделювання в інтервалах прямого та зворотного імпульсів із подальшим визначенням максимальних і мінімальних значень прикатодного спаду напруги та повного струму. Проведено чисельне порівняння з аналітичними результатами для перевірки точності моделі.

У результаті дослідження отримано замкнені аналітичні вирази, які описують часові залежності напруги та струму осадження. Показано, що індуктивність електроліту суттєво впливає на форму імпульсу струму та, відповідно, на кінетику росту покриття. Встановлено, що оптимальне співвідношення тривалості прямого та зворотного імпульсів лежить у межах τ/T≈0.73...0.78. У цьому діапазоні максимальні значення прикатодного спаду напруги не перевищують 0.6 В, а загальний струм та напруга джерела залишаються у безпечних межах (до 150 А та 13 В відповідно). Водночас середній частковий струм розряду іонів металу на катоді становить приблизно 70 А, що свідчить про стабільну швидкість осадження.

Запропоновано нову аналітичну модель електролізера, яка вперше враховує індуктивність електроліту в імпульсному режимі. Це дозволило розширити існуючі підходи до моделювання електрохімічних процесів та отримати точні формули для ключових параметрів без необхідності повномасштабного чисельного моделювання. Також встановлено кількісні критерії, що визначають граничні значення параметрів напруги й тривалості імпульсів, за яких забезпечується мінімізація дефектів кристалічної структури покриття.

Результати дослідження мають прикладне значення для галузей, де застосовується електрохімічне осадження – зокрема, у мікроелектроніці, гальванотехніці, машинобудуванні та енергетиці. Запропоновану модель можна використовувати як основу для створення сучасних імпульсних джерел живлення з оптимізованими режимами роботи. Крім того, вона стане в пригоді при розробці систем автоматизованого контролю процесів осадження та адаптації лабораторних рішень до умов промислового виробництва.

Ключові слова: *електроосадження металів, імпульсний електроліз, реверсована прямокутна напруга, аналітичне моделювання, прикатодний спад напруги, індуктивність електроліту, струм осадження, оптимізація режиму.*

Олег Бондар - к.т.н., доцент, кафедра електротехніки та електромеханіки, Український державний університет науки і технологій

Сергій Сіверський – аспірант кафедри електричної інженерії та кіберфізичних систем Інженерного навчально-наукового інституту Запорізького національного університету, Запоріжжя, Україна.

Євген Гурін - аспірант кафедри електричної інженерії та кіберфізичних систем Інженерного навчально-наукового інституту Запорізького національного університету, Запоріжжя, Україна, ORCID: 0009-0006-1346-5191

Олександр Коляденко – провідний фахівець кафедри електричної інженерії та кіберфізичних систем Інженерного навчально-наукового інституту Запорізького національного університету, Запоріжжя, Україна. kolyadenko.aleks@gmail.com; ORCID iD: 0009-0006-1983-8673

Башко Володимир - провідний фахівець, Інженерний навчально-науковий інститут Запорізького національного університету, Україна, v.bashko7@gmail.com;orcid.org/0009-0007-7820-1944

Владислав Кописов - студент, НТУ "Дніпровська політехніка", Україна, ORCID: 0009-0000-4950-4224, vlad.kopusta@gmail.com

Піліпенко В'ячеслав – провідний фахівець RnD відділу Playtika Holding Corp, Дніпро, Україна. E-mail: pilipenko992@gmail.com; https://orcid.org/0009-0004-7301-2501

Bondar Oleh - PHD, Associate Professor, department of electrical engineeringand electromechan-ics, Ukrainian State University of Science and Technologies.
Siversky Serhii - Graduate student, Department of Electrical Engineering and Cyber-Physical Systems, Zaporizhzhia National University
Gurin Yevgen - Graduate student, Department of Electrical Engineering and Cyber-Physical Systems, Zaporizhzhia National University, ORCID: 0009-0006-1346-5191
Oleksandr Koliadenko – Lead Specialist at the Department of Electrical Engineering and Cyber-Physical Systems, Engineering Educational and Scientific Institute, Zaporizhzhia National University, Zaporizhzhia, Ukraine.
E-mail: kolyadenko.aleks@gmail.com | ORCID: https://orcid.org/0009-0006-1983-8673
Volodymyr Bashko – Lead Specialist, Engineering Educational and Scientific Institute, Zaporizhzhia National University, Zaporizhzhia, Ukraine.
E-mail: v.bashko7@gmail.com | ORCID: https://orcid.org/0009-0007-7820-1944
Vladyslav Kopysov – Student, National Technical University "Dnipro Polytechnic", Ukraine.
E-mail: vlad.kopusta@gmail.com | ORCID: https://orcid.org/0009-0000-4950-4224
Vyacheslav Pilipenko – Lead Specialist of the R&D Department, Playtika Holding Corp, Dnipro, Ukraine. pilipenko992@gmail.com; ORCID: https://orcid.org/0009-0004-7301-2501