Розроблено математичну модель для дослідження ефективного управління продуктивністю конвеєрної машини при регулюванні швидкості переміщення випалювальних візків. Наведено результати моделювання в середовищі програмування Matlab/Simulink регулювання швидкості випалювальних візків на основі аналізу вантажопотоку збірного конвеєра, який впливає на продуктивність конвеєрної машини. Результати моделювання дозволяють рекомендувати модель для впровадження в схему автоматизації технологічного процесу термічної обробки котунів на конвеєрній машині

Ключові слова: конвеєрна машина, випалювальні візки, котуни, термічна обробка, електропривод, регулювання швидкості

Разработана математическая модель для исследования эффективного управления производительностью конвейерной машины при регулировании скорости перемещения обжиговых тележек. Приведены результаты моделирования в среде программирования Matlab/Simulink регулирования скорости обжиговых тележек на основе анализа грузопотока сборного конвейера, который влияет на производительность конвейерной машины. Результаты моделирования позволяют рекомендовать модель для внедрения в схему автоматизации технологического процесса термической обработки окатышей на конвейерной машине

Ключевые слова: конвейерная машина, обжиговые тележки, окатыши, термическая обработка, электропривод, регулирование скорости

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A STUDY OF THE SPEED EFFECT OF MOVING SINTERING TROLLEYS ON THE PRODUCTIVITY OF THE CONVEYOR MACHINE

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1. Introduction

Scientific and practical studies that have been carried out in industrial conditions show that the economic direction to increase the manufacturing of metallurgical products entails increasing the content of iron in the blast furnace charge and improving its granulometric composition. The purpose to provide these conditions under the need to use poor iron ore requires deep enrichment and the development of methods for pelletizing finely ground concentrates.

Larger volumes of the iron ore industry have extended and complicated transport links between ore-producing factories and metallurgical plants. In these conditions, there have appeared insufficient mechanical strength and chemical stability of the agglomerate, especially fluxed. Therefore, along with agglomeration, a different method called pelletizing is developing rapidly [1]. This makes it possible to produce iron ore pellets instead of agglomerates. However, the high technological capacity of the process of producing pellets and the possibility of their transportation at long distances without destruction gives pellets advantages over the agglomerate.

Iron ore pellets are one of the main components of the blast furnace charge. The metallurgical properties of iron ore pellets significantly determine the technological characteristics and smelter performance. As a result, iron ore pellets must be of improved strength, stable chemical composition, and increased production.

The latter requires an increase in the productivity of Ukrainian conveyor machines (CMs). In this direction, throughout the world, extensive scientific work is carried out as a result of which there are new developments that significantly affect the performance of CMs. The analysis of technical and economic performance indicators and the results of upgrading the mixing factories show that Ukrainian CMs have reserves for increasing specific productivity by up to 15 % [2].

One of the most promising directions for solving the tasks is to improve the methods and systems of automating the electric drive of the conveyor belt consisting of sintering trolleys that move through the technological zones of a CM. Simultaneously with the movement of the sintering trolleys, it is necessary to maintain a predetermined level of height of the pellet layer and to provide the maximum productivity of the technological process of heat treatment of the pellets, which is an important scientific and practical task.

2. Literature review and problem statement

A large number of publications are devoted to studying the control of the conveyor machine productivity when adjusting the movement speed of the sintering trolleys. However, the authors, while studying the issue of constructing automated control systems, do not pay enough attention to determining the modes of changing the movement speed of the sintering trolleys that significantly affects the height of the pellet layer and, accordingly, the process of heat treatment of iron ore pellets. The evenness of the height of the pellet layer determines the gas dynamics regime, which further determines the quality of the pellets and the energy indices of the CM that works under different modes, loads, disturbances, as well as with raw materials and energy carriers of various characteristics, and it requires detailed research. The height of the layer of raw pellets loaded in the sintering trolleys of the CM is maintained at 0.3 m by changing the speed of the sintering trolleys depending on the load of the raw pellets [1], or energy-efficient thermal schemes of the CM [2] are developed.

An electric drive that consists of two drive mechanisms is used to regulate the movement speed of the CM sintering trolleys. Each electric motor has an electric motor of a direct or alternating current [3]. Study [4] is devoted to the regulation of the movement speed of sintering trolleys in the CM by means of an electric drive with two electric motors of direct current. In this work, it is proposed to have fuzzy control of the CM electric drive by the circuit of a thyristor converter plus an electric motor. For the research on the basis of the system of differential equations, a mathematical model of a DC electric drive was constructed in the programming environment Matlab/Simulink (manufactured by The MathWork, USA). The model uses the components of the load torque of the electric drive and shows the power schedule that is registered in the online mode. However, the system does not stabilize the uniformity of loading raw pellets to the CM sintering trolleys as the flow of raw pellets on the assembly line is not analyzed.

In other studies, preference is given to synchronous electric machines and asynchronous electric motors with frequency converters. Thus, study [5] describes the application of a discrete system of fuzzy control of a synchronous electric drive of the CM. A mathematical model of the control object in the Z-plane is constructed. The nonlinear functions are approximated by the fuzzy Takagi-Sugeno algorithm. In a similar study [6], a synchronous electric drive of the CM is also presented, but with an adaptive controller based on the same fuzzy algorithm. Articles [7, 8] describe frequency control systems for the speed of an asynchronous electric motor with direct field orientation and with the principle of control of a predictive model. Known systems of controlling the electric drive do not take into account the parameters of the CM and the technological process [9].

As stated for the mathematical model in [1], it is necessary to regulate the speed of the sintering trolleys during the heat treatment of pellets in the sintering machine. However, it does not explain how, under what conditions, such a task should be solved. The mathematical model was not investigated and it was not determined how the change of the speed of the conveyor belt and the change in the flow of raw pellets affect the heat treatment of the pellets. In the development and implementation of new high-efficiency thermal circuits of conveyor machines [2] for burning pellets, a comprehensive study is completed on the heat engineering and physicochemical processes. The author of the study developed a model idea of the heat treatment of a layer of pellets that co-ordinates the parameters of gas streams and the qualitative parameters of the pellets but without taking into account the effect of the rate of loading raw pellets to the sintering trolleys on the productivity and technical and economic indicators of the production of pellets.

In [3], a technology of producing pellets is described in detail, along with equipment for the production of pellets. The issues of equipment operation and automation of the technological process are highlighted, but without detailed presentation or calculation of the electric drive of the conveyor belt when loaded with raw pellets. In this case, there are no calculations to determine the impact of the technological and technical parameters of raw pellets and the conveyor machine on the productivity of the conveyor machine.

In order to optimize the temperature mode in the CM process zones, various mathematical models are established for heat treatment of pellets, for example, as shown in [10]. Analytically, another model allows determining the temperature in a layer of iron ore pellets, taking into account the natural gas consumption by each burner when the movement of the CM sintering trolleys is changed [11]. Investigation of the temperature regime in the technological zones of CMs is carried out without taking into account the effect on the CM performance produced by the movement speed of the sintering trolleys when the loading of raw pellets is changed.

Study [12] presents a complex mathematical model that meets the requirements of the adequacy of the real thermophysical and physicochemical processes occurring in the layer during the sintering of iron ore pellets. The model represents the kiln aggregate as a whole and affects only some of the features of the process of burning the pellets. The use of this model is suitable only for studying the process of heat treatment of the pellets when considering the effect of the height of the pellet layer, but it does not consider the impact of the speed of the conveyor belt on the formation of the pellet layer, both in the continuation and the width of the conveyor belt.

Recently, scientists have considered the principles of controlling the temperature regime of the process of sintering pellets by using the predictive ANFIS-models [13], but it is not determined how the uneven loading of sintering trolleys with raw pellets affects the performance of the CM. There are solutions to provide the necessary heat treatment of pellets with the achievement of the necessary temperature of the horizon at 1250–1300 °C, based either on adding fuel [14, 15] or on modifying the CM in order to increase the recirculation of gas streams to improve the gas dynamic behavior of the pellet layer [16, 17]. However, the results of mathematical modeling do not fully reflect the effectiveness of the developed control scheme of the electric drive of the CM conveyor belt, and the question of changing the performance of the CM is practically not modeled at all.

3. The aim and objectives of the study

The aim of the work is to study the issue of controlling the performance of a CM in the function of the movement speed of sintering trolleys when changing the flow of raw pellets on the CM assembly line. This will help produce uniformity of raw pellets as to the height of the raw pellet layers in the CM furnaces as well as the temperature and gas dynamic modes of heat treatment of iron ore pellets.

To achieve this aim, it is necessary to do the following tasks:

– to develop analytical dependencies and a structural scheme of speed control of sintering trolleys, taking into account changes in the flow of raw pellets on the assembly line of the CM;

– to develop a mathematical model for studying the performance of the CM in adjusting the movement speed of the sintering trolleys, taking into account the actual parameters of asynchronous electric motors and the CM;

– to determine the stabilization limits of the height of the pellet layer and the efficiency of the CM when adjusting the movement speed of the CM sintering trolleys.

4. Studying changes in the productivity of the conveyor machine in terms of the function of the movement speed of the sintering trolleys

4. 1. Development of a structural scheme for adjusting the height of the pellet layer

Investigation of the influence on the basic modes and the CM performance in adjusting the movement speed of sintering trolleys requires the development of a structural scheme. A change in the height of the layer of raw pellets in the CM furnaces affects the process of heat treatment of the pellets and, accordingly, the performance of the CM. Therefore, in the mathematical model, the parameters listed must be represented in the function of the movement speed of the CM sintering trolleys. The developed structural scheme is depicted in Fig. 1. The scheme consists of the following structural elements: electromechanical conveyor scales – ESc, height regulator – HR, speed regulator – SR, two current regulators – CR1 and CR2, two current sensors – CS1 and CS2, two frequency converters – FC1 and FC2, an electric drive ED, which includes two asynchronous motors – AM1 and AM2, two reduction drives – RD1 and RD2, a working mechanism – WM, an actuating mechanism – AM, a tachogenerator – TG, and a height sensor – HS.

Provision of the required height of the layer begins with the supply of raw pellets from the pelletizing area to the CM assembly line. The electromechanical conveyor scales measure the performance of the assembly conveyor *q* and form the output proportional voltage signal *U*sc. The signals from the conveyor scales *U*sc, the height setter of the pellet layer *U*hset and the feedback of the height sensor of the layer on the CM *U*hs come to the adder, which forms the resulting *U*sc signal. The height regulator HR receives a summation signal and calculates the value of the *U*hr signal that is sent to the second adder. By the signal of the height regulator *U*hr and the signal from the tachygenerator of the electric drive *U*tg, the second adder forms and sends the resultant signal *U*sp to the speed regulator SR. The *U*r signal from the speed regulator SR is sent to the third and fourth adders. By the signal from the current sensors *UI*1 and *UI*2 of the starters of the asynchronous motors *AM*1 and *AM*2 and the output signal *U*r, the adders form the input signals *U*s1 and *U*s2 for the operation of the current regulators for *CR*1 and *CR*2.

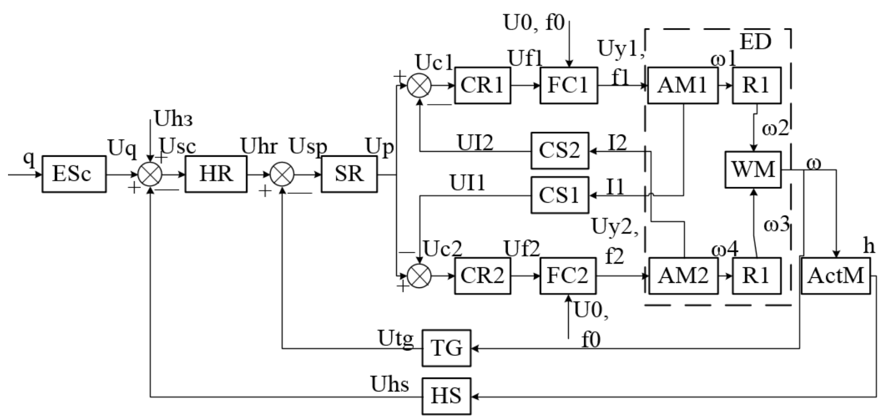


Fig. 1. The structural circuit of controlling the height of the pellet layer

The current regulators receive signals from the adders. The control signals *U*f1 and *U*f2 are calculated and sent to the frequency converters *FC*1 and *FC*2. Voltage of the alternating current *U*0 with frequency *f*0 feeds the frequency converters.

The output voltage of the variable frequency for each converter is formed, respectively, in the function of changes in the control signals *U*f1 and *U*f2. The frequency converters form the output voltage *U*y1 and *U*y2 with frequencies *f*1 and *f*2, respectively, for the asynchronous motors AM1 and AM2.

The rotors of the asynchronous electric motors AM1 and AM2, depending on the supply voltage and frequency, rotate with the frequencies ω1 and ω2, respectively. Each AM has a current sensor that measures the currents *I*1 and *I*2 in the stator winding. The gears change the rotor speed of the electric motors ω1 and ω2 to ω3 and ω4 and refer to the working mechanism, which is the toothed crown of the CM drive star. The total signal ω controls the electric drive of the belt of the CM sintering trolleys. The resulting rate of rotation ω in the feedback is controlled by the tachogenerator TG, and the height *h* of the pellet layer in the sintering trolleys of the CM is monitored by the height sensor HS.

4. 2. Determination of the parameters of the asynchronous electric drive of the conveyor belt

The process of transporting and adjusting the height of the pellet layer requires the use of a conveyor belt with a sufficiently large capacity. The power of the electric drive of the sintering trolleys' belt is spent on overcoming the resistance to the CM movement: rolling friction in the running rollers of the sintering trolleys, slip friction in the lower longitudinal, end and side seals with the movement of the sintering trolleys, friction in the clutches, and friction during loading pellets into the CM sintering trolleys. It is also necessary to take into account that the produced pellets create a moving moment with the help of the sintering trolleys on the unloading part of the conveyor belt, which facilitates the operation of the electric drive. Therefore, the calculation of the power of the electric drive is a priority task in the construction of an automatic control system. In the calculations of the required power of the electric drive, we use the output data of the conveyor machine LURGI-278 (Germany) [7] and the technological process.

Analytically, the strength of resistance of the sintering trolleys' movement of the CM is calculated as related to the rolling friction in the running rollers of the sintering trolleys, which depends on the weight: empty sintering trolleys, bottom bed, raw pellets, and pressure of the technological gases or air. The strength of resistance of the moving sintering trolleys is calculated as dependent of the slip friction in the sealants. For this, it is necessary to determine the static and nominal moments and the working moment in the driving stars of the CM conveyor belt and to calculate the power of the electric drive belt of the sintering trolleys.

The weight of empty sintering trolleys on a straight section of the upper and lower branches of the guides is determined by the following expression:

$$R_l = \frac{2 \cdot L}{l_t} \cdot m_t \cdot \text{g} = \frac{2 \cdot 85}{1.5} \cdot 7.32 \cdot 9.81 = 8{,}138.38, \quad (1)$$

where L is the distance (length) between the axes of the drive and the discharge stars, which is equal to 85 m; L_t is the length of a sintering trolley, 1.5 m; m_t is the mass of the sintering trolley, 7.32 tons; g is the acceleration of a free fall, 9.81 m/s^2.

The weight of the bottom bed in the sintering trolleys, which is on the upper branches of the guides, is determined by formula (2):

$$R_2 = b_t \cdot \text{l}_{bed} \cdot h_{bed} \cdot \gamma_{bed} \cdot \text{g} = \\ = 3.5 \cdot 80 \cdot 0.06 \cdot 2{,}000 \cdot 9.81 = 329.62 \text{ kN}, \quad (2)$$

where b_t is the working width of the belt of a sintering trolley, 3.5 m; l_{bed} is the distance from the beginning of the bottom bed loading onto the grates in the sintering trolleys to the axes of the unloading stars, 80 m; h_{bed} is the height of the bottom bed layer, 0.06 m; γ_{bed} is the bulk mass of the bed, 2,000 kg/m^3.

The weight of raw pellets in a sintering trolley of the upper branch of the guides is calculated as follows:

$$R_3 = \frac{b_t + b_{side}}{2} \cdot \text{l}_p \cdot \text{h}_p \cdot \gamma_p \cdot \text{g} = \\ = \frac{3.5 + 4.2}{2} \cdot 78 \cdot 0.26 \cdot 2{,}200 \cdot 9.81 = 1{,}685.08 \text{ kN}, \quad (3)$$

where b_{side} is the width of the belt of the sintering trolley at the top of the sides, 4.2 m; h_p is the height of the layer of raw pellets, 0.26 m; l_p is the distance from the start of loading raw pellets into the sintering trolleys to the axes of the discharge stars, 78 m; γ_p is the bulk mass of raw pellets, which is 2,200 kg/m^3.

The vertical load is created by the differential pressure of process gases or air applied to the sintering trolleys with pellets:

$$R_4 = b_t \cdot \left(\sum l_{SS} \Delta_{SS} - \sum l_{BS} \Delta_{BS}\right), \quad (4)$$

where L_{SS} and L_{BS} are the lengths of the working surfaces of the machine, respectively working with the suction and blowing through the pellet layer, m. For the CM LURGI-278 (Germany), the lengths of the sites have the following values: drying – 15 m; heating – 12 m; burning – 15 m; recuperation – 6 m; and cooling – 31.5 m. Δp_{SS} and Δp_{BS} are changes of pressure of the technological gases or air in the sections of suction and blowing through the pellet layer, Pa.

Pressures at the sites are of the following values: drying – 5,000 Pa; heating – 3,750 Pa; burning – 4,500 Pa; recuperation – 3,500 Pa; and cooling – 3,750 Pa. Then:

$$R_4 = 5{,}000 \cdot 3.5 \cdot 15 - 3{,}750 \cdot 3.5 \cdot 12 - 4{,}500 \cdot 3.5 \cdot 15 - \\ -3{,}500 \cdot 3.5 \cdot 6 + 3{,}750 \cdot 3.5 \cdot 31.5 = 208.69 \text{ kN}. \quad (5)$$

The total normal effort on the running rollers of the sintering trolleys, located on the curvilinear sections of the guides of the main and unloading parts of the CM, will be as follows:

$$R_5 = \frac{2 \cdot \pi \cdot Ra}{l_t} \cdot m_t \cdot g = \frac{2 \cdot 3.14 \cdot 2}{1.5} \cdot 7.32 \cdot 9.81 = 601.28 \text{ kN}, \quad (6)$$

where Ra is the radius of the star's initial circle, 2 m.

The strength of resistance of the conveyor belt as to the rolling friction in the running rollers of the sintering trolleys is determined as follows:

$$F_P = (R_1 + R_2 + R_3 + R_4 + R_5) \frac{\mu \cdot d_{st} + 2 \cdot \text{f}}{d_r} \cdot K = \\ = (8{,}138.38 + 329.62 + 1{,}685.08 + 208.69 + 601.28) \times \\ \times \frac{0.01 \cdot 0.1 + 2 \cdot 0.0005}{0.35} \cdot 1.25 = 78.12 \text{ kN}, \quad (7)$$

where μ is the reduced coefficient of friction in the rolling bearings of the running rollers, taken as 0.01; f is the coefficient of rolling friction of the rollers running on the guide, taken as 0.0005 m; d_{st} is the diameter of the stud of the running roller (bearing separator), 0.1 m; d_r is the diameter of the running roller, 0.35 m; K is the coefficient of friction in the reboards and sealants of the rollers, 1.25.

After calculating the strength of resistance of the CM sintering trolleys' movement to the rolling friction in the running rollers of the sintering trolleys, it is necessary to determine the strength of resistance of the rolling sintering trolleys to the slip friction in the sealants.

The strength of resistance to the movement of the sintering trolleys in view of the slip friction in the lower longitudinal seals is the following:

$$F_{LS} = P_{LP} \cdot n \cdot f_{LS} = 3{,}600 \cdot 190 \cdot 0.2 = 136.8 \text{ kN}, \quad (8)$$

where P_{LP} is the force of pressing the plates of the lower longitudinal seal on the length of one sintering trolley on both sides, 3,600 N; n is the number of sintering trolleys, 190; f_{LS} is the coefficient of friction of steel sliding on steel under conditions of bad lubrication, 0.2.

Let us determine the strength of resistance of the sintering trolleys depending on the friction during loading of pellets in the CM:

$$F_{PB}=m_{PB}\cdot g\cdot\phi=2.5\cdot 9.81\cdot 0.75=18.4\ \text{kN}, \quad (9)$$

where m_{PB} is the mass of the pellets in the feeder bunker of the pellet bed, which is 2.5 tons; φ is the coefficient of friction at loading pellets to the CM, 0.75.

The driving moment of easing the operation of the electric drive through the unloading part of the CM is defined as follows:

$$M_r=a_r(R_2+R_1)\frac{l_t}{l_{bed}}\cdot Ra_r\cdot z_r\cdot\eta_1= =0.08(329.62+1{,}685.08)\times \times\frac{1.5}{80}\cdot 2.73\cdot 2\cdot 0.93=15.35\ \text{kM·m}, \quad (10)$$

where a_r is the coefficient accounting for the position of the sintering trolleys in the unloading part of the CM, depending on the angle of the inclined grate, 0.08; Ra_r is the radius of the circle passing through the center of gravity of the pellets in the sintering trolleys, 2.73 m, z_r is the number of the sintering trolleys with pellets in the unloading part, 2; η_1 is the coefficient of friction losses when contacting the rollers of the sintering trolleys with stars, 0.93.

The operating moment on the driving stars of the conveyor belt and the drive power of the belt of the sintering trolleys is calculated as follows:

$$M_{WM}=(F_P+F_{LS}+F_{PB})R-M_r= =(78.12+136.8+18.4)\cdot 2-15.35=451.29\ \text{kN·m}. \quad (11)$$

The moment of static resistance given to the speed of the AM is determined by the expression:

$$M_{Stat}=\frac{M_{WM}}{i_r\cdot\eta_r^2}=\frac{451.29}{500\cdot 0.8^2}=1.41\ \text{kN·m}, \quad (12)$$

where i_r is the transmission number of reducers of the electric drive; η_r is the coefficient of efficiency of the reducer; in the electric drive with two mechanisms, the coefficient of each gearbox is taken into account.

The gear ratio of the gearbox is calculated by the formula:

$$i_r=\frac{\omega_{HS}}{\omega_S}=\frac{1{,}000}{2}=500, \quad (13)$$

where ω_{HS} is the frequency of the rotation of the AM, taken as 1,000 rpm; ω_S is the frequency of rotation of the drive star of the conveyor, 2 rpm. The efficiency for a gearbox with such a transfer number is about 0.8.

The estimated power of the electric drive of the sintering trolleys' belt is the following:

$$N_{culc}=M_{stat}\cdot\omega_{HS}\cdot K_T=1.41\cdot\frac{1{,}000}{60}\cdot 1.25=29.38\ \text{kW}, \quad (14)$$

where K_T is the tolerance factor, which accounts for the inaccuracy of calculating the resistance coefficients, taken as 1.25.

The practical operation of the CM shows that reliable work of the electric drive is ensured if its actual power exceeds the estimated value by at least 20 %.

The power of the AM for the electric drive can be determined using the equation $M_{stat}\approx M_{nom}$. Here M_{stat} is a given static moment for one AM, and M_{nom} is the nominal moment for one AM, the static moment of which is determined by the formula:

$$M_{stat}=\frac{M_{WM}}{2\cdot i_r\cdot\eta_r}=\frac{451.29}{2\cdot 500\cdot 0.8}=564\ \text{N·m}. \quad (15)$$

The nominal moment of the AM is calculated as follows:

$$M_{nom}=9.55\cdot\frac{N}{\omega_{HS}}, \quad (16)$$

where N is power of one AM.

Equating the static and nominal moments can help calculate the power of an AM:

$$\frac{M_{WM}}{2\cdot i_r\cdot\eta_r}=9.55\cdot\frac{N}{\omega_{HS}};$$

$$N=\frac{M_{WM}\cdot\omega_{HS}}{9.55\cdot 2\cdot i_r\cdot\eta_r}=\frac{451.29\cdot 1{,}000}{9.55\cdot 2\cdot 500\cdot 0.8}=59.1\ \text{kW}. \quad (17)$$

The nearest AM has a power output of 75 kW, so its power is taken as 75 kW. Then the total power of the electric drive will be 75·2=150 kW. To check the reliability of the electric drive, it is necessary to substitute the found values for the inequality:

$$N_{culc}\cdot 1.2\le N;$$

$$29.38\cdot 1.2\le 150;\ 35.3\le 150. \quad (18)$$

As can be seen from the expression of inequality (18), the total power of an electric motor having a value of 150 kW indicates that the calculated power of the electric drive is within the permissible limits.

4. 3. Calculations of the transfer functions of the control system elements of the conveyor belt speed

To construct a mathematical model of the control system for the speed of the CM conveyor belt, we will carry out analytical calculations of the transfer functions of the system elements. The simplified transfer function of the AM has mechanical and electromagnetic links with the speed feedback, which are described by the corresponding transfer functions. The electromagnetic link is as follows:

$$W_{em}(s)=\frac{\beta}{T_{em}s+1}=\frac{144.1}{0.0335s+1}, \quad (19)$$

where β is the electromagnetic rigidity, which is determined by the formula: Mcr/Scr ω_0. The critical moment of M_{cr} is 432.5 N·m, and s_{cr} is a critical slip, which is determined by the catalog and is equal to 0.095. The idle speed ω_0 is calculated by the formula $2\pi f/p_N$. The current frequency in the power supply f is taken to be equal to 50 Hz, and the number of pairs of the AM windings p_N is equal to three. Consequently:

ω_0=2·3.14·50/3=104.67 rpm;

β=1,432.5/0.095·104.67=144.1.

The electromagnetic constant of the AM is determined by the formula:

$$T_{em}=\frac{1}{2\pi\cdot f\cdot s_{cr}}=\frac{1}{3.14\cdot 159\cdot 0.095}=0.0335\ \text{s}. \quad (20)$$

The mechanical link of the AM is estimated as follows:

$$W_{\max}(s)=\frac{1}{Js}=\frac{1}{18,24s}. \quad (21)$$

The transfer function of the frequency converter has the form

$$W_{FC}(s)=\frac{K_{FC}}{T_{FC}s+1}=\frac{5}{0.01s+1}, \quad (22)$$

where K_{FC} is the coefficient of the converter, which is based on the formula f/U_{mfc}, where U_{mfc} is the maximum voltage at the output of the link, taken equal to 10 V; then the coefficient of the converter is K_{FC}=50/10=5 Hz/V.

The constant time of the converter T_{FC} in expression (22) is taken to be equal to 0.001 s. The link $2\pi/p_N$=2·3.14/3=2.1 is located between the FC and the AM, and it is necessary to convert the frequency of the supply voltage to the frequency of the AM rotation [8, 9].

To simplify the synthesis of the current regulator, let us neglect the feedback on the AM speed. Then the transfer function of the control object, taking into account the transfer function of the $W_{cro}(s)$ current controller, will be the following:

$$W_{cro}(s)=W_{cr}\cdot\frac{K_{fc}}{T_{fc}s+1}\cdot\frac{2\pi}{p_n}\cdot\frac{\beta}{T_{em}s+1}. \quad (23)$$

The transfer function of the open circuit of the current control will look as follows:

$$W_{bc}(s)=\frac{\frac{1}{K_{fbc}}}{2\cdot T_{\mu}s\cdot(T_{\mu}s+1)}, \quad (24)$$

where T_{μ} is an uncompensated constant time, which takes the value of the constant time of the frequency converter, equal to 0.001 s; K_{fbc} is the coefficient of the current sensor, transmitting the feedback coefficient of the current regulation, which is based on the ratio between the maximum voltage of the signal at the input of the controller U_{mcr} and the value of I_b at the output of the control object:

$$K_{fbc}=\frac{U_{mcr}}{I_b}=\frac{10}{210}=0.048, \quad (25)$$

where I_b is the baseline value of the current when using a frequency converter; it is taken as 50 % more than the nominal value. The value of the nominal current of the AM in the catalog is 140 A; hence, the baseline value of the current is I_b=140·1.5=210 A.

The transfer function of the current regulator is based on the formula:

$$W_{cr}(s)=\frac{T_{em}s+1}{T_i s};$$

$$T_i=\frac{p_n}{4\cdot T_{\mu}\cdot K_{fc}\cdot\pi\cdot\beta\cdot K_{fbc}}=$$

$$=\frac{3}{4\cdot 0.001\cdot 5\cdot 3.14\cdot 144.1\cdot 0.048}=6.9;$$

$$W_{cr}(s)=\frac{0.0335s+1}{6.9s}. \quad (26)$$

The object of speed control consists of an FC, an AM, a reducer, and a working mechanism. Then the transfer function of the object will be as follows:

$$W_{spro}(s)=W_{spr}\cdot\frac{\frac{1}{K_{fc}}}{2\cdot T_{\mu}s+1}\cdot\frac{1}{\text{Jp}}\cdot W_r\cdot W_{WM}, \quad (27)$$

where W_{spr} *(s)* is the transfer function of the speed regulator; K_{sps} is the coefficient of the speed sensor, which is the transmission coefficient of the feedback speed regulation:

$$K_{sps}=\frac{U_{mspr}}{\nu}=\frac{10}{0.067}=150, \quad (28)$$

where U_{mspr} is the maximum voltage at the input of the speed regulator, 10 V; W_r (*s*) is the transfer function of the gearbox, which is equal to the transmission coefficient of the gear unit and has the value of K_r=1/500=0.002; W_{wm} (*s*) is the transfer function of the working mechanism, which is the CM drive star. When connecting two AMs, it divides the total rotational speed in half, so the coefficient is K_{wm}=0.5.

The desired transmitting function of the open speed control loop will look as follows:

$$W_{bsp}(s)=W_{spr}\cdot\frac{\frac{1}{K_{sps}}}{4\cdot T_{\mu}s(T_{\mu}s+1)};$$

$$W_{spr}(s)=\frac{K_{fbc}\cdot \text{J}\cdot 3\cdot K_{wm}}{8\cdot T_{\mu}\cdot K_{sps}s\cdot\pi\cdot p_n\cdot K_r}=$$

$$=\frac{0.048\cdot 18.24\cdot 3\cdot 0.5}{8\cdot 0.001\cdot 150\cdot 3.14\cdot 3\cdot 0.002}=58.09. \quad (29)$$

The transfer function of the actuator receives, at the input, the value of the rotation frequency of the AM rotor and forms, at the output, the height of the pellet layer:

$$W_{ActM}(s)=\frac{h_{tot}}{\nu}=\frac{400}{0.067}=5{,}970.15, \quad (30)$$

where h_{tot} is the total maximum height of the pellet layer, 400 mm.

The formula for finding the transmitting feedback function as to the height of the layer is the following:

$$W_{fbh}(s)=\frac{U_{fbam}}{h_{tot}}=\frac{10}{400}=0.025, \quad (31)$$

where U_{fbmh} is the maximum voltage at the output of the transfer function of the feedback on the height of the pellet layer.

The transfer function of the conveyor scales has the form:

$$W_{ph}(s)=K_{ph}=\frac{U_{mph}}{q_{mph}}=\frac{10}{85}=0.118, \qquad (32)$$

where U_{CM} is the maximum voltage signal at the output of the scales, 10 V; q_{CM} is the maximum productivity of the conveyor scales, 85 kg/s [4, 12, 13].

5. Results of the study of the effect of the movement speed of the sintering trolleys on the performance of the conveyor machine

In order to proceed with studying analytical dependencies (1) through (32), the mathematical model of the system was synthesized for controlling the movement speed of the CM sintering trolleys in the Matlab/Simulink environment (produced by The MathWork, USA) (Fig. 2). The mathematical model has the following blocks: performance – P, conveyor scales – CSc, delays – DL, the height setter of the pellet layer in the sintering trolleys – HS, the element of difference – DS, height regulators – HRs and current regulators – CR1 and CR2, frequency converters – FC1 and FC2, feedback on the height of the pellet layer – FbH, movement speed of the CM sintering trolleys – FbSp, and the like.

The P block generates random numbers ranging from 55 to 85 times per second. This is necessary to simulate changes in raw pellets arriving from the partitioning area onto the CM assembly line. The CSc block simulates the transfer function of the conveyor scales based on calculations by formula (32). The DL block generates a delay signal; its value in the model is taken to be equal to one second. The assembly conveyor is located above the conveyor belt of the CM sintering trolleys. The conveyor scales are located at a distance from the edge of the assembly line. The raw pellets from the conveyor belt fall into the sintering trolleys of the conveyor belt with a delay. Therefore, the model uses the DL block.

The HS height of the layer generates a signal within the voltage range from 0 to 10 V. Between the HS and the MaxSet there is an element of DS. The value of the difference is equal to 10. The DS-element inverts the signal of the setter in the range from 0 to 10 V. This is necessary for the coordinated control of the electric drive. The FbH block simulates the feedback on the height of the pellet layer. The calculation of this block is made by formula (31). The HR unit simulates the operation of the height controller and is implemented as an R-regulator.

The value of the height regulator HR of the pellet layer is 1.051, and it is calculated using the component of the Simulink-Tune program. The simulation of the feedback on the movement speed of the CM sintering trolleys is performed by the FbSp unit according to formula (28). The calculation of the block of the speed regulator SpR is carried out by formula (29). The output signal of this block affects the blocks CR1 and CR2. The latter simulate the operation of the current regulators based on formula (26).

The blocks FbC1 and FbC2 provide feedback on the stator current of AM1 and AM2, based on formula (24). This makes it possible to implement the current synchronization of the electric motors AM1 and AM2. The blocks of the frequency converters FC1 and FC2 simulate the signal change according to the law calculated by formula (22). The coefficients of the conversion units C1 and C2 have a value of 2.09 and simulate the conversion of the power supply frequency to the frequency of the AM rotation.

The groups of blocks for the first electric motor – MM1, Mc1, and M1 – as well as for the second electric motor – MM2, Mc2, and M2 – cover the feedback. Thus, the transfer functions of the AM are realized. The blocks MM1 and MM2 simulate electromagnetic components of the electric motors. The blocks Mc1 and Mc2 are used to form a static moment. Other blocks – M1 and M2 – form mechanical links.

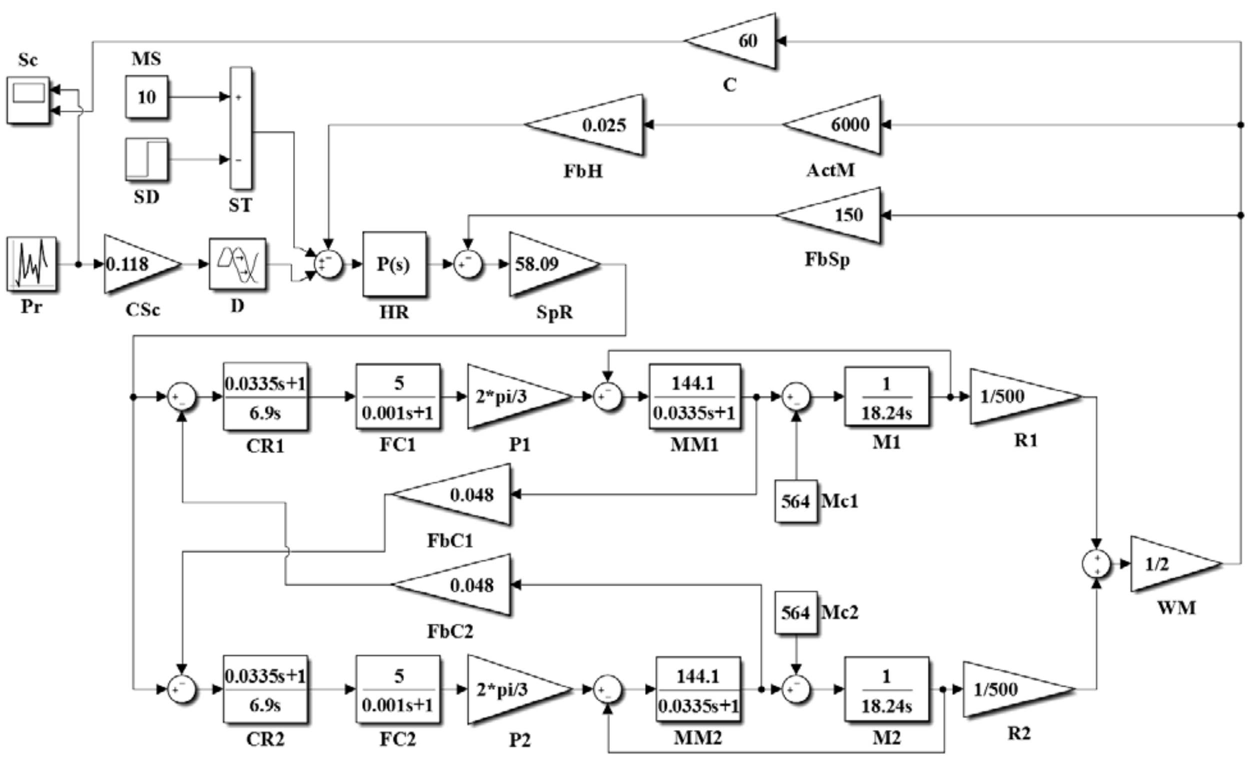
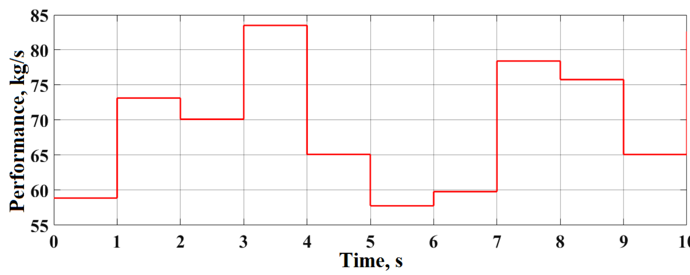


Fig. 2. A mathematical model for studying the CM performance when adjusting the speed of the sintering trolleys

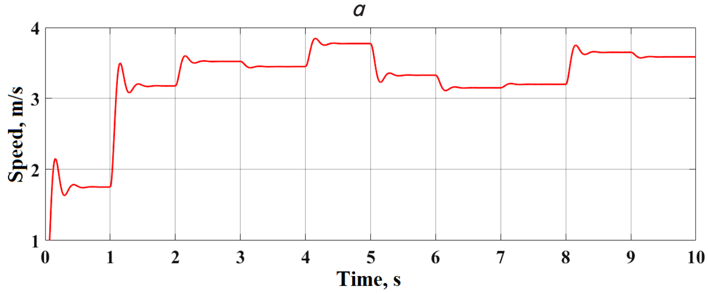
The function of the reduction unit is determined by blocks R1 and R2. This takes into account the transfer number. The value is 0.002. The block of the working mechanism WM simulates the drive star of the CM sintering trolley. The star divides the total frequency of both AMs in half, so its transfer function is 0.5.

The block of the actuating mechanism ActM simulates the transformation of the frequency of rotation of the driving star in the height of the pellet layer. The parameters of the ActM block are calculated by formula (30). To convert the rotational speed of a star to the movement speed of the CM sintering trolleys, the PT unit is used. The coefficient of the PT unit is 60. Changes in the performance of the assembly conveyor and the transition process of the speed of the conveyor belt of the CM sintering trolleys are displayed on the SCREEN.

With the help of this model, the behavior of the electric drive during the change in the performance of the assembly conveyor was studied. From the received graphs (Fig. 3), by changing the output signal of the performance of the assembly conveyor, an estimate was made of the change in the speed of the CM sintering trolleys. The study of the simulation results of this system demonstrates the relationship between the performance of the assembly conveyor and the movement speed of the CM sintering trolleys.



a



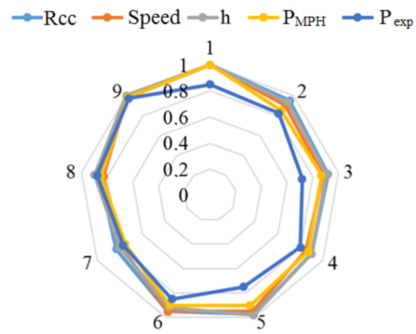
b

Fig. 3. Transitional processes of the freight flow of the assembly conveyor when changing the speed of movement of the sintering trolleys of the conveyor machine: *a* — productivity of the assembly conveyor; *b* — movement speed of the sintering trolleys

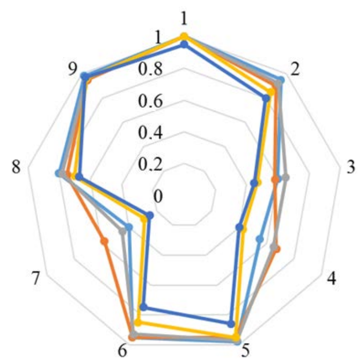
The oscillogram (Fig. 3) shows that the movement speed of the sintering trolleys varies under a set delay (to one second) depending on changes in the freight flow of the assembly conveyor. With a signal of 8 V at the output of the pre-setter, which corresponds to the height of 240 mm minus the bed, the speed of movement of the sintering trolleys is adjusted in the range from 3.2 to 4 m/s.

On the basis of the analysis of the cargo flow of the assembly conveyor, it has been found that the productivity of raw pellets varies within 20 %. This corresponds to the experimental performance of the CM being 250 t/h. At the maximum movement speed of the sintering trolleys of 4 m/min, it is about 55–85 kg/s within ±3 %. In the simulation, it was found that the fluctuations in the height of the pellet layer in the CM sintering trolleys are within ±3 % with a maximum speed of 4 m/min for the sintering trolleys. The received data differ by 6 % from the real ones under the operation of the CM in the conditions of the Northern Mining and Processing Plant (Kryvyi Rih, Ukraine). This indicates the adequacy of the mathematical model for the actual technological process and makes sense to recommend it for introduction into the automated control system of the technological process of heat treatment of iron ore pellets in the CM.

With fluctuations in the flow of raw pellets on the assembly line conveyor, it is necessary to adjust the speed of the transfer of CM sintering trolleys, as the height of the pellet layer *h* and, accordingly, the productivity of the CM R_{MPH} change (Fig. 4).



a



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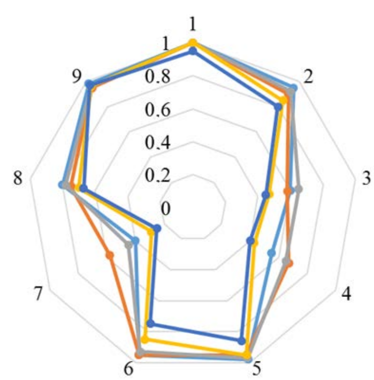

c

Fig. 4. Diagrams for changing the movement speed of the CM sintering trolleys, the height of the pellet layer *h* and the CM performance P_{MPH} in the performance function of the assembly conveyor P_{AC}: *a* — P_{AC}≤14 % P_{tot}; *b* — P_{AC}≤60 % P_{tot}; *c* — P_{AC}≤5 % P_{tot}

It has been determined that with a reduced freight flow of raw pellets of the assembly conveyor P_{AC} by 14 % of the nominal productivity P_{ACN}, there is a decrease in the movement speed of the CM sintering trolleys by about 21 %; the height of the pellet layer h is reduced by 20 %, and the CM performance P_{MPH} declines by 25 %. If the P_{AC} decreases by 60 %, then the decrease is the following: speed by 42 %, h by 55 %, and P_{MPH} to 71 %. A slight decline in the performance of a assembly conveyor (about 10 %) does not significantly change these figures. The diagrams of Fig. 4 show both the calculated performance data of the CM and experimental data, labeled as P_{EXP}. The experimental data correspond to changes in the productivity of the assembly conveyor belt P_{AC}. The calculated and experimental data in the diagrams of Fig. 4 are presented in relative units.

6. Discussion of the study results on the effect of the movement speed of the sintering trolleys on the performance of the conveyor machine

The value of the completed research is in providing the method of determining the effect of the speed of the sintering trolleys on the height of the pellet layer in the sintering trolleys along the whole length of the CM and the width of the conveyor belt. A change in the height of the pellet layer in the sintering trolleys has a significant effect on the heat treatment of the pellets; therefore, stabilization of this parameter is extremely necessary for optimizing the technological process. The obtained dependences (1)–(32), which are part of the mathematical model, are used to determine the limits of change in the movement speed of the CM sintering trolleys, the height of the pellet layer, and the efficiency of the CM. The effectiveness of the study on the speed control of sintering trolleys is determined by the use of the technical features of the electric drive and the CM in the model.

Another advantage of this study is that the performance of the CM is analyzed not only on the basis of the influence of the movement speed of the sintering trolleys but also when changing the flow of raw pellets on the CM assembly line.

A disadvantage of the study may be that the research did not reveal the effect of the speed of the CM sintering trolleys on the quality of the pellets during the heat treatment. However, such studies will be conducted in the future.

The recommended limits are to be used to stabilize the height of the pellet layer and to determine the performance of the CM. The first purpose expands the idea of thermal processing of the pellet layer. It will be possible to adjust the parameters of gas streams and to improve the quality of the pellets. The second purpose increases the technical and economic performance of pellet production.

The results of the research will be useful in the algorithms of an automatic control system for heat treatment of pellets in the modernization or development of new CM control systems.

The results obtained are a continuation of earlier studies that relate to researching the process of heat treatment of pellets, and it is aimed at improving the quality of produced pellets through the development of the latest methods of stabilizing the process of heat treatment of pellets. This significantly improves the energy efficiency of the CM by reducing the cost of gas and electricity. Therefore, such studies should be conducted in the future.

7. Conclusions

1. For the analysis of changes in the flow of raw pellets on the assembly conveyor, which affects the productivity of the CM, a mathematical model of the speed control system of the CM conveyor belt is constructed. For the system model, the force of resistance of the movement of the CM sintering trolleys is calculated with regard to the rolling friction in the running rollers of the sintering trolleys. This parameter is defined in the function of weight: empty trolleys, bottom bedding, raw pellets, and pressure of process gases and air. Another parameter required for the system model is the force of resistance of the sintering trolleys depending on the slip friction in the sealants. This parameter is determined by calculating slip friction in the lower longitudinal seals and when boilers were loaded onto the CM. The model takes into account the driving moment of ease of operation of the electric drive through the unloading part of the CM, the working moment on the driving stars of the conveyor belt, and the power of the electric drive of the belt of the sintering trolleys.

With the help of this model, the behavior of the electric drive is studied while changing the productivity of raw pellets on the assembly line. The results of the research have determined the ways of changing the speed of the sintering trolleys, the height of the pellet layer, and the productivity of the CM in the function of the productivity of raw pellets on the assembly line.

2. On the basis of the obtained analytical expressions, a mathematical model for studying the speed regulation of the sintering trolleys is considered, taking into account the actual parameters of the asynchronous electric motors and the CM. The use of the model makes it possible to investigate the process of changing the flow of raw pellets of the assembly line and to determine the effect on the height of the pellet layer in the CM sintering trolleys. The study of the system for controlling the movement speed of the CM sintering trolleys is performed in the Matlab/Simulink environment.

3. The limits of the CM performance are determined under changes in the movement speed of the CM sintering trolleys, the flow of raw pellets, and the height of the pellet layer that is necessary to stabilize the heat treatment process for the pellets. The efficiency of the CM is reduced by about 25 %, with a 21 % reduction in the speed of the CM sintering trolleys, due to the reduction of the flow of raw pellets of the assembly conveyor by 14 % and the height of the pellet layer by about 20 %. With a decrease in the flow of raw pellets of the assembly conveyor by 60 %, the productivity is reduced to 71 %, but a slight decrease by about 10 % does not affect the performance of the CM.

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