Algorithms Design for Fuzzy Control by Power Streams in Conditions of Underground Extraction of Iron Ore

1st Oleg Sinchuk
dept. of AESIT
Kryvyi Rih National University
Kryvyi Rih, Ukraine
email: speet@ukr.net

2nd Andrey Kupin
dept. of CSN
Kryvyi Rih National University
Kryvyi Rih, Ukraine
email: kupin.andrew@gmail.com

3rd Igor Sinchuk
dept. of AESIT
Kryvyi Rih National University
Kryvyi Rih, Ukraine
email: lab.133.136@gmail.com

4th Oleg Dozorenko
dept. of AESIT
Kryvyi Rih National University
Kryvyi Rih, Ukraine
email: ol.dozorenko2017@gmail.com

5th Roman Krasnopolsky
dept. of AESIT
Kryvyi Rih National University
Kryvyi Rih, Ukraine
email: speet@ukr.net

***Abstract*—The relevance of automated controlling of energy flows in conditions of underground extraction of iron ore has been shown. The vector of the object state, the main information parameters, controlling actions and disturbances have been determined. Algorithms of automated controlling have been developed using several strategies and controlling channels. The principles of the implementation of mentioned algorithms based on the using of fuzzy logic (Fuzzy Logic) have been proposed. The simulation of the fuzzy controllers operation in the environment of the software package MatLab has been implemented. The efficiency of the algorithms of the operation of fuzzy controllers in conditions of single-channel and multi-channel controlling has been proved.**

Keywords—automated controlling of energy flows, Fuzzy Logic, algorithms, criteria, system, mine.

I. INTRODUCTION

Mining and quarrying of iron ore are being developed in more than 50 countries. At the same time, about 90% of the world production of this type of minerals is concentrated in ten countries of the world, including in Ukraine, which occupies the 7th place in terms of both reserves and production volumes. This makes it possible, in addition to domestic consumption, to export Ukraine's foreign trade reserves annually to 10-15 countries of the world and to replenish the country's foreign currency reserves by 60-70%.

In general, the iron ore industry in the world is developing quite steadily. In 2017, total global iron ore production increased 3 times compared to 1995 [1]. In fact, an increase in the production of iron ore has led to a fall in prices in the global raw materials market. This jeopardizes the competitiveness of domestic iron ore enterprises and their products in the global raw material market. And this is a very significant potential loss in the macroeconomics of Ukraine. To prevent such an odious fact, domestic iron ore enterprises need to implement as soon as possible in the practice of their activities new, effective and content-effective measures to prevent the growth of the cost of mining.

II. ANALYSIS OF RESEARCH AND PUBLICATIONS

Issues of development of energy control systems in the structures of power complexes of general industrial and mining enterprises have not been, and are not, without the attention of scientists and industrialists. Moreover, the results of such «attention» have given some positive points [8-13].

However, as a rule, most of the known studies in the analyzed direction, according to the purpose of their research, tend to be extremely local directions – for a particular company without expecting my justification and recommendations for other objects.

In some works of authours [3, 4, 14] specifically and targeted various aspects for solving the problem of optimizing energy consumption (i.e., energy consumption, corresponding costs) are studied in conditions of iron ore mines of Ukraine using multi-zone energy metering tariffs (for example, two-part). It is shown that the using of automated controlling systems, modern informative and intelligent technologies can be a rather promising solution here.

III. FORMULATION OF THE PROBLEM

The main focus of improving the energy efficiency of the extraction and processing of iron ore was and remains the technology of extraction and preparation of ore raw materials for the stage of metallurgical redistribution. However, this unpopular statement is true and applies only to new projected enterprises in the industry, but it is known [2] that construction of new mining enterprises is not planned in the next 50 years in Ukraine, and the necessary level of modernization in the expected variant is impossible.

The scientific rationale, or «Road Map», for improving the energy efficiency of the extraction of iron ore underground in the current interpretation of the problem, essentially consists of two large-scale directions [3]:

- reduction of consumption volumes while reducing losses during transportation to the consumer;
- redistribution of flows between current electrical energy consumers.

The latter is most realistic in the context of the need for technology changes. Undoubtedly, the maximum effect in the problem of increasing the electric power efficiency of the production of CL can be achieved while simultaneously solving both of the above-mentioned directions. However, in the context of this study, let us focus on the second of these directions.

According to the analysis [4-6], despite the fact that mining enterprises with underground methods of extraction of minerals, including iron ore raw materials, which are those types of enterprises that by the technology of conducting work, belong to the category of continuous in hours of the day, yet the level of consumption of electrical energy in different periods of time of day is different fluctuating. These fluctuations differ even from their closest competitors – coal mines [9-10]. At the same time, this fact allows enterprises to optimize the level of consumption of EE in hours of the day, at the same time, to optimize the level of payment for it, since the price for the released EE differs hourly [7].

The enterprises have already approached the need for such a solution. However, in the «manual version» control to achieve the desired level of effect is not realistic. Maximum reach can be achieved when building a complex system of «Automatic control system of energy flows». Meanwhile, in turn, the effectiveness of such a system will depend on the quality of the algorithm of its work.

The purpose of the research is to substantiate the support decisions and the formation of the structure and parameters of the algorithm of development of «Automatic control system of energy flows» in the conditions of operating mining enterprises with underground methods of mining.

IV. Presentation of the Material and Results

The technological process under consideration as a controlling object is complex multi-parameter, non-linear and multi-connected [14, 15]. Using a system analysis, it is initially necessary to determine the phase space, goals and control tasks [16].

It's known the main consumers of electricity (EE) in mines are redistribution of extraction / transportation of ore mass, discharge of mine water (drainage), air supply and ventilation. With this in mind, potential control criteria should be identified [14, 17]:

$$\begin{aligned} &Z^e = F(RE, HT) \Rightarrow \min, \\ &P \Rightarrow \max \\ &B \Rightarrow \max \\ &B_d \Rightarrow \max \\ &B_m \Rightarrow \max \end{aligned} \tag{1}$$

where Z^e – is the total cost of the enterprise for consumed electricity (hourly, daily), UAH.; $RE = f(P, B, B_d, B_m)$ – electricity consumption (hourly, daily), kW; HT – current electricity tariff, UAH / kW; $F(\ldots)$ – some established functional dependency; P – ore mass production at the enterprise (hourly, daily), t; B – air supply (hourly, daily), m^3; B_d – volume of pumping of mine water (hourly, daily), m^3; B_m – ventilation (hourly, daily), m^3.

As shown in [18], all mentioned factors are sufficiently informative for the current state of the system. At the same time, depending on the particular mine, these parameters of ore flow, drainage, ventilation and air supply can have different impact on the resulting factor – energy consumption. Thus, all these indicators should be included in the state vector of our system $\overline{X} = \{Z^e, RE, HT, P, B, B_d, B_m\}$. At the same time, depending on the degree of correlation between them, some of the parameters can be considered as controlling actions (the corresponding vector $\overline{U} = \{P, [P, B_d, B_m]\}$ or as disturbing factors vector $\overline{V} = \{B, [P, B_d, B_m]\}$.

Composition of control vector elements $\overline{U}$ and disturbing influences $\overline{V}$ can differ depending on the particular mine. Parameters Z^e, RE, HT in turn are essential information components of the vector of the system state $\overline{X}$.

Thus, in this article the task of developing algorithms of fuzzy control of mine energy consumption, as well as checking their efficiency by computer simulation are set.

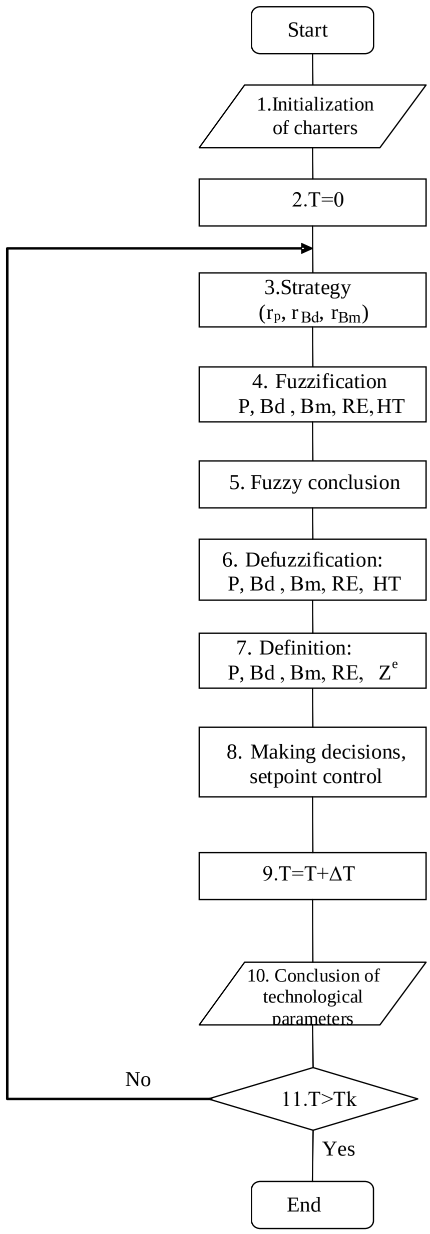

Fig. 1. The algorithm of the fuzzy ACS

Development of the controlling algorithm based on fuzzy logic (FL - Fuzzy Logic). According to the above prerequisites in conditions of non-linear characteristics, often incomplete information, and multi-channel in real production situations, a rather promising approach is the using of modern intelligent approaches for implementing automated controlling based on fuzzy logic (Fuzzy logic [19-20].

Based on this approach, algorithms of the operation of fuzzy controlling system have been developed and implemented (Fig. 1-2), which implement several strategies of the controlling (i.e. multichannel). Namely:

$$S = \begin{Bmatrix} P, P+B_m, P+B_d, B_m, 0, B_d + \\ + B_m, B_d, P+B_m+B_d \end{Bmatrix}. \quad (2)$$

Each strategy determines the number of possible controlling actions (controlling channels) that need to be further implemented in the ACS. For example, according to the certain set (2), the number of such parameters can be 0 (no control or «manual mode»), 1, 2, or 3.

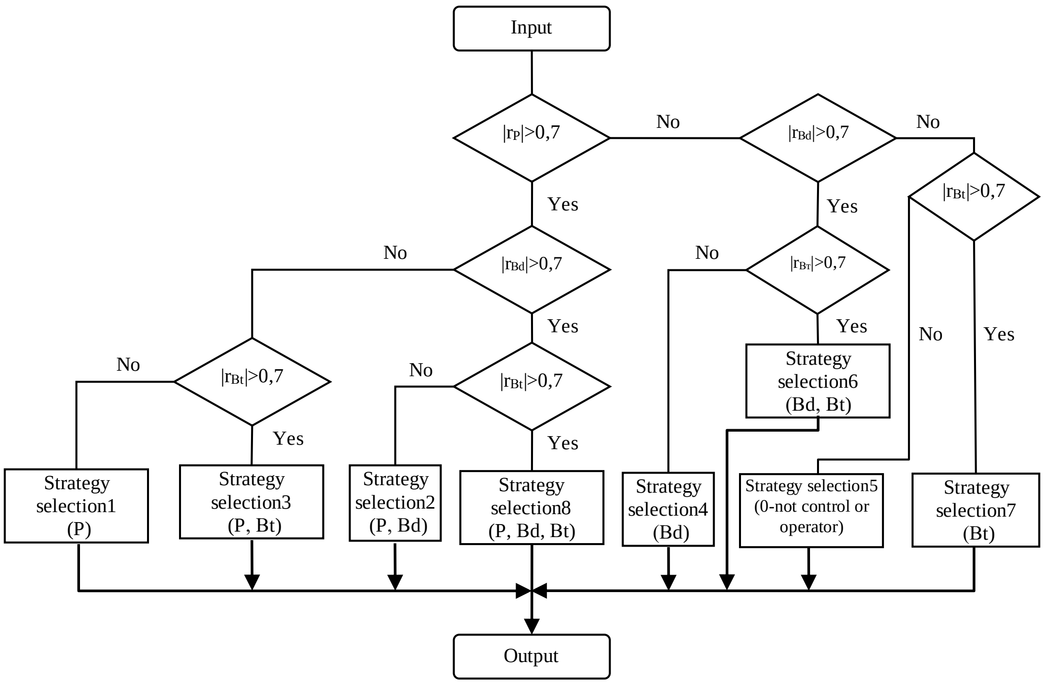

Fig. 2. Procedure algorithm for choosing a control strategy

It should also be noted that according to (1) and (2), the main controllable factor is the potential energy costs of the enterprise Z^e, which, in turn, depend on the energy consumption *RE* and hourly tariff *HT* (for example, «peak or nightly tariffs»).

Algorithms include a cascade of conditional operators with checking the values of the correlation coefficients between [*P*, B_d, B_m] and [*RE*] (pairwise), followed by aggregation with AND/OR connectives. Exceeding the threshold value (i.e) | rxy> 0.7 | will mean the need to consider this controlling channel (or controlling action) in the resulting strategy. Thus, a specific controlling strategy is determined at the output that corresponds to the number of controlling channels: 1, 2 or 3. For example, «by ore», «by ore and water», «by ore, water and ventilation».

The methodology of determining of the optimal settings for supporting decision. In the case of using a marginal criterion of type (1) with restrictions on the main controlling actions and / or disturbances of type (6)-(9), taking into account the functional dependence (10) and the two-zone tariff (β_2) for electricity («Peak [PS] / Night» [NS]) it makes sense to synthesize the corresponding optimal settings. The logic of obtaining such settings is based on the application of a minimax approach for controlling energy and material flows in a mine, namely:

- at the maximum (peak) value of the tariff (i.e. $\beta_2 = PS$) it is desirable to establish a minimum energy consumption by minimizing material flows (ore, water, air, etc.);
- at the minimum (night) value of the tariff ($\beta_2 = NS$) it is possible to allow maximum energy consumption due to maximum material flows.

Using this logic, we formalize such settings for each possible controlling channel. So for ore flow we have:

$$\underset{i=1..T^{\Delta}}{P_i^*} = \begin{cases} Max\left[P_i^{day}\right], & if\ (\beta_2 = NS) \\ Min\left[P_i^{day}\right], & if\ (\beta_2 = PS) \end{cases}, \quad (3)$$

where P_i^* – setting value (task) for ore extraction at the i-th control step ($i = 1..T^{\Delta}$); T^{Δ} – the number of discrete periods of measurement of the parameter (ore) per day (for example, if we take the periodicity of the discreteness of measurement of the parameter Δt =30 min.=0,5 hours, then T^{Δ} =48 ore measurements per day); $Max\left[P_i^{day}\right]$, $Min\left[P_i^{day}\right]$ – accordingly, the maximum / minimum of the possible discrete values of the indicator of mine ore extraction in days (from the entire sample of measurements).

Computer simulation of operation of fuzzy ACS. To simulate the work of ACS of mine energy consumption, the

Fuzzy Logic Toolbox (FLT) module has been used from the MATLAB mathematical software package. For this we use the standard fuzzy modeling technique described in [21, 22].

In Fig. 3 the results of modeling the operation of a fuzzy single-channel automated controlling system for energy consumption have been shown based on one controlling action – daily ore extraction, distributed over time. The resolution of the controller simulation has been 0.5 hours = 30 minutes.

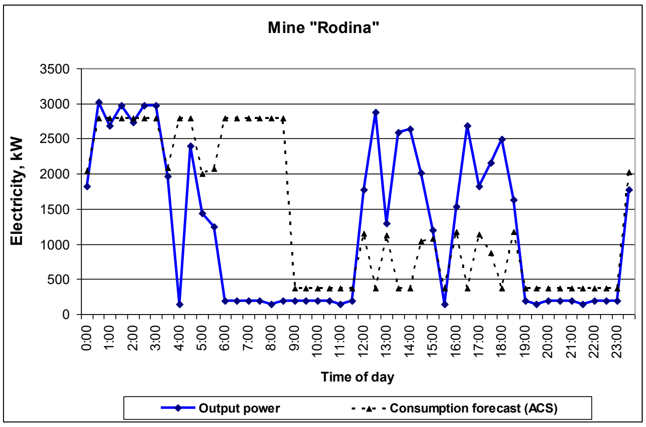

Fig. 3. Dependences of the consumed power of active electricity and the forecast of electricity consumption under the condition of minimax control

Hereinafter, all calculations have been carried out using the statistics of the Rodina mine as an example. Analysis of the simulation results Fig. 3 and the carried out analytical calculations shows that the using of fuzzy ACS obtained on the basis of expressions of type (3) allows optimizing energy costs per day due to a more rational redistribution of energy consumption over time. [23-24]

We present the results of modeling of the automated energy control using the example of two channels («Ore ...», «Water ...») and three channels («Ore ...», «Water ...», «Air ...»). However, as the made analysis using this methodology testifies, these results can be similarly reproduced for all strategies of algorithms (Fig. 2-3) and in conditions of other enterprises (mines) with underground mining of iron ore.

The implementation of controlling over the «Ore» channel in the MATLAB environment using a multi-channel fuzzy controller [14] shows similar results. Modeling the total energy consumption (as a controlled parameter) as a result of the operation of a fuzzy ACS in Fig. 4.

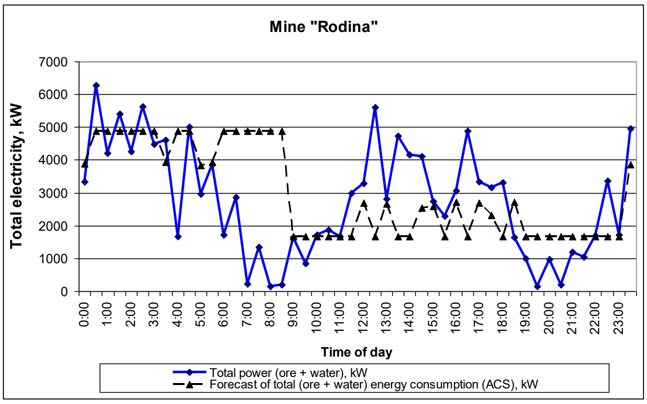

Fig. 4. Simulation of two-channel («Ore-Water») controlling of the total energy consumption based on the fuzzy ACS

The results of the analysis of other calculated values show a sufficient efficiency of using the controlling based on the fuzzy ACS of type (3). The average daily energy consumption is noticeably reduced by one third due to a more rational redistribution of energy consumption flows over technological redistributions in conditions of a two-zone tariff.

The implementation of the control of total energy consumption over the third channel «Air» (Fig. 5) shows similar trends for all technological redistributions in conditions of a two-zone tariff (3).

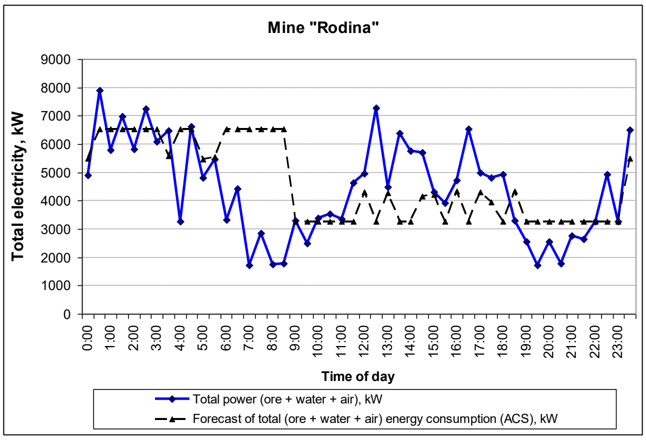

Fig. 5. Results of a three-channel («Ore-Water-Air») controlling of the total energy consumption based on the fuzzy ACS

CONCLUSIONS

1) Based on a systematic approach, the main technological redistributions (ore extraction, mine water discharge, ventilation) have been comprehensively analyzed, which have the greatest impact on the energy consumption process in underground extraction of iron ore [5, 14]. Thus, the parameters of the state vector and controlling criteria have been determined, which allowed us to set the task of developing algorithms, as well as confirming their efficiency by computer simulation.

2) Based on the use of fuzzy logic and correlation analysis, algorithms have been developed for controlling of the energy consumption of a typical iron ore mine, which compares favorably with the existing ones in that the number of controlling actions is variable and is determined based on the presence of a correlation connection between the controlling and controlled parameters of the main technological stages. This allows to implement automated decision supporting as part of the system in real production conditions of non-linear characteristics, incomplete information, multichannel.

3) Using the Fuzzy Logic Toolbox software module of the MATLAB package, one-, two- and multi-channel fuzzy controllers have been developed and modeled for controlling mine energy consumption based on the use of one, two or three controlling actions from the set {«Ore», «Water», «Air»}. As a result of the simulation, it has been confirmed that the using of fuzzy controlling based on ACS leads to decreasing of daily energy consumption (due to optimal redistribution in conditions of a 2-zone tariff) till

20-28% while maintaining the planned ore production indicators.

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Sinchuk Oleg
Doctor of Technical Sciences, Professor, Head of Department
Department of Automated Electromechanical Systems in Industry and Transport
Kryvyi Rih National University
Vitaly Matusevich str, 11, Kryvyi Rih, Ukraine, 50027
E-mail: speet@ukr.net
Contact tel .: 096-387-65-59
The number of publications in national databases - 280
The number of publications in international databases (Scopus, WoS) - 20
ORCID: http://orcid.org/0000-0002-7621-9979

Kupin Andrey
Doctor of Technical Sciences, Professor, Head of Department
Department of Computer Systems and Networks
Kryvyi Rih National University
Vitaly Matusevich str, 11, Kryvyi Rih, Ukraine, 50027
Email: kupin.andrew@gmail.com
Contact tel .: 067-604-83-26
The number of articles in national databases - 170
The number of articles in international databases (Scopus, WoS) - 18
ORCID: http://orcid.org/0000-0001-7569-1721

Sinchuk Igor
Candidate of Technical Sciences, Associate Professor
Department of Automated Electromechanical Systems in Industry and Transport
Kryvyi Rih National University
Vitaly Matusevich str, 11, Kryvyi Rih, Ukraine, 50027
Email: lab.133.136@gmail.com
Contact tel .: 067-465-55-54
Number of publications in national databases - 100
The number of publications in international databases (Scopus, WoS) - 5
ORCID: http://orcid.org/0000-0002-7702-4030

Dozorenko Oleg
Postgraduate student
Department of Automated Electromechanical Systems in Industry and Transport
Kryvyi Rih National University
Vitaly Matusevich str, 11, Kryvyi Rih, Ukraine, 50027
Email: ol.dozorenko2017@gmail.com
Contact tel .: 068-349-63-55
Number of publications in national databases - 5
The number of publications in international databases (Scopus, WoS) - 0
ORCID: https://orcid.org/0000-0002-7230-0630

Krasnopolsky Roman
Postgraduate student
Department of Automated Electromechanical Systems in Industry and Transport
Kryvyi Rih National University
Vitaly Matusevich str, 11, Kryvyi Rih, Ukraine, 50027
Email: speet@ukr.net
Contact tel .: 098-388-60-15
Number of publications in national databases - 5
The number of publications in international databases (Scopus, WoS) - 0
ORCID: https://orcid.org/0000-0002-0711-0232