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Improvement of monitoring and control system for copper electrolytic refining parameters

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Abstract: The utilization of modern automated control systems in copper cathode production offers the opportunity for remote access to control and regulate the electrolytic process parameters. This, in turn, enhances production efficiency while reducing energy costs. The significant parameters in copper electrolytic refining encompass the temperature and composition of the electrolyte, the circulation rate of the electrolyte, the level of sludge, and the frequency of short circuits occurring between the electrodes and the current density. These parameters directly impact the quantity and volume of cathode sludge. The occurrence of short circuits within the bath arises from the growth of dendrites, necessitating the monitoring of voltage, composition, and temperature of the electrolyte. Regular analysis of the electrolyte's composition and the accumulation of sludge volume at the bottom of the electrolyzer is also necessary. The intensification of the electrolysis process primarily involves increasing the current density, reducing the electrode spacing, enhancing the quality of electrodes, improving the electrolyte circulation system, and further mechanizing and automating the process and its auxiliary operations. These efforts contribute to increased productivity. The objective of this study is to expand the capabilities of automated process control systems by incorporating sludge level control sensors. This aims to mitigate irrecoverable losses resulting from dendritic sludge short circuits on the electrodes located in the lower section of the electrolyzer, utilizing new software. A sludge level control method to prevent short circuits has been investigated, and control software employing float-type level sensors has been developed. This measure is projected to decrease energy consumption by 15–20 % and can be effectively implemented in the production of electrolytic copper at the copper smelting plant in Lao Cai, Vietnam.

Key words: copper cathode, sludge sediment, electrodes, short circuit, sensor, electrolyte, control system, electrolytic refining.

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Совершенствование системы контроля и управления параметрами электролитического рафинирования меди

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Аннотация: Использование современных автоматизированных систем управления в производстве катодной меди обеспечивает возможность удаленного доступа к ресурсам для контроля и регулирования параметрами электролитического процесса, что определяет показатели эффективности производства при снижении энергетических затрат. Важными параметрами в электролитическом рафинировании меди являются температура и состав электролита, скорость его циркуляции, уровень шлама, частота замыканий между электродами и плотность тока, которые напрямую влияют на количество и объем катодного осадка. Наличие коротких замыканий на ванне обуславливается ростом дендритов, что влечет за собой необходимость контролировать напряжение, состав и температуру электролита и периодически анализировать состав и накопление объема шламового осадка на дне электролизера. Интенсификация процесса электролиза происходит в основном за счет повышения плотности тока, снижения межэлектродного расстояния, улучшения качества электродов, совершенствования системы циркуляции электролита при дальнейшей механизации и автоматизации самого процесса и его вспомогательных операций, ведущих к повышению производительности. Целью данной работы являлось расширение функций автоматизированных систем управления технологическими процессами (АСУ ТП) за счет внедрения датчиков контроля уровня шламового осадка для снижения безвозвратных потерь при наличии замыканий дендритного осадка на электроды в нижней донной части электролизера с использованием нового программного обеспечения. Рассмотрен способ контроля уровня шламового осадка для предотвращения коротких замыканий и разработана программа контроля при помощи датчиков уровня поплавкового типа. Данное мероприятие при внедрении позволит снизить расход электроэнергии на 15–20 %, что может быть полезным для внедрения в цехах электролитического производства меди на предприятии «Медеплавильный завод» (г. Лаокай, Социалистическая Республика Вьетнам).

Ключевые слова: катодная медь, шламовый осадок, электроды, замыкание, датчик, электролит, система контроля, электролитическое рафинирование.

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Introduction

Improving the efficiency of energy-intensive metallurgical production is of paramount importance for the further development of sustainable mineral resource operation. On the other hand, excessive fascination with new digital transformation techniques can only complicate the objectives of energy efficiency of large-capacity production [1; 2].

An analysis of the existing monitoring and control systems used at copper cathode production facilities indicates the insufficiency of the number of adjustable parameters for the stable operation of electrolyzers [3—5]. In order to achieve more effective control of the production process, new functional control points with additional sensors must be introduced. To some extent, this applies to the existing copper cathode production facilities, such as copper electrolytic production at the copper smelting plant (Lao Cai, Socialist Republic of Vietnam) [6; 7].

As part of the work performed, the problems of expanding the functional properties of the automated process control system (APCS) need to be addressed, and appropriate adjustments made to the database (DB) blocks. These blocks are produced by mathematical models to control and optimize processes associated with the formation of sludge in the lower part of an electrolytic cell. In this case, unit for matching indicators of the temperature sensor, electrolyte level controller and float regulator needs to be installed, taking into account their mutual influence. The objective is to compare the data obtained with standard parameters, in order to identify anomalies in the process. The aim of the solution is to adjust additional devices within the existing parameterization, in order to achieve optimum process conditions. In particular, a function for early detection of electrode short-circuiting due to various types of disturbances is needed, in order to warn the operator of any deviation in time. It will also facilitate faster data processing for a subsequent control action aimed at the destruction and elimination of local dendrite accretion places, taking into account their volume and number in the lower part of the bath. As the sludge level increases due to the sludge particles infiltrating the interelectrode distance, the electrolyte concentration changes.

This work will address the problems of expanding APCS functions by installing sludge level control sensors, in order to reduce irretrievable losses by reducing the number of dendritic sludge short-circuits on electrodes in the bottom part of the electrolyzer, as well as installing an additional electrolyte composition control sensor.

Adjustable process parameters of copper electrolytic refining

Copper electrolytic production is a physicochemical process functioning at a large array of adjustable parameters which the process depends on. It can be characterized by a significant number of hidden parameters which affect the course of electrochemical processes with the existing problems of adequate identification of different process stages [8—10]. The main input parameters of this process include primarily: the content of copper ions in the electrolyte; concentration of sulfuric acid; and their correspondence to the output parameters — determining productivity and current efficiency [11—13]. Thus, the efficiency of electrolytic refining of copper largely depends on the condition of electrolyzers (baths) with respect to sludge formation in the upper and lower parts of the electrodes. While dendritic short-circuits in the upper part of the cell can be seen and recorded through a thermal imaging camera, deposits on electrodes in the lower part of the bath represent a kind of "blackbox".

During the process, the current changes of the following parameters need to be monitored and analyzed (taking into account additional control conditions in the standard APCS) in the whole volume of the electrolytic cell [14—16]:

1) chemical analysis of the copper content in the electrolyte and sulfuric acid;
2) current electrolyte temperature;
3) electrolyte circulation rate;
4) current intensity on the series;
5) current density on the electrodes;
6) voltage of the electrolysis cell;
7) sludge level under control through a float-type submersible sensor;
8) concentration of chloride-ion in the electrolyte;
9) steam pressure and flow rate;
10) transfer and transportation of a part of the working electrolyte to the drain;
11) mixing of electrolyte after several circulation periods via feed and reserve tanks;
12) continuous estimated dosing of sulfuric acid and copper sulfate additives through batchers;
13) dilution and change of electrolyte concentration with spent flushing water and condensate when sulfuric acid is added to electrolyte;
14) cathodic current density;
15) loading and setting of anodes after a given period and time of their dissolution as a result of electrolysis.

In addition, the analysis of the interrelation between all operating parameters is necessary, in order to establish the necessity to specify and enter additional data such as the copper ions content and electrolyte and sludge level.

All production control and monitoring systems need to take into account the input process parameters which provide a high quality and purity of the output product — copper cathode. During electrolytic refining of copper, there are no functional relations between the amount of the formed sludge on electrodes and the sludge on the bottom of the bath — with the amount and volume of dendritic accretions and short-circuits on the electrodes, especially after their destruction. This can lead to a change in the electrolyte concentration in the bath. Known works [17—19] suggest many ways of determining he input parameter values for sustainable control of the electrolysis process, but mostly using current plant data (DB) [20—22].

In the course of the work, mathematical models were obtained for several process scenarios at different stages of the process during sludge formation at the bottom of the electrolysis cell.

Scenario 1 — formation of accretion in the lower part of the electrodes. This mechanism is related to the ingress of individual sludge particles to the lower part of the electrode surface at the uncontrolled height of the sludge when the dendritic accretion in the upper part of the cathode is destroyed. The "roiling" of the electrolyte causes changes in the electrolyte content, especially in the lower part of the bath.

Scenario 2 — rise of the upper layers of the sludge to the anode and cathode surface with the formation of accretions between the electrodes. The reason lies in the high turbulence of the electrolyte and the sludge itself.

Scenario 3 — complete short circuit between the electrodes when the sludge touches their lower parts. The reason is that the height of the sludge layer in the electrolysis cell is not controlled, and the amplitude of the electrolyte and sludge movement is not taken into account.

As a rule, according to the statistical data, at plants producing cathode copper by the electrolytic method for 24 hours, there can be up to 15—20 cases with different scenarios. Most frequent is the 1st scenario (up to 10 cases per day). Figures 1 and 2 show models for all three scenarios.

The parametric analysis of the electrolysis process helps to determine the relationship between electrolysis process input data (DB) (electrode spacing, current intensity, current density, electrolyte resistance with regard to copper ion concentration) and their influence on electrolytic refining output indicators, such as current efficiency and productivity [23; 24]. However, additional control parameters of the process need to be taken into account, for example, the sludge level on the bottom of the bath and the pH index [25].

The construction of a mathematical model of the parametrical analysis of the copper electrolytic refining process (processes 1.1, 1.2 and 2 in Figure 3) was used [26—28] as an auxiliary method to evaluate and analyze control actions in the case of a production situation which may arise (according to the scenario) as per the obtained block diagram.

The following designations were adopted for the block diagram and calculated mathematical model of the process: input parameters of the electrolyte composition — sulfuric acid content $C_{H_2SO_4} = 150$ g/L; concentration

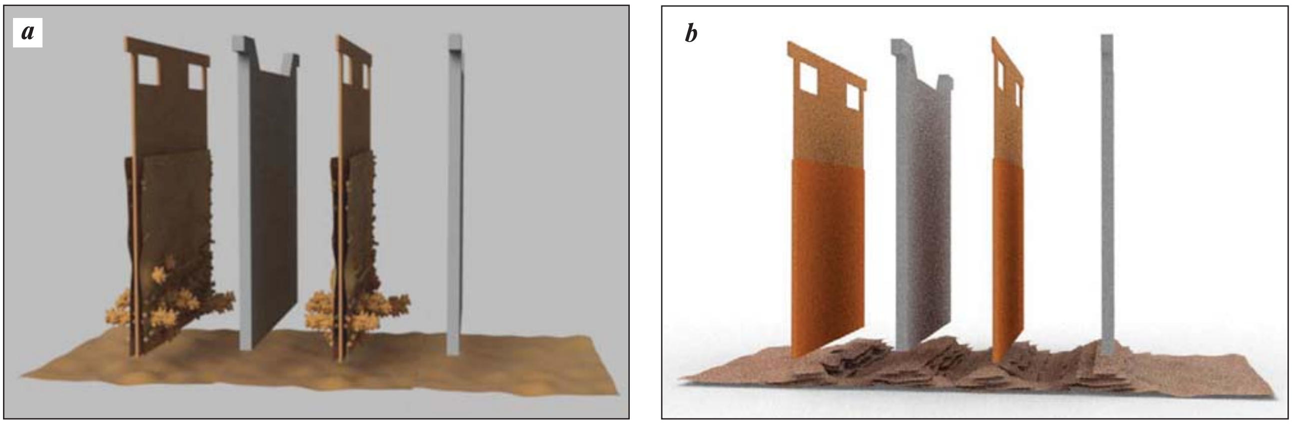

Fig. 1. Model of sludge formation and level change at medium (***a***) and high (***b***) electrolyte turbulence

Рис. 1. Модель образования и изменения уровня шламового осадка при средней (***a***) и высокой (***b***) турбулентности электролита

Fig. 2. Model of complete short-circuiting of the electrodes when the sludge touches the lower part of the electrodes

Рис. 2. Модель полного замыкания электродов при касании осадка нижней части электродов

of copper sulfate C_{CuSO_4} = 279.78 g/L; copper content C_{Cu} = 50 g/L. At a given electrolyte composition the following were obtained: current efficiency η^*_{Cu} = 96 % and productivity Pr^*_{Cu} = 50 t/day; d_{Pr}, d_{Cu} — process efficiency and current efficiency for electrolytic processes 1.1 and 1.2 respectively, which differ in value. In this case the controls are current density (D) and circulation rate (V).

There is a known mathematical model of the copper electrolytic refining process [3] Within its framework, multi-parameter mathematical models using multiple regression analysis can be obtained [29—31]. Equation (1) can be applied to the adjustment of the APCS and control of sludge, taking into account the current efficiency value. Equation (2) can be applied to productivity:

$$\begin{aligned}\eta_{Cu} &= 885.52052 + 0.01869V + 0.01048D^2 - \\ &- 5.79232D + 1.43\cdot10^{-4}(C_{H_2SO_4})^2 - \\ &- 0.01231C_{H_2SO_4} + 0.09\cdot10^{-5}(C_{Cu})^2 - 4.98\cdot10^{-3}C_{Cu} + \\ &+ 3.5\cdot10^{-4}(C_{H_2SO_4})^2 - 0.07688C_{CuSO_4}, \qquad (1)\end{aligned}$$

$$\begin{aligned}Pr_{Cu} &= -122.6664 + 0.0145V - 2.4\cdot10^{-3}D^2 + \\ &+ 1.30096D + 3.6\cdot10^{-4}(C_{H_2SO_4})^2 - 0.09653C_{H_2SO_4} + \\ &+ 4.4\cdot10^{-5}(C_{Cu})^2 - 2.7\cdot10^{-3}C_{Cu} + \\ &+ 2.1\cdot10^{-4}(C_{CuSO_4})^2 - 0.0436C_{CuSO_4}. \qquad (2)\end{aligned}$$

Additional parameterization reflects the true values of the current efficiency and productivity, taking into account the detected deviations with further correction of the process mode through control (see block diagram in Figure 3). The block diagram is based on the mathematical model of the electrolytic refining process, and on the model of functional relations of the current values of control variables (current density D and circulation rate V). This is achieved by a comparison of productivity values (Pr_{Cu}) and the current efficiency (η_{Cu}), with preset parameters of processes 1.1 and 1.2 with a delay factor. In contrast to the existing model, adjustments were made according to the three assumed mechanisms of sludge formation and dendritic accretions on the electrodes.

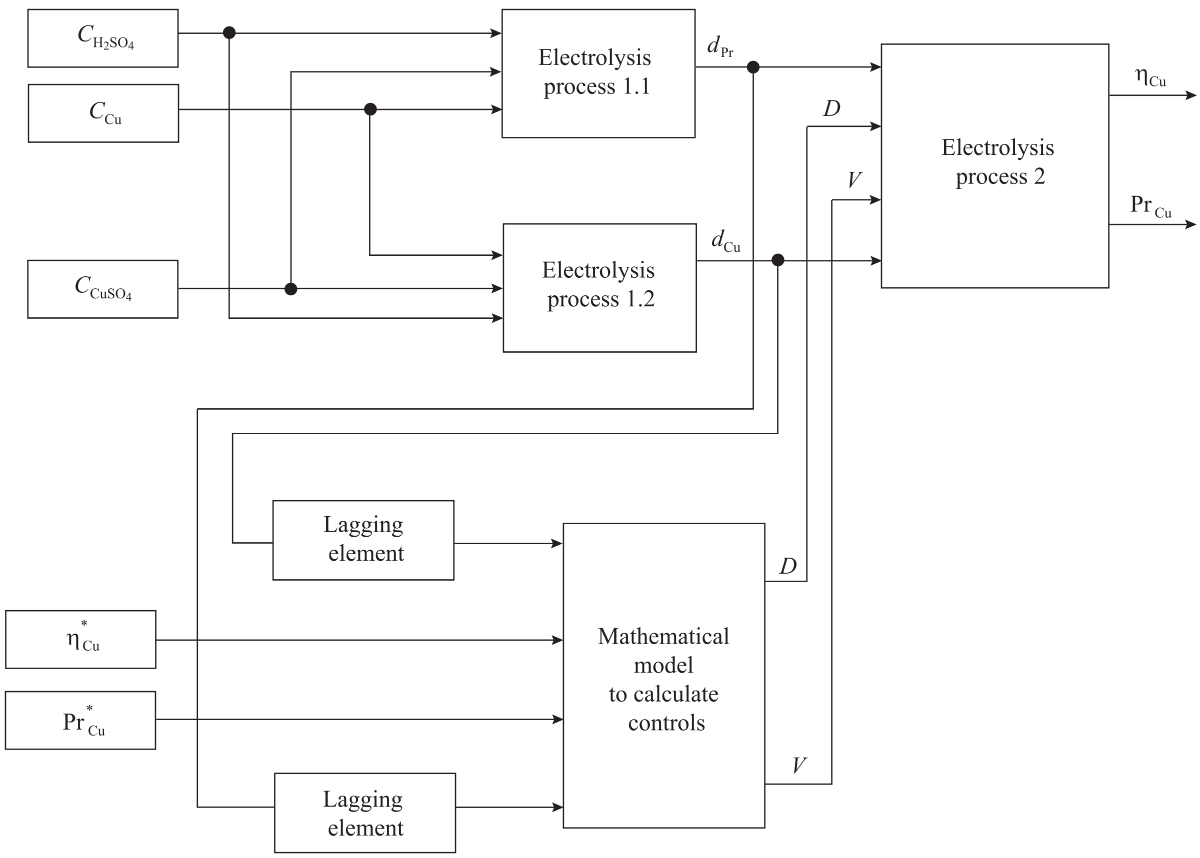

Fig. 3. Block diagram of the mathematical model for the parametric analysis of cathode copper electrolytic production

Рис. 3. Блок-схема математической модели параметрического анализа электролитического производства катодной меди

The dependence of the current density and resistance on the electrode spacing can be obtained with the help of the preset regime of control and monitoring under conditions (1), and also (2) on the basis of the completed mathematical model of the electrolytic copper refining process and the block diagram (Fig. 4). Data shows that the current density variation range is within the rational limits $D = 250÷300$ A/m^2, and the inter-electrode distance varies in the range of 0.045—0.055 m.

When evaluating the effect of current density, it was found that the rated productivity reaches an optimum value when the control D is in the range of 260—280 A/m^2 (Figure 5).

The introduction of additional input parameters for the electrolysis process can be justified, based on the performed parametric analysis.

The value of the copper ion content is also a very important factor. As the Cu^{2+} concentration increases, the current efficiency increases and the bath voltage decreases as the precipitation level decreases. A high copper concentration can increase current efficiency. The copper concentration is usually maintained at a level of 40—60 g/L in terms of the divalent copper cation.

It should be noted that the content of sulfuric acid significantly affects the current efficiency and power consumption. As a rule, its level is maintained in the range of $C_{H_2SO_4} = 100÷150$ g/L.

Temperature growth affects current efficiency growth. However, with decreasing voltage in the bath, the conductivity of the electrolyte increases. In the temperature range of 20—70 °C there is a general tendency towards an increase in dispersity. On the other hand, the physical properties of the electrolyte deteriorate and the cathodic precipitate begins to dissolve. Therefore, the temperature of the electrolyte is maintained at 50—60 °C, and its circulation in the baths is carried out, in order to maintain a given temperature therein. A further objective is to reduce the stratification of the electrolyte due to different densities of the $CuSO_4$ and H_2SO_4 solutions and its components,

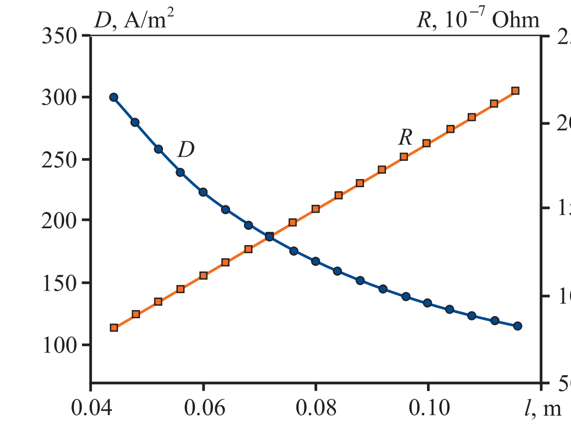

Fig. 4. Influence of inter-electrode distance on current density and resistance

Рис. 4. Влияние межэлектродного расстояния на плотность тока и сопротивление

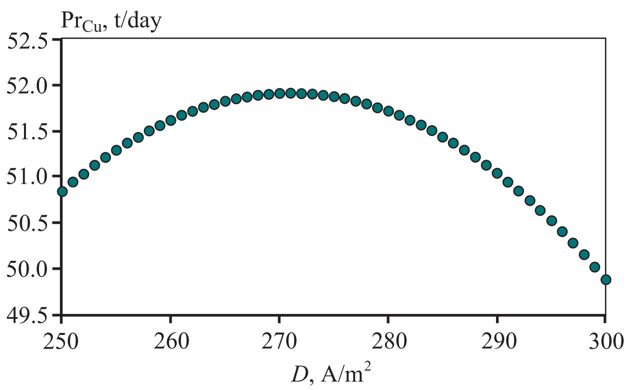

Fig. 5. Dependence of the process productivity on the current density

Рис. 5. Зависимость производительности процесса от плотности тока

while stabilizing the process of electrolyte mixing to saturate the cathode layer with copper ions [4]. It follows from the data obtained that the rate of electrolyte circulation should be kept constant at a level of 20 L/min.

Improving the monitoring and control system for the electrolysis process by introduction of additional parameters

During copper electrolytic refining, the weights of anodes and cathodes, anode residues, cathode scrap, initial cathodes, and used reagents are controlled. The volume of electrolyte removed from circulation and the introduced volume of sulfuric acid are calculated. The electrolyte level in the tank equipment is also determined, inter alia. It is most important that the composition and temperature of the electrolyte be controlled, as well as the process of detecting short circuits between the anodes and cathodes at the calculated values of the electrolyte circulation rate. There also needs to be additional control of the electrolyte content and the sludge level on the bottom of the bath.

Small-size analyzers (types MAK-1 and MAK-2) are used to control the content of copper and acid in the electrolyte. In order to determine the flow rate of steam, water, and electrolyte, differential pressure gauges with recorders are used, and the temperature is measured with resistance thermometers. The use of temperature sensors with remote control allows for electrolyte temperature control [32; 33] to be fully automated.

Various methods are used to detect and eliminate short circuits resulting in a disturbance of normal electrode current supply and a decrease in the current efficiency. Gaussmeters, thermal sensitive paints, and infrared sensors are used. Of great interest is the method of short-circuit detection by means of a camera with an infrared radiation sensor (thermal imager) installed on an overhead crane serving electrolysis baths [34—37]. Using modern methods, labor costs for short-circuit monitoring are reduced up to 30 %, when compared to traditional monitoring systems. Current efficiency is increased by 2 %.

Based on the above factors, software has been created that allows for a more effective control of the process characteristics of copper electrolysis. The working algorithm of the software is shown in Figure 6.

The block diagram includes the following designations for the input data and controls transfer:

1 — process start (input of parameters to the database);

2 — process duration check (τ, min) and final timing (when 48 hours are reached, the process is considered to be completed);

3 — collection of the following current data from sensors:

- electrolyte temperature (t, °C);
- voltage (U, V);
- sludge level (H_{sl}, m);
- electrolyte level (H_e, m);
- concentration of sulfuric acid in the electrolyte ($C_{H_2SO_4}$, kg/m^3);

4 — check of electrolyte temperature in the permissible range $t_e < 85$ °C;

5 — check of voltage between the electrodes with the necessary value of $U = 0.314$ V; voltage has the

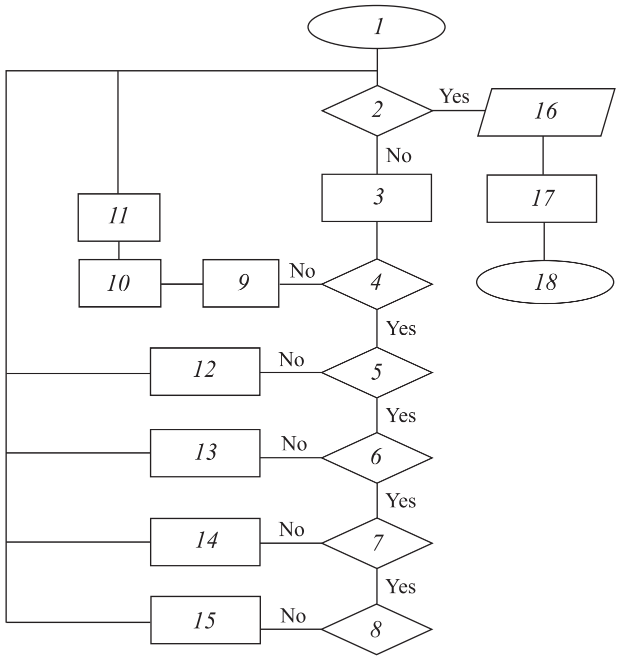

Fig. 6. Block diagram of the software algorithm

Рис. 6. Блок-схема алгоритма работы программы ЭВМ

function of response, which in practice is not regulated;

6 — check of the slurry level within the permissible limits H_{sl} < 0.4 m (no short circuit in the lower part of the electrode);

7 — check of the electrolyte level;

8 — check of the concentration of sulfuric acid in the electrolyte;

9 — beginning of scanning the cell surface (in the bath) with a thermal imaging camera;

10 — detection of the zones of electrolyte overheating (with short circuits); indicate the numbers of the cathode and anode on the screen;

11 — elimination of short circuit and fixing the time (timing);

12 — direct sludge to drain to the receiver;

13 — add electrolyte up to the set target level;

14 — add sulfuric acid to the electrolyte up to the target concentration value;

15 — displaying on the screen of the report about the electrolysis parameters change process;

16 — completion of the electrolysis parameters adjustment process;

17 — stabilization of the process and reaching the normal process mode;

18 — regulator of the overflow system for sludge removal.

Figure 7 shows the diagram of digital automation of the electrolysis bath for copper refining.

Figure 8 shows the screen shot of the developed software for sludge and dendritic accretions control.

The electrode spacing, and therefore the voltage setpoint, can be varied according to the changes occurring on the electrolyzer. Additionally, if significant deviations are detected, the ampere load can also be changed.

As a result, in the course of studying the problems of the stable operation of electrolysis cells, a system for monitoring and controlling the main parameters of the cathode copper production process was created. The software consists of the following products:

— BMXCPS3500 power supply unit;

— Modicon M580 P58 2040 processor module;

— BMXDDI 1602 digital input module, number of digital inputs 16;

— BMXAMM0600 analog input-output module, number of digital inputs 8 in accordance with the algorithm actions;

— BMXDDO 1602 digital output module, number of analog inputs 16.

The software was developed in the Unity XL Pro environment of Schneider Electric and is localized for Russian use in the SE (System Electric) environment.

Additional process control functions via an APCS allow for more efficient and timely elimination of process deviations. The increased frequency of cathode change and sludge removal result in the reduction of economic indicators of the process.

Conclusion

The intensification of the electrolysis process occurs mainly due to an increase in current density value and an improvement in the electrolyte circulation system operation for maintaining the constant copper ions concentration at electrolyte stabilizing temperature.

The introduction of sludge level sensors for the additional monitoring of the process will reduce irretrievable losses of cathode copper in the absence of short circuits of dendritic sludge on electrodes in the lower part of the electrolyzer. Models of cathode sludge formation and dendritic short-circuits on electrodes have been built. An analysis of possible problems and deviations associated with sludge formation allowed for a number of possible process scenarios to be simulated.

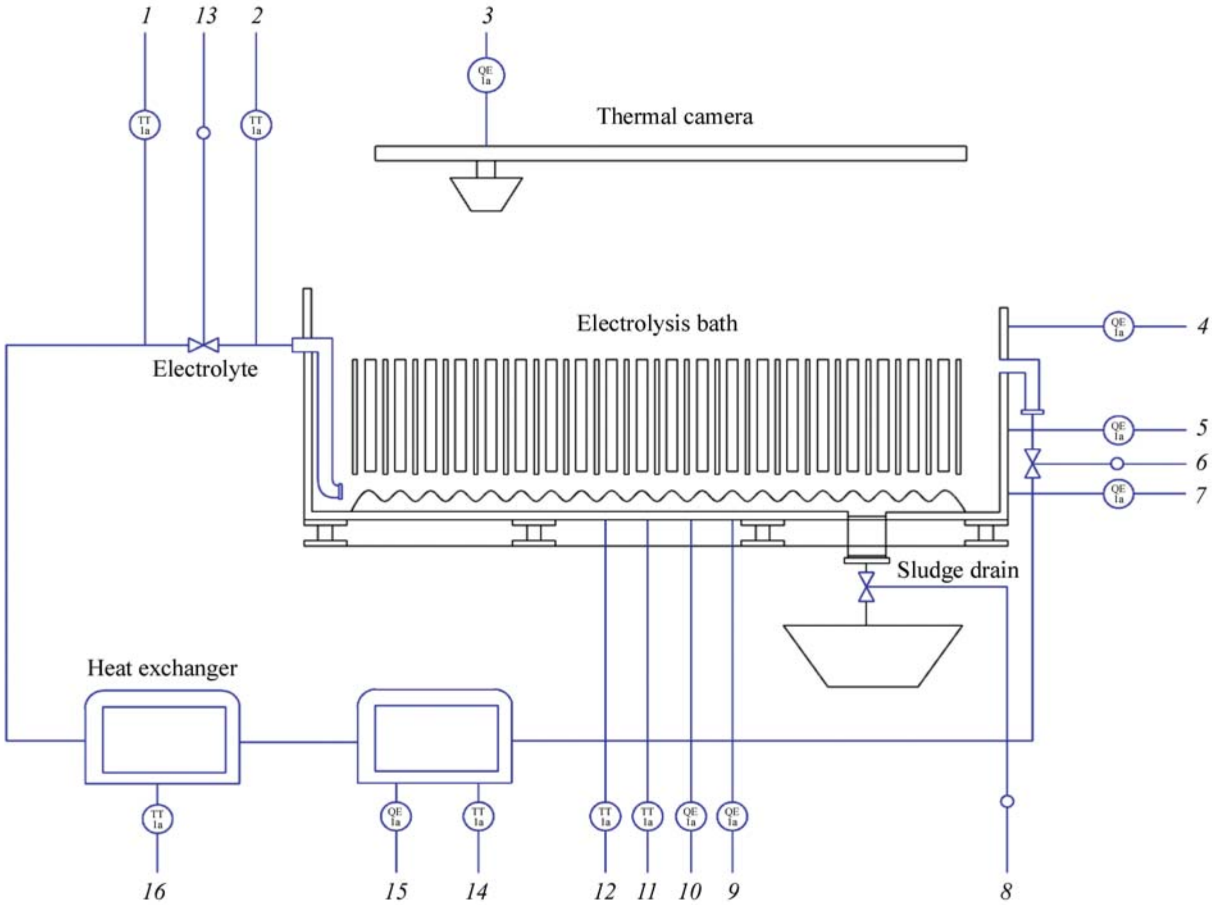

Fig. 7. Diagram of digital automation of the electrolysis bath for copper refining

Рис. 7. Схема цифровой автоматизации электролитической ванны для рафинирования меди

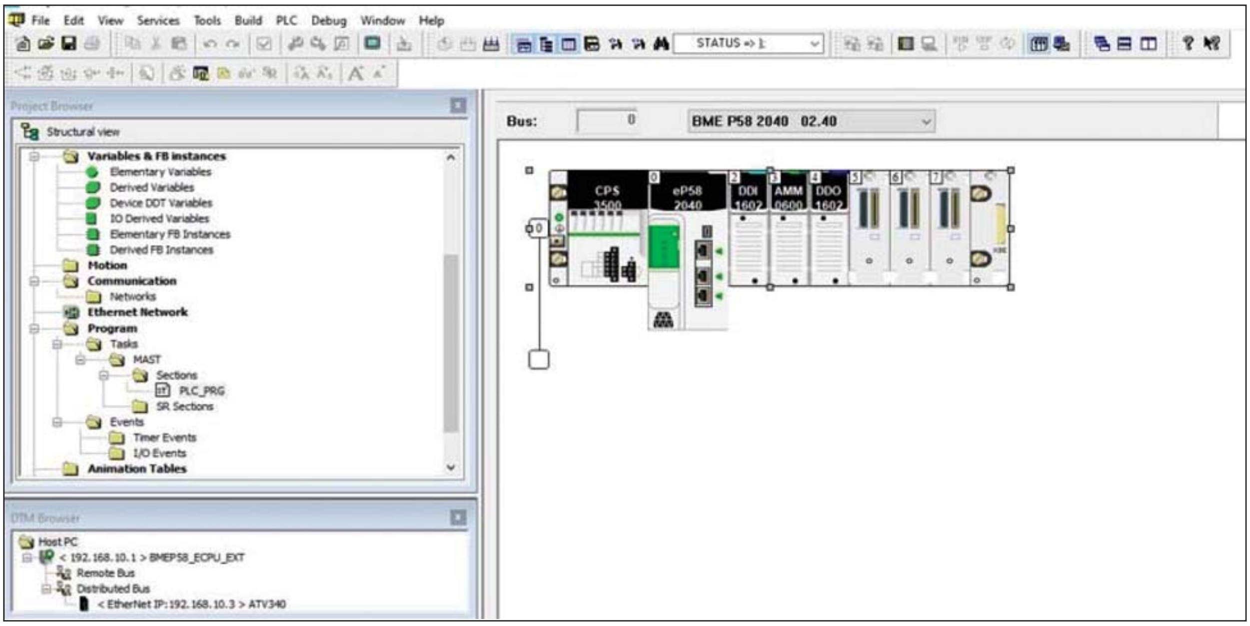

Fig. 8. Screen shot of the developed software for sludge and dendritic accretions control

Рис. 8. Скриншот разработанной программы контроля шламового осадка и дендритных срастаний

The control algorithm and software developed for additional actions in the APCS system help energy losses to be reduced (by 10—15 %) and current efficiency to be increased (by 2 %).

This work can be usefully implemented in existing APCS of copper electrolytic refining for the copper smelting plant (Lao Cai, Socialist Republic of Vietnam).

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