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Satbayev University

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ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ НАУК
РЕСПУБЛИКИ КАЗАХСТАН
Satbayev University

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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

НАН РК сообщает, что научный журнал «Известия НАН РК. Серия геологии и технических наук» был принят для индексирования в Emerging Sources Citation Index, обновленной версии Web of Science. Содержание в этом индексировании находится в стадии рассмотрения компанией Clarivate Analytics для дальнейшего принятия журнала в the Science Citation Index Expanded, the Social Sciences Citation Index и the Arts & Humanities Citation Index. Web of Science предлагает качество и глубину контента для исследователей, авторов, издателей и учреждений. Включение Известия НАН РК. Серия геологии и технических наук в Emerging Sources Citation Index демонстрирует нашу приверженность к наиболее актуальному и влиятельному контенту по геологии и техническим наукам для нашего сообщества.

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PRESENTATION OF CRUSHING AND GRINDING COMPLEX AS SYSTEM WITH DISTRIBUTED PARAMETERS FOR ADAPTIVE CONTROL OF ORE DRESSING PROCESSES

Abstract. The article proposes representation of crushing and grinding complex in form of a system with distributed parameters of the reducing function of the processed raw materials size in order to increase the energy efficiency of entire ore preparation process. Despite the fact that many different automated control systems for domestic and foreign production technological process are now used in the ore preparation processes, there is still a need to solve the problems of optimal control of such objects in order to both reduce energy costs and improve the quality of the final product.

In terms of energy consumption, grinding processes are superior to crushing processes, so it is necessary to consider the crushing and grinding complex as a whole to increase the whole process energy efficiency. Since the processes of crushing, grinding and classification are purely random and at any time are characterized by transient probabilities, and the crushing and grinding complex occupies a large area and is geographically distributed in space, it should be considered as a system with distributed parameters of raw material size reduction, recyclable. Redistribution of loads between the individual components of this complex in accordance with the current characteristics of processed ore and the state of process equipment allows to reduce the load on the final stage - it is grinding, which in turn contributes to the overall reduction of energy consumption.

The peculiarity of this approach is the need for the formation of spatial-temporal controls on basis of spatially distributed control of the object, the use of appropriate feedback signals and regulators with spatially distributed control effects.

Key words: adaptive control, crushing and grinding complex, distributed parameters, function of ore size reduction

Introduction. Up to 70% of the electricity consumed by the mining and processing plant is used for the operation of crushing and grinding ore. Its consumers are crushing and grinding complexes, which include several stages of crushing and grinding, which carry out consistent reduction in size of the ore in order to fully disclose the useful component. The desire to reduce these costs leads to new modern solutions, in particular, to the use of adaptive systems of coordinated management of technological stages of reducing the size of the ore. It should be noted that important in economic terms is not only the optimal performance of the crusher in the processing of ore, but also the rate of stable operation with the smallest size of the final crushed product. Since the energy costs of grinding cycles significantly exceed the costs of crushing, and the efficiency of mills significantly depends on the product homogeneity, so obtaining a homogeneous composition of incoming ore becomes a priority.

Related work. Many works are devoted to the issue of optimal management of ore preparation processes. Thus, in [1] a method of controlling the crushing and grinding complex is given, according to which the change of crusher productivity on the source ore is carried out by measuring the power consumed by the crusher motor and changing the material supply to the crusher by the deviation of the measured value cone. The disadvantage of this method is the low control efficiency, because the level of measured power consumed by the crusher engine depends on the physicochemical properties of the source ore and contains in its spectrum perturbing effects that distort the actual load characteristics and crusher performance. Also, changing the frequency of oscillations of the cone leads to faster wear. Work [2] illustrates the method of control of the crushing and grinding complex, according to which the loading of ball mills with ore implements the principle of stabilization of ore flow, supplied by the operator or by signals from automatic control systems of the processing line. The disadvantage of this method is the low control efficiency, because the level of loading of the mill is constantly changing and does not provide maximum performance of the mill on the finished size class at its output. The simplest and most common is a method of estimating the flow of sands using measurements of active current or power of the drive motor of the spirals of the hydraulic classifier [3]. However, its error is more than 30% in the range of performance due to the presence of disturbances, which does not allow to recommend it for widespread use. The most appropriate is a method of controlling the crushing and grinding complex, which includes its presentation in the form of a model of series-connected crushing and grinding units [4]. The disadvantage of this method is the use for mathematical description of the particle size distribution of ore using the Rosin - Rammler equation in General, as this equation has a fundamental disadvantage - it does not meet the boundary conditions.

The purpose of this article is to present the crushing and grinding complex in structure with distributed parameters form, the formation of a coordinated adaptive control of the multi-stage process of reducing ore size, providing with minimal energy consumption formation and maintenance of optimal characteristics of the control object that change significantly over time.

Presentation of the main research material. The most effective control effect for changing the product size in cone crushers is to change the width of the unloading slit. As shown in a number of works with increasing width of the unloading gap, the productivity of the cone crusher increases (Fig. 1), power consumption at a given consumption of output power decreases significantly (Fig. 2), and the size of the crushed product increases (Fig. 3) [5,6].

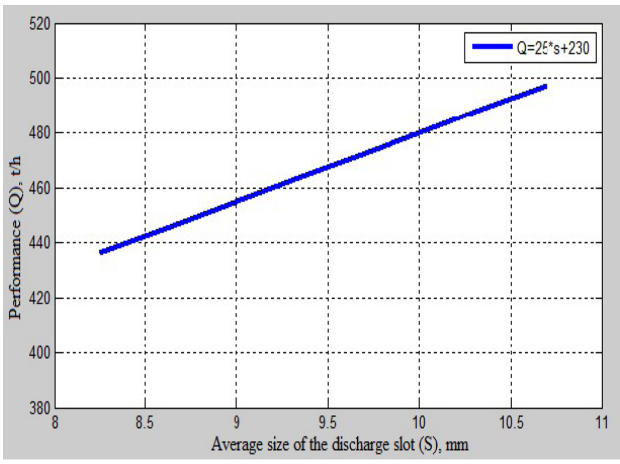

Figure 1 – Dependence of cone crusher productivity on discharge slot average size

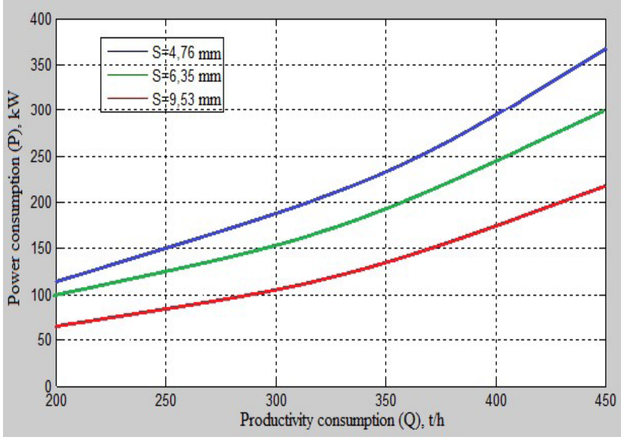

Figure 2 – Dependence of power consumption on the power upply costs with following crusher discharge slot

From the above it follows that if you maintain a constant power consumption and the width of the unloading slit, with more power the product is larger. At the same time there is a big increase in circulating loading [7,8]. This means that the consumption of feed ore must be significantly reduced to avoid overloading the cycle. To optimize the crushing process for the new technological situation, it is necessary to redistribute the load between the stages of crushing [9]. The latter approach is very important for the redistribution of the load from one stage of crushing to another in the implementation of a coordinated management of the multi-stage process of reducing the size of the ore.

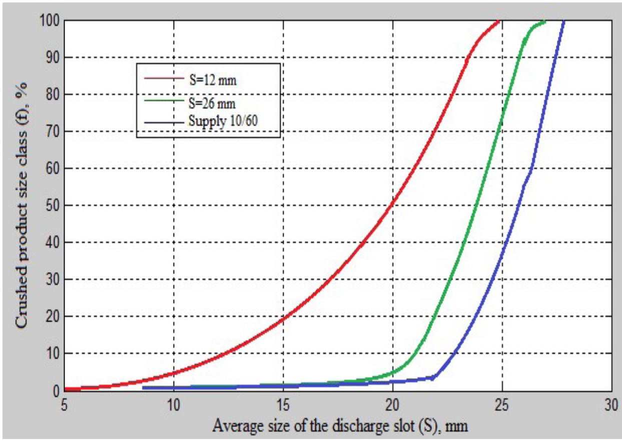

Figure 3 – Dependence of the size of the crushed product of the cone crusher on the width of the discharge slot

Since the processes of ore preparation are random and at any time are characterized by transient probabilities, and the crushing complex is territorially distributed in space and there is a change in the particle size distribution of ore, it can be argued that the size parameter is distributed over the object "ore that is being processed ", and the complex itself should be considered as a structure with distributed parameters [10]. The processed ore consists of particles of certain size classes, and taking into account the uneven ore flow in different technological areas with simultaneous movement of ore mass from stage to stage, the behavior of the system is described by differential equations, each of which describes a separate class and stage of processed ore. and by particle size distribution [11]. We introduce additional notation: Qicx – is productivity of the original product; Qp – is productivity in unloading the unit; Qtr – is conveyor belt productivity; Fi (x, t) is the function of ore size distribution in the i-th class, k1-k4 are the coefficients that characterize the particle size distribution of the size classes.

$$(\partial Q_{1j}(x,t))/\partial t=k_1 (Q(P,j)(x,t)-Q_{ij}(x,t))+k_2 (Q_{ucx,j})(x,t)-Q_{ij}(x,t))+k_3 (Q_{2,j}(x,t)-Q_{1,j})(x,t)), \quad 1)$$

$$(\partial Q_{ij}(x,t))/\partial t=k_3 (Q_{i+1,j}(x,t)-Q_{ij}(x,t))+k_3 (Q_{i-1,j})(x,t)-Q_{ij}(x,t))+k_3 (Q_{1,j} x,t)-Q_{1,j})(x,t)), \quad 2)$$

$$(\partial Q_{nj}(x,t))/\partial t=k_4\cdot(Q_{TP}(x,t)-Q_{nj}(x,t))+k_3\cdot Q_{n-1,j}(x,t)-Q_{nj}(x,t)) \quad 3)$$

$$(\partial F_{1j}(x,t))/\partial t=k_5 (F_{2j}(x,t)-F_{1j}(x,t))+k_6 (Q_{ucx,j})(x,t)-Q_{ij}(x,t))\, F_{1j}(x,t), \quad 4)$$

$$(\partial F_{ij}(x,t))/\partial t=k_6\cdot(F_{i+1,j})(x,t)-F_{ij}(x,t))+k_6\cdot(F_{i-1,j)})(x,t)-F_{ij}(x,t)), \quad 5)$$

$$(\partial F_{nj}(x,t))/\partial t=k_6\cdot(F_{n-1,j})(x,t)-F_{nj}(x,t)). \quad 6)$$

The algorithm for such system developing is shown in Fig.4.

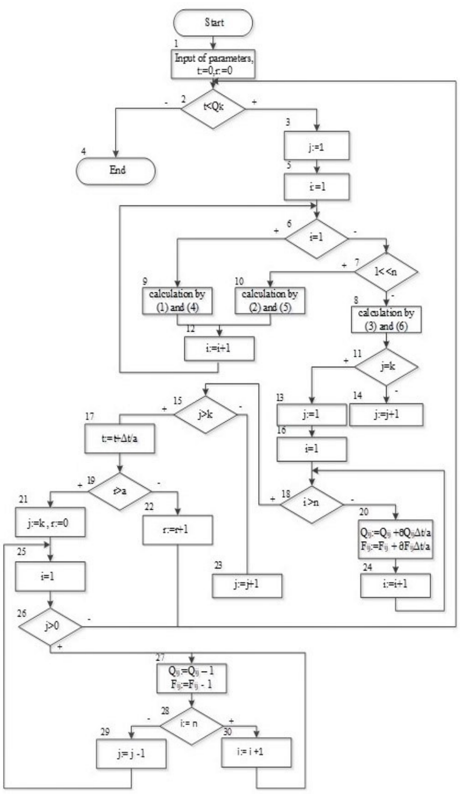

Figure 4 – Algorithm for developing systems with different parameters

The peculiarity of the algorithm is that it contains, in addition to the time cycle (beginning of the cycle block 2) and the size class (beginning of the cycle - block 6) another nested cycle by stage number (beginning of the cycle and its verification blocks 12,16). The cycles are nested in each other, due to which the distribution of the calculated parameters is achieved. Differential equations describing the system are in blocks 8,9,10 and are nested in cycles by size class and stage number. That is, on each cycle it is necessary to calculate separately changes not only characteristics on a size class of processed ore, but also on each stage.

To solve the problem of optimization of large dynamic systems, characterized by interactions between their components, used decomposition-coordination approach, which involves the transformation of the system structure by decomposing the global system and control tasks into many separate subsystems and individual subtasks [12]. To solve a global problem, two- or multi-level structures with coordinating variables are used, which reduces the complexity of their solution by reducing the main problem to a number of subtasks, each of which is smaller and easier to solve. The proposed procedure for the synthesis of decentralized management in the form of a structure with distributed parameters is based on the work [13-15]. Thus, for the synthesis of optimal control of the complex it is necessary to form subsystems of the lower level of control of each stage of the technological process as a structure with distributed parameters and control of the upper level, which realizes the achievement of the general criterion of optimality. This approach involves the decomposition of the control problem (CS) into temporal (TS) and spatial (SS) synthesis in a closed loop control system with distributed parameters (Fig. 5). In such a system, the loops in the TS block can be configured as normal closed control loops, in which the transfer functions describe the dynamics between the input and output sequences [15].

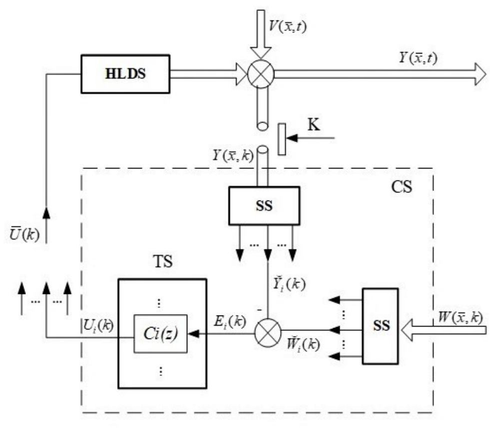

Figure 5 – Closing the control loop with different parameters

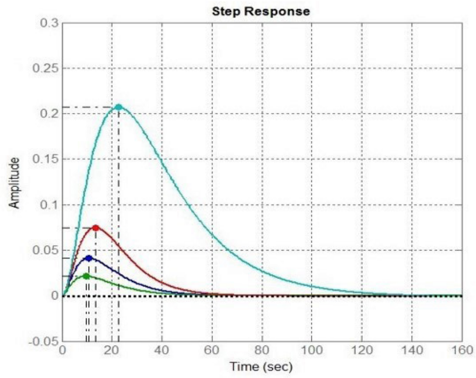

Figure 6 – Influence of the static transfer coefficient of the control object model on the quality of the transient process: K1 = KH; K2 = 2KH; K3 = 0,5KH; K4 = 0,1KH

Fig. 5 uses the following notation: K – sample shaper, – perturbation, – distributed adjustable variable, – selective distributed adjustable variable, – parameters of approximation of the adjustable variable, – impact of the task, – parameters of approximation of the impact of the task, – management error, – concentrated variable controllers, – concentrated control variables.

Analysis of the results of synthesis of the optimal linear-quadratic controller in the closed control loop TS shows high qualitative characteristics, the control synthesis is performed by solving a spatial problem based on approximation of the distributed objective control function and time - by optimizing the closed control loops SISO with concentrated parameters. Fig. 6 shows the influence of variations in the static transmission coefficient of the control object model on the quality of the transition process in a closed control loop TS at different values of K. For coordinated control separating stages the complex, method is optimization of nonlinear dynamical systems with a decentralized control structure is used, which applies the principle of minimizing generalized work [14,15] and the decomposition-coordination approach proposed in [16]. In which controllers of local subsystems receive current information about their subsystem and information about the trajectories of reference models of all other subsystems. Such a scheme is classified as an adaptive decentralized control scheme with model coordination and guarantees not only the stability of a closed system, but also asymptotic tracking of given reference trajectories with zero error in the presence of uncertainties in subsystems and relationships.

In which controllers of local subsystems receive current information about their subsystem and information about the trajectories of reference models of all other subsystems. Such a scheme is classified as an adaptive decentralized control scheme with model coordination and guarantees not only the stability of a closed system [20], but also asymptotic tracking of given reference trajectories with zero error in the presence of uncertainties in subsystems and relationships.

For coordinated control of individual stages of the complex, the method of optimization of nonlinear dynamical systems with a decentralized control structure is used, which applies the principle of minimizing generalized work [14] and the decomposition-coordination approach proposed in [15] in which controllers of local subsystems receive current information about their subsystem and information about the trajectories of reference models of all other subsystems. Figures 7–8 show for example the coordinating and resulting actions under this control law.

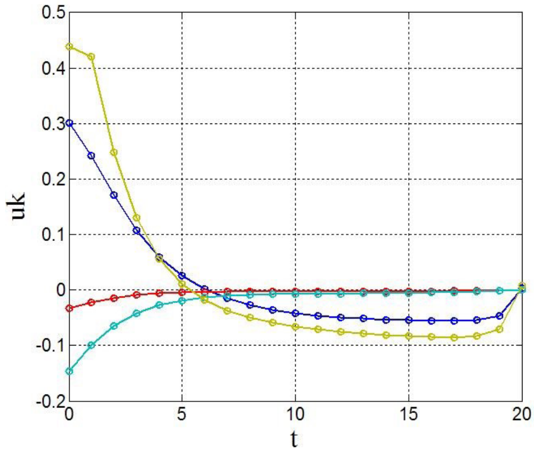

Figure 7 – Coordinating controls uk(t)

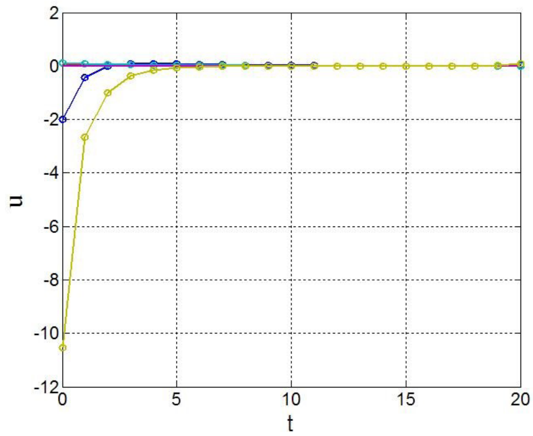

Figure 8 – The resulting control actions u(t)

The use of the considered approach for solving optimization problems of decentralized control of the crushing and grinding complex made it possible to make iterative procedures for synthesizing algorithms more efficient and obtain better convergence rates compared to traditional ones [13,17].

Model coordination of local subsystems allows, on the one hand, to reduce the complexity of calculating optimal controls, and on the other, provides the system with additional robustness properties in the presence of various uncertainties in the system model, while remaining within the optimality for the nominal system model [18,19].

In Fig. 9 is a functional diagram of the ore preparation process control system based on a model with distributed parameters, which consists of a distributed regulator 1, which receives correction information from

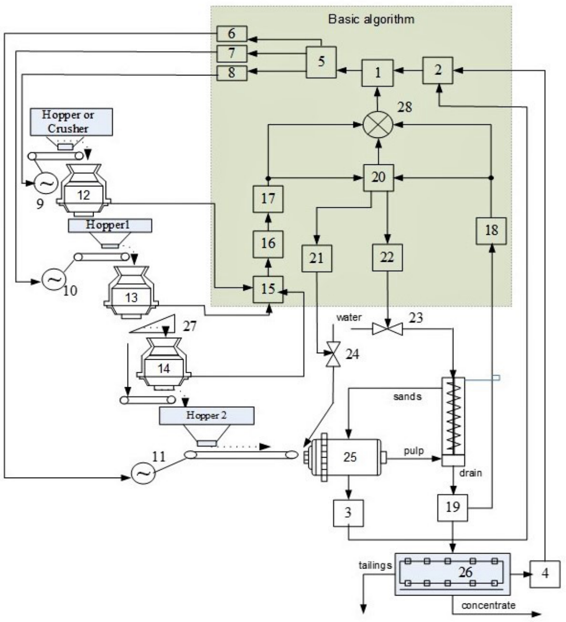

Figure 9 – Functional block diagram of the ore preparation process control system

the second unit 2 of calculations of the ratio of parameters of the consumed active power from the active power sensors of the ball mill drive motors 3 and the magnetic separator 4 respectively, and the output of the distributed regulator is connected in series to the unit 5 of the implementation of the coordinated control of ore performance regulators 6, 7, 8, which, controlling the speed of feeders 9, 10 11 corresponding stages 12, 13, 14, change the productivity of the technological line for ore in such a way as to provide an optimal mode of processing raw materials, subsystems for collecting information from technological sensors 15, which receives information about the level of filling and productivity of the corresponding stages of crushing, connected in series with the unit 16 of transformation and rationing, the output of which is connected to the input of the unit 17 calculation of parameters of the ore distribution function by size, the second Block 18 calculation of parameters of the ore distribution function by size to the input of which the sensor 19 of the content of class 74 microns is connected in the drain of the classifying device, the outputs of two blocks of calculation of parameters of the ore distribution function by size are connected to the input of the block 20 calculation of the ratios of granulometric characteristics, one of the outputs of which is connected to the regulator 21 the control position of the water supply valve 22 in the classifying device of the first stage of grinding 23, and the second output together with the outputs of the units of calculation of parameters of the ore distribution function by size is connected to the adder 24, which is connected to the second input of the distributed regulator.

The main part of the algorithm works as follows [18]. Information about the state of the technological process coming from subsystem 15 collecting information from sensors of productivity and filling level at the first 12, second 13 and third 14 stages of crushing passes primary processing and transformation into a convenient form for further operations in the block 16 transformation and rationing, after which it falls into the first Block 17 calculations of parameters of the function of distribution by size of raw materials that are processed.

Since for effective control it is advisable to consider the crushing and grinding complex as a single whole, so the device contains the second Block 18 calculations of parameters of the ore distribution function by the size of the first stage of grinding, the input of which receives information from the sensor 19 of the content of the class 74 microns in the drain of the classifying device, and the output is connected to the block 20 calculations of the ratio of granulometric characteristics, to which the first block 17 calculations of parameters of the ore distribution function by the size of all stages of crushing. Using the data of the calculation blocks 17 and 18 in the block 20 for calculating the ratio of granulometric characteristics, the optimal control characteristic of the regulator 21 connected to its output controlling the position of the water supply valve 22 in the classifying device of the first stage of grinding 23 is calculated, which further maintains the calculated ratio. The output of the block 20 is also connected to the adder 24 to which the outputs of blocks 17, 18 are connected for calculating the parameters of the ore distribution function by size of all stages of crushing and grinding, respectively, and the output of the adder 24 is connected to a distributed regulator 1, which performs coordinated control of the distributed process. Correction of the parameters of the distributed regulator 1 is carried out by the second unit 2 calculation of the ratios of the parameters of the active power consumed 3 consumed by the ball mill drive motor and the active power sensor 4 consumed by the magnetic separator drive motor, which acts as a natural indicator of the quality of the technological process. Moreover, the maximum value of the active power consumed by the drive electric motor of the magnetic separator corresponds to the maximum productivity of the complex of extracted magnetic iron and is determined by the optimal values of the degree of filling of the mill with ore, balls, pulp density in the mill, and the drain density of the classifying device. The output of the distributed regulator 1 is connected to the control unit 5 of the ore productivity regulators, which, using an integral criterion, forms a coordinated control of the multi-stage process of reducing the ore size by a crushing and grinding complex, taking into account the speed of formation of certain ore size fractions, productivity and unit costs for the production of a unit of the initial product of each stage. The control signals of the unit 5 are sent to the regulators 6, 7, 8 of the ore productivities of the corresponding stages, which control the speed of feeders 9, 10 and 11, changing the productivity of the technological ore treatment line in such a way as to ensure with minimal energy consumption the formation and maintenance of optimal productivity and granulometric composition of the initial products of interconnected crushing and grinding units.

Conclusion. Method for controlling a crushing and grinding complex, which includes presenting it as a model of series-connected crushing and grinding units, as well as managing their productivity based on the formed model, which differs in that the model is crushing - the crushing complex is represented as a multi-stage structure with distributed parameters of the ore size reduction function, each stage of which is characterized by an area of optimal productivity, specific energy consumption and resource intensity, and the lowest energy consumption per unit of the initial product of the crushing and grinding complex is achieved by controlling its productivity and the degree of reduction of the size of each stage.

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РУДАҒЫ ДАЙЫНДАЛУ ПРОЦЕССТЕРІН БЕЙІМДЕП БАСҚАРУ ҮШІН БӨЛІНГЕН ПАРАМЕТРЛЕРІМЕН ҚҰРЫЛЫС ТҮРІНДЕ ҰНДАУ-ҰСАТУ КЕШЕНІНІҢ ҰСЫНЫСЫ

Аннотация. Мақалада бүкіл кенді дайындау процесінің энергия тиімділігін арттыру мақсатында кен көлемін кішірейту функциясында таралған параметрлері бар жүйе түрінде усату – ұнтақтау кешенін ұсыну ұсынылған. Қазіргі кезде кенді дайындау процесінде отандық және шетелдік өндірістің технологиялық процесін басқарудың әртүрлі автоматтандырылған жүйелері қолданылып жатқанына қарамастан, энергия шығындарын азайту үшін де, өсіру үшін де мұндай объектілерді оңтайлы басқару мәселелерін шешу қажеттілігі бар соңғы өнім сапасының тиімділігі. Энергия тұтыну тұрғысынан ұнтақтау процестері ұсақтау процестерінен жоғары, сондықтан бүкіл процестің энергия тиімділігін арттыру үшін ұсақтау және ұнтақтау кешенін тұтас қарастыру қажет.

Ұсақтау, ұнтақтау және жіктеу процестері тек кездейсоқ болғандықтан және кез-келген сәтте ауысу ықтималдығы мен сипатталады, ал усату және ұнтақтау кешені алкен аумақты алып, кеңістікте географиялық таралған, он таралған параметрлері бар жүйе ретінде қарастыруға болады. Осы кешеннің жекелеген компоненттері арасындағы жүктемелерде өңделген кеннің ағымдағы сипаттамаларына және технологиялық жабдықтың күйіне сәйкес қайта бөлу соңғы сатыдағы – ұнтақтау кезіндегі жүктемені азайтуға мүмкіндік береді, бұл өз кезегінде энергия шығындарының жалпы төмендеуіне ықпал етеді .

Бұл тәсілдің ерекшелігі – объектіні кеңістіктік үлестірілген басқару негізінде кеңістіктік – уақыттық басқару элементтерін қалыптастыру, кері байланыс сигналдарымен кеңістіктік бөлінген басқару әрекеттері бар контроллерлерді қолдану қажеттілігі.

Түйін сөздер: адаптивні бақылау, ұсату және ұнтақтау кешені, үлестірілген параметрлер, кен мөлшерін азарту функциясы.

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ПРЕДСТАВЛЕНИЕ ДРОБИЛЬНО-ИЗМЕЛЬЧИТЕЛЬНОГО КОМПЛЕКСА В ВИДЕ СТРУКТУРЫ С РАСПРЕДЕЛЕННЫМИ ПАРАМЕТРАМИ ДЛЯ АДАПТИВНОГО УПРАВЛЕНИЯ ПРОЦЕССАМИ РУДОПОДГОТОВКИ

Аннотация. В статье предлагается представление дробильно-измельчительного комплекса в виде системы с распределенными параметрами в функции сокращения крупности руды с целью повышения энергоэффективности всего процесса рудоподготовки. Несмотря на то, что в настоящее время в рудоподготовительных процессах используется множество различных автоматизированных систем управления технологическим процессом отечественного и зарубежного производства, по-прежнему существует необходимость решения задач оптимального управления такими объектами с целью как снижения затрат энергии, так и повышения эффективности качества конечного продукта. С точки зрения энергопотребления процессы измельчения превосходят процессы дробления, поэтому необходимо рассматривать дробильно-измельчительный комплекс в целом, чтобы повысить энергоэффективность всего процесса.

Поскольку процессы дробления, измельчения и классификации являются чисто случайными и в любой момент характеризуются переходными вероятностями, а дробильно-измельчительный комплекс занимает большую площадь и географически распределен в пространстве, его можно рассматривать как систему с распределенными параметрами в функции сокращения крупности руды. Перераспределение нагрузок между отдельными компонентами этого комплекса в соответствии с текущими характеристиками перерабатываемой руды и состоянием технологического оборудования позволяет снизить нагрузку на завершающую стадию - измельчение, что в свою очередь способствует общему снижению энергозатрат.

Особенностью данного подхода является необходимость формирования пространственно-временных элементов управления на основе пространственно-распределенного управления объектом, использования соответствующих сигналов обратной связи и регуляторов с пространственно-распределенными управляющими воздействиями.

Ключевые слова: адаптивное управление, дробильно-измельчительный комплекс, распределенные параметры, функция сокращения крупности руды.

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