https://doi.org/10.31713/m1216

METHODS OF RECOGNITION IN THE METHODOLOGY OF ENERGY-EFFECTIVE INVARIANT CONTROL OF CRUSHING-CLASSIFICATION OF ORE DURING ENRICHMENT

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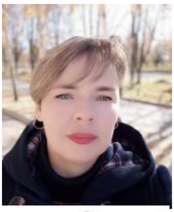

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Abstract

The object of the research is the processes of managing the technological redistribution of ball grinding of iron ore at ore processing plants in closed cycles, including a mill, a mechanical single-spiral classifier and a spiral feeder. The subject of the research is a complex of automated systems for the implementation of energy-efficient invariant control of grinding and classification of ores as part of the automated process control system of the first stage of ore preparation based on the developed methodology and indirect predictive estimates of the characteristics of raw materials and equipment. The methodology of the article is considered as a set of research methods in accordance with the specifics of the object of knowledge and is based on the principles of the unity of theory and practice, certainty, concreteness, recognizability, objectivity, causality, development. The aim is to increase the efficiency of the ore preparation technological process by applying a new developed methodology for the implementation of energy-efficient invariant control of grinding ore classification based on indirect predictive estimates of the characteristics of raw materials and equipment. It is shown that the system of selected methods, including a number of general scientific and special ones, as well as those proposed (more than 20 methods), makes it possible to solve the overwhelming majority of general issues of the implementation of energy-efficient invariant control of grinding-classification of ores, which increases the accuracy of assessing technological parameters and, as a result, quality indicators. control processes within the framework of technological requirements. It is proved that a ball mill can be represented by the initial and main parts of the drum and ball loading, and the mechanical single-spiral classifier can be represented by a double-pass spiral, the upper part of the spiral with a sand product and a sand gutter, a classifier basin with a lower part of the spiral and a drain threshold, which are independent. autonomous systems, where processes run independently and practically do not affect each other, which will allow the use of independent automatic control systems and the ability to take into account additional useful connections between controlled processes, which will lead to a further improvement in the quality of the complex of systems.

1. Introduction

Ukraine produces a significant part of ferrous metallurgy products and raw materials for it - iron ore concentrate, which accounts for the overwhelming majority of revenues from the export of these products. The higher cost of domestic products in comparison with foreign counterparts puts Ukraine in different conditions on the world market. This is due to the fact that the iron ore concentrate, from which more than half of the metallurgical products are now produced, is distinguished by a higher cost due to significant cost overruns of electricity, materials in the form of balls and lining and the production of a substandard product when grinding ore, especially in the first stages of ore preparation. One of the ways to improve ore preparation is to improve the automatic control of this technological process, since the automated control systems used at domestic ore processing plants do not meet modern requirements in many ways. At the same time, scientists and practitioners point to possible ways to improve the situation. Initially, this refers to the improvement of the grinding medium of ball mills, the transition to direct methods of controlling the volumetric filling of mills with ore, the use of such important parameters as the viscosity of the pulp, the speed of movement of the pulp along the drum, liquefaction of the pulp in specific situations, energy efficiency of destruction. As shown by inspections at operating enterprises, due to the risk of overloading mills and putting them into emergency mode, operators reduce productivity by at least 10-15% [1].

2. Actuality of the paper

The foregoing, first of all, indicates that this situation is generally due to the imperfection of existing methodological approaches to solving the problem, as well as methods, models and tools for automated control of the process of grinding ore by ball mills operating in a closed cycle with mechanical single-spiral classifiers. As a result, the enrichment indicators deteriorate, and in the face of an increase in the cost of iron ore concentrates, the industry suffers significant damage. Therefore, the transfer of automated control of ball grinding of ore to a qualitatively higher level by implementing progressive ideas for organizing control systems based on new or improved mathematical models and established dependencies for this equipment, methods and systems of invariant energy-efficient automated process control in conditions of iron ore processing plants, approaches and means evaluation of the main technological parameters is an urgent scientific problem. Of course, such a transition can be carried out on the basis of a new developed methodology for energy-efficient control of the grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment.

3. Unresolved parts of a common problem

Among the unresolved parts of the problem, one can single out the processes of controlling the technological stages of ball grinding of iron ore at ore-dressing plants in closed cycles, including a ball mill, a mechanical single-spiral classifier and a volute feeder, as well as a complex of automated systems for implementing energy-efficient invariant control of grinding-classification of ores as part of an automated control system technological process of the first stage of ore preparation based on the developed methodology and the methodology itself for the implementation of these automated control systems.

4. Aim of the research

The aim of this work is to develop a methodology for implementing energy-efficient invariant control of ball grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment.

The formulated aim of the work necessitated the solution of the following tasks:

- briefly describe the essence of the methodology of knowledge;
- consider and analyze the methods of cognition in technical systems;
- consider the essence of empirical research methods and their suitability for the developed methodology;
- determine the place of special methods of cognition in this methodology;
- to establish the role of the general special method of knowledge
- the decomposition method in the methodology of energy-efficient invariant control of ball crushing and ore classification based on indirect predictive estimates of the characteristics of raw materials and equipment.

5. Method

5.1 Methodology of cognition

Methodology is a rather complex concept, since it covers different areas, starting with philosophy. However, it can be represented as a set of research methods used in any science in accordance with the specifics of the object of its knowledge. It implements the following functions: determination of methods for obtaining scientific knowledge that reflects dynamic processes and phenomena; direction, prediction of special ways, where a certain research goal is achieved; ensuring the comprehensiveness of obtaining information about the process or phenomenon under study; organizing the use of new knowledge in practical activities, etc.

The methodology of cognition is based on the principles of the unity of theory and practice, certainty, concreteness, recognizability, objectivity, causality, and development.

In methodology, it is customary to single out the object, subject and purpose of the study. The processes of controlling the technological stages of grinding iron ore at ore-dressing plants in the first stages belong to closed cycles, which include a ball mill, a mechanical single-spiral classifier, a scroll feeder and raw materials coming from quarries and crushed to a given weighted average size. Deposits of poor iron ores in Ukraine are quite diverse. Even the ores of one quarry are divided into several technological varieties.

The methodology is based on the method – a system of rules and techniques for studying the object and subject of research. According to the degree of generality and scope, methods can be conditionally represented in the form of four main groups: general or philosophical, operating in all sciences and at all stages of knowledge; general scientific, used in the humanities, natural and technical sciences; partial (with an interdisciplinary scope); special – for specific sciences.

5.2 Methods of knowledge in technical sciences

In technical sciences, general scientific research methods are mainly used, which are represented by empirical research methods, theoretical research methods and general logical research methods. For empirical research in this work, the methods of experiment, comparison, description and measurement are most suitable. Among the methods of theoretical knowledge, hypothetical and ascent from the abstract to the concrete may be the most suitable. General logical methods are most commonly used here – these are analysis and synthesis, abstraction, idealization, generalization, induction, deduction, analogy, modeling, system analysis, statistical methods.

Empirical scientific research is primarily aimed at revealing facts and laws that establish through the generalization and systematization of the results obtained in relation to technical systems through experiments. Theoretical studies consider processes more abstractly. In them, under normal conditions, it is impossible to study and observe objects. The empirical and theoretical levels cannot be separated from each other, although they have a certain autonomy. However, above the empirical level, the superstructure is always the theoretical one. A feature of the theoretical level is that ideal objects are used here. The theoretical level is based on empirical data. However, the result obtained by empirical research depends on theoretical concepts. The results obtained by empirical research reflect reality only when they can be explained from the standpoint of certain theoretical concepts. The facts obtained in the process of scientific research become scientific knowledge only when they can be presented in a systematic scientific form. It should be borne in mind that the experiment is the basis for the formation of hypotheses and theories, serves as a criterion for the truth of the theoretical results of the study. However, the determining side of the experiment is always theory. The theoretical method is the highest level of scientific research, where idealization and mental experience are especially of fundamental importance. An imaginary experiment is carried out on an idealized object, intellectually controlled and analogous to the material. The algorithm of the theoretical level of research can be represented by the following chain: imaginary experiment and idealization based on the results of practical actions; presentation of results in logical forms; logical verification of the validity of theoretical results; application of theoretical results in practice.

General logical research methods are widely used in the cognition of technical objects. The use of general logical research methods can be represented as follows. The method of analysis should be applied when studying the influence of factors on the wear of balls in a mill, the use of balls of different sizes, structural relationships between pulp parameters in the classification process, the influence of bed placement and spiral dynamics on the output of the finished product, the behavior of individual components of a ball mill and a single-spiral classifier during operation. The synthesis method must be used when combining the dissected and analyzed parts of a ball mill and a mechanical single-spiral classifier into separate units and together them into a grinding cycle. The idealization method should be applied in theoretical studies, where it will be necessary to neglect certain facts that will not lead to a distortion of the results obtained. This is the supply of crushed hard particles in the form of particles of a cubic or spherical shape, the neglect of an insignificant amount of material when determining the volume of sand between the turns of the spiral of a mechanical single-spiral classifier. Generalization allows an imaginary transition from individual facts to a more general concept or judgment. This in this work makes it possible to conclude on the nature of the propagation of the magnetic field in the electromagnetic system used to assess the weighted average size of the crushed material in the unloading of the mill and the sands of the mechanical single-spiral classifier. Analogy is a method in which, thanks to knowledge about a known object, they are transferred to an unknown, but similar object. In this case, it is necessary to adhere to the following requirements: basing on the essential features of objects and as many common properties as possible; tightness of links between comparable features; establishing not only similarities, but also differences between objects. In this method, conclusions are drawn by analogy. The method of analogy is the basis of modeling, ie it is used in conjunction with other methods. In this paper, it is advisable to apply it together with the experiment. Then it is called a model experiment, which is expedient to carry out by proving the adequacy of determining the volume of sand between the turns of the spiral by a theoretical approach. Modeling is a method of studying objects on their models. At the same time, complex objects are replaced by models that are specially created and are more convenient. In the work of modeling, you need to use quite extensively. Usually they model either the structure of an object or its behavior. Simulation provides reliable results when the model closely matches the real object.

The systems approach serves as the foundation of systems engineering, which studies the problems of analysis and synthesis of complex information and control systems based on computer technology. For such systems, it is almost impossible to create a general theory for solving specific problems. Therefore, in systems engineering, the place of theory in a certain sense was replaced by a model. And yet, several components are distinguished in it that complement each other - these are empirical-intuitive, deductive-axiomatic, constructive and associative. Any act of cognition is based on these components, and the process of cognition is simultaneously directed from the individual parts of the object to the whole and from the whole to the parts. In addition, the systematic approach is usually based on the following provisions: each part of the object is described not in isolation, but taking into account its influence on the entire object; the object is not limited to the characteristics of its constituent parts, but takes into account the relationship between them; hierarchical structure of the system; taking into account the operating conditions of the system; taking into account the dependence of the state of the system on its components and the state of the components on the state of the entire system; the practical impossibility of taking into account only the analysis of the functional characteristics of the object under study, since it is often important to establish the functioning of the entire system; if the source of the change in the state of the system is in itself, the prerequisites for its self-government are taken into account. In this method, when studying any problem, it is advisable to single out several interconnected main subproblems: problem identification, description, formulation of criteria, idealization, decomposition, composition, solution. In this work, it is advisable to apply this method when creating a hierarchical system for ensuring the solid/water ratio in a ball mill, taking into account the initial feed, its size, and the liquefaction of the sands of a mechanical single-spiral classifier.

Statistical research methods should be used in processing experimental data, determining the errors of information tools and control systems, and proving the adequacy of models to real processes. The specificity of the object under study gives preference in the use of certain methods. In technical research, so-called special methods are also widely used, which are specific to specific objects under study.

5.3 Methods of empirical research

Empirical research methods - experiment, comparison, description, measurement also occupy an important place in the study of energy-efficient invariant control of grinding and ore classification based on indirect predictive estimates of the characteristics of raw materials and equipment.

An experiment is understood as a system of cognitive operations carried out in relation to objects placed in specially created conditions that contribute to the identification of the sought-after objective connections. In technical objects, two main areas for experiments should be distinguished, conducting laboratory and industrial research. The results of experiments serve as criteria for the truth of theoretical knowledge, despite the fact that theory is the defining side of the experiment. In laboratories, experiments should be carried out on physical models. So, on a physical model of the interturn space of the spiral, made in full size, it is possible to remove the dependence of the volume of sands on their height along the vertical passing through the point of contact of the cylindrical bed and the lower edge of the feed turn. It is possible to remove the dependence of the volume of sands along the horizontal on their surface at different heights. According to the developed methodology, it is possible to conduct laboratory experimental studies of nodes that are not mathematically accurately described. The program of such research should include the processes and tools shown in Fig. 1. As can be seen from Fig. 1, there will be ten such studies. In addition, it is necessary to conduct experimental studies (tests) of the grinding-classification cycle under production conditions in order to obtain data for linking the results of a theoretical nature and modeling to real technological processes. After experimental studies, it is necessary to consider the issues of practical implementation of a complex of energy-efficient invariant control of ball grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment.

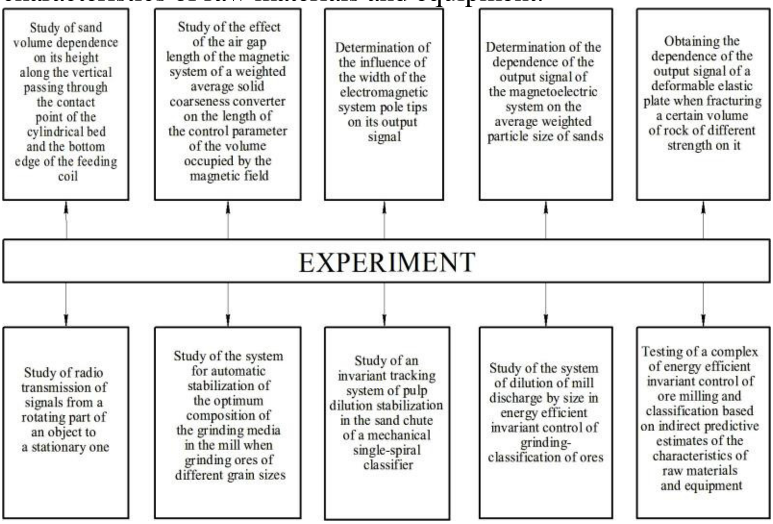

Fig. 1. Scheme of experimental studies of a complex of energy-efficient invariant control of grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment

The method of comparison in this work should also be widely used when considering tabular and graphic material. The areas of application of the method are shown in Fig. 2. As can be seen from

Fig. 2, the method covers almost all components of the complex: ball loading, lining wear, classifier bath, sand volume between spiral turns, classifier sand trough, information transmission channel, pulp movement along the mill drum and energy efficiency of ore grinding in a ball mill.

Description is a specific method of obtaining empirical knowledge, the essence of which is the systematization of data obtained using other methods, which serves as the basis for further logical operations. In this case, the object of study is reflected as a whole. The description is carried out by means of the language, tables, graphs, diagrams, series, indices, etc. In the work it is used almost continuously, where such fragments are obtained.

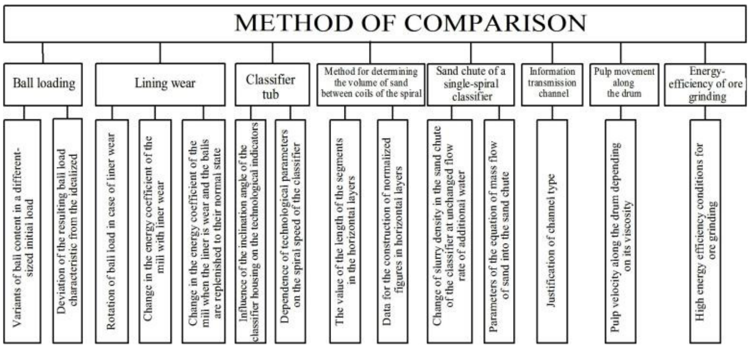

Fig. 2. Areas of application of the comparison method in creating a complex of energy-efficient invariant control of grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment

The measurement method is a system for recording the quantitative characteristics of the object under study and should be used in all experimental studies of this work. In technical systems, it requires taking into account the unity of quantitative and qualitative aspects, which makes it possible to mathematically reproduce the quantitative and qualitative characteristics of an object in an experiment.

In addition to experimental studies, measurements (estimates) are also used in the management of objects. Often, already known information tools are used for this, however, when managing new processes or moving to a qualitatively higher level with already known objects, there is a need for new methods for measuring parameters. The analysis showed that during the transition to a qualitatively higher level of management and the implementation of energy-efficient invariant control of the grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment, it is necessary to develop 21 new methods of measurement (estimation). They are shown in Fig. 3. As can be seen from Fig. 3, the new methods include mechanical single spiral classifier sands, ball mill initial parameters, mill pulp condition, ore grinding energy efficiency, ore grinding and ball loading. Most of these parameters have never been operationally evaluated.

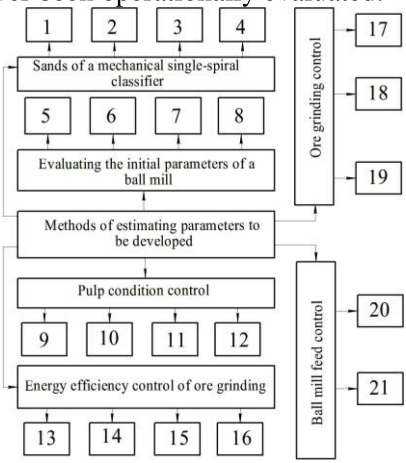

Fig. 3. Estimation of parameters by methods that do not exist and that need to be developed for energy-efficient invariant control of grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment: *1* - method of indirect predictive assessment of sand consumption; *2* - method for determining the instantaneous values of the flow rate of sands; *3* - method for estimating the height of sands in the interturn space of a spiral; *4* - sand volume measurement error compensation method; *5* - method for measuring the ore size of the initial feed; *6* - method for measuring the size of sands of a mechanical single-spiral classifier; *7* - method for estimating the size of ore at the ball mill inlet; *8* - method for ensuring a given solid/water ratio at the inlet of a ball mill; *9* - pulp viscosity evaluation method; *10* - assessment of pulp movement along the ball mill drum; *11* - method for determining the speed of movement of the pulp depending on the viscosity; *12* - method of providing a fictitious speed of movement of the pulp by changing its viscosity; *13* - criterion for assessing the energy efficiency of ore grinding; 14 - method for determining the energy efficiency of ore destruction; *15* - method for evaluating the energy efficiency of ore breaking in mills with high pulp levels; *16* - method for evaluating the energy efficiency of ore breaking in low pulp mills; *17* - method of fixing the basic parameters of the crushed ore; *18* - method for assessing the thickness of the lining in a ball mill; *19* - method for accounting for

lining wear and ball load slippage in a ball mill; *20* - method of indirect prognostic estimation of the state of optimal ball loading; *21* - method for determining the number of balls to be loaded into the mill

5.4 Special methods of cognition

In addition to general scientific methods for studying technical objects, so-called special methods should be used. The use of certain special methods is determined by the specifics of the object under study. Many technical sciences have given rise to a huge number of special ways of research. The field of science in the specialty "automation of control processes" primarily includes methods of the theory of automatic control and its individual parts – the method of invariance, methods of adaptive systems, optimal systems, servo systems, mathematical forecasting, stabilization of operating modes of technical systems, other means, statistical dynamics of systems control, spectral theory of signals, signal filtering theory, minimax criterion, superposition method, algorithmic method, etc. As auxiliary methods, methods of the theory of random processes, metrology, measurement errors, information tools, sensitivity, methods of the theory of accuracy, approximation of dependencies, transitional actions are used. All of these methods can be used in the process of solving this problem.

Among the special methods, one can single out those that are used for various technical sciences, in other words, general special methods. These include methods of decomposition and composition, systems theory, theory of experiments, hydraulics of Newtonian fluids, etc. Most of these methods also need to be applied when solving this problem.

As grinding agents in the first stages of ore preparation, ball mills with a high drain level and central unloading of the МШЦ 4.5×6.0 type are mainly used, however, the most promising are technological units with a low pulp drain level and three-phase ball movement, which have great advantages over others [2]. In [2] it is shown that the ball mill is a complex control object. The analysis found that the mechanical single-spiral classifier is the same. Therefore, it is supposed to use a large number of methods of this group of their knowledge. A special place should be occupied by the decomposition method, which makes it possible to simplify the study of complex aggregates by representing them in the form of separate units and parts.

Central among the special methods of this work are the methods of the theory of automatic control, the theory of the radio engineering method and improving the accuracy of information tools. Among the ways to improve the accuracy of information tools, their own, related to the peculiarities of their device, operation and implementation principle, should prevail. Methods of the theory of radio engineering systems cover the transmission and reception of radio signals at high frequencies. The methods of automatic control theory should be widely used. They should cover all technological units of the grinding cycle and the most important processes. To achieve the set goals, it is necessary to apply a large number of basic science methods in the direction of research in this work, as shown in Fig.4. As can be seen from Fig. 4, there are basically ten such methods.

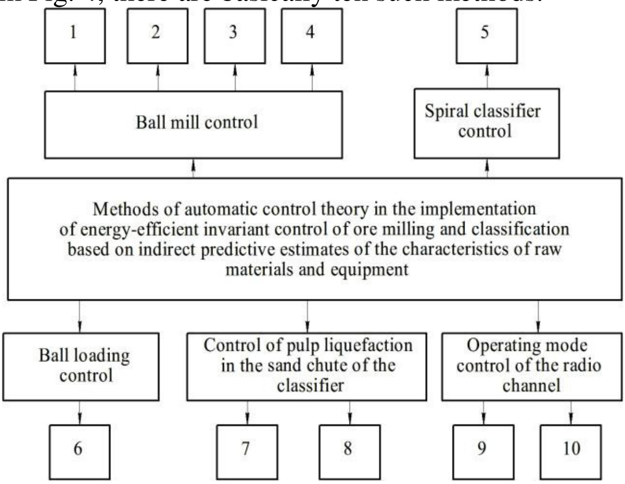

Fig. 4. Methods of the theory of automatic control, which should be applied in the implementation of energy-efficient invariant control of grinding and classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment: *1* - software methods for determining ore productivity and pulp liquefaction and the theory of digital systems; *2* - methods of multilevel automatic control of pulp liquefaction; *3* - methods of the theory of closed systems when loading ball mills with ore; *4* - methods for developing mathematical models of controlled objects when finding the transfer function of the mill according to the energy efficiency of ore grinding; *5* - methods of invariant control when dividing the discharge of the mill into overflow and sands; *6* - methods of flexible cyclic control of

the supply of balls to the mill; *7* - follow-up control methods for liquefying classifier sands; *8* - methods of invariant control at liquefaction of classifier sands; *9* - methods of strict cyclic control in coordinating the actions of individual nodes; *10* - methods of cyclic continuous control with mode memorization

5.5 General special methods - decomposition method

The study of a ball mill [2,3,4] as a controlled object was carried out in [5], which shows that it has the main features noted in [6] and therefore belongs to complex control objects. The mechanical single-spiral classifier is the same object [7,8]. Together, in the ore grinding-classification cycle, they form an even more complicated object, which is rather difficult to control [9], and it is not surprising that the necessary indicators of automatic control have not been achieved here for a long time.

The decomposition method [10,11] is ideal for studying such complicated objects. The idea of decomposition is to simplify the task of studying a complex object by analyzing its structure with subsequent transformation - dividing into simpler components. Moreover, each selected element is simpler than the original object. In addition, often in the process of selecting individual parts, the number of inputs and outputs of each such element is reduced compared to the original object. All this greatly simplifies the study of the entire object. Often, a technical system, in accordance with its characteristics, is divided into separate subsystems with a certain autonomy. In the understanding of automatic control, such subsystems can be controlled not from a system-wide device, but from a local regulator. When decomposing, it is advisable to divide the object into constituent elements according to its structure, using weak links or their practical absence between the separated parts. In the studied cycle of grinding-classification of ores, such weak links between individual components are observed.

The most common technological cycle for grinding-classifying low-grade iron ores at concentrating plants contains a ball mill with a volute feeder and a mechanical single-spiral classifier operating in a closed cycle. The decomposition of the technological cycle, firstly, involves the separation and separate consideration of both a ball mill and a mechanical single-spiral classifier. Secondly, these individual technological units are supposed to be divided into smaller and at the same time practically independent structural components. In such a division, it is necessary to consider in detail the operating parameters and characterize their impact on the operation of both each structural unit and each node, as well as the classification grinding cycle as a whole. It is necessary to disclose incoming, outgoing quantities and disturbing factors. Disturbing factors should be analyzed in detail, their impact on the process should be identified and evaluated, and the methods of neutralizing the negative impact should be considered.

The technological cycle of grinding-classifying low-grade iron ores can be represented as two autonomous systems - a ball mill and a mechanical single-spiral classifier, as shown in Fig. 5, where DF are disturbing factors.

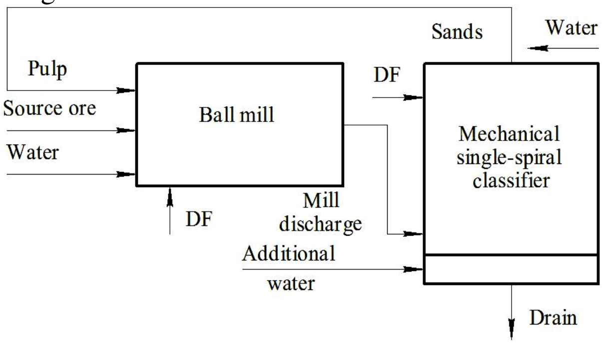

Fig. 5. Decomposition of the grinding cycle of low-grade iron ore into a ball mill and a mechanical single-spiral classifier

The initial ore, water and pulp created by the sands of a mechanical single-spiral classifier and water added to them are fed to the cycle inlet to the ball mill. The mechanical single spiral classifier at the inlet receives mill discharge and additional water. The loop output is the classifier drain parameters. Perturbing factors of the DF (Fig. 5) are applied to each of the technological units, which deviate the process from the normal mode.

The analysis showed that a ball mill and a mechanical single-helix classifier can be fed by five almost autonomous components each, as shown in Fig.6. The ball mill is represented by the volute feeder, the initial part of the drum, the main part of the drum, the ball load and the electric drive of the drum. The mechanical single-spiral classifier contains a two-start spiral, an electric drive of the spiral, a classifier bath with the lower part of the spiral, an upper part of the spiral with a sand product and a sand chute. Disturbing factors of the DF act on each of the selected autonomous parts (Fig. 6). The general perturbing factor of the cycle is the original ore, the properties of which can vary within fairly wide limits. It was shown in [12] that ores at the first stages of grinding at ore-dressing plants are represented by several technological types. Thus, the totality of the ore of a particular open pit can be represented by several separate types. In other words, it is possible to decompose raw materials into six separate types with their own specific technological properties - strength, density, magnetic iron content, fineness of inclusions of a useful component. It is much easier to study and process a separate technological variety of ore, however, for the most part, they are formed according to similar characteristics into almost two technological varieties.

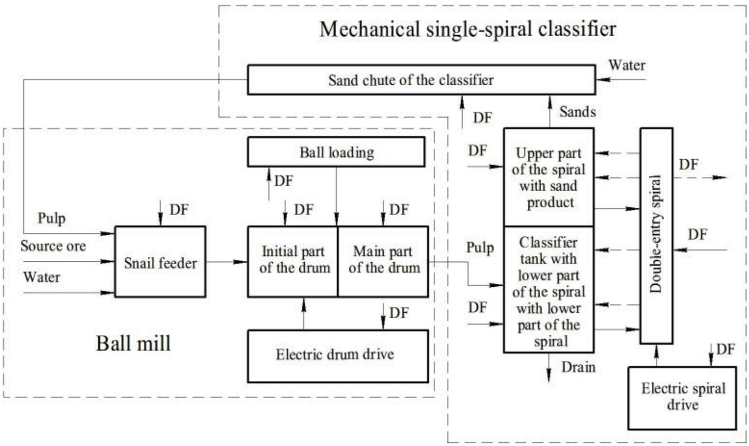

Fig. 6. Decomposition of the grinding-classification cycle of low-grade iron ores into a ball mill and a mechanical single-spiral classifier and into their components

From the analysis of Fig. 6, it follows that different components of the decomposition of the ore grinding-classification cycle make different contributions to its general properties. In this case, the nodes that have less effect on the general properties of the grinding-classification cycle of ores include a volute feeder, an electric drive of a ball mill, and an electric drive of a spiral of a mechanical single-helix classifier. Let's briefly consider their features.

The volute feeder ensures the rise of the pulp from the bottom mark to the axis of the ball mill drum. Sands and additional water in the form of pulp enter the inlet from the sand chute of the mechanical single-spiral classifier. The pulp captured by two curls enters the drum of the ball mill in doses. In the intake device of the scroll feeder, it is possible to measure the pressure and pulp level, and by their values to evaluate the solid/water ratio in the pulp. However, this can be done only at sufficiently high costs of sands. In this cycle, the consumption of sands is relatively small, so such measurements cannot be carried out. With this in mind, it can be argued that in this technological cycle, the volute feeder performs the functions of a vehicle. Therefore, in this case, when controlling the grinding-classification of ores, the snail feeder does not play a big role and can be excluded from further consideration.

The electric drive of the ball mill drives the drum with the ball charge, ore and water into rotation. It is built on a synchronous AC motor and ensures the invariability of revolutions n per unit time. The electrical parameters of the electric drive are determined by the state of the drum. The decomposition of the ball mill electric drive assembly is shown in Fig. 7, which shows the input, output and perturbing effects. Among the initial parameters, we can distinguish the weighted average size of the solid d_{AS}, the consumption of solid Q_S, the consumption of the finished product Q_{FP} and the ratio of solid/water $K_{S/W}$. The disturbing factor is the active power P_w consumed by the electric motor of the mill. The active power P_w consumed by the ball mill electric drive at a constant drum rotation speed and a certain degree of filling it with balls φ is unchanged regardless of the amount of material fed per unit time. The productivity of the mill is proportional to the energy consumption for grinding, and it is determined by the degree of filling the drum with balls. The productivity of the mill increases up to φ=50%, then decreases with the growth of φ. The maximum power consumption and productivity of the mill is achieved at the drum rotation speed ψ=85% critical [2], which is the most advantageous. The above applies to the theoretical curve [2]. The experimental power consumption curve [2] corresponds to 40% filling of the drum with balls, which is maintained at a number of enterprises. Since both the theoretical and experimental extremes are on gentle dependences, in order to save balls at almost the same performance, it is more expedient to work with a somewhat smaller filling of the drum with balls. Passing through the point φ=40% also does not threaten anything, which is permissible with automatic control.

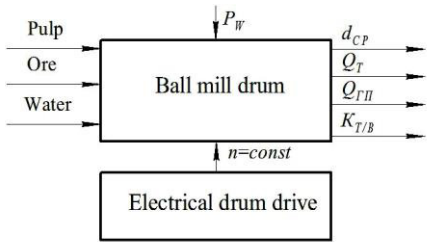

Fig.7. Decomposition of the electric drive unit of the ball mill drum

The balls and lining wear out during the operation of the ball mill, which reduces the degree of filling of the drum with grinding medium and, accordingly, the useful power consumption and productivity. At the same time, with a decrease in the degree of filling of the drum with balls, the distance of the center of gravity of the grinding medium from the axis of rotation increases, which, under the same conditions, increases the shoulder of the counteracting moment and, as a result, increases the amount of unproductive power consumed, which is spent unproductively. Therefore, under any conditions, the mill must be loaded with balls up to 40% of the drum filling. If the balls are reloaded once a day, then the productivity of the technological unit is reduced by 2%, and the power consumption is relatively large, corresponding to an increased productivity by 4%. Usually additional loading of balls is carried out in three days. Under such conditions, the productivity of the mills will decrease by 6%, and the electricity consumption will increase by 2%. This confirms the fact that the ball loading of the mill is practically an autonomous system and it needs to be given due attention. If the problems of ball loading are solved by a different approach, then the electric drive of the mill can be excluded from further consideration.

The electric drive of the spiral of a mechanical single-spiral classifier is designed for agitation of the pulp and transportation of sands to the sand chute. Therefore, the spiral forms a perturbing effect on the pulp, and the pulp on the spiral. Let us consider the perturbing effects that the pulp has on the spiral, which is fixed by its electric drive in the form of consumed active electric power. It is generally accepted that the main load on the spiral is made by the sands located between its turns in the upper part of the classifier. This is the basis for measuring the circulating load of the ore grinding-classification cycle. However, disturbing influences also act in the same direction. Among them, the following factors can be noted – the level and density of the pulp in the process unit, the amount of sand in its lower part, the temperature of the pulp, the peculiarity of the classifier bed, the wear of the working elements of the spiral and the decrease in its diameter, the condition of the working elements of the spiral, the state of the electric motor and gearbox. The analysis shows that the influence of these factors on the active power of the spiral electric drive is quite significant and it is impossible to determine the circulating load by its level within the accuracy requirements of the technological process. Therefore, the classifier spiral drive can be excluded from further consideration, assuming its rotation speed to be unchanged.

The last components of the decomposition of the grinding cycle of the ore classification, including the effect of the spiral on the pulp, must be considered in more detail, highlighting the perturbing factors, evaluating them and looking for ways to compensate or take them into account.

It follows from the considered that the decomposition of the ore grinding-classification cycle can be simplified and presented in the form of Fig.8. It can be seen from Fig. 8 that a ball mill can be represented by three components, and a mechanical single-spiral classifier by four. Let's consider these components in more detail.

Initial ore, pulp and water are supplied to the ball mill inlet to the initial part of the drum.

These dissimilar materials for effective grinding must be mixed qualitatively, the mixture should be averaged in terms of the content of components, usually performed by special devices – drum mixers.

However, given that the ball mill is an efficient mixer, these units are not installed in front of the ball mills. This, however, gives rise to negative consequences - the initial part of the drum acts as a stirrer, significantly reducing the performance of the ball mill.

Therefore, the task is to increase the efficiency of mixing and averaging in terms of the content of material components to ensure effective grinding of large solid inclusions in the ore.

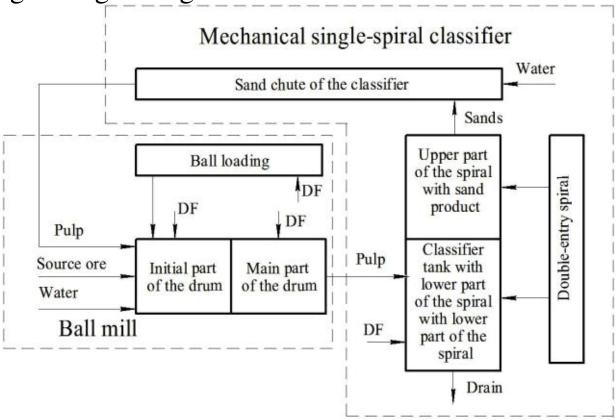

Fig. 8. Simplified grinding cycle decomposition – poor iron ores classification

To convert the sand product into pulp, additional water is supplied to the sand trough of the mechanical single-spiral classifier. The density of the pulp is determined by the productivity of unloading sands and the flow of water into the sand trough, which is usually taken unchanged. Mixing at the inlet of the initial part of the drum will be effective when the pulp from the sand product is maximally liquefied, and the original ore is moistened before entering the mill, supplying additional water to the ore entry zone. At the same time, it is advisable to divide the water that must be supplied to the ball mill into two streams - onto the surface of the ore for wetting and directly into the drum, into its initial part. An amount of water must be supplied to the surface of the ore, which will be proportional to the surface of the solid.

By modeling pulp liquefaction in a sand trough of a mechanical single-spiral classifier at a constant water flow, it was found that the density of the pulp changes with a period of 10s in accordance with a dependence close to harmonic [13]. For example, at average values of the circulating load and an average pulp density of 2 kg/dm^3, the maximum and minimum of the indicator are 2,5 and 1,3 kg/dm^3, respectively [13]. These are highly concentrated and watered zones of sand pulp, which reduce the efficiency of the balls. It is possible to correct the situation and significantly increase the efficiency of the balls by stabilizing the density of the pulp in the sand trough, i.e. γ_P=const. However, for this it is necessary to raise to a new, qualitatively higher level of measuring the circulating load in the grinding-classification cycle. Therefore, the system for automatic stabilization of pulp liquefaction in the sand trough of a mechanical single-spiral classifier is an autonomous system and can operate outside the entire cycle control system.

The specificity of the initial part of the drum is closely related to the ball loading. It is accepted in enrichment that large balls are located in the initial zone of the drum, and small balls are in the discharge of the ball mill. Consider how this affects the efficiency of ore grinding. At the beginning of the drum are the largest pieces of ore and the thinnest pulp, created from sands with additional water. The destruction mainly occurs between the surface of the lining and the balls, and the liquid pulp weakly fixes large pieces of ore in the massif. The probability of a large ball hitting an unfixed piece of ore is quite small. Therefore, the ore destruction efficiency is expected to be low. A completely different result is expected in this zone from the smallest balls in the mill feed. It is known that the power-to-weight ratio of small balls in an array is much higher compared to large ones. Small balls in the array in the process of moving to the lining easily pass liquid pulp through the holes, and large pieces of ore are retained. When they come into contact with the lining, large pieces of ore sandwiched in an array of small balls are effectively destroyed. Therefore, the ball load must be formed taking into account these features. Therefore, the initial part of the drum will perform its functions of material averaging and effective ore grinding and can be an independent autonomous ball mill system, which, however, is provided by autonomous control systems for water supply to the ball mill, automatic stabilization of pulp liquefaction in the sand trough of a mechanical single-spiral classifier and formation of a ball load at the input of the technological unit.

Ball loading is perhaps the main structural unit of the grinding cycle of the classification of low-grade iron ores. At present, a lot of a priori information on its improvement has been accumulated. With regard to the initial part of the drum, this is noted. In the discharge of a ball mill with small balls, large balls must be at the inlet. Here, the pulp is thick and viscous due to a decrease in the size of the solid. Small balls, neither alone nor in aggregates, can overcome such a viscous medium and grind the material. On the contrary, the viscous pulp flow will carry small balls out of the mill, reducing their required stay in the process unit and thereby increasing the consumption of ball material for grinding ore. Large balls will overcome the resistance of the viscous pulp, larger solid particles will be fixed on their surface and effectively crushed when the balls interact with each other, also the balls and the lining. Therefore, there is a prospect of improving the ball load of the mill, but all this must be proven.

Now in Ukraine there is an opportunity to switch to the use of balls of the 5th hardness group. The effectiveness of their use has been scientifically proven. It is necessary to make the transition to a multi-dimensional spherical load, however, this requires effective approaches to the development of its particle size characteristics and a criterion for assessing its approximation to the idealized characteristic.

To increase the efficiency of the balls can control the energy efficiency of the destruction of the ore directly in the drum of the ball mill, which have never been used. The development and use of such tools will be a significant contribution to the improvement of ball loading.

In the process of grinding the ore, the lining wears out and the ball loading changes the degree of filling of the drum, which worsens the performance of the mill. Currently, this is practically not taken into account. The solution of this problem will significantly improve the performance and energy performance of the mill.

A large number of factors influence the wear of balls, so for a long time there have been no significant changes in the issue of stabilizing the optimal ball load both in terms of the volume of the balls and in terms of their particle size. Many of these factors can be made unchanged during operation. Among them there is the property and fineness of the crushed ore. If the technological composition of the ore is not changed, then the influence of factors will become constant and then it will be easier to establish the wear of the balls and their corresponding introduction into the technological unit. A ball load will fully realize its functions when it is created optimal in composition and fineness, experimentally verified and will not change during operation. It, as an autonomous system, should be supported automatically. To do this, it is necessary to develop a theory for creating an optimal ball load and its automatic stabilization during operation.

In the main part of the ball mill drum, the process of grinding the ore to a predetermined size is carried out, depending on the size of the inclusions of the useful component. If the technological type of the ore will have unchanged properties, and the ball load will be optimal and stabilized, then the main disturbing effect will be a change in its size. The effect of changing the size of crushed ore occurs in the process of its unloading from cylindrical storage bins [14]. Crushed ore along the conveyor belt when unloading such bunkers is located in sections of considerable length - with fine ore, material of medium and largest size. Since the technological equipment of the crushing process, when using special bins, stabilizes its weighted average fineness, and it, adjusted to a certain largest fineness, will tend to increase in the process of wear of the working surfaces.

In the main part of the drum, the pulp density does not change at constant material consumption, the solid/water ratio also remains constant, and the viscosity increases from the beginning to the end of the drum. A change in pulp viscosity leads to a change in the speed of its movement along the drum, and, as a result, a change in the duration of ore grinding. This effect can be used to control the grinding process of a solid when its weighted average fineness changes. The weighted average size of the original ore can be estimated according to the proposed method [15]. It is possible to influence the speed of movement of the pulp in the drum with a predictive assessment of its viscosity at a certain final grinding size by setting and providing the required value of the solid/water ratio at the ball mill inlet. Thus, it is possible to provide the necessary grinding time of the ore, depending on its size at the mill inlet. Methods for evaluating pulp viscosity and the effect of pulp viscosity on its velocity need to be developed for the first time.

However, secondary disturbing factors will also act in the main part of the drum, which will also negatively affect the ore grinding process - this is lining wear and possible slippage of the ball load relative to the drum surface. In this case, the grinding of ore will be somewhat worse. This fact has never been taken into account, but it can have a significant effect on the grinding process and it is desirable to take it into account in this work.

A mechanical single-spiral classifier separates the material ground in a ball mill rather inefficiently. This negatively affects the performance of the ore grinding-classification cycle. Therefore, it is necessary to study its selected components in more detail. The classifier sand trough as an independent autonomous system has already been considered. It is necessary to maintain the density of the pulp at a given level.

The upper part of the sand helix was not explored far enough, as the circulating load of the cycle was measured almost outside of it. As already proven, the approaches used do not allow the determination of the circulating load with the accuracy required by the technological process as a result of the action of pulsating flow effects or other similar factors. Attempts to calculate the volume of sand between two turns of the spiral also did not lead to an increase in the accuracy of measuring the circulating load. Then this line of research was continued. At the first stage of the theoretical study of estimating the volume of sands between two turns of the helix of a mechanical single-helix classifier, a measurable parameter associated with the amount of material was found. This parameter turned out to be the height of the sands in the interturn space of the spiral, measured along the vertical passing through the lowest point of contact of the cylindrical bed and the edge of the feed turn. The analysis showed that it is possible to decompose the material between the turns of the spiral, representing it with two geometric figures – a part of a cylinder cut at an acute angle (lower part) and a cut pyramid (upper part). Their volume can be determined by exact analytical dependencies. These bodies are connected in the same horizontal plane. That is, where the lower part of the sands ends, their upper part begins there. These studies resulted in two papers [16, 17], which improved the previous solutions to this problem. In [18], a mathematical modeling technique was developed for the method of determining the total volume of sands according to the data of two geometric figures. The result of such modeling was the dependencies shown in Fig.9. Figure 9 shows that dependence 1 for the upper part of the sands is almost linear. Dependence 2 for the lower part of the sands is non-linear. However, the non-linear dependence belongs to the range of 0...15

cm, corresponding to small values of the circulating load, which are not used in practice. Therefore, the overall dependence, taking into account the linear parts 2 and 3, which characterizes the upper part of the sands, is almost linear. The considered dependences 2 and 3 are described by simple analytical expressions and therefore differ in accuracy. This solution is devoid of the disadvantages that are inherent in the preliminary developments for this purpose, however, as the analysis showed, it does not allow determining the instantaneous values of the material consumption during its unloading through the sand threshold, although the total volume is determined quite accurately due to the absence of pulsations. So, the initial parameter itself - the height of the sands - is an effective solution, and its use in this approach does not allow solving the problem of stabilizing the liquefaction of the pulp in the sand trough. Therefore, the proposed approach requires further improvement that needs to be implemented. The implementation should be directed in the direction of determining the amount of material that passes through the threshold of the classifier in time. Then, in accordance with it, a certain proportion of water can be supplied to ensure that the density of the pulp in the sand trough remains unchanged.

The two-lead spiral is an independent component of the mechanical single-spiral classifier. In the upper part of the classifier, it performs the usual functions of transporting sands. In the lower part, these functions are more complex, since it interacts with the pulp, where the separation of the solid by size occurs. In a mechanical single-spiral classifier, the separation of solids by size occurs according to the rate of fall of solid grains. On the one hand, gravitational forces of gravity act on solid particles, and on the other hand, the influence of a spiral in the opposite direction. Therefore, smaller solid particles cannot settle to the bottom and are taken out into the drain, while larger ones settle and fall into the sands. The operation of the helix has not been analytically described, so this separation is not clear. To improve the separation of solids by size, one should mathematically describe the operation of the spiral and consider the fall of solid particles in water under conditions of their high concentration [19]. When creating a theory of a spiral to control the process, one should determine the duration of the updraft, its speed, the length of the conditional path traveled, the time of free fall of solid particles, etc. In the theory of controlling the separation of solids according to a given grain size, it is necessary to substantiate the parameter or criterion for separation, which would be automatically provided.

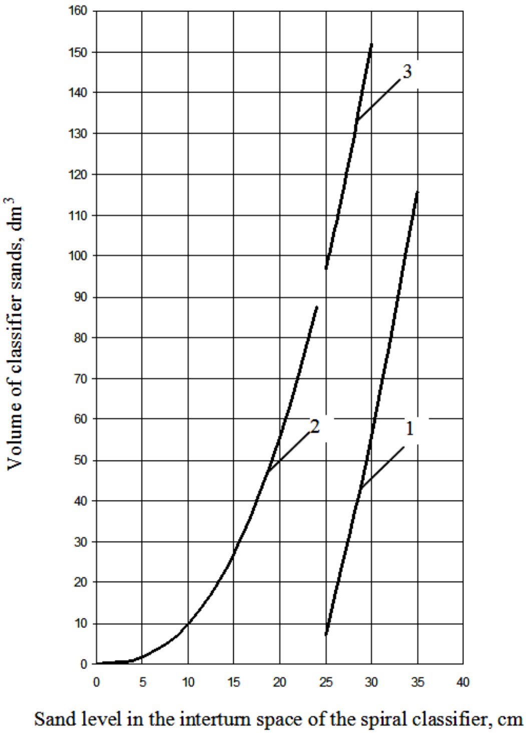

Fig. 9. The dependence of the volume of sands in the interturn space of the spiral of a mechanical single-spiral classifier on their level: *1* - 25-35 см; *2* - 0-24 см; *3* - 0-30 см

It is necessary to pay attention to the conditions for separating the solid by size from the point of view of the interaction of the spiral and the falling solid. Along the diameter, the spiral will have variable inclinations in the space where the working elements are located, which will affect the parameters of the upward flow under constant conditions of falling solid. In addition, the height of the bed of sands in the classifier will change according to the radius of the spiral, which leads to a change in the pulp level in the basin of the process unit. A lower level value affects the mechanism of throwing large fractions into the upper part of the basin. It is desirable to eliminate such a shortcoming in the classifier. Another factor is the influence of the spiral dynamics on the level of classifier drain. Along the spiral axis, the pulp level has an approximate value to the nominal value. From the side of the entry of the spiral, the level of the pulp decreases somewhat, and at its exit it rises with the casting of large solid fractions. This negatively affects the process of hard separation and the results of these factors must either be eliminated or reduced.

6. Conclusions

The conducted studies of the methodology for implementing energy-efficient invariant control of grinding-classification of ores based on indirect predictive estimates of the characteristics of raw materials and equipment allow us to draw the following conclusions:

1. The analysis showed that the system of rules and techniques for studying the object and subject of research, functions, principles, scope of methods and the formulation of the research goal make it possible to solve almost any technical problem using the existing specific methodology, including the implementation of energy-efficient invariant control of grinding-classification of ores based on indirect predictive assessments of the characteristics of raw materials and equipment.

2. In the technical sciences, general scientific research methods are mainly used, which are represented by methods of empirical, theoretical and general logical research.

The empirical and theoretical levels cannot be separated from each other, although they have a certain autonomy. It should be borne in mind that the experiment is the basis for the formation of hypotheses and theories, serves as a criterion for the truth of the theoretical results of research, but the determining side of the experiment is always theory.

Theoretical is the highest level of scientific research. General scientific methods in technical sciences are the most common - these are analysis and synthesis, abstraction, idealization, generalization, induction, deduction, analogy, modeling, system analysis, statistical methods. In fact, all these methods should be used in solving this problem, but the methods of analysis and synthesis, idealization in theoretical studies, the method of analogy in the development of mathematical models of actions and equipment, statistical methods in the processing of experimental data, determining the errors of information tools and control systems, are more widely implemented. proof of the adequacy of models to real processes.

3. Methods of empirical research - experiment, comparison, description, measurement (estimation) occupy an important place in the implementation of the methodology of energy-efficient invariant control of grinding-classification of ores.

The description method must be used almost continuously in the work. It has been established that the experiments should cover ten processes, means and systems of automation and a cycle of grinding the classification of ores. As shown, the comparison method in solving this problem should cover almost all the nodes of the complex: ball loading, lining wear, classifier bath, the volume of sand between the turns of the classifier spiral, the classifier sand trough, the information transmission channel, the movement of the pulp along the mill drum and the energy efficiency of grinding ore in ball mill. It is shown that, in addition to experimental studies, measurements (estimation) must also be applied in the automatic control of objects.

The analysis showed that during the transition to a qualitatively higher level of control and the implementation of energy-efficient invariant control of the grinding-classification of ores, it is necessary to develop a new method for measuring (estimating) technological parameters. These characteristics have never actually been evaluated operationally.

4. The multiplicity of technical sciences has given rise to a wide variety of special research methods. The science of "automation of control processes" includes methods of the theory of automatic control and its individual parts. In the problem under consideration, first of all, it is necessary to single out invariance methods, methods of adaptive systems, optimal systems, servo systems, stabilization of operating modes of technical systems, statistical dynamics of control systems, spectral theory of signals, signal filtering theory, algorithmic method, superposition method.

Auxiliary methods will also find their application - methods of the theory of random processes, measurement errors, information tools, sensitivity, approximation of dependencies. Among the general special methods, the decomposition method, the theory of systems, the theory of experiments, and the hydraulics of non-Newtonian fluids will be applied in the first place. Among the special methods of these studies, the central place is undoubtedly occupied by methods of the theory of automatic control, and then - methods of radio engineering systems and improving the accuracy of information means, among which preference should be given to their own approaches related to the features of their design, operation and implementation principle.

5. It follows from the foregoing that the considered methods of cognition, including a number of general scientific and special, as well as the proposed own methods (more than 20), can solve the vast majority of general issues of implementing energy-efficient invariant control of grinding-classification of ores, which increases the accuracy of estimating technological parameters and, as a result, provides quality indicators. control processes within the technological requirements.

6. It is shown that a ball mill can be represented by the initial and main parts of the drum and a ball load, and a mechanical single-spiral classifier can be represented by a two-way spiral, the upper part of the spiral with a sand product and a sand chute, a classifier basin with the lower part of the spiral and a drain threshold, which are independent autonomous systems, where the processes run independently and practically do not affect each other, which will allow the use of independent automatic control systems and the ability to take into account additional useful links between controlled processes, which will lead to a further improvement in the quality of the system complex.

7. The prospect for further developments in this scientific direction is the development of a complex of systems for energy-efficient invariant control of grinding-classification of ores using this methodology based on indirect predictive estimates of the characteristics of raw materials and equipment at the first stages of ore preparation at processing plants.

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