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Automated process control in electric arc furnaces in the aspect of digital twin technology

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Abstract. An approach to managing the main modes of smelting steel in heavy-duty electric arc furnaces (EAF) using digital twin technology was defined and formulated. It was noted, that the existing power regulators do not have the function of balancing the effective power of phases and, accordingly, electric arcs because they are focused on working with a certain average value of the signal. It is proposed to use the analysis of dynamic characteristics based on instantaneous values of input parameters instead of operating ones, as it's usually implemented in most devices. This allows us to obtain more accurate data on the arc state and reduce the amount of time and computing power required to obtain a result and form recommendations. Based on the data obtained as a result of long - term observations of the heavy-duty EAF-135 operation, the relationship of the constant component of the arc voltage (CCAV) with the metal oxidation is shown. An example of its use as a criterion for controlling the melting oxidative stage is given. This reduces the consumption of electrochemical sensors for each melting in the case of serial metal production. Based on the recorded data, it is possible to timely determine the unevenness of the arc power release between the furnace electrodes and issue recommendations on gas burners operation regulating to equalize the rate of scrap melting at electrodes with less power release. The authors propose the idea of using digital twins based on models of the active power distribution across the melting bath zones and dependence of metal oxidation on oxygen blowing for monitoring and controlling the electric mode and the oxygen blast mode at the oxidative stage of the melting process. Simplified schemes of these twins are given.

Keywords: electric arc furnace, digital twin, control system, electric mode, electric arc, refining period, constant component of arc voltage

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Проблемы автоматизированного управления технологическим процессом в дуговых сталеплавильных печах в аспекте применения технологии цифровых двойников

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Аннотация. В работе определен и сформулирован подход к управлению основными режимами выплавки стального полупродукта в сверхмощных дуговых сталеплавильных печах (ДСП) с использованием технологии цифровых двойников. Существующие регуляторы мощности не обладают функцией симметрирования полезных мощностей фаз и, соответственно, электрических дуг, так как они ориентированы на работу со средней величиной сигнала. Авторы предлагают использовать анализ динамических характеристик, построенных на мгновенных значениях входных параметров вместо действующих, как принято в большинстве реализованных устройств. Это дает возможность получить более точные данные о состоянии столба дуги и снизить количество требуемых времени и вычислительных мощностей на получение результата и формирование рекомендаций. Длительная регистрации данных при работе сверхмощной ДСП-135 показала связь постоянной составляющей напряжения дуги с окисленностью металлического расплава. Приведен пример ее использования в качестве критерия управления окислительной стадией плавки, что позволяет снизить расход электрохимических датчиков на каждую плавку в случае серийности выплавляемого металла. На основе регистрируемых данных подтверждена возможность своевременного определения неравномерности выделения дуговой мощности между электродами печи и выдачи рекомендаций по регулированию работы газогорелочных устройств для выравнивания скорости осаждения лома у электродов с меньшим выделением мощности. Авторами предложена идея использования цифровых двойников на базе моделей распределения активной мощности по зонам ванны и зависимости окисленности металла от расхода кислорода для контроля и управления электрическим режимом и режимом газового дутья на окислительной стадии процесса. Приведены упрощенные схемы этих двойников.

Ключевые слова: дуговая сталеплавильная печь, цифровой двойник, система управления, электрический режим, электрическая дуга, рафинировочный период, постоянная составляющая напряжения дуги

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Introduction

Currently, many industries and economic sectors exhibit a clear trend towards the large-scale adoption of digital twin technology for process management [1; 2]. This approach has proven effective in numerous cases by reducing energy consumption and saving raw materials. The essence of this approach involves creating a virtual counterpart, essentially a digital twin of the controlled unit, technological mode, or process, achieved through mathematical modeling [3 – 5].

One of the key prerequisites for applying this approach is ensuring bidirectional communication between the object and its virtual counterpart. In general, this communication can be implemented either through direct impact on the furnace control elements or in the form of advice to the technologist or operator of electric arc furnaces (EAF) regarding the application of specific control actions to the process. It is quite likely that the development of automated process control systems with advisory functions can be considered part of digital twin technology, at least as prerequisites for their creation. Therefore, studying the features of processes occurring in electric arc furnaces to develop methods for controlling key technological parameters remains relevant.

In steel and cast-iron production, digital twin technologies have not yet found significant application. Preliminary work on mathematical modeling of technological processes in steelmaking [6; 7] and blast furnaces [8 – 10] could serve as the basis for their creation. One of the first significant steps in applying digital twins to EAF control is the work of scientists from Nosov Magnitogorsk State Technical University (NMSTU) [11], which describes the algorithm in detail and provides an example of its use in a power regulator.

The electric mode of EAFs changes significantly during melting [12 – 15]. As regulatory practice shows, operators and technologists very rarely use such an effective control lever as changing the voltage tap during the melting process. Having set a certain tap at the beginning of a technological stage, they operate on it almost throughout the entire stage, regardless of changes in the technological situation and arc burning conditions.

Using the digital twin algorithm and the results of their previous research [16; 17], the authors implemented the tracking of situations where the PI controller settings are not optimal and iteratively selected new, optimal settings corresponding to the current state of the system. This significantly stabilized the electrical mode by reducing the standard deviations of currents and arc powers by 15.9 and 4.8 %, respectively, decreased the specific energy consumption (SEC) by 3 %, and reduced the furnace operating time under current by 2 min.

However, this approach involves controlling the electrode movement based on the parameters of the conditionally average phase and does not ensure the symmetry of the furnace's useful load. This leads to significant uneven distribution of arc power in the areas of individual electrodes, given the asymmetry of the short network inherent in almost all steelmaking furnaces. This issue requires a rather complex technical solution involving the organization of voltage signal sampling points directly from the furnace electrodes. It is desirable that in their further research, the authors address this aspect of optimizing the electrical mode.

Methodology for recording signals from the research object

The purpose of the electric mode is to deliver and rationally distribute electrical power within the working space of the furnace. In this context, the electric arc serves as the main component of the useful electrical load – an element with distinctly pronounced properties and features. The efficiency of the melting process and the main technical and economic indicators (TEI) depend on the degree of development (power) and stability of the arc discharge. The root mean square (standard) deviations of the actual values of arc current and phase power from certain values set according to the stage of the process can undoubtedly serve successfully as indicators of discharge stability and even the thermal state of the furnace. For the digital twin model of the power regulator, this approach is acceptable. However, for the control subsystem of the electric mode, which aims to ensure the rational distribution of power in the furnace bath, more detailed information about the characteristics of the electric arc is required.

Therefore, it is proposed to use instantaneous values of input parameters in the electric mode model rather than actual values. The feasibility of this approach is confirmed by the recent interest in hybrid models of the alternating current Cassie-Mayer arc, based on solving the equations of electrical conductivity of the arc column [18 – 21]. However, using such models involves a rather complex mathematical framework and calculations, requiring significant time and computational resources. Moreover, model representations do not always correspond to the real characteristics of the object, particularly the oscillograms of the arc current and voltage. Therefore, preference should be given to analyzing dynamic characteristics constructed from instantaneous signal values:

– dynamic voltage-current characteristic (VAC-characteristic): the dependence of the active component of phase voltage on current;

– phase trajectory: dependence of the current derivative on the arc current.

Their typical forms are shown in Fig. 1.

Based on the shape of the dynamic VAC characteristic, particularly the slopes of its linear sections relative to the current axis, it is possible to uniquely determine the values of the resistances connected in series with and shunting the arc. This forms the basis of the dynamic VAC characteristic method, which is thoroughly detailed in [22].

Using this method, one can determine the parameters of the equivalent electrical circuit in the EAF's working space. These parameters include the voltage drop across the arc, the resistance connected in series with

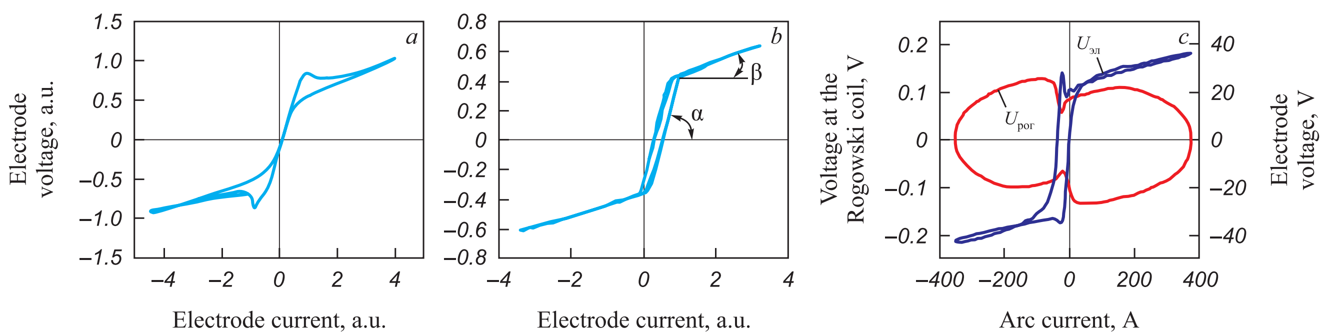

Fig. 1. Typical forms of dynamic VAC and phase trajectory of circuits with non-shunted (*a*) and shunted (*b*) electric arc; data from a real EAF during the combustion period for liquid metal (averaging) (*c*)

Рис. 1. Типичные формы динамической ВАХ и фазовой траектории цепей со свободно горящей (*a*) и шунтированной (*b*) электрической дугой, а также данные с реальной ДСП в период горения на жидкий металл (усреднение) (*c*) it, the short network segment, and the arc power. During the refining stage, when the arcs are shunted by slag, it is possible to determine the currents in both the slag and arc branches, as well as the power released in these zones. Additionally, the analysis of the phase trajectory has practical applications in developing a mathematical model for automated control of the EAF's electric mode parameters.

Unlike the use of standard deviations of power and actual values of electrode current and phase voltage to assess the stability of the arc discharge, analyzing the forms of phase trajectories and dynamic VAC characteristics provides more illustrative information. It allows for monitoring the thermal state of the furnace during melting and timely applying control actions to the process. To assess arc plasma instability over specific time intervals, effective signal processing methods are used, including short-time Fourier transform (STFT) [22]. The arc instability index

$$\tilde{\nu}_{\text{a}} = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\frac{u_{\text{ф}i}^2 - \tilde{u}_{\text{ф}i}^2}{U_1^2}} \qquad (1)$$

employed by the authors represents the mean quadratic deviation of the phase voltage signal from its averaged Fourier representation $\tilde{u}_{\text{ф}i}$ over several (8 – 12) periods, normalized to the amplitude of the first harmonic (U_1), across the digital realization ($i = 1 \ldots N$) of the signal $u_{\text{ф}i}$. The procedure for the averaged Fourier transform is described in more detail in [23].

Experimental testing of the methodology

Fig. 2 shows the real and averaged dynamic VAC characteristics and phase trajectories typical for various stages of melting, from the beginning to the end of the melting process. These were obtained by sampling and analog-to-digital conversion of electrical voltage signals from the furnace transformer outputs and derivatives of currents in the electrodes, sampled using Rogowski coils. The dynamic VAC characteristic exhibits hysteresis since it is constructed for the values of the total phase voltage. It is evident that as the charge heats, melts, and forms a single bath of liquid alloy, the thermal content of the furnace increases, and the characteristics stabilize, concentrating in an increasingly narrow area.

This process is reflected in the changes in the arc instability indicators for individual phases, presented in Fig. 3. The data were obtained on a heavy-duty EAF-135 during the smelting of a steel semi-product. The charge was loaded in two stages, so the first section of the characteristic corresponds to the melting of the first batch of the charge, the second section to the melting of the second batch and the refining period. The practical significance of monitoring this indicator lies in providing advice to the steelmaker on changing the electric mode settings, switching the voltage tap, and making decisions about turning off the furnace for loading the second batch or starting the oxidation stage of the process.

Timely decision-making will reduce the melting time and specific energy consumption (SEC). It is also noted

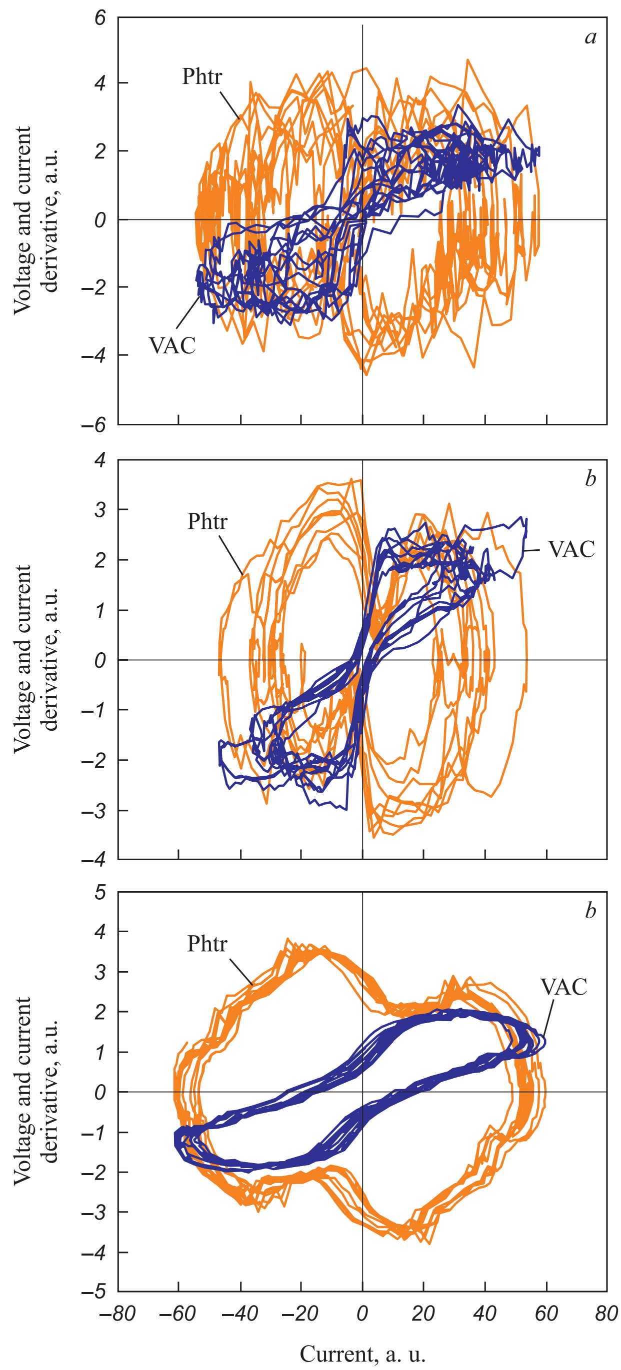

Fig. 2. Change in dynamic characteristics of a circuit with electric arc at the stages of scrap melting (*a*), liquid metal bath forming (*b*) and oxidative refining (*c*)

Рис. 2. Изменение динамических характеристик цепи с электрической дугой на стадиях плавления лома (*a*), горения дуги на ванну жидкого металла (*b*) и окислительного рафинирования (*c*)

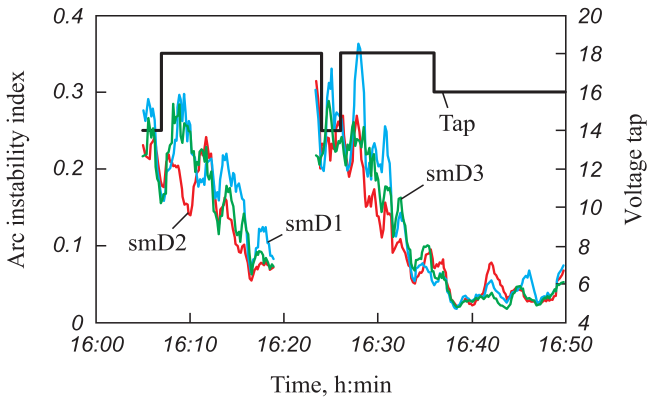

Fig. 3. Changes in arc instability index during melting

Рис. 3. Изменения показателя нестабильности дуги в ходе плавки

that there is a delay in voltage stabilization on the first phase. Due to the asymmetry of the arc power, the instability indicator reaches values characteristic of the other electrodes only after a few minutes. To compensate for the energy deficit and accelerate the melting process, it is necessary to increase the gas consumption in the burners operating in the area of the lagging phase.

Regarding the development of the digital twin for the electric mode control subsystem, its simplified schematic can be presented in Fig. 4.

According to this scheme, signals of phase voltage and currents in the electrodes (or, in the presence of Rogowski coils, the derivatives of the current) from each phase are fed into the subsystem. They are normalized, digitized using an analog-to-digital converter, subjected to discrete Fourier transform (DFT) with subsequent determination of the arc instability index, and processed using the dynamic VAC characteristic method. The output characteristics – arc power and instability index – are sent to the mode asymmetry determination block and directly to the advisory block for the technologist. The advice formed based on the state of the object includes recommendations for the operator on applying specific control actions, such as changing the voltage tap, adjusting current setpoints (conductance or phase impedance), or altering gas flow intensity.

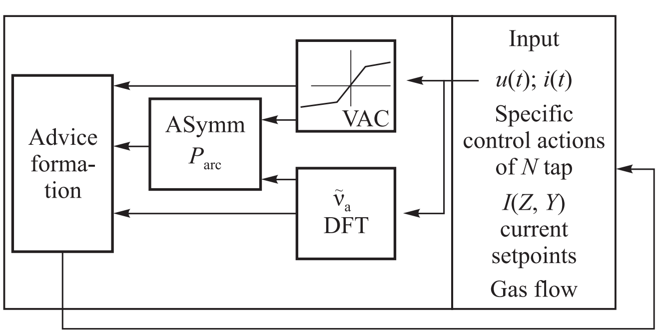

Fig. 4. Simplified block diagram of a digital twin of electrical mode control subsystem in the "Advice to the technologist" function

Рис. 4. Упрощенная блок-схема цифрового двойника подсистемы управления электрическим режимом в функции «Совет технологу»

Regulating the electric mode is an important but not the primary task in managing the steelmaking process. The quality of the produced steel has always been the highest priority among the main production goals. With the continuously decreasing quality of scrap metal, its importance only increases.

The quality of the steel produced in heavy-duty furnaces largely depends on the oxidation period during melting. This period also impacts the energy efficiency of the process, particularly the specific energy consumption (SEC) and the furnace operating time. An under-oxidized alloy increases the phosphorus content in the final product, while excessive oxidation leads to higher consumption of ferroalloys during the ladle furnace treatment stage, extending this stage and increasing both oxygen and specific energy consumption. Therefore, continuous monitoring of the oxidation degree of the metal melt during the refining period is crucial for effective process management.

In practice, the oxidation of the metal is determined episodically (2 – 3 times per melt) using disposable electrochemical probes. Due to the irregularity of measurements and frequent probe failures, this control method can be considered as an estimate and not meeting the needs of operational control. Hence, an alternative method based on measuring an electrical parameter closely related to the oxidation of the metal is required [24; 25].

This parameter is the constant component of the arc voltage (CCAV), which arises in AC circuits due to the difference in thermionic emission currents from electrodes of different chemical compositions [26 – 29]. The thermionic emission current density is described by the Richardson-Dushman equation

$$j = AT^2 \exp\left(-\frac{\varphi_e}{kT}\right), \qquad (2)$$

where A is the emission constant; φ_e is the work function of the electron; k is the Boltzmann constant, and T is the absolute temperature.

As the equation suggests, the difference in emission currents is influenced by two factors: temperature and chemical composition. Since the electrode temperatures are limited by the sublimation of graphite and the evaporation of iron, the chemical factor – the difference in electron work functions – exerts the greatest influence on the current difference, especially since this parameter is in the exponent. Impurities significantly affect the work function. While the chemical composition of graphite does not change during melting, the metal melt always contains impurities whose concentrations vary. Thus, during the oxidation stage, changes in the CCAV will most often be related to changes in the melt composition.

The refining stage of steel melting is organized such that after the melting of the scrap, slag-forming materials and a reductant, in the form of coke or anthracite, are added to the furnace. Coke is used to promote slag foaming. The dissolution of carbon in the liquid metal increases the work function of electrons from the melt, thereby reducing the CCAV. Conversely, saturating the melt with oxygen increases the CCAV.

Thus, continuous monitoring of the CCAV during the oxidation period allows for real-time assessment of the oxidation state of the metal in the furnace bath. In works [30 – 32], the authors comprehensively describe the methodology for determining oxidation based on the CCAV. Here, only a brief description of the algorithm for establishing the relationship between these characteristics is provided, along with the resulting dependence

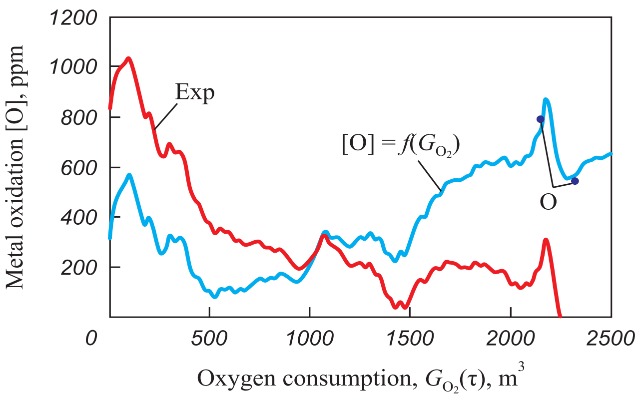

Fig. 5. Dependence of metal oxidation degree on oxygen consumption at refining stage

Рис. 5. Зависимость степени окисления металлического расплава от расхода кислорода на стадии рафинирования

of the metal oxidation degree on oxygen consumption (Fig. 5). Furthermore, it is shown how this can be used in the digital twin technology for the refining stage of steel melting in heavy-duty furnaces.

The foundation of the digital twin mathematical model is a statistical relationship linking the average values of CCAV and metal oxidation. As shown in [31], its graph represents a rather broad cloud of points stretched along an upward linear trend. The correlation coefficient of this relationship is low, not exceeding 0.5. Nevertheless, this approximation is used in the model as a static characteristic, serving as an initial approximation for the desired relationship.

The dependence shown in Fig. 5 initially represented a time series that was smoothed using a moving average filter, reflecting changes in CCAV during the oxidation stage of the process and approximated by an exponential function (Exp). Based on the exponential nature of the alloy decarburization process and the linearity of the oxidation process, we use linear approximations of the final segments to derive the function $[O] = f(G_{O_2})$ from the initial Exp characteristic. By accounting for changes in the oxygen lance parameters, the time axis is transformed into an oxygen consumption axis.

Individual points on the graph represent the oxidation values of the melt obtained using electrochemical sensors. It is evident that these points, while qualitatively mirroring the characteristic jump, lay significantly higher than the initial Exp curve. However, after the transformations, they nearly matched the corrected function $[O] = f(G_{O_2})$. The block diagram of the digital twin for metal oxidation control and oxygen lance regulation is presented in Fig. 6.

The digital twin receives electrical signals from all phases (instantaneous values), the oxygen consumption rate at the burners, time, and the mass of corrective charge

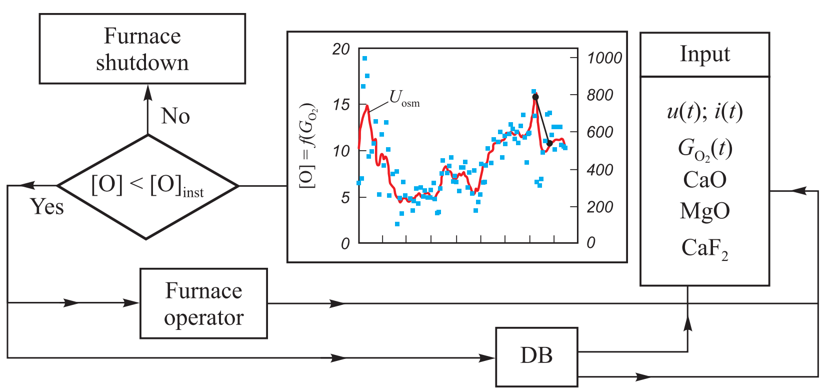

Fig. 6. Simplified block diagram of a digital twin for regulating the oxidative stage parameters: $u(t)$; $i(t)$ – input electrical signals of phase voltages and electrode currents; $G_{O_2}(t)$ – oxygen consumption; CaO, MgO, CaF_2 – magnesia-lime additives; fluorspar; DB – database

Рис. 6. Упрощенная блок-схема цифрового двойника регулирования параметров окислительной стадии процесса: $u(t)$; $i(t)$ – входные электрические сигналы фазных напряжений и токов электродов; $G_{O_2}(t)$ – расход кислорода; CaO, MgO, CaF_2 – магнезиально-известковые добавки, плавиковый шпат; DB – база данных materials. The algorithm determines the oxidation level of the melt, checks if the current value meets the setpoint, and provides advice to the operator, who then decides on the control actions to take. Simultaneously, the information is recorded in a database for further statistical processing to refine the algorithm's adjustable parameters. The parameter settings should be adapted to the specific unit, considering the quality of the raw materials, furnace characteristics, the nature and magnitude of the response to control actions, and possibly the grade of the product being produced.

Conclusions

Effective management of the electric mode requires a broader approach than simply ensuring the reliable operation of the power regulator at set voltage taps and control parameter setpoints. Issues such as phase and arc active power asymmetry, which remain unresolved even with modern regulators, can be effectively addressed using a digital twin of the electric mode control subsystem. This will significantly expand both the range of controllable parameters and the functional capabilities of the control system.

The most rational way to monitor and regulate the oxidation stage of the steel semi-product melting process is by using a digital twin based on the relationship between metal oxidation and the constant component of the arc voltage, as well as analyzing its dependence on oxygen consumption by the gas burners. This approach, combined with the accumulation and systematization of statistical information in a database, will significantly reduce the system's adaptation time to a specific unit.

Digital twin technology is still a new and continuously evolving field in process and equipment management within the metallurgical complex. Its potential for saving material and energy resources and improving the technical and economic indicators of production is vast and particularly valuable as we transition from automated control systems to automatic regulators of technological modes and individual units in steelmaking production.

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