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Fuzzy Model for Predicting the Energy Consumption of Alumina Production

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***Abstract*— There are a number of energy-intensive industrial productions in the world's energy systems. Unstable functioning of such industries leads to load fluctuations in the power system. At the same time, the instability of each specific industrial production may be dictated by market requirements. The article discusses one of the methods of solving this problem. The method is based on the creation of a model for predicting the energy consumption of one of such energy-intensive industries: alumina production, raw materials of electrolytic aluminum production. This production has the properties of non-linearity, inertia and closure. Even a slight change in the operating parameters of this production can lead to very serious changes in its energy consumption. The model is based on the principle of deterministic modeling using fuzzy set theory. As a result, the model can determine the values of material flows in production and its energy consumption under the existing regime. and also calculate the hourly change in production parameters, including energy consumption, with any change in the mode. The article presents graphs of the simulated processes, as well as proof of the effectiveness of the proposed model.**

Keywords—modeling, fuzzy model, alumina production, power consumption, predicting the energy consumption

I. Introduction

There are a number of energy-intensive industrial productions in the world's energy systems. Unstable functioning of such industries leads to load fluctuations in the power system. At the same time, the instability of each specific industrial production may be dictated by market requirements. Various measures are proposed to solve the problem of stabilizing the operation of the power system[1,2,3,4].

One of the methods to solve this problem is to involve consumers in load balancing. The method consists in maintaining penalty rates of payment for exceeding or reducing energy consumption from the level set by the contract for the supply of electricity (capacity). To more accurately determine the volume of energy consumption and the dynamics of its change, it is necessary to develop predictive models [5,6,7,8,9] that are able to take into account the specifics of a particular production. For energy-intensive industries, this issue is very important, since fines can be very significant.

II. Problem Statement

This article discusses the construction of an energy consumption forecasting model for energy-intensive hydrochemical production of alumina (raw material for aluminum production) using the Bayer method. This technology is used by most factories in the world. The average capacity of such a plant is 200 MW. Production has a number of features. It is non-linear, inertial and closed. The characteristic of nonlinearity is explained by the absence of a proportional relationship between the input and output of production stages. Therefore, even a slight change in any technological parameter, for example, the chemical composition of raw materials, can lead to significant changes in material flows. This situation causes a serious change in power consumption. This fact is explained by the fact that in this production more than 90% of the electricity is spent on the movement and transformation of material flows. The technological processes of this production require the maintenance of certain concentrations of reagents in material flows. The structure of alumina production [10,11,12] with its electrical complex is shown in Figure 1.

In this diagram, electric motors are marked with the letter "M". In section P1, the original ore - bauxite containing aluminum oxide Al_2O_3 is ground (synchronous motors) in the presence of a reagent. The main flow of the reagent (caustic soda) comes with the circulating solution (asynchronous motors of pumps), and the additional one to compensate for the loss of the reagent from the ring of sections - with the external flow (asynchronous motors of conveyors) of caustic soda. The obtained bauxite slurry (pulp) at the P2 section is leached (asynchronous stirrer motors) at high temperature with sharp steam and then diluted with recycled industrial water. At section P3 the prepared slurry is separated into a solid part (red slurry) and a liquid part (aluminate solution). The red mud is washed in a series of consecutive washers (asynchronous pump motors) with water (section P4) and sent to a dump (or for additional processing by sintering in another process), and the Al2O3-rich solution goes to further processing (sections P5 - P8) (asynchronous pump motors and conveyors) to realize the reverse process - extraction of aluminum oxide from solution.

The reverse reaction of solution decomposition in the threads of series-connected reactors (section P5) is carried out when the solution is cooled in the presence of a catalyst - small crystals of return Al(OH)3. Section P7 - evaporation of the recycled alkaline solution to the required concentration.

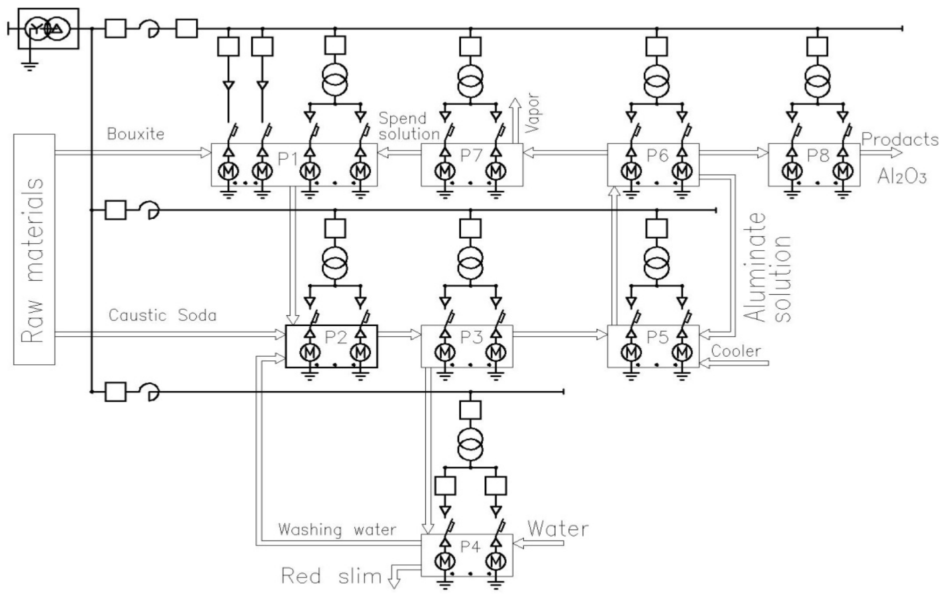

Fig. 1. Block diagram of alumina production with its electrotechnical complex

III. Problem Solution

To solve the problem of forecasting energy consumption by the electrical complex of alumina production, a model was developed that determines the energy consumption by volume of material flows [10,11], depending on the concentration process modes. The structure of the model is presented in Fig.2.

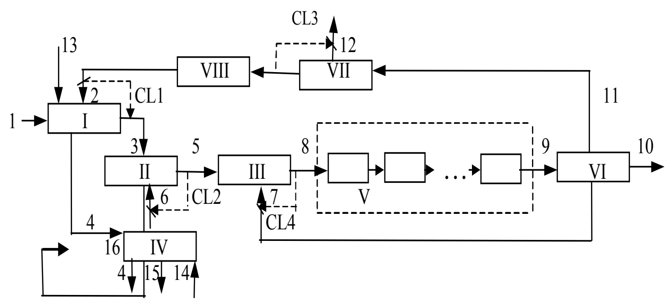

Fig. 2. Principle structure of the model for forecasting energy consumption by hydrochemical production using Bayer's method

In the figure the digitized arrows indicate the input and output material streams (t/hour or m3/hour), where the raw material, stream 1 (bauxite) and 13 - reagent (alkali) are milled (unit I) and mixed with the recycled alkaline solution, the slurry, containing milled bauxite and alkali, is separated under heating (treatment II) into an alkaline solution of Al_2O_3 and 4 - the slurry, which is washed with water (flow 16) to return the alkali to the process cycle, Stream 5 - a stream with dissolved Al2O3 is mixed with the catalyst (Block III), Stream 7 - catalyst (fine crystals of Al2O3), Stream 6 - alkali returned to production, 8 - a solution with high concentration of Al2O3 in reactors (Block V) is separated by cooling into precipitated alumina and alkaline solution - Stream 9, alkaline solution 11, evaporated to the required concentration (Block VII), 10 - finished product, alumina.

The model consists of eight blocks describing the technology of the conversion of the Bayer cycle, in each of which, based on the material balance, the volumes of flows passing through the conversion and the consumption of electricity by engines that convert or move these flows are determined. In real production, there are 4 control circuits that support the necessary concentration mode. The proposed model also has four control circuits. In Figure 2, they are designated CL1, CL2, CL3, CL4.

The energy consumption of this production is determined by the capacities of the engines of pumps, mills, agitators, etc. and is related to the volumes of flows by means of proportional dependencies determined a priori:

$$W = K_e \cdot \sum_{i=1}^{16} K_{ie} \cdot F_i \,, \tag{1}$$

Kie is the specific energy consumption of the Fi-th material flow (kW h / unit of measure F). Ke is a correction factor reflecting the share of unaccounted for electricity costs, defined as a quotient of real electricity consumption and calculated according to the model.

$$\begin{aligned} &\sum_{i=1}^{n} L_{ij} \cdot A_i \cdot G_i \cdot F_i = 0 \quad \sum_{i=1}^{n} H_{ij} \cdot F_i \cdot G_i = 0 \\ &\sum_{i=1}^{n} I_{ij\cdot} \cdot F_i = 0 \qquad \sum_{i=1}^{n} I_{ij}.F_i \cdot D_i = 0 \qquad . \\ &\sum_{i=1}^{n} K_{ij} \cdot B_i \cdot G_i \cdot F_i = 0 \qquad M_i = 1.645 \cdot \frac{B_i}{A_i} \end{aligned} \tag{2}$$

F_i - flows of solutions, D_i densities of solutions, - H_{ij} weight ratio of liquid to solid, A_i and B_i - concentrations of the liquid phase of Al2O3 and $Na_2O_к$, respectively, G_i - concentration of the solid phase of Al_2O_3; I_i, K_i, L_i, H_{ij} -are non-linear functions of the i-th flow, having a positive value if the flow is incoming, and negative if it is outgoing, and equal to 0 if this flow does not pass through the simulated block. The concentrations described above can be easily determined by measurements or calculations. Mathematical model of block 5:

$$\begin{aligned}
&F_{n-1} = F_n + 0.53V_{\text{Dk}}V_{\text{n}}G_n^* \qquad G_n^* = 1 - \frac{G_n}{2.43} \\
&V_{\text{Dk}}\frac{d}{dt}G_n = F_{n-1}G_{n-1} - F_nG_n + 1.53V_{\text{Dk}}V_{\text{n}}G_n^* \\
&V_{\text{Dk}}\frac{d}{dt}G_n^*A_n = F_{n-1}G_{n-1}^*A_{n-1} - F_nG_n^*A_n - V_{\text{Dk}}V_{\text{n}}G_n^* \\
&V_{\text{Dk}}\frac{d}{dt}G_n^*B_n = F_{n-1}G_{n-1}^*B_{n-1} - F_nG_n^*B_n \\
&V_{\text{n}} = -U_{\text{D}}K_{\text{d}}(B_{\text{n}}, T_{\text{n}}, S_{30})\frac{(A_{\text{n}} - A_{\text{E}}(B_{\text{n}}, T_{\text{n}}))^2}{A_{\text{E}}(B_{\text{n}}, T_{\text{n}})^2}
\end{aligned} \tag{3}$$

In dependencies (3) Fn is the volume of material flow of hydrate slurry at the outlet of the n-th apparatus, V_{Dk} is the volume of the apparatus, Gn is the content of the solid phase Al_2O_3, An is the content of the liquid phase, Bn is the content in the liquid phase Na2Ok, Vn – is the rate of solution decomposition in the apparatus, Кd is a factor that determines the reaction rate at the current temperature Tn, alkali concentration Bn and catalyst surface area S_{30} in the n-th decomposition apparatus. The value of Кd is calculated using fuzzy logic theory. The procedure for obtaining it is described below. A_E is the equilibrium concentration of Al_2O_3, a nonlinear function of Bn and Tn. Ud is the identification coefficient of the model as a whole.

In alumina production, the largest retention capacity has the buffer capacity of the circulating solution (material flow 8), so it was modeled as a generalized.

$$\frac{dV_8(t)}{dt} = F_{11}(t) - F_2(t). \tag{4}$$

The value of Kd is described by a very complex dependence on temperature, reagent concentration and amount of catalyst. The computational task is complicated by the fact that it is impossible to determine the exact values of these parameters in reactors where substances are transformed. To solve this problem, which has many indeterminate values, this velocity Kd was represented by a fuzzy quantity and calculated using the theory of fuzzy sets [13,14,15] (Fig. 3).

At the first stage of the solution, the membership functions for each of the parameters were determined in the form of a triangular function. The form of the functions is explained by the ease of application for describing real processes in the reactor. The second stage is finding the degree of truth for each parameter at specific current values of T_d, B_8 и S. These functions were determined using expert assessments as the effect of each parameter on the speed Kd. The verification was carried out by calculating the values of the existing complex dependence at the same values. At the third stage, all fuzzy subsets of each variable were combined into one fuzzy subset. The fourth stage was the calculation of the Kd value based on the Mamdani rule using the expression:

$$K_d = \frac{\int_{K_d} K_d \mu_\Sigma(K_d)dK_d}{\int_{K_d} \mu_\Sigma(K_d)dK_d} \tag{5}$$

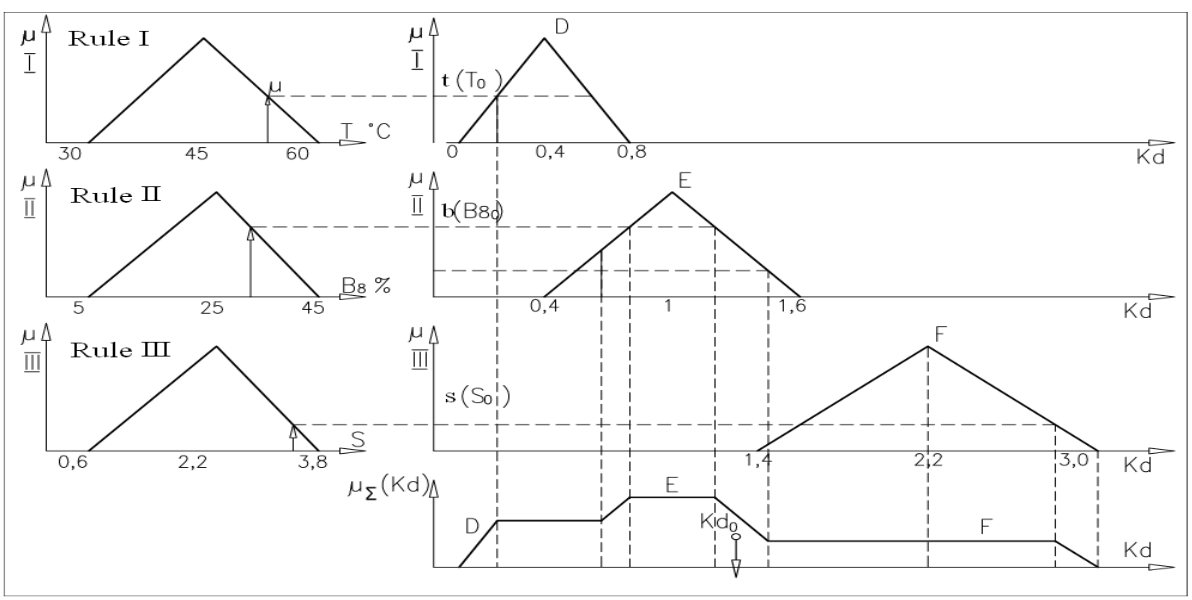

Fig. 3. Illustration for solving the problem of determining Kd, the coefficient of the rate of decomposition of the solution, based on the use of fuzzy logic theory

After identifying the model for the real process, the discrepancy between the simulation results and real values did not exceed 3%.

Then, experiments were carried out on the model, which made it possible to determine its dynamic characteristics, two of which are shown in Fig. 4.

IV. Practical Relevance. Results

The analysis of the obtained dynamic characteristics made it possible to draw the following conclusions: a) in general, the results obtained correspond to the data obtained experimentally, b) the average duration of the transient process in the ring is 5 days. In reality, such sharp jumps in parameters are not observed, but the model gives an idea of the dynamics of changes in parameters in such a difficult-to-predict production as alumina.

Forecasting the volume of electricity consumption (capacity) is necessary when drawing up contracts for the purchase of electricity. In addition to the total volume of electricity consumption for energy-intensive enterprises, the contract may contain a requirement for hourly detail. This requirement is well illustrated in Figure 4: when switching to other technological modes of production, there is a significant change in energy consumption, and a change in the technological mode can occur, for example, when changing suppliers of raw materials or changing the volume of output of the main product.

For the energy system of the Union Independents States countries, consumers of the retail market with a connected capacity of more than 750 kVA (which include the production in question) with interval or integral accounting in the event of deviations in the actually supplied volume of electric energy from the contractual one for each hour of the month, the supply pays in addition to the cost of planned consumption and the cost of the indicated deviations calculated by the formula:

$$S_{\text{deviation}} = \sum_{i}^{m} S_i^{\text{deviation}}, \qquad (6)$$

$S_i^{\text{deviation}}$ here - the cost of deviations of the actual volume of electricity consumption from that specified in the contract per hour i, m - the number of hours of the billing period, calculated by formula (7):

$$S_i^{\text{deviation}} = \begin{cases} V_i^{\text{real}} \times I_i \times (k_{\text{hight}} - 1), \text{if } \dfrac{V_i^{\text{real}} - V_i}{V_i} > 0.02 \\ V_i^{\text{real}} \times I_i \times (1 - k_{\text{low}}), \text{if } \dfrac{V_i - V_i^{\text{real}}}{V_i} > 0.02 \\ 0, \text{if } \left| \dfrac{V_i - V_i^{\text{real}}}{V_i} \right| \le 0.02 \end{cases}, \qquad (7)$$

where Vi- is the contractual volume of electricity consumption, V_i^{real} is the actual volume, I_i - is the cost in terms of planned consumption. The value of the coefficients k_{hight} and k_{low} are determined by the contract for the supply of electricity.

Figure 5 shows the curves of planned and actual energy consumption, when changing the M3 parameter, and curves reflecting the price of energy consumption with and without a pre-presented hourly schedule.

Analysis of the graphs gives an idea of the significant economic effect of using the energy consumption forecasting model when drawing up contracts for the supply of electrical energy for energy-intensive alumina production.

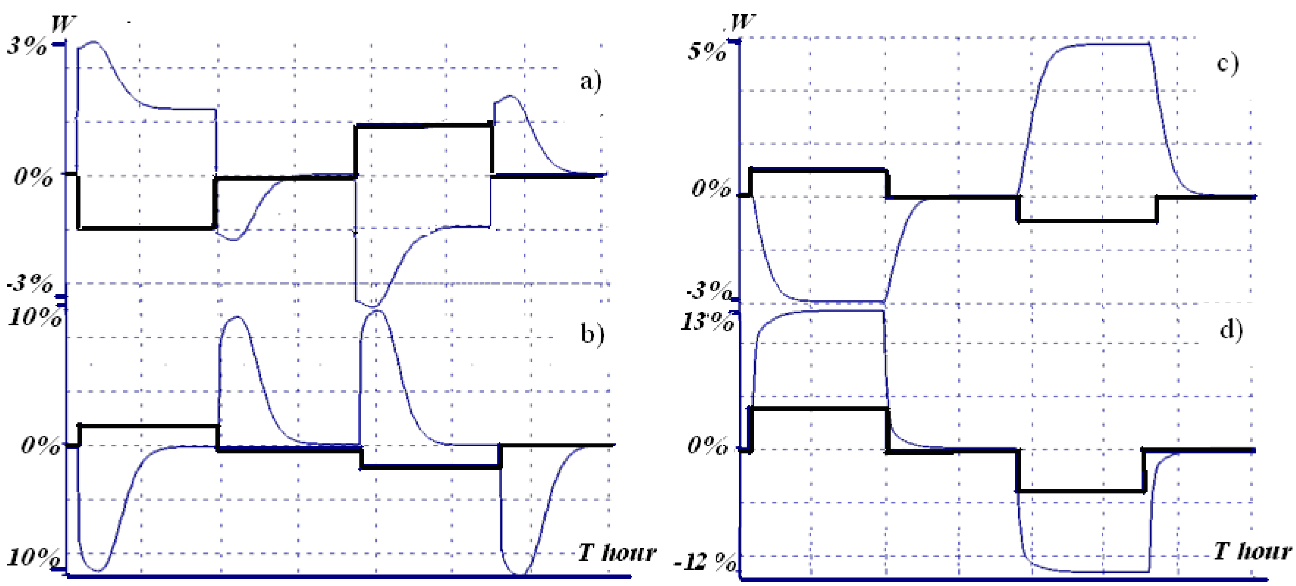

Fig. 4. The reaction of power consumption change W of alumina production at sudden change of technical parameters (the black chart) regarding the nominal values: content of seed hydrate (a), B_5(b), area of seed hydrate(c), M_3(d). Division value of the x-axis is 54 hours

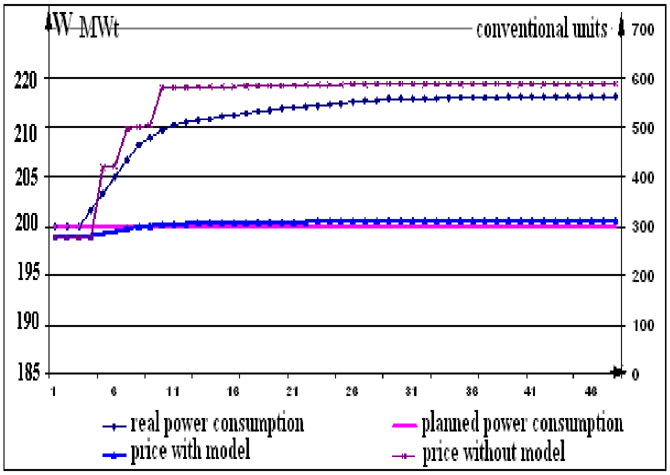

Fig. 5. Energy consumption and its cost in case of deviation from the contractual volume when changing the production parameter M_3 (aluminate module) by + 5% without using the hourly forecasting model ( ) and using this model ( )

Conclusion

1. Methods of fuzzy logic simplify the solution of problems of modeling real technological processes. They allow you to solve problems with fuzzy or uncertain data.

2. The proposed predictive model will make it possible to calculate in advance the amount of energy consumption of alumina production during the transition to other technological modes and the dynamics of changes in energy consumption by this production.

3. Application of the proposed model will make it possible to timely present graphs of hourly electricity consumption by this energy-intensive production and thus reduce the payment for its consumption.

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