UDC 622.7: 658.562

O.I. Savytskyi, M.A. Tymoshenko

AGENT CONTROL OF THE PROCESSES OF THE THREE-STAGED IRON ORE ENRICHMENT

Annotation. *The processes of iron ore enrichment from the point of view of automated control are considered. Complexity of measurement, non-stationary and inertia of processes require the use of combinations of methods of modern intellectual means of automated control. The efficiency of multi-agent control in complex with intelligent controls in comparison with the methods used today is established. The expediency of using intelligent controls, in particular fuzzy logic devices for controlling technological equipment, has been proved. The method of control of three-stage enrichment, taking into account the relationships between agents and application of methods of fuzzy logic, is proposed.*

Keywords: *Automation, enrichment, multi-agent control, fuzzy logic, system approach.*

The problem and its relation to scientific and practical tasks

Taking into account the directions of development of the modern world market, the main goal of production is to reduce the cost and improve the quality of the product. This goal is achieved through the integrated optimization of production processes based on the introduction of modern technologies. Improvement of the quality of automation of industrial technological processes is the main way in addressing the issue of production efficiency.

The enrichment complex includes various technological mechanisms, which carry out various operations and are different in design, and therefore require different approaches in the construction of control systems. In addition, they are interconnected and directly affect each other's work; require the use of many measuring devices that capture the values of different physical nature. This leads to an increase in the required design capacity [1-4].

Analysis of research and publications

The specified complexities can be avoided by using distributed control. Considering the complex of enrichment of iron ore as one large decentralized system of distributed mechanisms, it is possible to synthesize control systems of each mechanism of each stage separately, which are in constant interconnection. This approach provides an opportunity to increase the speed and reduce the load on the general system and reduce the requirements for the calculated capacities of the executive system [5].

However, distributed control has its own disadvantages, the most important of which is the presence of a certain "command center". Although the mechanisms operate independently of each other under distributed control, there is still an existing center that processes all the data that is needed to regulate the interaction between controlled mechanisms and it has significant accounting resources. In the event of a failure of the control center, the system objects will not be able to interact.

Multi-agent control (MAC) avoids specified disadvantage. Multi-agent control is one of the leading concepts of the fourth scientific and technological revolution, informational (Industry 4.0). It implies complete decentralization of control, the absence of some of the main system and the free work of each control system (agent) by the technological mechanisms of each other. However, while the agents interact with each other and exchange information with each other. The main difference in the approach based on the principles of collective multi-agent control is the relatively low calculated complexity of implementing its algorithms, which allows you to quickly take solutions, that are if not optimal, but close to them in a dynamically changing situation.

Problem statement

A general description of the multi-agent system (MAS) can be shown in the form of an algebraic [6] system:

$$MAS = (A, E, R, ORG) \tag{1}$$

where A - set of agents, ie a set of creators; E - set of MAS, ie the communication environment in which MAS interacts with other MAS; R - set of interactions between agents, ie an array of configurations; ORG - represents the current MAS as an image.

In this model, the i-th agent (creator) in terms of organizing its interface with other elements of the system can be written as a triple:

$$A_i = (E_i, R_i, ORG_i) \tag{2}$$

where E_i – MAS of the communicating environment, in which agents interacts with each other ($E_i \in E$); R_i – a subset of agent bonds with other agents ($R_i \in R$); ORG_i - representing of the current MAS as an image.

The connection between the technological mechanisms of the enrichment factory is very important as it allows to consider the entire enrichment process in aggregate and to control it according to the general picture.

Material presentation and research results

According to the proposed scheme **(Fig. 1)**, four operations are carried out in the section of the enrichment plant - grinding, classification, desliming and wet separating of iron ore. Accordingly, there are such technological mechanisms as mills, magnetic separators, desilmers and classificating mechanisms. For the first stage it is a spiral classifier, for the following - a hydrocyclone. Also shown are the parameters of the enrichment operations necessary for monitoring the process and calculations of control effects, namely pulp consumption and density. Parameters have been calculated taking into account the presence in the section of recycles and sumps between some mechanisms. Also measured is the amount of iron in the final product, which in this case is 64.23%.

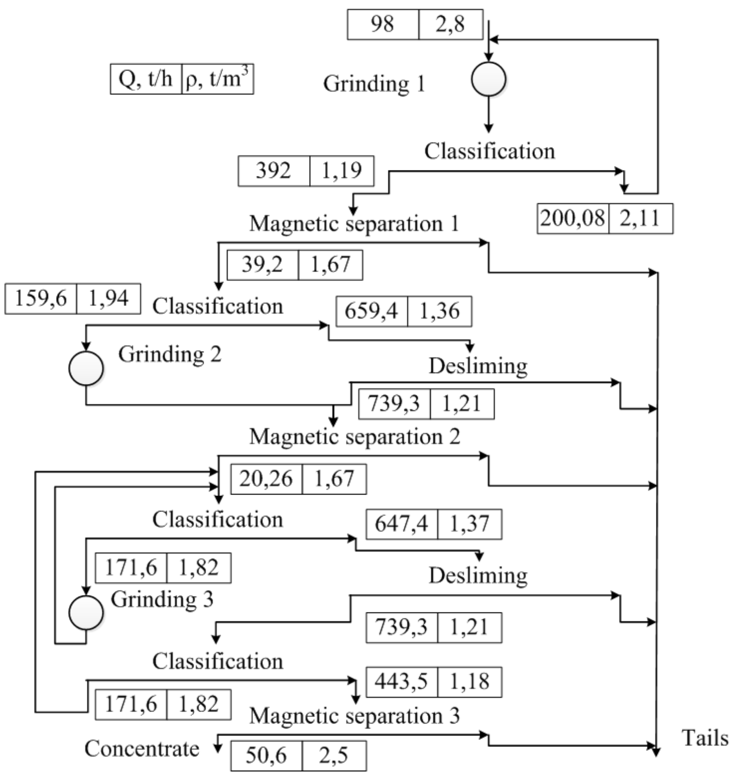

Fig. 1 Technological scheme of the process of three-stage iron ore enrichment

The scheme depicted in Figure 1 is represented by the interaction of the agents in Figure 2. It shows the multi-agent control system of the three stages of enrichment taking into account the connection between them and the transmission of information signals from sensors to the PAC (programmable automation controller). To the mill in the first stage, iron ore falls from the feeder. The regulation of the amount of ore is controlled by the drive feeder by the drive mechanism of the feeder (Af) based on information from the performance sensor (Qo). After the first and second grinding stages, intermediate density measurements are performed between the stages using a densitymeter (ρ). In addition to the density in the final product, after the third stage, many more parameters are required, such as the size of the grinded material with use of a granulometer (GM), the content of the useful component (magnetic iron), fixed by the sensor indicated in the figure as (%), and the productivity for water and for pulp in general (respectively Qw and Qp flow meters). Each stage has its own PAC that collects data and processes it. On the basis of the data obtained, the algorithm calculates the controlling impact and presents it to the executive mechanisms (A1, A2 and A3), which, in turn, regulate the supply of additional water into the mill. Taking into account that the optimum levels of hydrocyclones are constantly maintained, we can control not only the supply of additional water, but also control the supply of pulp. Therefore, three more control impacts are applied to the pumps of the hydrocyclones (P1, P2 and P3). Also, the separators and deslimers are controlled on the basis of the mechanisms Rs and Rd. At the same time, the first stage is visualized in the SCADA system on the basis of the data calculated in the first stage PAC. The parameters of the regulators shown in Figure 2 depend on the input ore parameters. That is, the structure of the stage remains unchanged with variable parameters of control objects, links between stages and regulators.

Let's consider the difference between the classical measurements of the parameters of the mechanism's work and its work in the agent form, in which case parameters are mostly calculated. The supply of hydrocyclone comes from a sump, to which the pulp under industrial conditions comes directly from several mechanisms and mixes. In this case, fluctuations of the values of the pulp's parameters - such as its density, the amount of solid, etc., occur. For example, in order to calculate the average content of the solid phase in the mixture of pulp, which arrives to a sump with known costs (measured by flow meters), solid content and iron content in the solid phase, appropriate calculations should be taken [7].

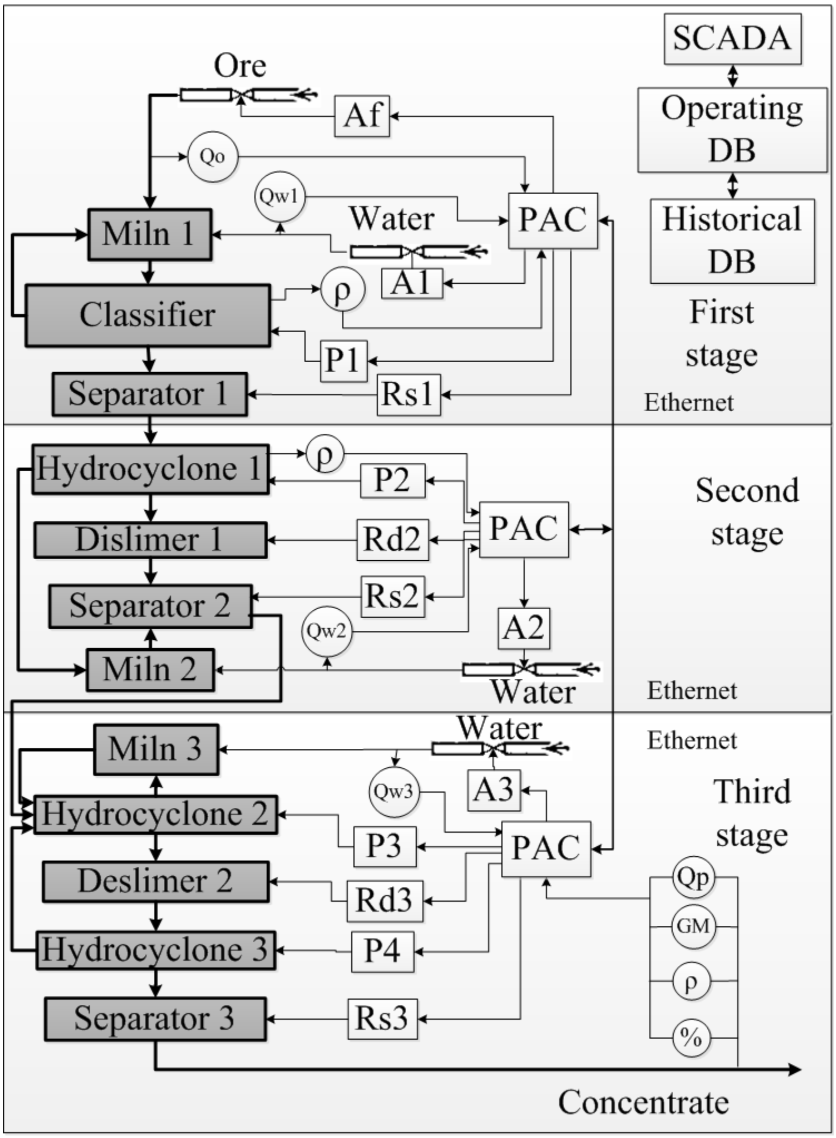

Fig. 2 A three-stage enrichment control scheme, with taking into account the relationships between agents

$$\delta_0 = \frac{1}{a - b\alpha}, \; a = \frac{1 - \dfrac{\delta_0^* \alpha_0^*}{\delta_м \alpha_м}}{\alpha_0^* (1 - \dfrac{\alpha_0^*}{\alpha_м})}, \; b = -\frac{(a - \dfrac{1}{\delta_м})}{\alpha_м} \tag{3}$$

where $\alpha, \alpha_м, \alpha_0^*$ - the iron content in the enriched pulp, in the original ore and the estimated content of iron in the enriched pulp; $\delta_м$, δ_0^* - magnetite density and initial ore density.

$$T_0 = \frac{\sum \frac{\hat{c}_i' \delta_i T_i}{T_i + (1 - T_i)\delta_i}}{\sum \frac{\hat{c}_i' \delta_i}{T_i + (1 - T_i)\delta_i}} \quad (4)$$

where T_i – the content of solid phase by mass in the i-th stream of pulp (i=1, 2, ..., n); δ_i – density of solid phase of the i-th stream; $\hat{c}_i'$ - the relative fraction of solid and liquid phases in volume in the i-th stream.

$$\delta_0 = \frac{\sum \hat{Q}_i' \frac{\delta_i T_i}{T_i + (1 - T_i)\delta_i}}{\sum \hat{Q}_i'} \quad (5)$$

where $\hat{Q}_i'$ - volume flow rate of the i-th flow of pulp.

$$T' = \frac{T}{T + (1 - T)\delta} \quad (6)$$

First, according to the formula (3), the densities of the solid phases of the pulp's streams entering the sump are determined, then the average content of the solid in the mixture by mass is calculated according to formula (4). After calculating the density of the solid phase in the mixture by the formula (5), the mass content of the solid in the pulp mixture is converted to volume content by formula (6).

In this case, the above-mentioned operations are used to calculate only one characteristic of the pulp from the many required for the calculations. They can be greatly simplified, by presenting the basic parameters of the functioning of the technological mechanism in the form of parameters of the control agent, and by modeling less important parameters on the basis of already measured information. The system is much simpler and faster in agent representation.

Measurement of a large number of characteristics of the processed product is very valuable in terms of the use of numerous measuring and converting devices, loading I/O modules on programmable automation controllers (PACs), and the whole load of the system. The application of fuzzy logic, and in this particular case of fuzzy controllers, will avoid the majority of emerging problems. For example, in case of stabilization of the hydrocyclone overflow, the fuzzy controller will contain the following rule base.

 ISSN 1562-9945

Table 1

Fuzzy rules for regulating the overflow of hydrocyclone

№	Name	Description	Action
1	Measuring the density and productivity of overflow and comparison with the given values	ρ LESS ρз & Q LESS Qз	W:=W-w & P:=P+p
2		ρ LESS ρз & Q EQUALS Qз	W:=W-w
3		ρ LESS ρз & Q MORE Qз	W:=W-w & P:=P-p
4		ρ EQUALS ρз & Q LESS Qз	P:=P+p
5		ρ EQUALS ρз & Q EQUALS Qз	-
6		ρ EQUALS ρз & Q MORE Qз	P:=P-p
7		ρ MORE ρз & Q LESS Qз	W:=W+w & P:=P-p
8		ρ MORE ρз & Q EQUALS Qз	W:=W+w
9		ρ MORE ρз & Q MORE Qз	W:=W+w & P:=P-p

In this case ρ, ρз – measured (average) and nominal density of overflow; Q, Qз – measured (average) and actual productivity of hydrocyclone's overflow; W, w – actual (average) the value of the amount of water supplied to the hydrocyclone and the predetermined value of the quantity of regulating water; P, p – the current value of the pump's feed and the preset value of the pump's regulating feed. Thus, the first entry in the table in the syntax of fuzzy logic is understood as "if the overflow's density (average) and the productivity of the hydrocyclone's overflow (average) are less than specified, then it is necessary to reduce the flow of water into the sump and increase the pump's feed". This approach allows reducing the number of used measuring devices in general and using more simple sensors, in this case, a density meter and flow meter. If this does not help to get the given density, then it is necessary to form a signal on the first agent to increase the supply of ore.

In order to control the quality of the output products of the mill, the magnetic separator and the deslimers, the fuzzy rules will look like respectively in tables 2, 3 and 4.

Table 2

Fuzzy regulator rules for controlling miln's work

№	Name	Description	Action
1	Measuring of density and productivity of miln's final product and comparsion with given values	ρ1 LESS ρ1з & Q1 LESS Q1з	V:=V+v & A:=A+α
2		ρ1 LESS ρ1з & Q1 EQUALS Q1з	V:=V+v
3		ρ1 LESS ρ1з & Q1 MORE Q1з	V:=V+v & A:=A-α
4		ρ1 EQUALS ρ1з & Q1 LESS Q1з	V:=V+v & A:=A+α
5		ρ1 EQUALS ρ1з & Q1 EQUALS Q1з	-
6		ρ1 EQUALS ρ1з & Q1 MORE Q1з	V:=V-v & A:=A-α
7		ρ1 MORE ρ1з & Q1 LESS Q1з	V:=V-v & A:=A+α
8		ρ1 MORE ρ1з & Q1 EQUALS Q1з	V:=V-v & A:=A+α
9		ρ1 MORE ρ1з & Q1 MORE Q1з	V:=V-v & A:=A-α

Table 3

Fuzzy regulator rules for stabilizing of magnetic separator's overflow

№	Name	Description	Action
1	Measuring of density and productivity of overflow and comparsion with given values	ρ2 LESS ρ2з & Q2 LESS Q2з	P:=P+p
2		ρ2 LESS ρ2з & Q2 EQUALS Q2з	K:=K-k
3		ρ2 LESS ρ2з & Q2 MORE Q2з	K:=K-k & P:=P-p
4		ρ2 EQUALS ρ2з & Q2 LESS Q2з	K:=K+k & P:=P+p
5		ρ2 EQUALS ρ2з & Q2 EQUALS Q2з	-
6		ρ2 EQUALS ρ2з & Q2 MORE Q2з	-
7		ρ2 MORE ρ2з & Q2 LESS Q2з	P:=P+p
8		ρ2 MORE ρ2з & Q2 EQUALS Q2з	-
9		ρ2 MORE ρ2з & Q2 MORE Q2з	-

ISSN 1562-9945

Table 4

Fuzzy regulator rules for stabilizing of magnetic deslimer's overflow

№	Name	Description	Action
1	Measuring of density and productivity of overflow and comparsion with given values	ρ3 LESS ρ3з & Q3 LESS Q3з	D:=D+d & P:=P+p
2		ρ3 LESS ρ3з & Q3 EQUALS Q3з	P:=P-p
3		ρ3 LESS ρ3з & Q3 MORE Q3з	D:=D-d
4		ρ3 EQUALS ρ3з & Q3 LESS Q3з	D:=D+d
5		ρ3 EQUALS ρ3з & Q3 EQUALS Q3з	-
6		ρ3 EQUALS ρ3з & Q3 MORE Q3з	P:=P-p
7		ρ3 MORE ρ3з & Q3 LESS Q3з	D:=D+d
8		ρ3 MORE ρ3з & Q3 EQUALS Q3з	D:=D+d
9		ρ3 MORE ρ3з & Q3 MORE Q3з	D:=D+d & P:=P-p

Here ρ1, ρ1з – measured (average) and nominal density of product, grinded in miln,; Q1, Q1з – measured (average) and actual productivity of miln; ρ2, ρ2з – measured (average) and nominal density of magnetic separator's final product; Q2, Q2з – measured (average) and actual productivity of magnetic separator; ρ3, ρ3з – measured (average) and nominal density of magnetic deslimer's final product; Q3, Q3з – measured (average) and actual productivity of magnetic deslimer; V, v – actual value of productivity of feeder, which supplies the ore to the mill, and the predetermined value of the regulating power supply value; A, α – the actual value of the water flow after the valve supplying the process water to the mill and the predetermined value of the regulating value of the water flow; K, k – the current value of the number of magnetic separators in the battery and a predetermined value of the regulating quantity of the number of switched-on separators; D, d – current value of the diameter of the discharge nozzle of the deslimer and the preset value of the regulating diameter of the deslimers nozzle of the discharger.

When controlling magnetic separation it is quite difficult to pick up a controlling influence that would not violate the physical nature of the process and would not be too expensive, therefore, magnetic separation control is usually carried out indirectly. In this case, through the control of the number of separators simultaneously working in the stage of and through the control of the previous mechanism in the stage - setting the supply of the hydrocyclone's pump.

Application of the agency structure requires the use of PACs, which allows the following benefits:

- Using of Data Science platform;
- Providing agent clients with cost-effective and convenient forecasting analytics tools that improve application performance, increase the level of intellectual data analysis, productivity of the decision-making process.
- Application of custom code in several languages, such as SAS, R, SQL and Python, controllers language.
- Optimization of complex control problems by choosing the best solution with the most efficient use of limited resources.
- Minimize training time and increase the effectiveness of cooperation between agents of all levels in transferring skills.
- Reduce costs, resources, and maintenance by performing all of the analytics tasks on a single platform.
- Improved data preparation.
- Advanced predictive modeling techniques and algorithms for supporting applications.
- Advanced visual analyzers available through a series of graphs and reports.
- Easily connect to many data formats and databases from virtually any data source.
- Improved productivity and automation of the decision making process.
- Analyzers allow agents to analyze data directly in their database without having to export them in order to quickly and effectively apply analytics to themselves and all agents.
- The function of automatic code generation, which reduces the amount of programming time by more than 30%.
- An intuitive graphical user interface that reduces manual interference and allows users of all levels of skill to easily navigate through software [8, 9].

Conclusions and directions of further research.

The analysis makes it possible to argue that the use of multi-agent control will greatly increase the accuracy of control of the technological mechanisms of the ore mining complex and, in general, will make control more adapted to real conditions and requirements related to the quality and quantity of concentrate. The use of modern control means, such as fuzzy logic, artificial intelligence, in general, will improve the quality and accuracy of control.

The direction of further research is a more detailed study of the links between the technological mechanisms of different stages of enrichment and their impact on the parameters of the final product.

REFERENCES

1. Morkun V. Optimization of the second and third stages of grinding based on fuzzy control algorithms / V. Morkun, O. Savytskyi, M. Tymoshenko // Metallurgical and Mining Industry. – 2015. – №8. – P. 22–25.
2. Ragot J. Transient study of a closed grinding circuit / [Ragot J., Roesch M., Degoul P., Berube Y.] — 2-nd IFAC Symp. "Automat. Mining, Miner. and Metal. Proc." – Pretoria. – 1977.- P. 129-142.
3. Schubert. H. Aufbereitung fester mineralischer Rohstoffe. – Leipzig, 1967, Bd. 11, 472 p.
4. Sbarbaro D. Advanced control and supervision of mineral processing plants / D. Sbarbaro, R. del Villar., 2010. – 311 p.
5. Bezgubova Yu.O. Multiagentnoe upravlenie raspredelennyimi informatsionnyimi potokami / Yu. O. Bezgubova // Obrazovatelnyie resursyi i tehnologii. - 2015. – #9. - P. 113-119.
6. Mezentsev K. N. Raschet i multiagentnoe modelirovanie v srede NetLogo / K. N. Mezentsev // Avtomatizatsiya i upravlenie v tehnicheskih sistemah (AUTS). – 2015. - #1. – P. 10-20.
7. Zubkov G.A. Avtomatizatsiya protsessov obogascheniya rud tsvetnyih metallov : uchebnoe posobie / G. A. Zubkov, V. L. Zabelin, G. V. Korendyasev i dr. - M. : Nedra, 1967. - 484 p.
8. Uskov A.A. Printsipyi postroeniya sistem upravleniya s nechetkoy logikoy // Priboryi i sistemyi. Upravlenie, Kontrol, Diagnostika. 2004. # 6. P. 7-13.
9. Morkun V. Multiagent control and predictive diagnostics of distributed system of iron ore enrichment based on CPS / V. Morkun, O. Savytskyi, M. Tymoshenko // Advances in Cyber-Physical Systems. – Lviv, 2016. – №2. – P. 119-124.