2016 13TH INTERNATIONAL SCIENTIFIC-TECHNICAL CONFERENCE ON ACTUAL PROBLEMS OF ELECTRONIC INSTRUMENT ENGINEERING (APEIE) – 39281 PROCEEDINGS

APEIE – 2016

In 12 Volumes

Volume 1

Part 2

Novosibirsk, October 3-6, 2016

ТРУДЫ XIII МЕЖДУНАРОДНОЙ НАУЧНО-ТЕХНИЧЕСКОЙ КОНФЕРЕНЦИИ АКТУАЛЬНЫЕ ПРОБЛЕМЫ ЭЛЕКТРОННОГО ПРИБОРОСТРОЕНИЯ

АПЭП – 2016

В 12 томах

Том 1

Часть 2

Новосибирск, 3-6 октября, 2016

2016 13TH INTERNATIONAL SCIENTIFIC-TECHNICAL CONFERENCE ON ACTUAL PROBLEMS OF ELECTRONIC INSTRUMENT ENGINEERING (APEIE) PROCEEDINGS

IEEE Catalog Number: CFP16471-PRT

ISBN: 978-5-7782-2991-4
978-5-7782-2992-5 (т. 1)

ISBN: 978-1-5090-4068-1

Information about proceedings placed in http://apeie.conf.nstu.ru/apeie2016/

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Solution of the Problem of Searching for an Energy-efficient Functioning Mode of a Continuous Production Using Simulation and Artificial Intelligence Methods

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Abstract. **The article examines the problem of searching for an energy-efficient functioning mode for a power-consuming continuous production characterized by nonlinearity, inertness and closed-circuit operation. It suggests a method to construct a multi-criterion target function on the basis of technological production process simulation. A genetic algorithm was used to solve an optimization problem, which made it possible to receive values of controlling technological production parameters that ensured decrease in energy consumption.**

Keywords — **energy efficiency, modeling, genetic algorithm. alumina production, energy saving technological decisions**

I. Introduction

MODERN economic conditions demand that industrial enterprises improve their energy efficiency[1,2,3]. This task is particularly important for energy-intensive enterprises with continuous inertial process production, such as enterprises in nonferrous metallurgy and chemical industry. A complex of measures helping to achieve this goal includes searching for a strategy to control production technology and minimize its energy consumption.

Solution of this optimization problem requires development of a multi-criterion target function which should be based on simulation[4,5,6] of basic technological processes of the production in question. It is obvious that such function cannot have analytical expression, and, consequently, is it impossible to define its properties. This circumstance makes it diffi apply classical optimization methods, because most of t based on applying a priori information to the behavior pa the target function.

Therefore, solution of such optimization problem sh made on the basis of one of artificial intelligence me genetic algorithm[7,8,9], and to obtain values of techn production parameters ensuring improvement of its efficiency.

II. Simulation

Solution of this problem was made on the exar hydrochemical production of technical aluminum oxide a raw material for electrolytic aluminum production. resources used in the production are electric energy and s

In order to solve the optimization problem we deve model describing this technological production process input parameters. The model is built on the basis of balance equations imitating basic technological transfor in production[10,11]. Fig. 1 shows the structure of the m alumina production using the Bayer method, applied majority of alumina plants in the world.

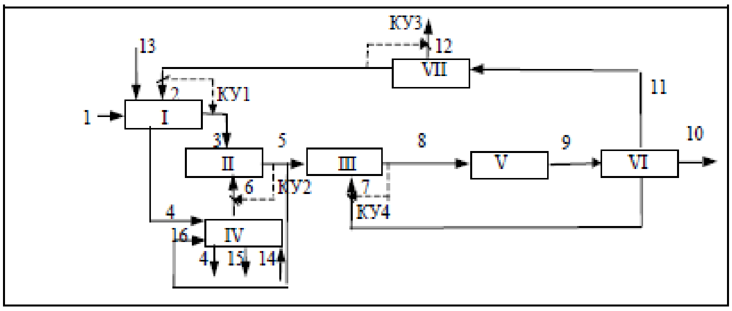

Fig. 1. The structure of the suggested model of aluminous production using the Bayer method.

The model consists of seven blocks describing the Bayer process (fig. 1). Block I – bauxite leaching, block II – bauxite pulp dilution with alkaline water from sludge washing, III block – pulp mixing with seed alumina, block IV – sludge washing for alkali extraction, block V – pulp decomposition and obtaining alumina, block VI – separation into alkaline solution, production and seed hydrate, VII – evaporation of circulating alkaline solution with steam to the required concentration.

The diagram shows that the process being modeled has four control circuits (KU1-KU4), existing in the production. Those control circuits help to support the concentration mode of the process units. Input and output material flows of seven blocks-production units are shown on the scheme with numbered arrows.

Energy consumption in this production accounts for transformation and movement of material flows. It is connected to volumes of those flows by proportional dependences determined a priori and is calculated by the formula:

$$W = K_e \cdot \sum_{i=1}^{16} K_{ie} \cdot F_i . \qquad (1)$$

Here Kie is specific costs of electric energy of the i-th material flow in the production (kWh/unit.F), Ke is a correction factor reflecting the share of unaccounted costs of electric energy.

Consumption of steam used for evaporation of the circulating solution with a reagent in block VII is determined by the amount of material flow F_{12} ($m^3 \cdot hour$).

The simulation of j-th of blocks–process units (j=I, II..., VII) is based on nonlinear algebraic material balance equations written down for all i-th flows (i=1,2... 16), passing through the modeled block:

$$\sum_{i=1}^{n} L_{ij} \cdot A_i \cdot G_i \cdot F_i = 0 \quad \sum_{i=1}^{n} H_{ij} \cdot F_i \cdot G_i = 0 \quad \sum_{i=1}^{n} K_{ij} \cdot B_i \cdot G_i \cdot F_i = 0$$

$$\sum_{i=1}^{n} I_{ij} \cdot F_i = 0 \quad \sum_{i=1}^{n} I_{ij} F_i \cdot D_i = 0 \quad M_i = 1.645 \cdot \frac{B_i}{A_i}$$

where F_i are flows of solutions, D_i is density of solutions, H_{ij} is a weight ratio between liquid and solid, A_i and B_i are concentrations of a liquid phase of Al_2O_3 and Na_2O_k respectively, G_i is a concentration of the solid phase of Al_2O_3; I_i, K_i, L_i, H_{ij} are nonlinear functions of the i-th, having a positive value for the input flow, negative one for the output flow and value equal to 0 if the flow does not pass through the modeled block.

Simulation of block IV is carried out using the Montvid formula: $C_n = \frac{R_n \cdot C_B - 1}{(R_n \cdot C_B)^{N_n+1} - 1}$, where $C_B = \frac{F_{14} \cdot D_5}{F_4 \cdot H_{sn}}$, where H_{Sl}, R_n are technological parameters, N_n is a number of sludge washing steps.

Simulation of block V (aluminum oxide transition from the solution into a solid phase) is based on a kinetic equation of the 2nd order: $\frac{dA}{dl} = -R_d \cdot K_d \cdot (A - A_p)^2$, where A is the aluminum oxide concentration in the solution, A_p is its equilibrium concentration, l is duration of the decomposition process, K_d is its speed.

K_d value is described by a complex dependence on temperature, reagent concentration and other parameters, this is why its value in this work was determined using a theory of fuzzy sets.

The present model has significant nonlinearity, and due to the interconnection between the parameters of the production in question, all equations of the model, including differential ones, should be solved in a single iteration cycle. As the result we performed analytical transformation of the systems of nonlinear equations into a form enabling convergence of the iteration process in three variants depending on the desired values of the variable found in the iteration process. We developed an algorithm according to which search for the solution was performed using one of three variants ensuring convergence.

III. CONSTRUCTION OF THE TARGET FUNCTION

The following criteria were specified for the solution of this optimization problem: minimization of energy consumption and steam consumption without increasing cost price of the finished goods. The following study was made to develop the multi-criterion target function.

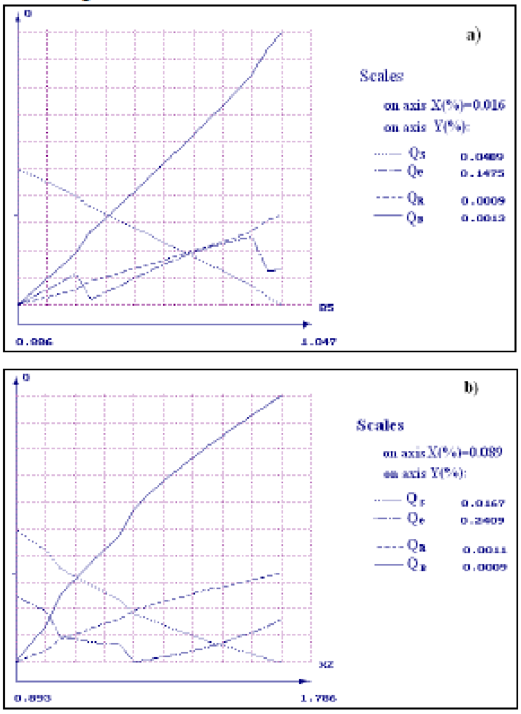

Fig. 2. Change of specific consumption of electric power (Qe), steam (Qs), and raw material (QB, QR) from the controlled parameters a) B5 in the range 0.11…0.13 and b) XZ in the range 1 …2

Using a static model we plotted the functions of electric energy (Qe), steam (Qs) and raw material (QB, QR) consumption per ton of the finished goods from the controlled parameters X={B2,B5,XZ,M3}. Graphical representation of the dependences for these two parameters is given in figure 2.

Analysis of the obtained dependences allowed us to make the following conclusions: all dependences are nonlinear, the global minimum is observed for parameters B5 and XZ in their variation range, but there are also local minima (fig. 2a, 2b), cost reduction for one parameter could lead to increase in the consumption of other parameters.

Therefore, it was decided to include in the criterion the costs of all kinds of consumption to make it possible to find a strategy to choose between conflicting tendencies. The following target function was developed as a result:

$$S = C \cdot Q(X) / F_{10} \to \min, \qquad (2)$$

where

$Q(X) = (K_1 \cdot W(X),\ K_2 \cdot Q_S(X),\ K_3 \cdot F_1(X),\ K_4 \cdot F_{13}(X))$,

W is energy consumption calculated by formula (1),

Q_S is steam consumption, $Q_S = K_S F_{12}$ (K_S – coefficient of steam consumption per $1 m^3$ of evaporated water (MJ/m^3),

F_1 and F_{13} are raw material consumption with values of operating parameters determined by vector X,

F_{10} is output of the finished goods,

C are prices for electric power, steam and raw materials respectively, CL1 — CL4 are coefficients determining the share of unaccounted costs.

Thus, we obtained a criterion described by one analytical expression and taking into account the required consumption and prices for energy and raw materials. Therefore it could be used as unified criterion in this multi-criterion problem.

IV. SOLUTION OF THE OPTIMIZATION PROBLEM

It is obvious that for this 4-parameter optimization problem it is impossible to provide an analytical description of the target function and to determine its properties, because Q(X) is determined using a model of the whole production with operational parameters value X. This circumstance complicates application of classical optimization methods because most of them are based on use of a priori information on the target function behavior pattern.

Recently such problems started being solved using artificial intelligence methods based on the mechanism of evolutionary development of the Nature, or so-called evolutionary search methods. From the point of view of information transformation evolutionary search is a consecutive transformation of one finite fuzzy set of intermediate solutions into another. In this statement differentiability, continuity and other conditions imposed on the target function in classical mathematical methods are not an obligatory property for the class of problems in question.

One of artificial intelligence methods – a classical genetic algorithm[7,8,9] was chosen for the solution of this optimization problem. This classical genetic algorithm looks as follows:

1. Initial population is created.
2. Fitness of each individual in the population is evaluated.
3. Individuals with high fitness are selected for cross-breeding.
4. Cross-breeding of the chosen individuals and obtaining descendants.
5. Mutation.
6. Formation of a new generation.
7. Check - if the population did not converge, than transition to point 2, otherwise the end of searching.

Since a genetic algorithm does not work with the parameters of our problem, but with a coded set of parameters, originally in its application we need to solve the problem of coding all parameters of the optimization problem, that is mapping of the solution domain onto a genetic code.

Coding of the initial population elements for this was performed in a binary code for the whole domain of acceptable values for 4 controlling parameters. Each parameter was coded by 5 binary symbols with values from 00000 to 11111. This code reflected the values of technological parameters constituting the domain of their acceptable values. So, for example, coding of the value of B5 parameter was performed in the range from 0.111 to 0.1265 with a step of 0.0005, and the value of M3 was coded in the range from 1.60 to 1.755 with a step of 0.005.

4 initial populations of "parental" chromosomes were created using random selection ("shotgun") from the whole solution domain for the problem in question. Left most column of markers in the form of small squares for parameter B5 in Fig. 3 and triangles for M3 parameter shows our random selection of initial populations on the solutions domain 0.111…0.1265 and 1.6…1.755 respectively.

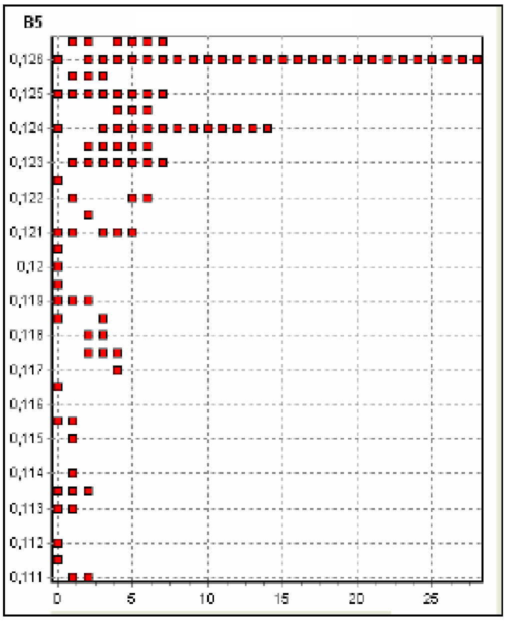

Fig. 3. Graphical representation of chromosome generations during the problem solution provided that the genetic algorithm is completed by restricting the number of generations (it is equal to 28).

The next step of the genetic algorithm is evaluation of each chromosome of the population by the fitness function. The higher is the value of this function for the selected individual, the higher is its quality. The fitness function depends on the problem being solved; this is why it was developed on the basis of criterion (2). We also took into account basic requirements to the fitness function: it has to have non-negative values and to tend to a maximum. Moreover, as it was found during adjustment of the genetic algorithm for the solution of the given optimization problem, the fitness function for neighboring chromosomes (ch – is a symbol of a chromosome) has to take values that are considerably different from each other to ensure correct selection of the chromosomes forming the optimal solution of our problem.

As a result the fitness function for the optimization problem being solved got the following form:

$$G(ch) = MAX(S) - \mathbf{C} \cdot \mathbf{Q}(\mathbf{X}) / F_{10} \rightarrow \max \quad (3)$$

where MAX (S) is the greatest possible value of expression (2) for this problem

Probability $P_s(ch_i)$ equal to the relation of its fitness function to the total fitness of the whole population was calculated to form parental chromosomes for each individual of the population:

$$P_s(ch_i) = \frac{G(ch_i)}{\sum_{i=1}^{N} G(ch_i)} \quad (4)$$

Then N chromosomes were selected (with replacement) into a so-called parental pool for further genetic processing according to the value of Ps (chi) on the basis of the simplest proportional selection – "roulette".

An operator called "cross-breeding" (crossover) in genetic algorithms is responsible for the transfer of parental properties to the descendants. In the solution of the given optimization problem each pair of parents had a single-point crossover, and crossover points were determined randomly. A couple of descendants was formed as a result. The crossing operation was carried out for the whole population of each generation, and the mutation operation was carried out with the probability of 0.01. In a chromosome subject to mutation one of randomly chosen bits was changed to the opposite one.

A program was developed and debugged for realization of this algorithm. The result of the solution by 2 parameters is shown in Fig. 3. It is clear from the figure that from population to population individuals closest to the optimal solution survive from the originally selected population of individuals-solutions: B5=0.126, M3=1.61.

After completion of the search process using a genetic algorithm the average value of the fitness function of chromosome population grew from 341.17 to 546.17, and values of technological parameters became B5=0.126, M3=1.61, Z=1.1 B2=0.18. The obtained values of technological parameters make it possible to reduce electric energy consumption by 10 % and steam consumption by 14 % in comparison with the mode when the controlled parameters were kept at a level of their average acceptable value.

V. CONCLUSIONS.

Analysis of the results of the solution of the optimization problem showed, that a genetic algorithm helped to find values of technological parameters allowing to reduce energy consumption for production of 1ton of the finished goods without increasing its cost price.

Solution of the optimization problem using classical methods of gradient descent and random search strongly depends on initial approximation and does not always bring the expected results because of the absence of functional dependence between output and input parameters.

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