

METHOD OF IMPROVING ENERGY EFFICIENCY IN MULTI-MOTOR VARIABLE FREQUENCY ELECTRIC DRIVES OF TRUNK BELT CONVEYORS

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Abstract

The article proposes a method for improving the energy efficiency of multi-motor variable frequency electric drives of trunk belt conveyors, based on the conveyor speed changing and controlling of the magnetic state of the motor. At the conclusion is estimated an economic and energy effect of the implementation.

Keywords: *electric drive, frequency converter, energy efficiency*

INTRODUCTION

Currently, the effective utilization of energy resources and energy efficiency improvement are coming to the foreground. Energy saving, i.e. rationalization of energy production, distribution and utilization has become one of the important areas of technical policy in all developed countries, including Russia. In Russia, the normative basis in this field has formed. It includes the Federal Law "On Energy Saving" from 1996, the Federal Law "On energy saving and energy efficiency ..." from 2009, the Order of the Ministry of Economic Development of Russia "On approval of the indicative list of activities in the field of energy saving and energy efficiency ..." from 2010. These documents show that a significant part produced energy (about 60 %) is consumed by electric drives of various applications, and talk about high effectiveness of energy efficiency measures in the electric drive.

A special category of industrial applications with electric drive is mining machines for coalmines. Among the technological processes in the mine, one of mostly important is process of coal transportation to the surface via the trunk belt conveyors. This conveyor operates in a changing load. This leads to the development of automatic electric drive, which should provide the energy saving by choosing the rational operation mode of the conveyor. The major reserves of economy and rational use of not only electricity, but also equipment resource are in the field of automatic electric drive with frequency converter. For example, it can provide the saving of electrical energy by reducing the losses in the electric drive or it can avoid operation with unnecessary load by smoothing start and stop of the belt in a controlled mode. In last case, the conveyor will serve for a long time and provide the resource saving as the most expensive component of any belt conveyor is a belt. This confirms that the research and development of behaviors and operation modes of energy-efficient electric drive of the trunk belt conveyor are relevant for its practical implementation.

OPTIMIZATION IN THE ELECTRIC DRIVES OF BELT CONVEYORS

Frequency-controlled AC electric drive is gradually becoming the standard of electric drive for the belt conveyors. It is simple and it has good control behaviors. The improvement of such frequency-controlled AC electric drive is the subject of many scientific researches.

In the basic researches [1-4] authors propose the control methods and the estimate methods of the energy efficiency for automatic electric drives to optimize the energy consumption, but there is no method specifically for the belt conveyors.

In [5] author takes up the using an active rectifier in the structure of the frequency converter aimed at mine equipment. In the main circuit of such rectifier is used fully controlled power switches (IGBT-

transistors, IGCT-thyristors) which gives wide opportunities for cost-effective conversion of electric energy parameters. The frequency converter with the active rectifier improves the power factor. This leads to reduction of energy losses and improving the quality of energy saving, so consumption of mains supply current is reduced by 20-35 % and reactive energy consumption is reduced by 8-16 %. The frequency converter of such structure is best for mine equipment, including belt conveyors, as to maintain the quality of power supply in the mine is a challenge.

In [6] proposed a scientific substantiation of the possibility of increasing the energy efficiency of processes by means of the electric drive. Describes the general established regularities that are tested on the conveyor. The author has received the relationships between the energy parameters of the conveyors and their productivity at different control modes. Based on these relationships have been established parameters of the most energy efficient operating mode of the conveyor, has been defined dependence of the extreme type of the energy outlay from the speed mode at constant conveyor performance and has been calculated the speed of the conveyor, in which the energy outlay on cargoes transportation is minimal. Reduction of the mean conveyor speed while maintaining a constant unit load of the belt reduces unproductive energy loss per unit weight of the transported cargoes, i.e. the unit outlay.

This is also stated in [7]. While reducing productivity and maintaining a constant conveyor speed the efficiency is decreasing and the relative share of power to overcome the idling torque is increasing. In underloading of the conveyor more economical in terms of power inputs is a variable speed mode. The speed should ensure the continued performance at constant load torque. Fig. 1 shows the dependence of the specific motor shaft power P^* on the specific performance Q^* of the conveyor to a constant and adjustable speed of belt. In this case, the idle torque T_{idle} is 30 % of the nominal torque T_{nom} . The shaded area corresponds to a saving power in case of speed controlling. Thus, the effect of speed controlling is the higher if the idle torque is larger and if the conveyor productivity significantly decreases.

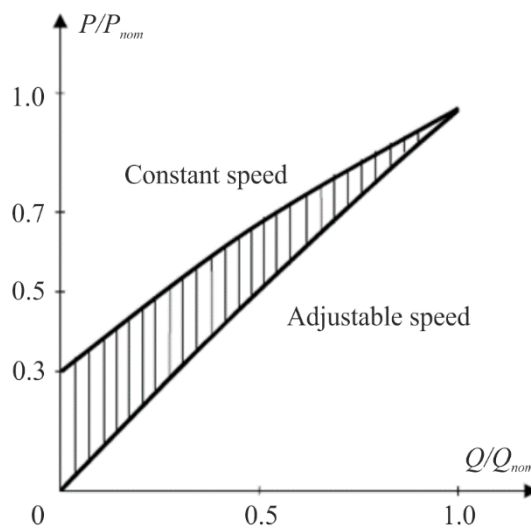


Fig. 1 – Dependence of the specific motor shaft power P/P_{nom} on the specific performance Q/Q_{nom} , $T_{idle} = 0,3T_{nom}$

According to a joint research of German and Polish specialists [8] the advantages of the speed controlling of the conveyor are evident on the main transport routes of the mine. Reducing the speed of the conveyor belt with incomplete loading provides significant decreasing the number of belt revolutions and reducing the wear of the mechanical parts of the conveyor.

In the Westfalen mine in Germany carried out operational investigations of a multi-motor conveyor with the speed controlling used for stabilizing the specific belt load. This conveyor is equipped with four electric motors with total capacity of 320 kW. The speed of the conveyor belt was considerably below the nominal speed V_n . Operational investigations produced the following results. At the same specific performance, with the speed valued at 0-0.25 of V_n working run time of the conveyor was 47.6 % of the total operating time, at 0.25-0.65 of V_n was 42.3%, and at 0.65-1.0 of V_n was only 10.1 % of the total operating time of the conveyor.

Similar operational investigations carried out at the mine ANNA in Poland showed that with the speed valued at 0-0.4 of V_n working run time of the conveyor was 53.3 %, at 0.4-0.6 of V_n was 38.3 %, at 0.6-0.8 of V_n was 7.1 %, and at 0.8-1.0 of V_n was only 1.3 % of the total operating time of the conveyor. So, operation with a constant specific load was a source of decreasing the belt wear and the wear of electric drive mechanical components. The good belt condition after three operation years allowed trouble-free operation for a few years after the end of the warranty period. According to the authors of the publication, the useful life of the conveyor belt by adjusting the speed increased by 50 % relative to the warranty period of trouble-free operation. This gives the significant economic effect. Controlling of the conveyor speed allow to save electricity consumed by electric motors of the controlled conveyor by 39 % compared with an uncontrolled conveyor per ton.

According to the article [9], the conveyor transport of mining enterprises of the Republic of Belarus consumes about 1 million kw·h of electricity per year per 1 km length of the conveyor. Thus actual consumption is achieved at around 0.3 million kw·h. About 70 % of the consumed energy be used up on wear of conveyors equipment, but speed control of the conveyors eliminates this drawback and provides significant energy saving.

Paper [10] also confirms that the automatic control of the loading of the conveyor belts according to the principle of maintaining a given level of per unit length loading provides energy saving the value of which is equal to:

$$E_s = \frac{1-k_u}{k_u k_p} \cdot 100 \% ,$$

where k_u and k_p are utilization factor and factor of packaging of the conveyor. Here $k_u = q_m / q_n$, $k_p = q_n / q_{p.u.}$, where q_m and q_n are medium and nominal per unit length loading of the conveyor belt, and $q_{p.u.}$ is per unit length belt weight (weight of 1 m of belt).

The automatic control of loading of the conveyor belt can be implemented using a various automatic control systems. Stabilizing automatic control system of the per unit length loading (Fig. 2) supports the load at a given level by the following equation:

$$q = q^* = const .$$

This system has several drawbacks, such as high changing frequency of the belt speed and high level of the dynamic load, which force decreasing of belt resource. Another drawback is the transport delay and the complicity of maintaining of required control quality.

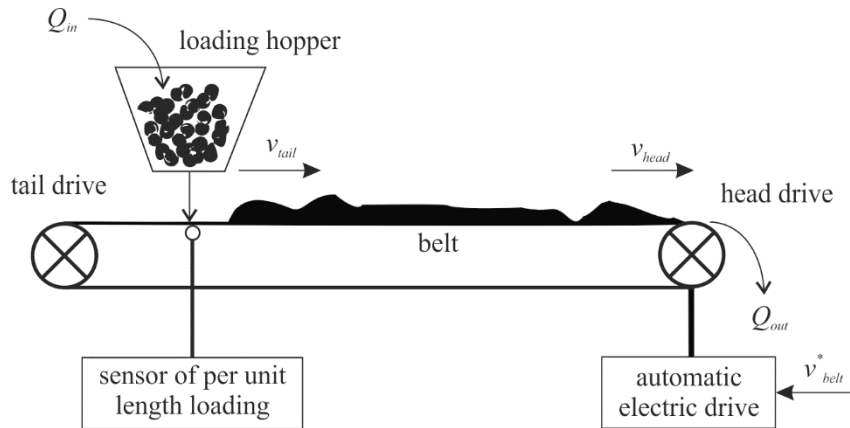


Fig. 2 – Structure of stabilizing automatic control system

Some part of these drawbacks is eliminated by the two-channel and three-positional automatic control system of the per unit length loading (Fig. 3) [10]. The system uses a loading hopper with the productivity adjustable batcher and with the automatic electric drive for the head drive of the conveyor. As a control device used three-position controller with two control channels. Channels form a step change in the speed of the belt $\pm\Delta v$ and performance of the batcher $\pm\Delta Q$ depending on the level of the material in the hopper h_{hopper} .

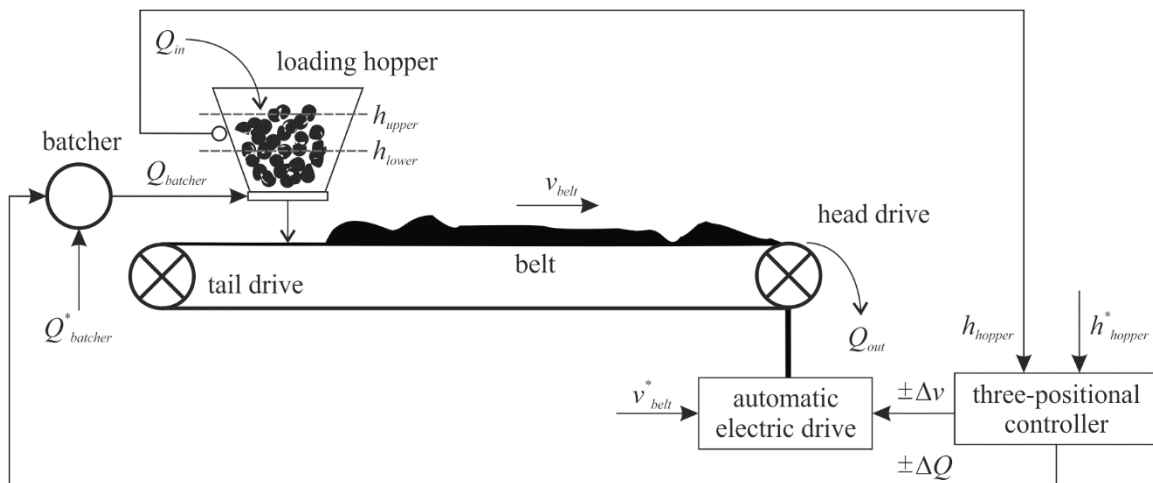


Fig. 3 – Structure of two-channel and three-positional automatic control system

If the input traffic flow Q_{in} and the level of material in the hopper are changing, the control system adjusts the speed of the belt and the performance of the batcher according to expressions:

$$\begin{cases} v_{belt} = v_{belt}^* \pm \Delta v; \\ Q_{batcher} = Q_{batcher}^* \pm \Delta Q. \end{cases}$$

Such work of the control system supports constant per unit length loading of the conveyor belt.

The above control systems consider the energy efficiency of electric drives from the position of an operating process. However, the ability to influence the operating process is not always available, so

one of the important criteria of the energy efficiency of electric drives is level of electric power losses. Optimality of losses can be considered in relation to the motor, to the frequency converter and as a whole to the electric drive. Between these variants, take a closer look at the optimisation for power losses of the induction motor. To solve this optimisation task it is necessary to analyze the extremal energetic behaviors of the induction motor, which show character of dependence between power losses and the absolute slip of the motor.

In [11] the results of calculation of extremal behaviors of the induction motor are obtained and Fig. 4 shows plots of these behaviors. Charts confirms the possibility of operation of the induction motor at a given speed and a given load torque for different values of the slip.

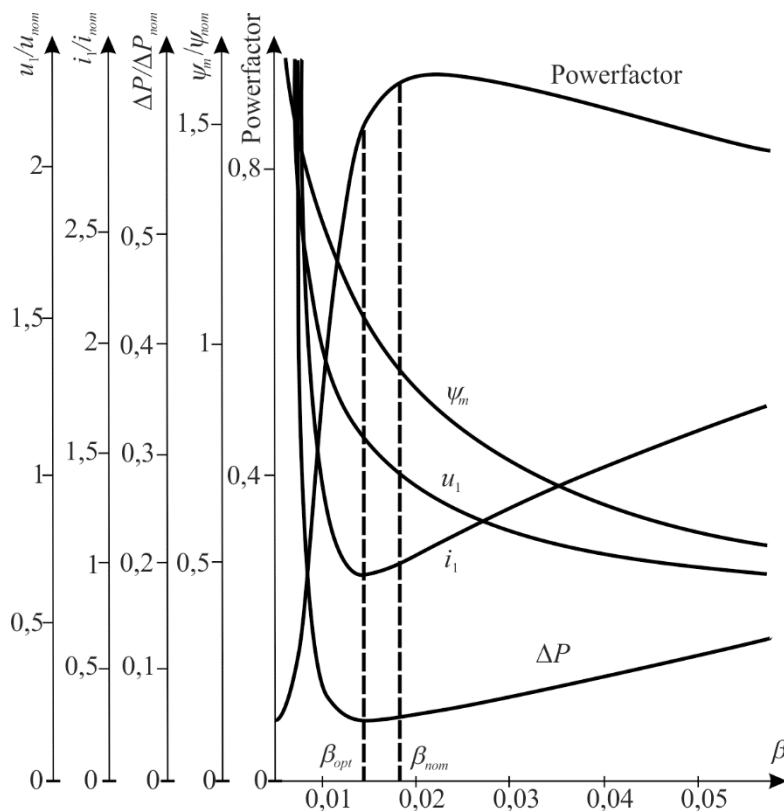


Fig. 4 – Behaviors of induction motor as an object of optimal control

Variation of slip for a given operating mode allows identify the conditions for the loss minimization of the induction motor. Thus, plots in Fig. 4 show that at the rated load a minimum of electric power losses of the induction motor is achieved when the value of the absolute slip β_{opt} is smaller than the nominal slip β_{nom} . In this case, the main flux linkage ψ_m is larger than the nominal flux ψ_{nom} , for which the supply voltage u_1 forms too high relative to the nominal voltage u_{nom} . In the nominal slip the induction motor exhibits specific properties, so while increasing the stator voltage u_1 stator current i_1 is reduced.

The search algorithm of magnetic state of the induction motor in order to minimize of electric power losses is shown in Fig. 5. This algorithm is most suitable for induction motor electric drives with u/f control, but also it can be used for any other control systems.

The higher torque and lower speed of the induction motor, the more critical changing of losses depending on the absolute slip. Changing of the motor torque significantly affects the optimum value of the absolute slip, thus, it is inadmissible to neglect this dependence. In the optimal control, the magnetic flux varies widely and depends on both the electromagnetic torque M and the speed ω . Similarly, the load torque M_{load} increasingly affects at a magnetic flux. With the increasing of the torque, influ-

ence of the speed on the magnetic flux decreases. Ensuring the minimum loss mode requires forcing the magnetic flux relative to its nominal value, which is achieved by increasing the stator voltage. Fig. 6 shows plots of the optimal stator voltage of the induction motor in the optimal control for minimum losses [12]. These plots confirm that under the nominal speed a higher voltage supplies the stator winding to ensure optimal mode.

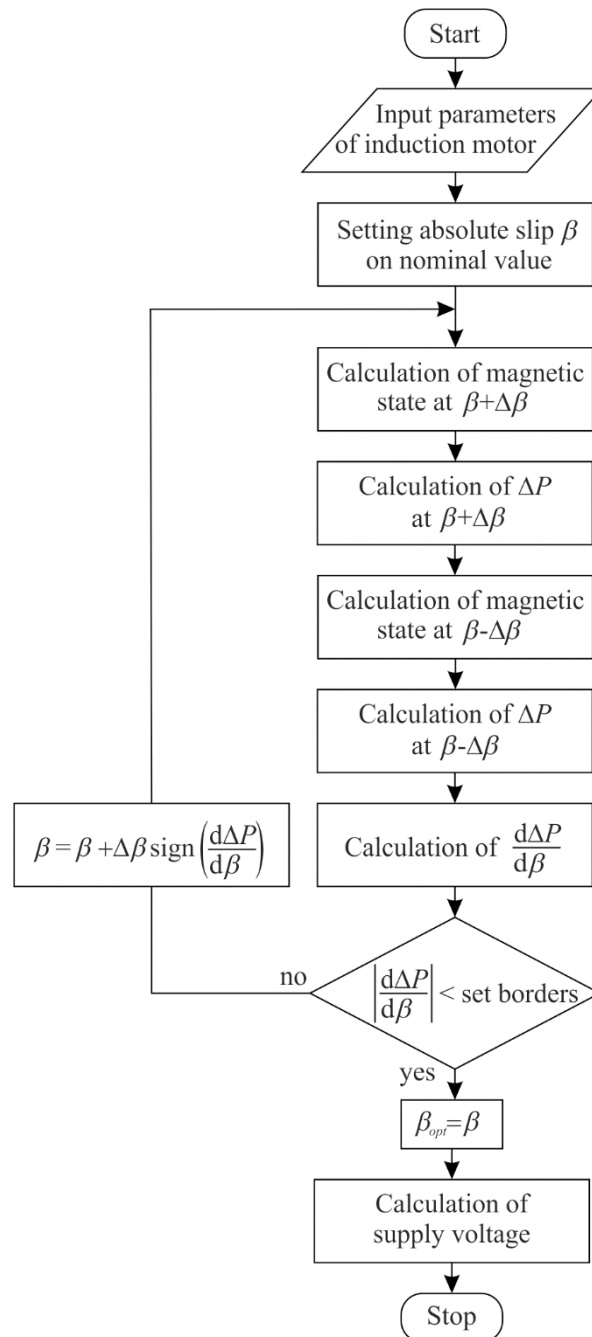


Fig. 5 – The optimisation search algorithm

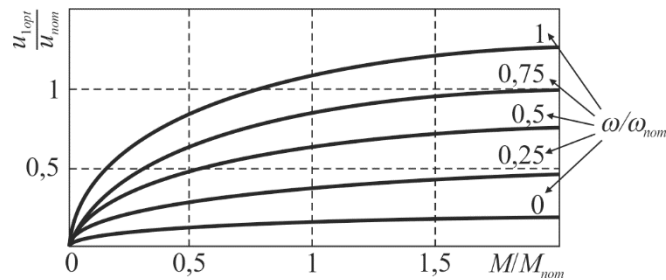


Fig. 6 - The optimal stator voltage for the minimum losses

For vector control systems problem of loss optimization can be reduced to the search for optimum flux. For example, in [13], this problem is solved for the optimal stator flux ψ_{1opt} . The value of such optimal stator flux ψ_{1opt} is between the optimal flux for copper losses $\psi_{1opt(copper)}$ and optimal flux for iron losses $\psi_{1opt(iron)}$ for calculation of which author [13] suggests expressions. Using ψ_{1opt} minimizes the total electric power losses ΔP , and for its numerical search is proposed a special method, which is shown in Fig. 7.

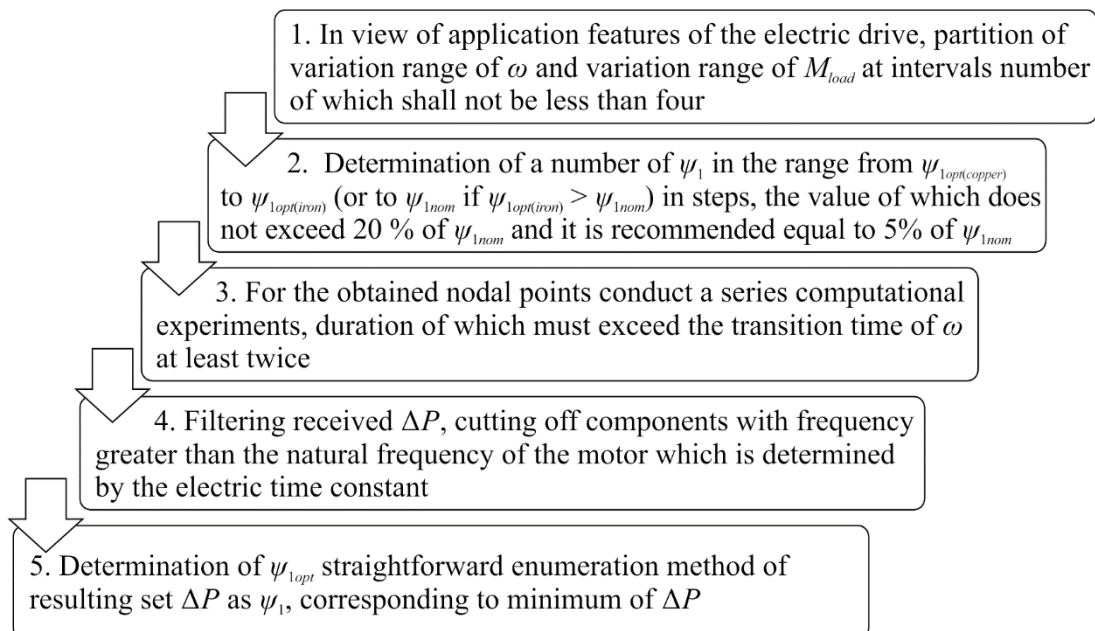


Fig. 7 – The method of numerical search for the optimal stator flux for the minimum losses

The advantage of the proposed method of determining ψ_{1opt} is its applicability with any control systems of induction motor electric drives, which provide the ability to control the state of the motor, such as field-oriented control (FOC) or direct torque control (DTC).

EFFICIENCY OF SIMPLE INSTALLATION OF THE FREQUENCY CONVERTER

The above analysis shows that the effect generated by the implementation of variable frequency drive exhibits not only in a simple installation of the frequency converter, but in using correctly selected and configured control system. To verify this conclusion has been analyzed the trunk belt conveyor working on one of the Kuzbass mines, with three motor power 500 kW at head drive and two motor power 500 kW at half-way drive. These motor are by MORLEY Company. ACS 800 frequency converters

by ABB Company control each motor and all converters are connected to the overall automation system.

A feature of this trunk belt conveyor is a need for rigorous load leveling of individual drives. The conveyor has a high length, so in the design accepted a very high coefficient of power headroom. Due to this, the average load of the conveyor motor is not more than 30 % of the nominal. Electric motors of head and half-way drives support the required electromagnetic torque and work with the constant average speed and the constant reference flux in the direct torque control system by ACS 800.

ACS 800 frequency converters give the monitoring data, which are used to analyze the operation of the described trunk belt conveyor. The analysis considers the data on operation of the conveyor electric drives during one working shift. The purpose of the analysis is to determine the energy saving in monetary terms in the operation of variable frequency drives in comparison with uncontrolled.

To obtain the required estimates initially has been analyzed characteristics of the 500 kW MORLEY motor (Fig. 8). It has been calculated dependence of number of variables on motor load: output motor power P_2 , consumed motor power P_1 and electric power losses of motor ΔP . Dependence P_1 and ΔP on the motor load has been approximated by the curve of the first and third order respectively.

Evaluation of energy efficiency of variable frequency electric drive in comparison with uncontrolled one is correct if it conducts from the condition of comparable load of uncontrolled electric drive. This is important because monitoring data are talking about the motor speed is below the nominal level. Therefore, to ensure the adequacy of the comparison has been accepted the following assumption. Increasing the conveyor speed when dealing with uncontrolled electric drive provides a smaller layer of transported cargo on the belt. The torque M_{ucd} produced by uncontrolled motor will be less than the torque M_{vfd} of variable frequency motor. The speed ω_{vfd} of variable frequency motor will be lower than the nominal synchronous speed ω_{ucd} . This dependence is proportionate:

$$M_{ucd} = M_{vfd} \frac{\omega_{vfd}}{\omega_{ucd}}.$$

On this basis, it has been processed monitoring data by ACS 800. Monitoring data contain information on the speed, the electromagnetic torque, the stator current, the consumed power and the supply voltage of each motor. During processing of each variable frequency drive for each instant have been calculated the output power P_{2vfd} , the motor load and electric power losses ΔP_{vfd} depending on M_{vfd} with the approximation. Also has been calculated the estimated consumed power P_{1ucd} of uncontrolled motor with the equivalent load in accordance with the approximation. Finally, processed data allow to build two sets of results.

The first result is the analysis by time. During the analysis is visualized the difference between the consumed power P_{1vfd} of variable frequency motor and the estimated consumed power P_{1ucd} (Fig. 9). In the case of the considered conveyor it is quantitatively small. During operation of electric drives in the same mode throughout the year by integrating per shift has been defined annual saving in monetary terms. For this trunk belt conveyor saving is 667 296,07 kW·h per year total for all five motors.

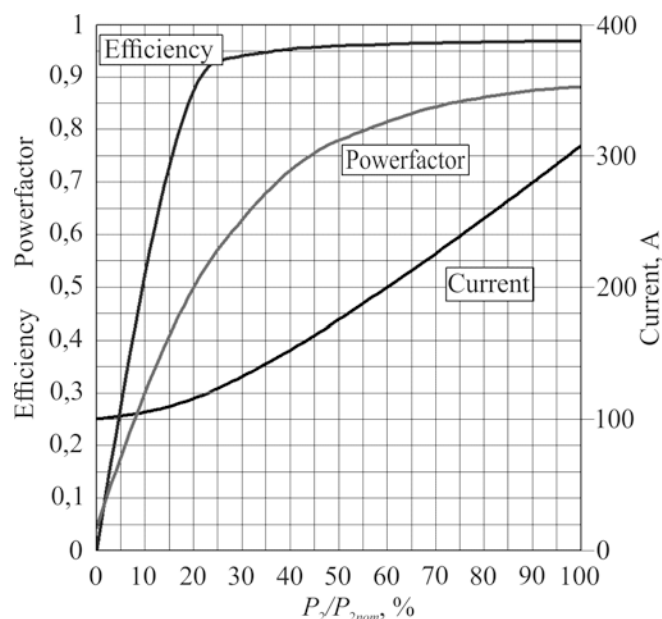


Fig. 8 – Characteristics of the 500 kW MORLEY motor

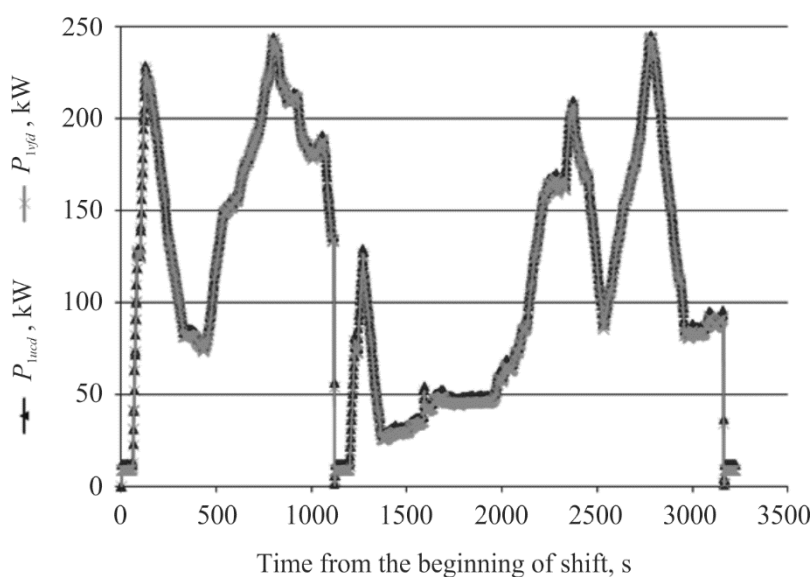


Fig. 9 – Visualization of saving on the example of the first motor

The second result is the analysis of saving depending on the load of motors. An analysis of the of operation intervals of the conveyor have been found the dependences of consumed power P_{1vfd} and estimated consumed power P_{1ucd} on motor load. Further, it has been determined saved power depending on the load and actually saving S_{vfd} by the formula:

$$S_{vfd} = \frac{P_{1ucd} - P_{1vfd}}{P_{1ucd}}.$$

The results indicate that the simple installation of the frequency converter for the given conveyor provided energy saving from only 1,5 to 10 % in the zone of small loads.

EFFICIENCY OF ENERGY OPTIMIZATION

Illustrated calculations suggest that without using of the special control system of electric drive the trunk belt conveyor has a low energy savings. Nevertheless, the theory says that the value of saving can be increased.

The value of consumed electricity at motor operation determines by the share of energy consumed to create the magnetic field, share of energy required to overcome the load and the share of energy passing directly in losses. Uncontrolled motor supplies by the voltage with constant average level. Its magnetic flux is formed regardless of the load and it is practically constant. Thus, the magnetizing current generates electrical losses in the active stator resistance even at idle. The magnetic losses at lower load does not decrease.

When using direct torque control with a constant reference flux as a control method of the induction motor the level of magnetic losses does not change. The resulting S_{vfd} in the calculations determined by the speed reduction of the motor and corresponding to this the voltage reduction (Fig. 10). According to monitoring data, the voltage level is lowered of 80 % to 85 % of nominal.

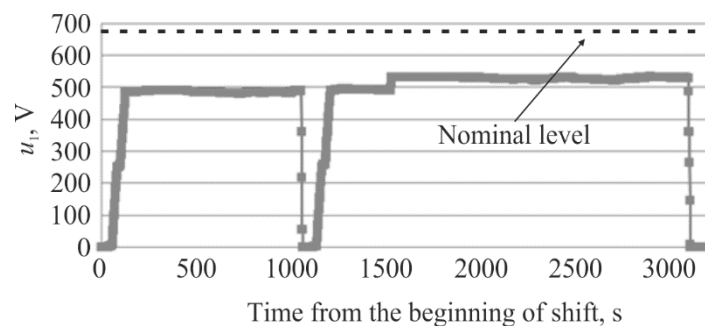


Fig. 10 – The voltage of the first drive

In accordance with this theory, when operating in above conditions, a significant effect of implementation of the variable frequency electric drive with the same load may be achieved by impact on the magnetic flux. In ACS 800 frequency converters, it is achieved by using the option «flux optimization». This option allows reducing the consumption power and a noise level when the motor is below the nominal load. Depending on the load torque and the motor speed according to information by ABB, the increasing of efficiency is from 1 % to 10 % [14].

In determining the potential saving S_{opt} in electric drives of the trunk belt conveyor from the using the option «flux optimization» should be noted at the outset that the formula for determining of the proper motor voltage does not specify by producers of ACS 800. It is the know-how by ABB. Therefore, the estimation of the saving by using the «flux optimization» can only be approximately. It looks like an estimation of «region of saving». This term under the above analysis refers to the maximum and minimum boundary of the economy and real savings S_{opt} will be located between them.

One of the boundaries of the «region of saving» forms by a maximum voltage drop so that the critical motor torque exceeds the real motor torque is not more than 20 %. The loss will be the lowest, but such operation of the induction motor is theoretically possible, but it is unacceptable from a practical point of view.

The second border of the «region of saving» forms by such reduction of voltage that the minimum critical motor torque at the maximum voltage drop corresponds to starting torque of the motor. The remaining values of the voltage at intermediate values from the minimum load to the nominal load form by s-shaped characteristic.

Further calculations have been carried out in basis on the mathematical description of different components of the electric power losses of the induction motor and the parameters of 500 kW MORLEY

motor. They give the results illustrated in Fig. 11. On the diagrams in Fig. 11 are observed deviations of number of points from the average curves. The deviation should not be considered as significant data, as their presence is explained by start and stop transient processes of the conveyor (Fig. 10).

The voltage at both borders of «region of saving» is lower than the motor supply voltage according to monitoring data. This fact confirms the existence of a reserve to energy saving for the given conveyor.

As a result, the «flux optimization» really is able to increase the energy efficiency of electric drives of trunk belt conveyor. Thus, at low motor load the saving is quite considerable and the load increases the saving approaches zero (Fig. 12). In quantitative terms, on the investigated motor load range the saved power on the first boundary is equal 3,51..6,11 kW and on the second one is equal 0,79..3,75 kW.

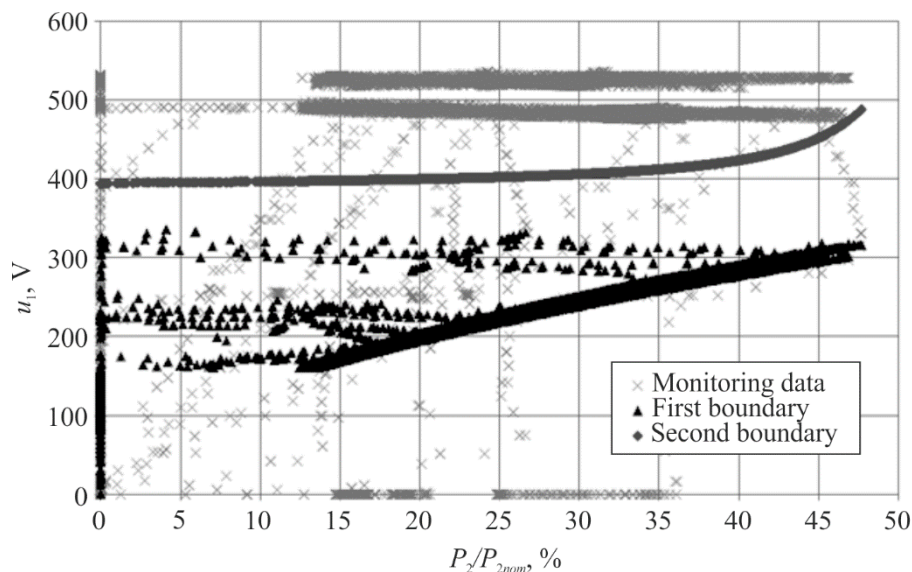


Fig. 11 – The motor voltage depending on the load

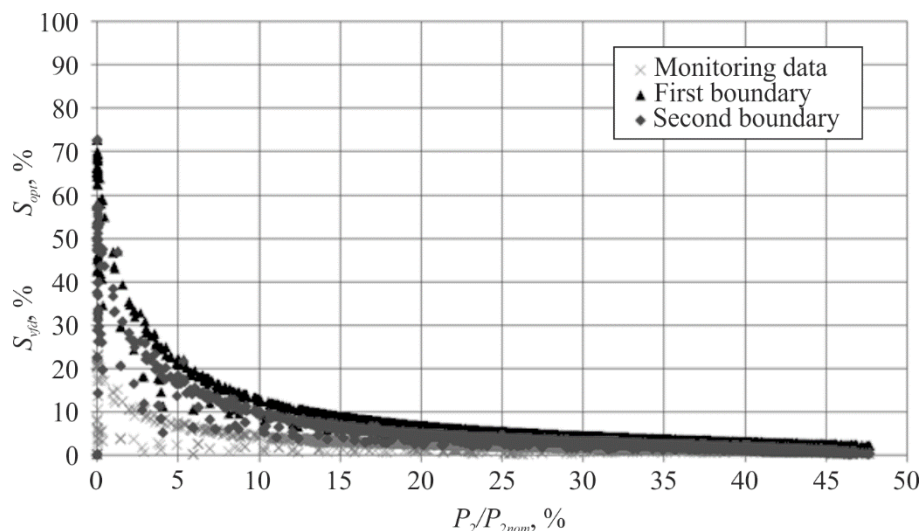


Fig. 12 – The saving depending on the load

Thus, our research shows that the simple implementation of ACS 800 frequency converters on electric drives of trunk belt conveyor gives the energy saving from 1,5 % to 10 %, and the «flux optimization» energy saving can grow up to 40 %.

CONCLUSIONS

To summarize experience in field of improving the energy efficiency of belt conveyor by varying the belt speed, as well as due to the optimization of the motor losses, method to select the most suitable control system of the electric drive of trunk belt conveyor has been formed (Fig. 13). This method may be useful on engineering practice of staff of mines are operated such conveyors, as well as design and research companies in the design of new or upgrading of existing belt conveyors.

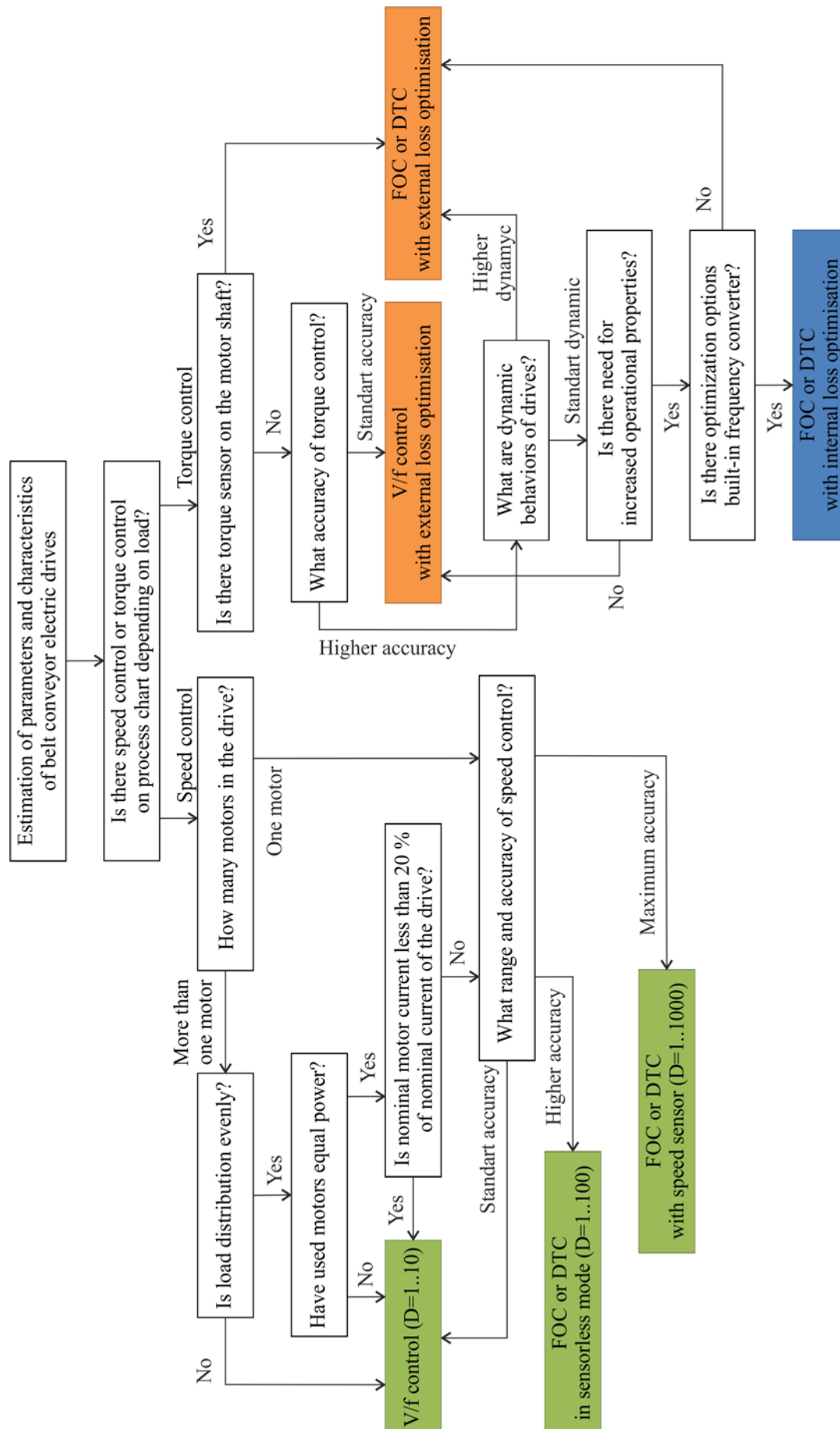


Fig. 13 – Method of control mode selecting for electric drives of belt conveyors maximizing energy efficiency under definite conditions

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