

## The Energy-Saving Control Criterion for Impact Crushing Machines

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**Abstract.** The purpose of the article is to substantiate the use of a new criterion for controlling the grinding technological process to improve the use of electrical energy. The subject of the study is the process of using electrical energy in impact grinding machines. The set goal is achieved by solving the following problems: analyzing the energy of the grinding process, determining the parameters of raw materials and operating modes of the electric drive that affect the efficiency of electrical energy usage. Based on theoretical research, a mathematical model of energy consumption in grinding processes has been developed. Analytical studies of the resulting mathematical model showed the nonlinear extreme nature of the specific energy consumption of the grinding process with changing raw material parameters and operating modes. This creates the prerequisites both for using specific electrical energy costs as a control criterion and for the use a controlled electric drive to achieve maximum energy savings. The most important result is that the operating modes of grinding machines could be established by more efficient use of electrical energy. The significance of the work lies in the fact that by adapting the operating modes of the electric drive to the current parameters of the raw materials and the state of the equipment make possible to reduce the specific electrical energy consumption up to 15% and this is the basis for using a criterion based on specific costs in control systems for technological processes with grinding impact machines. For further application of the obtained results it is necessary to conduct experimental studies to confirm the increase in the efficiency of electrical energy use.

**Keywords:** control criterion, energy consumption, mathematical model, adjustable electric drive, grinding.

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### Criteriul de control al economisirii energiei pentru mașinile de șlefuit cu impact

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**Rezumat.** Scopul articolului este de a fundamenta utilizarea unui nou criteriu de control al procesului tehnologic de măcinare pentru a îmbunătăți utilizarea energiei electrice. Subiectul studiului este procesul de utilizare a energiei electrice în mașinile de șlefuit cu impact. Scopul stabilit este atins prin rezolvarea următoarelor probleme: analiza energiei procesului de măcinare, determinarea parametrilor materiilor prime și a modurilor de funcționare ale acționării electrice care afectează eficiența utilizării energiei electrice. Pe baza cercetărilor teoretice, a fost elaborat un model matematic al consumului de energie în procesele de măcinare. Studiile analitice ale modelului matematic rezultat au arătat natura extremă neliniară a consumului specific de energie al procesului de măcinare cu modificarea parametrilor materiilor prime și a modurilor de operare. Acest lucru creează premisele atât pentru utilizarea costurilor specifice cu energia electrică ca criteriu de control, cât și pentru utilizarea unei acționări electrice controlate pentru a obține economii maxime de energie. Cel mai important rezultat este că modurile de funcționare ale mașinilor de șlefuit ar putea fi stabilite printr-o utilizare mai eficientă a energiei electrice. Semnificația lucrării constă în faptul că, prin adaptarea modurilor de funcționare ale acționării electrice la parametrii actuali ai materiilor prime și starea echipamentului fac posibilă reducerea consumului specific de energie electrică cu până la 15% și acesta este baza de utilizare a unui criteriu bazat pe costuri specifice în sistemele de control pentru procesele tehnologice cu mașini de șlefuit cu impact. Pentru aplicarea în continuare a rezultatelor obținute este necesară efectuarea unor studii experimentale care să confirme creșterea eficienței utilizării energiei electrice.

**Cuvinte-cheie:** criteriu de control, consum de energie, model matematic, acționare electrică reglabilă, mărunțire.

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**Аннотация.** Целью статьи является обоснование применения нового критерия управления технологическим процессом измельчения, который позволит достичь улучшения использования электрической энергии. Предметом исследования является процесс использования электрической энергии в измельчающих машинах ударного действия. Поставленная цель достигается решением следующих задач: анализом энергетики процесса измельчения, определением параметров сырья и режимов работы электропривода, влияющих на эффективность использования электрической энергии. На основании теоретических исследований разработана математическая модель энергозатрат в процессах измельчения. Исследования полученной математической модели показали нелинейный экстремальный характер удельных энергозатрат процесса измельчения при изменяющихся параметрах сырья и режимах работы. Это создает предпосылки как для использования в качестве критерия управления удельных затрат электрической энергии, так и необходимости применения регулируемого электропривода для достижения максимального энергосбережения. Наиболее важным результатом является то, что установлено наличие режимов работы измельчающих машин, позволяющих более эффективно использовать электрическую энергию, затрачиваемую на технологический процесс. Значимость работы состоит в том, что за счет адаптации режимов работы электропривода к текущим параметрам сырья и состоянию оборудования достигается снижение удельных расходов электрической энергии на величину до 15%, а это является основой для использования критерия на основе удельных затрат в системах управления технологическими процессами с измельчающими машинами ударного действия. Для дальнейшего применения полученных результатов необходимо проведение экспериментальных исследований с подтверждением повышения эффективности использования электрической энергии.

**Ключевые слова:** критерий управления, энергозатраты, математическая модель, регулируемый электропривод, измельчение.

**INTRODUCTION**

The search for methods and means of reducing energy consumption for technological requirements is a problem that will be relevant both in the present and in the near future. The solution to the problem lies not only in the search for non-traditional sources of electricity and methods of their use, but also in an in-depth study of the technological process energy. At the same time, the implementation of energy saving in technological systems is a more difficult task. As a rule, this is due to the presence of certain restrictions on the operation of machine drive modes that is determined by technological requirements for input raw materials, intermediate stages of the process and finished products. Thus, to solve the problem of finding energy-saving methods in impact grinding machines with an adjustable electric drive, the following problems must be solved:

1) analyze the energetics of work processes that take place in impact crushers and determine the main factors affecting the energy consumption of the process;

2) develop a theoretical model that allows you to determine the relationship between raw material parameters, equipment operating modes, and energy consumption for work processes in impact crushers;

3) conduct an analytical study of the model and establish the nature of the influence of operating modes and raw material parameters on energy consumption in impact crushers;

4) to establish the presence of the prerequisites for influencing the work process energy consumption in impact crushers due to the change of operating modes and the application of new control criteria when using an adjustable electric drive;

5) to determine a new criterion for energy-saving control of impact crushers and justify the feasibility of its use in the control of technological systems with an adjustable electric drive;

6) to draw conclusions and give an assessment of the application of the energy-saving criterion for the control of the impact crushing machines with an adjustable electric drive.

Bringing the input raw materials to the required granulometric composition is one of the key technological operations in the food, fodder and mining industries of the national economy. In the vast majority, this technological stage is the foundation for ensuring the quality indicators of finished products within the given limits. At the same time, as the analysis of modern production shows, this technological operation is the stage of the technological process in which the energy intensity is the greatest [1, 2]. It is natural that the general situation in today's energy resources market determines the constant scientific interest in conducting research in the field of energy efficiency analysis of grinding technological processes. This is evidenced by the number of scientific studies in this direction in recent years [1, 3, 4-7].

As a rule, all modern technological processes are controlled by automatic regulation systems, the behavior of which is based on a certain criterion or a system of criteria [1, 5-9].

Thus, in work [1] the authors analyzed various strategies for controlling the grinding process and gave their comparative analysis. The study of the processes occurring during grinding was given by the authors in [10] and it has as a criterion the achievement of maximum equipment performance. The search for a solution to the problem of overall economic efficiency of production is also proposed as a management criterion in work [8]. The authors of the work proposed an extreme search management system based on an economic quality criterion.

The research results presented by the authors in [3] give reason to assume an extreme nature for optimal operating modes and their instability when the composition and properties of raw materials change. This article also talks about the shortcomings and difficulties encountered when using standard control criteria based on the load current of the electric drive of grinding machines.

The research results presented in [5] are of particular interest. Here it was considered the influence of the design parameters of machines for grinding biomass on the specific costs of electrical energy. The research materials make it possible to significantly narrow the range of many factors influencing energy costs.

It should be noted that the analysis of the energy efficiency of the technological process from the point of view of the electrical energy

use efficiency is practically not used in the control criteria. The need to conduct research in order to develop such a criterion becomes even more relevant in view of both the situation on the energy market and from the point of view of the constant increase in the electricity cost share in the production total costs [12, 13].

At the same time, scientific research in the field of studying the working processes of impact crushers provides a stable basis for the analysis of the working process energy use efficiency and the synthesis of the appropriate control criterion [14-16]. The expediency for a such research conducting is additionally supported by the availability of the modern technical tools in the field of adjustable electric drives and their control hardware. It becomes possible to find a relatively simple implementation for the complex technological system disintegration into elementary operations based on the architecture using local control controllers, so it makes possible some significantly simplify for the solution to improve the electrical energy use efficiency due to its implementation separately in each technological unit, but with the presence of appropriate control criteria.

## I. RESEARCH METHODS

Impact grinding machines used in flow processing systems can be classified by the presence of a corrugated deck, the angle of coverage of the sieve and the direction of feed of raw materials into the grinding chamber [3, 11]. At the same time, regardless of the design features of the machine, the process of grinding raw materials can be divided into two stages: grinding by hitting the raw materials against the hammer and deck and subsequent processing by grinding in the annular area formed by the rotating edges of the hammers and the surface of the sieve [10,11]. In this way, the use of electric power for grinding work processes in impact crushers can be described by the equation:

$$W_{cr} = W_{idl} + W_{ht} + W_{fr}, \quad (1)$$

here  $W_{ht}$  - the energy consumption when the hammers of the rotor collide with the flow of raw materials fed into the crushing chamber, J;  $W_{fr}$  - energy consumption in the annular layer, J;  $W_{idl}$  - idling energy consumption, J.

In order to obtain the necessary results, let us consider the processes in more detail. When raw materials enter the working chamber of the

machine, a collision of raw material particles with the rotor hammers occurs. As a result, the particles either collapse or bounce off the hammer. In this case, an exchange of energy and momentum occurs between the hammer and the particle. As a result, the rotor loses energy and slows down, and the energy transferred to the particle goes towards its destruction and (or) heating [11]. This case represents a partially elastic collision of two bodies. Suppose that the impact of a particle on a hammer is central - then according to [11] the energy consumption during the collision of two bodies can be described by the equation:

$$\Delta W = \frac{m_1 m_0}{2(m_1 + m_0)} (v_m - v_0)^2 (1 - k^2), \quad (2)$$

Here  $m_1$  – hammer mass, kg;  $m_0$  – particle mass, kg;  $v_m$  – linear speed of the hammer before co-impact, m/s;  $v_0$  – linear velocity of the particle before the collision, m/s;  $k$  – the recovery coefficient determined by the type of raw material and which characterizes the degree of elasticity [11].

The material flow moves at speed  $\bar{v}_0$  under the axial feed (see Fig. 1a, point 1). At the same time, the tangential component of the initial velocity is much smaller than the radial one  $\bar{v}_{0p}$ . Besides, the velocity of the particle before the collision is much smaller than the velocity of the hammer ( $\bar{v}_0 \ll \bar{v}_m$ ), so in equation (2) it can be assumed that  $v_0 \approx 0$ .

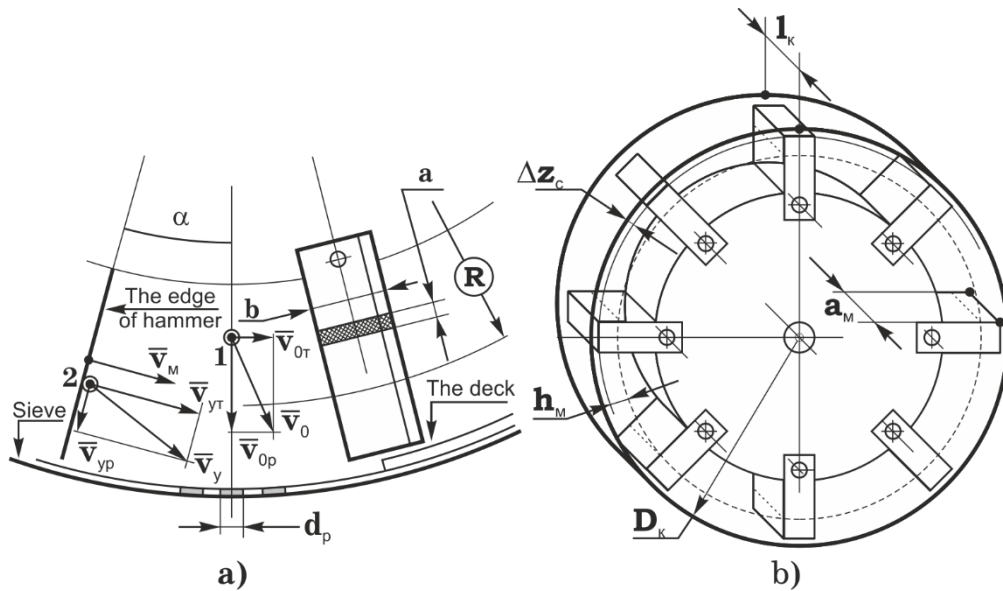


Fig. 1. The scheme for the grinding process energy calculation.

Let us assume that the flow of raw materials entering the crushing chamber is distributed evenly across the width of the row of crushing drum rotor hammers and that particles of the loaded material do not pass between the hammers. Thus, further interaction can be considered as the interaction of a monolithic row of hammers with a flow of components. Based on the above and equation (2), we can write down the expression that determines the energy consumption per second:

$$\Delta W = \frac{m_1 m_0 v_m^2}{2(m_1 + m_0)} (1 - k^2), \quad (3)$$

Here  $m_0$  – the mass of particles colliding with a row of hammers, kg,  $m_1$  – the mass of a row of hammers, kg.

Let us assume that the flow of raw materials entering the crushing chamber is distributed evenly across the width of the hammers of the crushing drum rotor. In this case, due to the high rotation speed of the rotor and the small distance between the hammers in a row (and in addition, hammers in two adjacent rows of the rotor are usually installed in a checkerboard pattern), it can be assumed that particles of the loaded material do not pass between the hammers. Consequently, further interaction can be considered as a collision of a continuous row of hammers with a flow of components, while the mass of the row is:

$$m_l = m_l z_{hl}, \quad (4)$$

Here  $m_l$  – the mass of one hammer, kg;  $z_{hl}$  – the number of hammers in a row.

Preliminary calculations show that due to the significant total mass of a series of hammers compared to the mass of colliding particles ( $m_0 \ll m_l$ ), it can be assumed that:

$$m_l + m_0 \approx m_l. \quad (5)$$

Then equation 3 will take the form:

$$\Delta W = \frac{m_0 v_m^2}{2} (1 - k^2). \quad (6)$$

Let  $q$  be the value that determines the second loading of the crusher, then the mass of particles colliding with a row of hammers:

$$m_0 = \frac{q}{n_c x_{hm}}, \quad (7)$$

here  $n_c$  – the rotor rotation frequency, rpm;  $x_{hm}$  – the number of rows of hammers on the rotor.

Let's determine the power consumption required to overcome the moment of resistance caused by the rotor collision with the material flow:

$$\begin{aligned} \Delta P_{ht} &= \frac{\int_0^t \Delta W}{t} = \frac{q v_m^2 (1 - k^2)}{2 n_c x_m} n_c x_m =, \quad (8) \\ &= \frac{1}{2} q v_m^2 (1 - k^2) \end{aligned}$$

Here  $t$  – the time spent on the grinding process, s.

After integrating equation (8) over time, we've got a simplified expression which can be used to determine the energy consumption for the destruction of raw materials by impact:

$$W_{ht} = \frac{1}{2} \int_0^T q v_m^2 (1 - k^2) \cdot dt. \quad (9)$$

The linear speed at a co-impact can be calculated as [17, 18]:

$$v = 2\pi n R, \quad (10)$$

here  $R$  – the radius at which the hammer collides with the raw material particles, m.

Then equation (8) can be rewritten in the form:

$$W_{ht} = \frac{1}{2} \int_0^T q (2\pi n R)^2 (1 - k^2) \cdot dt. \quad (11)$$

The working process in the grinding chamber occurs in such a way: a layer of material is formed and here the final destruction of particles occurs to a given granulometric composition. Let's determine the energy consumption of this part of the work process. In its essence and nature, the process occurring at this stage of the process is similar to the energy of the processes that occur when cultivating the soil with the rotor of a working tool such as a cutter [3, 19]. Moreover, the peculiarity of this case is that the energy can be determined as in the case of a complete absence of linear supply of the working body into the grinding medium. The power required to drive the cutter rotor in the absence of its supply to the environment can be calculated according to the equation [19]:

$$P_{fr} = 10^{-4} \frac{\kappa_{ev} c h z_h n_p}{6}, \quad (12)$$

Here  $\kappa_{ev}$  – the coefficient of specific resistance of the medium to cutting, N/m;  $z_h$  – the number of cutter teeth on the rotor;  $c$  – tooth width, m;  $h$  – penetration of the teeth into the soil layer, m;  $n_p$  – rotation frequency of the drive shaft, rpm.

Taking into account certain assumptions, the model of the process of rotation of the crusher rotor in the chamber material layer can be adapted to equation (12). During the operation of the cutter, only the sector of the lower part of the working body is in direct contact with the soil, and power losses are caused by the movement of the knives in this volume of material [9]. The energy consumption during the operation of the hammers in the annular layer between the sieve and the rotor is determined by the work to overcome the forces of friction against the side walls of the hammer and the resistance of the medium to the hammer

movement. Moreover, unlike a milling cutter, the entire surface of the rotor is in contact with the material layer (see Fig. 1b). Thus, power losses in the annular layer of the camera can be determined by the equation [19]:

$$\Delta P_{\kappa} = \kappa_c a h_h \pi (D - \Delta z_c) \cdot z_h n, \quad (13)$$

Here  $\kappa_{cp}$  – the specific resistance of the raw material in relation to the movement of the rotor hammers in it, MPa;  $a$  – width of a row of hammers, m;  $h_h$  – depth of hammers in the annular layer, m;  $D$  – diameter of the crusher chamber, m;  $\Delta z_c$  – the gap between the ends of the hammers and the sieve surface, m;  $n$  – the rotation frequency of the crusher rotor,  $s^{-1}$ .

Let's determine the depth of the knives in the material layer of the crushing chamber. In the steady mode of operation of the crusher, the amount of incoming product is equal to the amount removed from the working chamber. Moreover, the maximum value of the last value is limited and determined by the granulometric composition of the finished raw material and the throughput capacity of the crusher sieve. From the above, it can be concluded that the height of the material layer in the crushing chamber is a function of the crusher loading  $q$ . Let's determine the depth of the rotor hammers  $h_{hm}$  depending on the substance amount in the chamber.

According to fig. 1 the ring area formed by the deepening of the hammers in the material layer is calculated as:

$$S = \pi \left( \left( \frac{D}{2} - \Delta z_c \right)^2 - \left( \frac{D}{2} - \Delta z_c - h_{hm} \right)^2 \right). \quad (14)$$

After performing the transformation:

$$S = \pi h_m (D - 2\Delta z_c - h_m). \quad (15)$$

Then the volume of the cylinder formed by the deepening of the hammers  $h_{hm}$  and the ends of the rotor knives (see Fig. 1b) across the entire width of the crusher chamber will be determined by the equation:

$$V = \pi h_m h_{hm} (D - 2\Delta z_c - h_m). \quad (16)$$

If we divide the right and left sides of equation (16) by  $\pi h_m$  and open the brackets in the right side of the equation we get:

$$\frac{V}{\pi h_m} = \frac{\pi h_m h_{hm} D - 2\pi h_m h_{hm} \Delta z_c - \pi h_m h_{hm}^2}{\pi h_m}. \quad (17)$$

After performing the transformation:

$$h_m^2 + h_m (2\Delta z_c - D) + \frac{V}{\pi h_m} = 0. \quad (18)$$

Solving the quadratic equation (18) with respect to  $h_{hm}$  we've got:

$$h_{hm} = \frac{(-2\Delta z_c + D) \pm \sqrt{(2\Delta z_c - D)^2 - \frac{4V}{\pi h_m}}}{2} \quad (19)$$

For physical reasons (due to the fact that  $h_{hm} < D/2$ ) in solution of equation (19) the root can be unambiguously preceded by the sign "-". In steady state the amount of raw material entering the chamber is equal to the amount of raw material removed from the chamber through the sieve:

$$q = \frac{dm_2}{dt}, \quad (20)$$

here  $m_2$  – mass removed from the working chamber, kg.

According to [16]:

$$\frac{dm_2}{dt} = \beta m_{\kappa}, \quad (21)$$

Here  $m_{\kappa}$  – mass of the product in the crushing chamber, kg;  $\beta$  – proportionality factor.

The crushing process in hammer crushers is built in such a way that the interaction between the rotor hammers and the surrounding layer of material in the crushing chamber is possible only when  $h_m > 0$ , i.e. when  $m_{\kappa} > m_0$  (since usually  $m_{\kappa} \gg m_0$  then equation 21 in general is valid), where  $m_0$  is the mass of material in the chamber, which corresponds to the filling of the chamber to the level  $\Delta z_c$  (see Fig. 1b). So, a more accurate description of the raw material removing from the impact machine chamber will be given by the equation:

$$\frac{dm_2}{dt} = \beta \cdot (m_k - m_0). \quad (22)$$

According to (20-22) we got:

$$q = \beta \cdot (m_k - m_0). \quad (23)$$

So:

$$m_k = \frac{q}{\beta} + m_0. \quad (24)$$

According to [11, 19], the coefficient  $\beta$  is proportional to the rotor rotation frequency and can be determined as:

$$\beta = \alpha \cdot n_p. \quad (25)$$

here  $\alpha$  – a dimensionless coefficient (depends on the sieve parameters and the gap between the hammers and the sieve),  $\alpha = 0,0015 \dots 0,0023$  [19].

From the known definition of specific gravity, we get:

$$V = \frac{m}{\gamma}, \quad (26)$$

here  $m$  – weight of the product layer, kg;  $\gamma$  – specific weight of the product in the layer, kg/m<sup>3</sup>.

Since the gap  $\Delta z_c$  is sufficiently small in the normal mode, it can be assumed that:

$$m_{hm} = \pi D \Delta z_c \rho_k. \quad (27)$$

So:

$$V = \frac{1}{\gamma} \left( \frac{q}{\alpha n_p} + \pi D \Delta z_c \rho_k \right). \quad (28)$$

If we put (28) into (19):

$$h_{hm} = (D - 2\Delta z_c - \sqrt{(2\Delta z_c - D)^2 - \frac{4 \left( \frac{q}{\alpha n_p} + \pi D \Delta z_c \rho_k \right)}{\rho_k \gamma}}) / 2 \quad (29)$$

After performing the transformation in equation (29) and substituting the value of the layer height, we obtain the equation that determines the power loss in the annular layer:

$$\Delta P_k = (D - 2\Delta z_c - \sqrt{(2\Delta z_c - D)^2 - 4 \left( \frac{q}{\alpha n_p \rho_k \gamma} + D \Delta z_c \right)}) \frac{\rho_{ev} \pi (D - \Delta z_c) z_m \alpha n_p}{2}. \quad (30)$$

By substituting the value (30) into (2) we get an equation that allows us to determine the power consumption for work processes in the chambers of hammer-type crushers:

$$\Delta P_{cr} = \Delta P_{xx} + \frac{1}{2} q v_{hm}^2 (1 - k^2) + (D - 2\Delta z_c - \sqrt{(2\Delta z_c - D)^2 - 4 \left( \frac{q}{\alpha n_p \rho_k \gamma} + D \Delta z_c \right)}) \times \frac{\rho_{ev} \pi (D - \Delta z_c) z_m \alpha n_p}{2}. \quad (31)$$

The raw materials crushed in impact crushers possessing different parameters have a different ability to destroy under impact. In addition, it is known that the humidity of products has a significant impact on energy consumption [10, 12, 20, 21]. On the basis of the conducted research the corresponding coefficients were determined. The introduction of coefficients makes it possible to estimate the actual energy consumption for the process. The numerical values of these coefficients are functionally dependent on the type of raw material and can be estimated according to literature data [19].

The working surfaces of the machines wear out during the normal exploitation. Let  $\zeta$  be a coefficient characterizing the wear degree of the machine working surfaces. Let's assume that it has a directly proportional effect on the amount of energy consumption. Taking into account the condition of the equipment and the type of raw materials the power losses for the work processes in the chamber of hammer-type impact crushers will be determined as:

$$\Delta P_{cr} = \Delta P_{xx} + \frac{\xi q v_{hm}^2 (1-k^2)}{2 \cdot \kappa_{\theta i} \kappa_{pi}} + (D - 2\Delta z_c - \sqrt{(2\Delta z_c - D)^2 - 4 \left( \frac{q}{\alpha n \pi l_{\kappa} \gamma} + D\Delta z_c \right)}) \times \frac{\kappa_{ev} \pi (D - \Delta z_c) z_{\kappa} a n_p}{2} \quad (32)$$

here  $\kappa_{pi}$  – coefficient of rejuvenability of raw materials;  $\kappa_{\theta i}$  – raw material moisture factor.

## II. RESULTS

Using this equation, it is possible to determine the amount of electrical energy spent on technological operations. However, this integral indicator is not sufficiently informative as it does not allow to evaluate the efficiency of the use of electrical energy and realize the reduction of electrical energy consumption in impact crushers. From the point of view of controllability of work processes in impact machines the performance is a function of its loading. At a finite time, the performance can be described by the technological load parameter. Taking into account (32) the specific consumption of electrical energy in the power drive electrical equipment of the grinding machines will be described as:

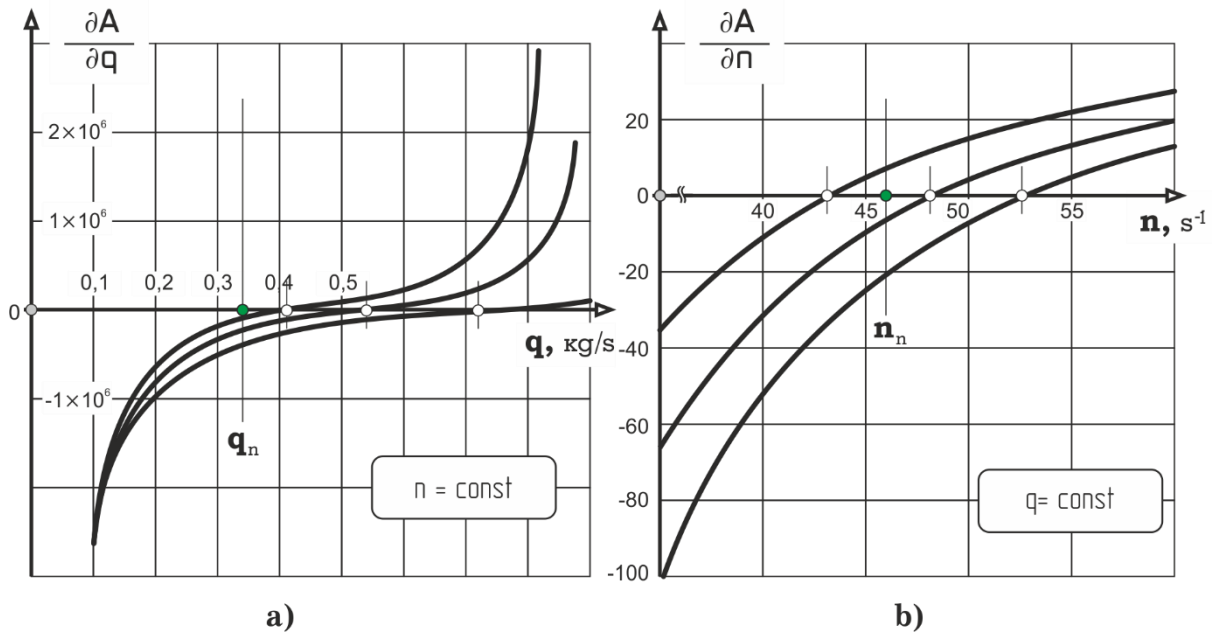
$$A_{cr} = \frac{W_{xx}}{q \eta_{en} \eta_{tr}} + \left[ \frac{\xi v_{hm}^2 (1-k^2)}{2 \cdot \kappa_{\theta i} \kappa_{pi}} + (D - 2\Delta z_c - \sqrt{(2\Delta z_c - D)^2 - 4 \left( \frac{q}{\alpha n \pi l_{\kappa} \gamma} + D\Delta z_{hm} \right)}) \times \frac{\pi \kappa_{cp} (D - \Delta z_c) z_{hm} a n_p}{2 q \eta_{en} \eta_{tr}} \right] \quad (33)$$

Here  $\eta_{en}$  – asynchronous motor efficiency;  $\eta_{tr}$  – engine-working machine transmission efficiency.

It can be seen from the above equation that the factors that most affect the electrical energy use efficiency of impact crushers are: electric drive modes (speed of rotation and loading) and physical and mechanical properties of raw materials (moisture and specific gravity). Thus, it is advisable to analyze the electrical energy use efficiency based on the consideration of the nature of the electrical energy specific consumption for the grinding process for those parameters described above and could be applied as control inputs.

To fulfill the tasks one should conduct a study of equation (33) for the presence of extrema and determine the nature of the behavior of the electric energy specific consumption function within the limits of physically acceptable values of the above-mentioned controlling influences. Let's assume that the mentioned function is defined and differentiated in the entire range of physically permissible values of the control parameters. Then the nature of the behavior of this function can be determined on the basis of the behavior of its derivatives according to the above-mentioned operating mode control parameters. Based on the parameters of a typical unit for grinding using the Mathcad package, one could separate derivative functions of the specific consumption of electrical energy  $A$  calculated based on the variable parameters of the electric drive: the loading of the crushing chamber  $\partial A / \partial q$  and the rotation frequency of the crusher rotor  $\partial A / \partial n$ . On this basis, the graphical dependences  $\partial A / \partial q$  were constructed for various parameters of raw materials in the range of physically permissible loads of the machine (Fig. 2a) as well as  $\partial A / \partial n$  in the range of permissible regulation of the rotation frequency by the electric drive (Fig. 2b).



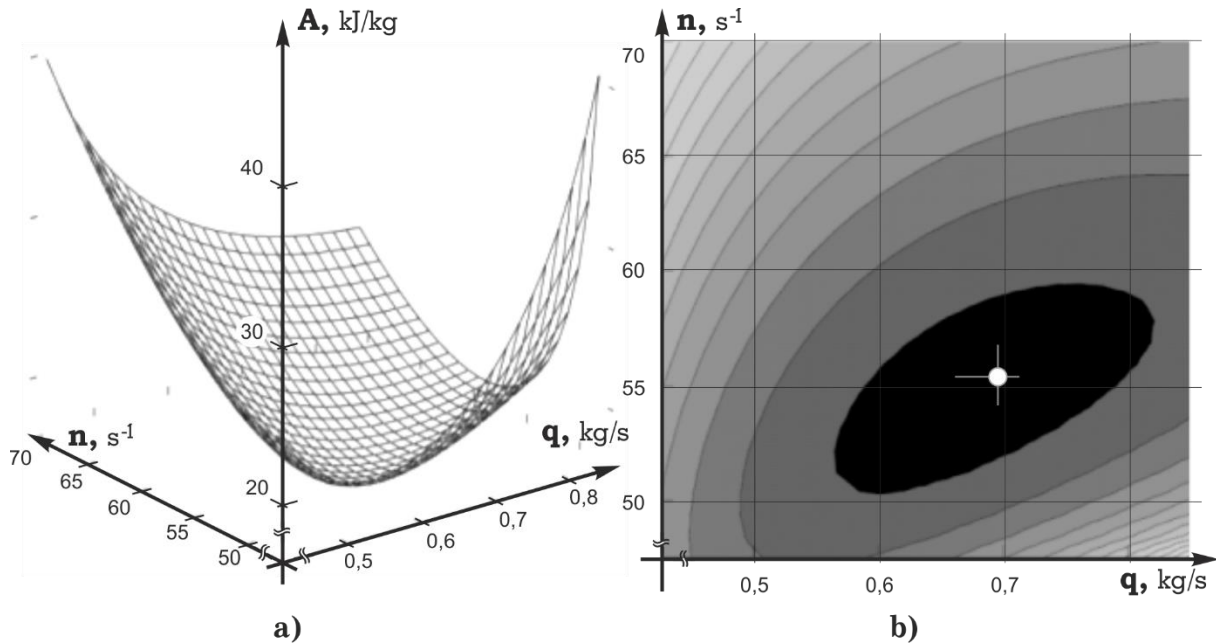


**Fig. 2. Graphical dependences of the private derivatives of the function of the grinding process electrical energy specific consumption according to the variable parameters of the electric drive control:**  
**a – when the load of the crusher chamber changes,**  
**b – when changing the rotation frequency of the crusher rotor.**

Based on the analysis of the above graphical dependencies, it can be concluded that in the plane of both variable operating modes of the electric drive (rotor rotation frequency and camera loading) the function of the specific consumption of electric energy of the grinding process has an extremum [22, 23]. At the same time, it is clearly visible that in the case of adjustment of both electric drive operating modes, like the case of loading, the derivatives change their sign from "-" to "+". It can be asserted that the set points of the extremum are definitely the minimum point according to [22, 23]. It can be stated that in the technologically permissible range of changes in the electric drive operating

modes the function of the electrical energy specific consumption is continuous and has no other extremum points. So, the function reaches its smallest value at the calculation points of the minimum.

Further theoretical studies were carried out by means of analytical calculations also using the Mathcad package. The specific consumption of electrical energy of the power drive electrical equipment was calculated depending on the crusher electric drive operation modes. The corresponding analytical response surface (Fig. 3a) and a map of the electric energy specific consumption level lines (Fig. 3b) were obtained.



**Fig. 3. Theoretical dependences of the electrical energy specific consumption when controlling the variable modes of electric drive operation (the frequency of rotation of the rotor and the loading of the working chamber of the crusher): a – response surface, b – level line map of the response function.**

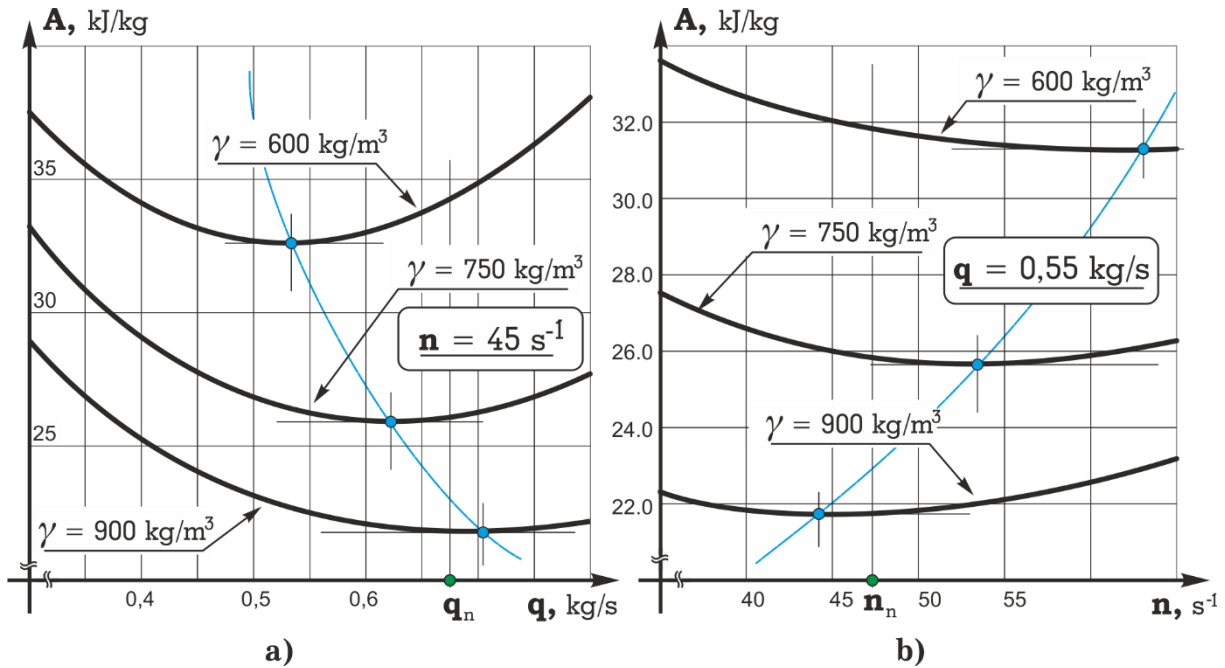
From the analysis of the obtained analytical dependences of the specific consumption of electrical energy it can be concluded that the efficiency of the use of electrical energy for the grinding process in the plane of the above-mentioned variable operating modes of the electric drive has a non-linear extreme character.

At the same time, when controlling the operating modes of the electric drive, both in the plane of changing the rotation frequency ( $n$ ) and in the loading plane ( $q$ ), there is always a value of the operating mode of the electric drive, which corresponds to the minimum specific energy consumption, and therefore to the maximum efficiency of the electric energy use. An important fact is that this mode of operation

is not fixed and changes when a certain value of the control parameter is applied and vice versa.

In order to obtain a complete picture of the energy consumption of the grinding process. It is advisable to study the influence of variable physical and mechanical parameters of raw materials on the efficiency of the electrical energy use in the grinding process. As evidenced by the analysis of literary sources, the most influential parameters are moisture ( $\psi$ ) and specific gravity ( $\gamma$ ) of raw materials.

The obtained calculated graphical dependences (Fig. 4) clearly confirm that the value of the variable operating modes of the electric drive according to the parameters of load and rotation frequency which ensures the



**Fig. 4. Theoretical dependencies of the specific consumption of electrical energy on the grinding process when the specific weight of the raw material changes in different operating modes of the electric drive: a – as a function of load, b – as a function of rotation frequency.**

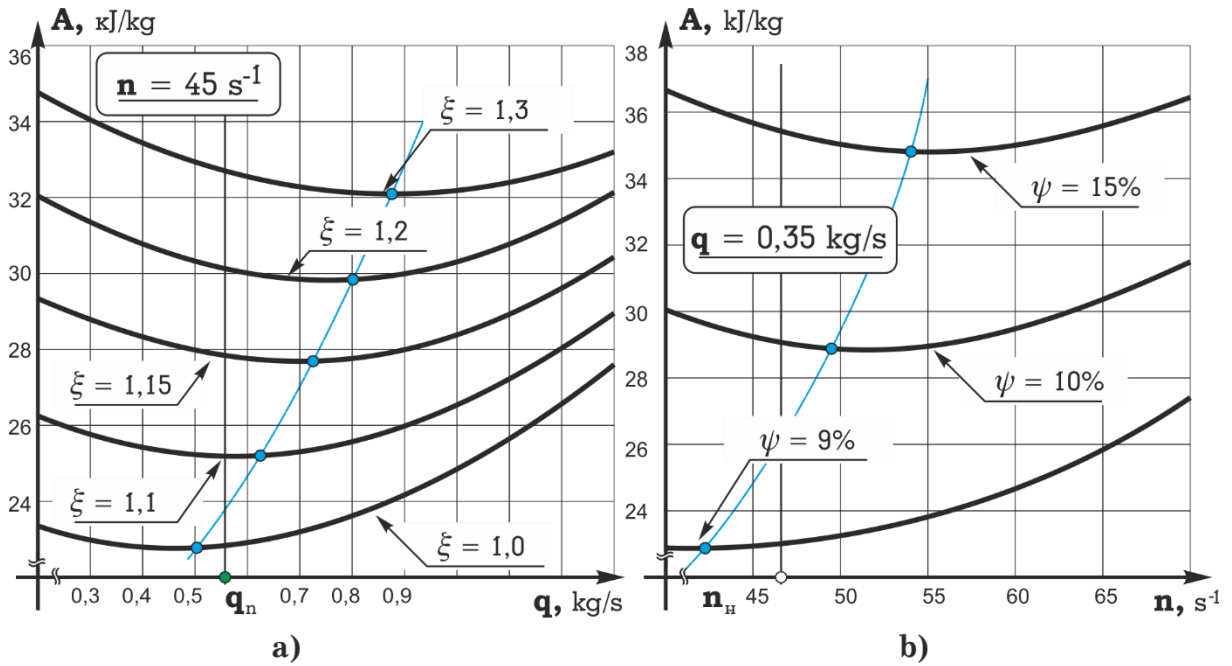
rational use of electrical energy changes when the above physical parameters of the raw materials are varied.

It can be seen that with an increase in  $\gamma$ , the optimal value of  $q$  shifts to a higher direction, and the value of  $n$  - to the zone of lower rotation frequencies. The value of specific costs is inversely proportional to the specific weight change.

With increasing humidity, the optimal value of the rotation speed shifts to the zone of higher speeds, while the change in  $q$  is insignificant, and the value of the specific electrical energy consumption is directly proportional to this parameter of the component (Fig. 5).

An increase in the wear coefficient of working surfaces  $\zeta$  also leads to an increase in specific energy consumption. But the main thing is that the value of the adjustable parameters of the electric drive, which ensure the operation of the equipment with maximum efficiency in the use of electrical energy, also changes.

The reason for this behavior of the electrical energy use efficiency at different loads is most likely the behavior of power losses in the drive power electrical equipment caused directly by work processes. It is clear that the main destruction occurs when the hammers of the rotor collide with the flow of particles. At the same time, with fixed parameters of the rotor and constant frequency of its rotation, the number of particles destroyed by impact is finite. Undestroyed particles fall into the annular layer in the area of the sieve, where they are destroyed by friction, reducing the overall efficiency of the process. It is logical that the moment of the rotor rotation resistance in it depends on the layer height. Thus, exceeding the load above the maximum number of crushed particles leads to additional energy consumption and, therefore, to a decrease in the efficiency of the use of electrical energy.



**Fig. 5. Theoretical dependences of the specific consumption of electrical energy of the grinding process: a – depending on the load at different wear rates; b – depending on the rotation frequency at different humidity**

The nature of the electrical energy use efficiency depending on the rotor rotation frequency and the physical properties of the component can be explained by the fact that the efficiency of direct grinding is functionally dependent on the critical rate of destruction of raw materials. The critical rate of destruction, in turn, depends on the initial physical and mechanical properties. That is, there is always a rotation frequency that corresponds to the maximum efficiency of the electrical energy use for the grinding process.

At the same time, it turns out from fig. 4 and 5 that non-compliance with the operation modes of the electric drive, which ensure the maximum efficiency of the use of electrical energy, can lead to overspending of up to 15% of electrical energy per unit mass of finished products.

This feature is not used both when making decisions in the existing criteria for controlling grinding machines and in the principles of hardware implementation of control systems for these machines. Accordingly, typical systems for controlling the operating modes of electric drives implemented on the basis of ensuring the nominal load current do not guarantee the maximum efficiency of the use of electrical energy in the technological process. Improvement of indicators of the electrical energy use is possible when applying an integral criterion for controlling the electric drive operating modes of impact crushing machines, which is based on the analysis of the specific

consumption of electrical energy. As evidenced by the above analytical dependencies, the application of this criterion allows not only to improve the energy indicators of the technological process, but also to adapt the operating modes of the electric drive both to the variable physical parameters of the component and to the variable state of the working machine.

### III. CONCLUSIONS

1. It was established that the typical criteria for controlling the modes of operation of the electric drive of impact crushing machines do not ensure the maximum efficiency of the use of electrical energy in the technological process. It was determined that the factors affecting the efficiency of the use of electrical energy can be divided into two groups: operating modes of the electric drive and physical properties of raw materials.

2. The dependence has been obtained that allows one to determine the specific consumption of electrical energy for the grinding process. The model allows us to determine the operating modes of the electric drive that will ensure grinding with minimal electrical energy consumption under variable physical properties of the raw materials and the condition of the equipment.

3. The nonlinear extreme nature of the specific electrical energy consumption of the grinding process has been established depending on

the variable operating modes of the electric drive: rotor speed and loading of the working chamber of the grinding machine. It has been established that the values of operating modes that ensure maximum efficiency in the use of electrical energy vary depending on the variable properties of the raw materials and the condition of the equipment.

4. An energy-saving criterion for determining the operating modes of impact grinding machines based on the minimum specific energy consumption, determined according to (33) based on the changing parameters of raw materials and the condition of the equipment, is substantiated.

5. It was found out that due to the adaptation of the operating modes of the electric drive to the variable parameters of the raw materials and the condition of the equipment, it is possible to achieve a reduction of the specific consumption of electrical energy by up to 15%. This, in turn, forms the basis for the use of the specified criterion in control systems and the synthesis of relevant technical solutions.

6. For the further practical application of the obtained analytical results, it is necessary to conduct experimental studies in order to confirm the effect of increasing the efficiency of the use of electrical energy when applying the new criterion for controlling the operating modes of the electric drive.

7. The need to substantiate new approaches to control the operating modes of the electric drive of impact grinding machines becomes even more relevant in view of the emergence of new hardware solutions in the field of adjustable electric drive, which makes it possible to apply the results of research for some other types of machines.

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