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NEURAL NETWORK MODEL OF THE MECHATRON COMPLEX "CRUSHER MILL"

Abstract: *The paper discusses the use of the technology of artificial neural networks to improve technical and economic performance of crushing and milling complex. Formulated the goal and major tasks of constructing a system of automated control and monitoring to optimize the power consumption of crushing and milling complex is analyzed modes of complex mechatronic and development of multicriteria models to provide optimal technological parameters of the equipment.*

Keywords: *crushing and grinding complex, modelling, neural network*

Introduction

The technology of crushing and grinding rocks is one of the most energy intensive technologies. Effective management of crushing and grinding is possible with the most complete mathematical model of the situation. Studies show that the work of crushing and grinding complex is determined by dozens of factors, many of which are random. Each combination corresponds to a specific techno-power mode of operation. The more fully taken into account in the operational management factors and system properties that affect the characteristics of the mode, the more effective it management and lower the energy consumption of the processes of crushing and grinding. The increase in the number of considered factors complicates the model, so it is necessary to form the control action, finding a compromise solution that takes into account the degree of informativeness of the factor field and its complexity. It is necessary to solve a number of tasks such as: analysis of operation modes of the equipment of grinding to determine the parameters, which correspond to different operation modes; development of a multicriterial model of optimal technological parameters of equipment of the crushing and grinding complex subject of power consumption, productivity and quality of grinding; development of the model of crushing and grinding complex, which could provide optimal power consumption management of crushing and grinding complex.

Literature review

The simulation of crushing and grinding complex is used to optimize its energy consumption. This particular task contains a number of subtasks such as: description of kinematics and dynamics of internal processes, the establishment of energy intensive of processes of destruction of rocks, the construction of control systems for crushing and grinding complex. The analysis of works in the field of simulation of the grinding aggregates and management highlights the following researchers [1].

The most famous equation that establishes a relationship between the energy expended and the fineness of the product resulting from grinding are equations of Rittinger, Kick-Kirpichev, Bond. Comparison of the curves constructed according to the laws of Rittinger, Kick-Kirpichev, Bond, showed that the law of Rittinger can be applied in the case of high specific power consumption regardless of the size of the grains, the law of the bond – in a significant range of intermediate values of the specific energy consumption, the law Kick-Kirpichev – at low specific power consumption. Based on the works of Andreev, Davis, Perov, Tovarov, Olevskii, Kantorovich established that the greatest power consumption characterizes, however, and most work of grinding. Knowing the useful power consumed by the mill and taking into account losses occur in all elements of the system can provide a complete energy picture of the mill as a control object, thereby providing the possibility of its rational exploitation, in terms of energy consumption.

Automatic control of operation of the mills, the variables determining them, the construction of control systems for crushing aggregates considered in the works of Nazarenko V.M., Uteus Z.V., Uteus E.V., Gelfand J.E. and Ginzburg I.B.

The use of modern CAE-systems for optimizing of parameters of mechatronic systems and complexes, investigated the Pivnyak G.G., Samus V.I., Kirichenko O.E., Kirichenko V.E. [2-4].

Purpose and research objectives

The purpose of this work is to develop a model of a crushing and grinding complex. To achieve this goal, the following tasks are solved in the work: analysis of factors and parameters that determine the processes of crushing and grinding in grinding units, selection of the structure and parameters of a neural network corresponding to a multifactorial task, determination and description of the factors most affecting power consumption.

Object of research: neuron model of the crushing and grinding complex.

Subject of research: power consumption of the crushing and grinding complex.

Material and research results

Technological processes are the basis of many industries and virtually all industries. This process involves primary environment and additionally enter components used physico-chemical, mechanical or hydro-mechanical effects, which are inside of the workspaces of the devices to obtain the final products. Technological processes in grinding equipment belong to the group of mechanical processes that determines the regularities of the processes that are common to the group. Crushing and grinding stands out as a separate subgroup, which characterizes the specifics of the processes and their characteristics.

The technology of crushing and grinding is one of the largest and most energy intensive, therefore costly operations. In concentrating factories and production of building materials, crushing and grinding operations account for up to 50-70% of the total capital expenditure and the same share of total operating costs. The ways to solve the problem of optimal energy consumption of crushing grinding complexes can be further improvement of the grinding and crushing, the use of the most efficient and economical methods of grinding, the simplification of the scheme of layout of crushing plants.

One of the ways to ensure rational operating modes of technological mechanisms of crushing and sorting factories is the use of adaptive control systems, which relate to robotic systems, the element base of which is microprocessor technology. To operate the process control system, the technological process requires mathematical support, which adequately describes the technological processes and the operation of certain types of equipment participating in them. In choosing the mathematical description of technological processes, it is necessary to take into account the regular connections that are repeated in time, and random ones, caused by the variability of process parameters.

The task of constructing an automated control system for simplification can be divided into a number of sub-tasks such as:

1. The definition of the factor of the field system and the allocation of the main factors.
2. Establishment of regularities of changing factors.
3. Identify the relationships between dependent variables.
4. Identification of the current state of the object (nominal, pre-emergency, emergency, ineffective mode).
5. Prediction of the state of the managed object based on its current state.
6. Formation of the control action depending on the available data on the system and their projected values.

As an example, the technological process of production of silicate bricks in the construction industry enterprises is considered, which is a sequence of the following operations:

- delivery of raw materials for making bricks (lime and sand);
- lime burning;
- transportation of burned lime with a conveyor belt to the feed hopper of the crusher;
- crushing of lime in hammer crushers up to size 1 mm;
- transportation of the crushed product by pneumatic transport to the mill feed hopper;
- grinding in the ball mill of cooked lime and sand (binder preparation);
- transportation of ready-made binder by pneumatic transport to a molding shop for manufacturing bricks from prepared raw materials;
- warehousing of finished products.

At each stage of the technology, the physical state of the substance changes at a certain energy expenditure. Changes in the physical state can be both positive (necessary for technology changes, such as reducing the size of the material, giving the necessary properties of lime by burning it, forming the finished product) and negative (re-grinding of the substance, undesirable change in humidity, loss during transport). Regardless of whether a technologically useful or harmful effect occurs, the amount of energy consumed during the transition from one stage to another is constantly increasing, therefore, in order to ensure rational energy-efficient management of the complex, it is necessary to take into account how energy-intensive each stage of production is and how much this energy expenditure is justified. At the same time, for each stage it is necessary to identify the factors determining its energy consumption and those indicators by which its energy state can be estimated.

From the given technological chain of greatest interest are the factor fields of the crusher and mill, as the key objects of the complex.

Research carried out at concentrating plants and enterprises for the production of building materials have made it possible to identify a number of factors that have the most significant effect on the nature of the power consumed. These factors include the magnitude of the ball load, the mill speed and the productivity of the grinding unit. The mode of operation of the mill and the amount of power consumption depend not only on the factors listed, but also on the magnitude of the frictional force between the inner surface of the drum (lining and ball loading) and the type of lining. For the electric drive of such a mill, it is characteristic that the power consumption depends little on the productivity, that is, the specific costs of producing the binder are significantly reduced with increasing productivity.

In the practice of grinding a substance has the following properties density, strength, abrasiveness, moisture content, flowability, lumpiness, specific surface area of mineral raw materials crushability and grindability.

The researches have shown, that the specific expenses of the electric power on binder production essentially change depending on the above mentioned factors (up to 30%). The change in the fineness of the grinding occurs intensively at the beginning of the mill, at a time when there are practically no changes at the last meters, which indicates an inefficient grinding of the material.

In addition to the physical properties of matter, there are a number of technological variables that determine the operation of grinding aggregates. These include fineness of grinding; number of grinding media; the size of grinding bodies; the presence of inter-chamber partitions; state of armor; intensity of aspiration; resistance of the material to grinding; introduction of an intensifier of the grinding process. The factorial field of the ball mill can be represented by the Ishikawa diagram (Fig. 1) [5].

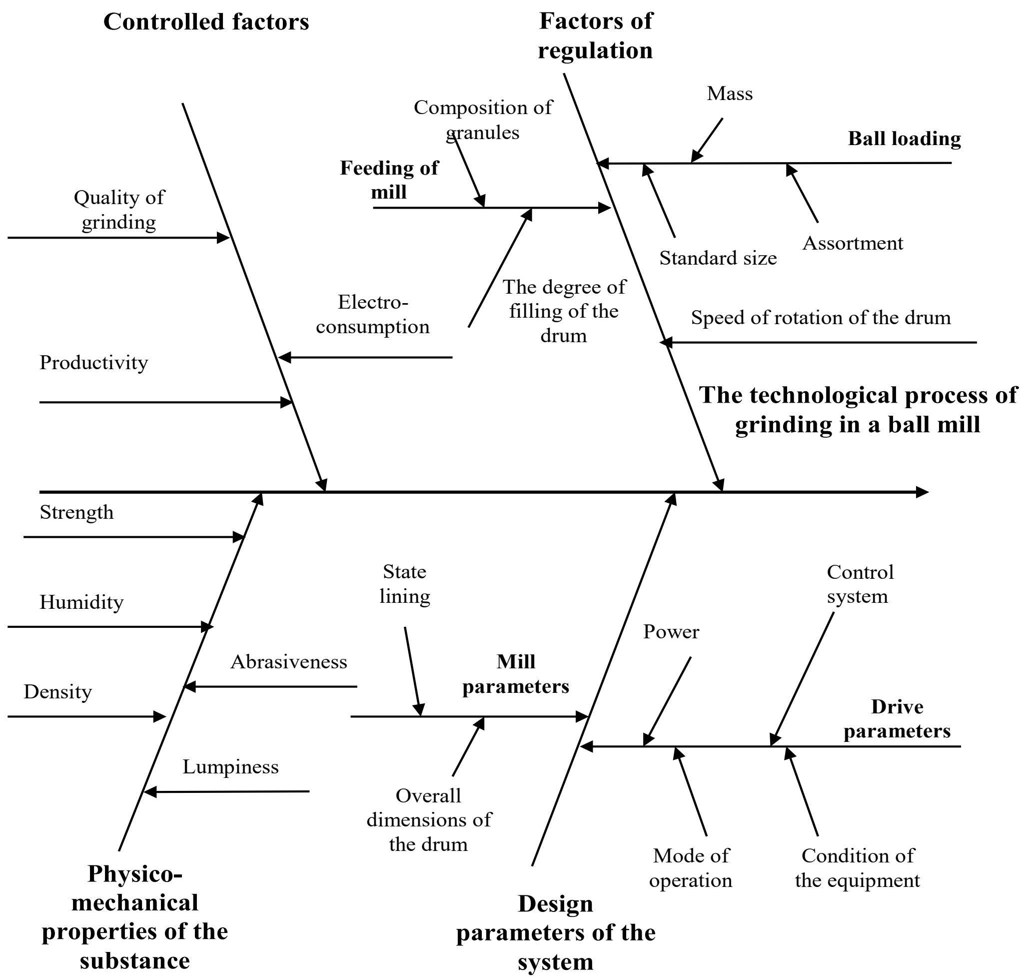

***FIGURE 1.** Factor field of a ball mill*

The main positions in the diagram are assigned to four groups of factors that determine the technological process (Table1). The breakdown and sorting of factors within each group makes it easier to assess the impact of a factor.

***TABLE 1.** The main groups of the factor field of crushing and grinding equipment*

Output Vector	Vector of input measurable control variables	Vector of input measured uncontrolled variables	Vector of input non-measurable variables
Electroconsumption (W), productivity (Q), quality of grinding (T)	Ball and raw materials, rotational speed (n) of the working body	Physical and mechanical properties of incoming raw materials	Condition and operating conditions of equipment (lining, balls, drive)

Based on the above data, it is possible to construct a neural network to control the crushing and grinding complex. The controlled parameters act as the output vector, and the corresponding values of the regulated quantities, the parameters of the equipment and the crushed material are the input vector.

In the generalized model, the selected factors will be used as inputs, and as output values, the process parameters or those control actions that will regulate them. A similar network is shown in Figure 2.

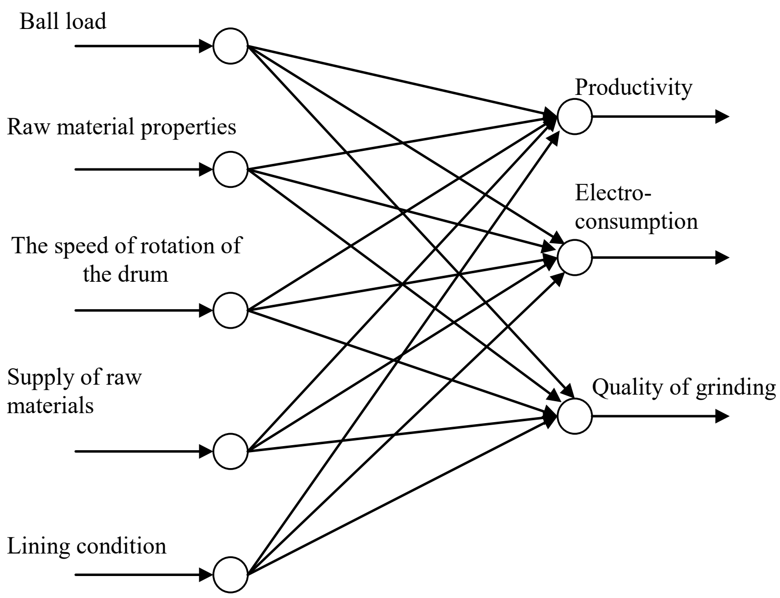

FIGURE 2. *The grinding control model*

The mathematical model describes a real object with some approximation. The degree of correspondence of the description to the real process is determined, first of all, by the completeness of the calculation of disturbing influences. In the absence or insignificance of disturbances, it is possible to unambiguously determine the influence of the input and control parameters on the output.

An objective model of the grinding object can be created under the condition of good awareness of the properties of the object under study, the main groups of which are represented in the factor field. According to the degree of completeness of information about real objects and processes occurring within them, we can distinguish:

- objects with a zero level of information; in this case the object is represented as a "black box", its mathematical model is constructed by statistical tests of a real object on the basis of regression, dispersion and correlation analysis and factorial design of the experiment;
- objects whose behavior has empirical information; when creating models of such objects, physical modeling methods are used; a complete closed model is obtained by methods of experiment planning;
- objects with known basic deterministic regularities; their models are formulated by methods of mathematical modeling; deterministic dependencies are partially complemented by empirical relationships, the values of constants are established from experience.

The objects of the crushing and grinding complex belong to the first group.

The power consumed by the mill depends on its load and the speed of rotation, so the mill's power consumption model can be represented in the form of two interacting components: the speed n and intra-milling filling (IF). The speed component is unambiguous, not below a certain value at which grinding is generally possible and is easily controlled by means of an adjustable drive. On the other hand, intramural filling is a function of many variables. First of all, this value is determined by the set productivity and quality, then it must take into account as much as possible the number of perturbations and, in addition, be a function of time – to perform the functions of the predictor (PR) – to determine the influence of the previous values of the factors on their current values. Such a notion of intramelic filling will allow to take into account the multifactority of the object and eliminate the influence of its inertia.

Separately, it should be noted systems consisting of several working together crushers or mills. In a sense, they are a model of a single multi-chamber mill (in operation in series), which makes it possible to optimize their operating mode not only by regulating the rotational speed, but also by regulating the stage of grinding.

The considered model of the mill as a component element is included in the multi-stage grinding scheme: successive operation of two objects. In this case, we have a system of two power consuming objects and the task will be to select a combination of speeds that ensure minimum power consumption. In this case, the first mill will perform for the second function of the feeder, but in addition to the productivity there will be the possibility of regulating the fineness of grinding and there is an additional condition: selection of the degree of grinding by the first mill for optimal system operation (Fig. 3). That is, if in the case of single work speed was a regulating parameter, and productivity and quality of grinding are internally calculated, then when working together, all three variables for the first mill become adjustable.

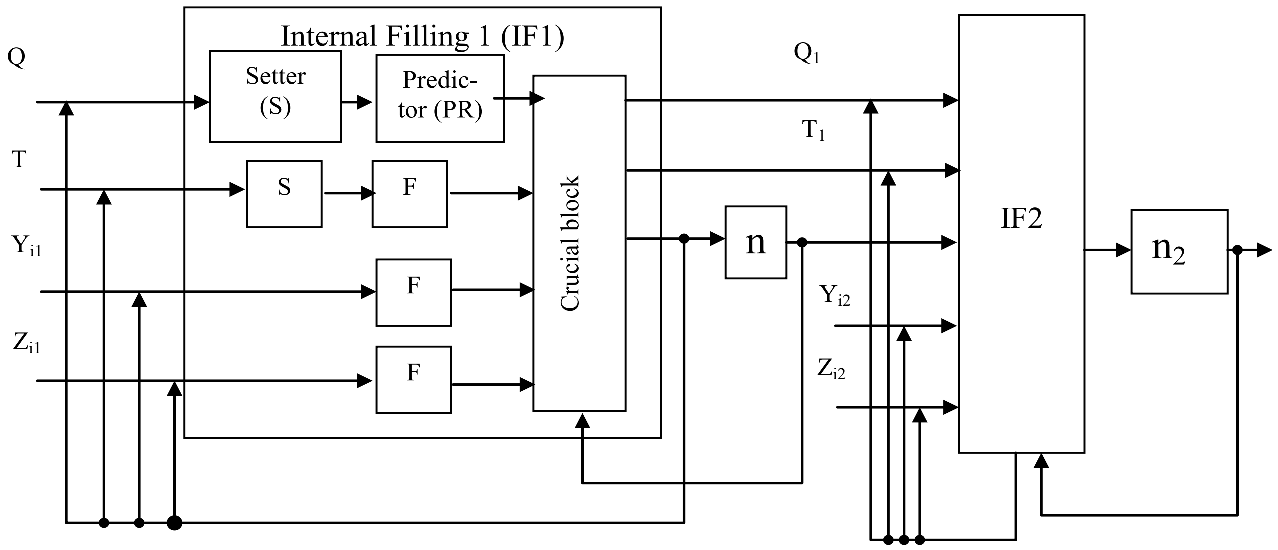

FIGURE 3. *Simulation of the joint work of mills*

Let the crushing complex consist of several grinding aggregates, included in the sequential work (Fig. 4). Each unit that is part of the complex is characterized by a certain amount of power consumption or power consumption per ton of ground material, the value of which depends on a number of factors (we take into consideration such factors as the mass of grinding bodies *M*, the productivity of the aggregate *Q* and the size of the raw material *T*) and size of the finished product. The size of the finished product is determined by the mode of operation of the unit and the grinding time, which affects the amount of power consumed).

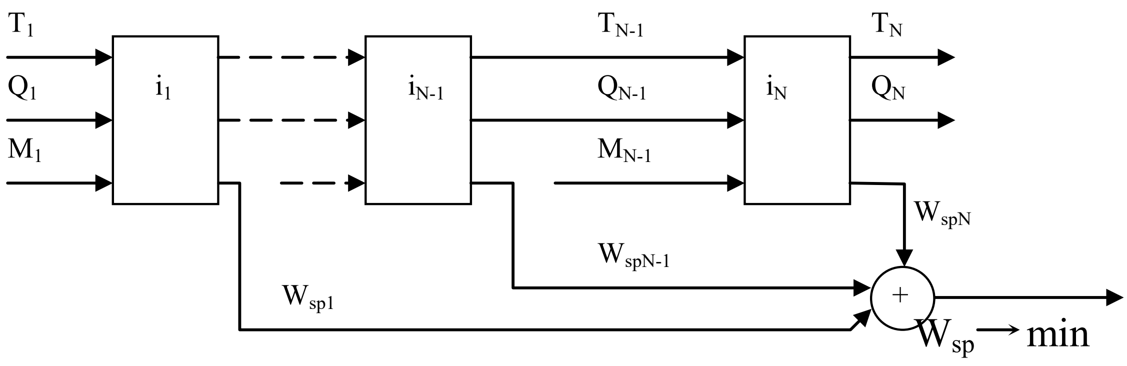

FIGURE 4. *Model of crushing and grinding complex*

The ratio of the size of the product at the inlet to the size of the product at the outlet determines the degree of crushing of the product *i*. For *N* consecutive objects, the total degree of grinding is determined by multiplying the degrees of grinding at each stage [6]:

$$i = \prod_{K=1}^{N} i_K \tag{1}$$

The value of the power consumption for the complex consists of the sum of the power consumption of individual units:

$$W = \sum_{K=1}^{N} w_K \tag{2}$$

Using the specific power consumption as an optimization function, it should be taken into account that this value is determined not only by the value of the received power, but also by the productivity. Summation of specific power consumption is possible only for quantities characterizing the same mode of operation of the complex. Then the total specific power consumption of a group of objects (for a material flow that does not vary from an object to an object-the condition for the joint operation of the elements of the complex included in series) is determined by summing the specific power consumption of each stage:

$$W_{sp} = \sum_{K=1}^{N} w_{sp\_K} \tag{3}$$

Then, the optimization problem for a crushing complex with a performance varying in a narrow range will be written in the form

$$\begin{aligned} & W_{sp}(Q, i, k_N) \to \min \\ & \begin{cases} Q = \text{const} \in [Q_{\min}, Q_{\max}] \\ i \geq i_{permiss} \end{cases} \end{aligned} \tag{4}$$

With this representation of the complex, the specific power consumption is represented by a nonlinear function determined by the state of each element of the complex, each of which in turn is a function of many variables. Two possible solutions are possible here: the first is the reduction of all variables to one, artificially introduced (the expression of all variables through one of them) and the second is the numerical solution of the problem, by sequentially supplying to the inputs of the model possible states of the system. The second option is more labor-intensive, however, its accuracy will be determined by the accuracy of its models. At the initial stage of solving the problem with the help of a numerical model, it is sufficient to identify zones of local minima of a function with the aim of more detailed investigation of them in the future, since each of them can be a minimum in one of the incoming variables and characterize only certain operating modes. Since the objects of the crushing complex are inertial and multi-variable, there may be some discrepancy between the calculated optimal mode and the "real" optimal mode, therefore, one must take into account the accuracy constraints imposed by the properties of the object. In addition, depending on the selected priorities, preference can be given to a particular local minimum.

To implement the monitoring and management system, it is advisable to use neural networks with the help of which it is possible to implement a model of the system and regulator. Neural networks are trained, designed to work with a large number of variables, successfully perform predictions. The task of grinding control using neural networks is implemented as follows (Fig. 5).

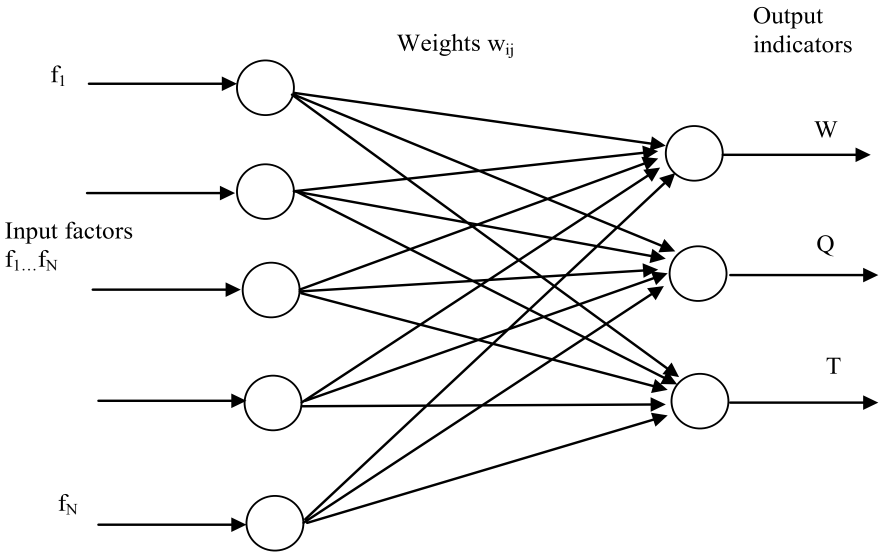

FIGURE 5. *Neural network model for grinding control*

Each input of the network corresponds to one of the factors. The network outputs correspond to performance, subtlety and power consumption. Network weights determine the significance of factors. In addition to identifying the factors, the network can detect the forecasted state of the system based on the available data and optimize the work for a given parameter. As optimization parameters, we can take *T*, *W* and *Q*, or the introduced generalizing indicator that reflects all three criteria, depending on their significance.

System control using neural networks provide an alternative to the control systems, constructed according to the classical methods of management. This possibility is based on the fact that a neural network consisting of two layers and containing in the hidden layer is arbitrarily large number of nodes can approximate any function of real numbers with a given degree of accuracy [7].

To ensure monitoring system with the prediction function, it is necessary to build a neural network model of the form [8]:

$$y(k+d) = N\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), u(k), \\ u(k-1),...,u(k-n+1) \end{bmatrix} \tag{5}$$

where:

$y(k)$ – the output of the model;

d – the number of prediction cycles;

$u(k)$ – the output of the model.

To design a tracking system that provides a given trajectory of the form

$$y(k+d) = y_r(k+d) \tag{6}$$

it is necessary to design a nonlinear controller of the following general form

$$u(k) = G\begin{bmatrix} y(k), y(k-1),..., y(k-n+1), \\ y_r(k+d), u(k-1),...,u(k-m+1) \end{bmatrix} \tag{7}$$

In Figure 6 shows the structure of the corresponding controller in the form of a neural network. Here we should pay attention to the sections of the network that performs the approximation of non-linear operators *g* and *f* in outputs $\hat{g} = a_2(t)$ and $\hat{f} = a_4(t)$.

The controller outputs are the signals $y(t+1)$ and $u(t+1)$, the latter is implemented as a feedback and a reference signal $y(t+2)$. The delay units include remembering the relevant entry and exit, and then used a two-layer neural networks, which form estimates of the nonlinear operators and compute the control signals.

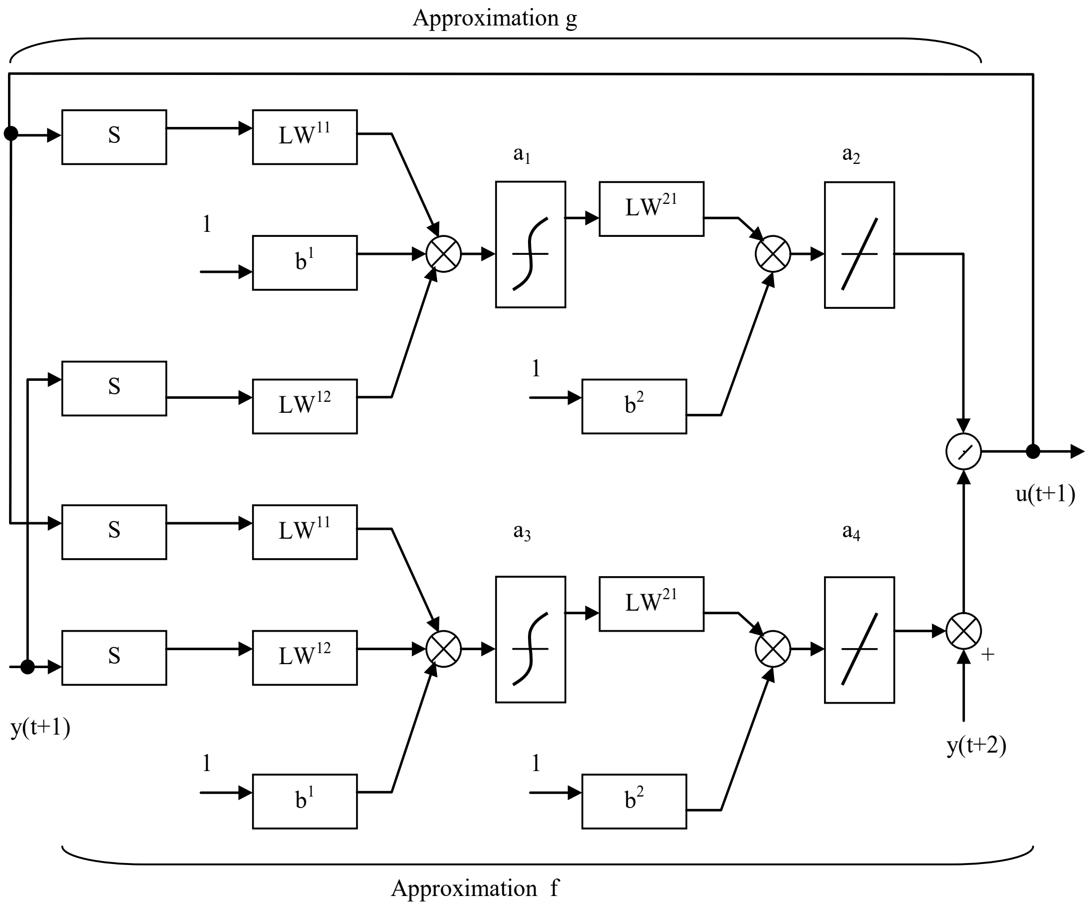

FIGURE 6. *Model of the neural network controller*

The result of the operation of the system with a trained controller is shown in Figure 7 where curve 1 shows the input stimulus; and curve 2 is the output signal.

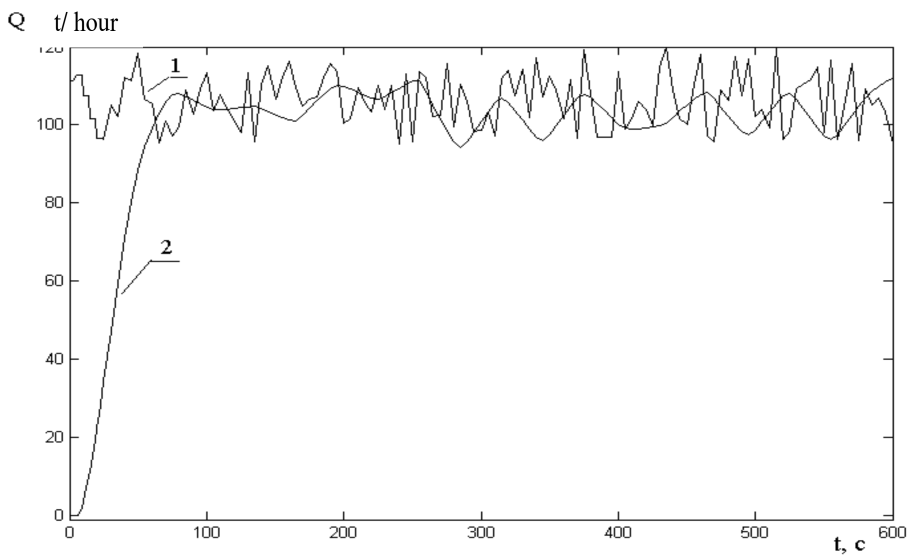

FIGURE 7. *Learning outcomes of the neuromodel*

Comparison charts of the input (random) signal and output of the system shows that the use of the controller allows to achieve a more stable work area for the output product, in case of random changes of the input traffic.

Conclusions

The technological process at the enterprises of the crushing and grinding complex is a sequence of operations, each of which changes the physical state of the substance and increases the amount of energy consumed by the complex.

Qualitative indicators of the change in the state of a substance and the amount of energy expended on it are determined by factors whose totality forms the factor field of the object. The factor field of the complex includes four groups of factors: controlled, regulating, equipment characteristics and substance characteristics.

The proposed new model of the crushing and grinding complex, which takes into account multi-factor field of the system and displays its internal links based on the mathematical apparatus of artificial neural networks lies in accounting for the formation of the objective function components that determine energy consumption and other technical and economic indicators of the complex "crusher mill" that allows you to increase the energy efficiency of the system by ensuring operation at the optimum power consumption mode.

The energy-saving effect in crushing and grinding complex is achieved by optimal power consumption mode, which is characterized by the calculated grinding fineness at which the transition from grinding from one grinding stage to the next (thinner) is carried out.

The developed model of crushing and grinding complex, which consists of several crushing units, which operate sequentially to determine the optimal parameters for a given criterion the operation mode of the complex, which reduces the power consumption of the complex by selecting an optimal mode for reducing the substance.

Application of neural networks in the implementation of the algorithm for finding the optimal operating mode.

Conflicts of Interest: The author declares no conflict of interest.

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