Conveyor Belt Speed Control Efficiency Using the Energy Management Methodology

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Abstract—The article presents an algorithm for optimal regulation of the speed step using the energy management methodology. Methods of reducing the cost of transport costs for conveyor systems are considered. The perspectives of using the energy management methodology as a tool to reduce the cost of energy are shown. Comparative analysis of energy management tariffs has been carried out. The problem of synthesizing stepwise speed regulation is formulated taking into account the tariffs for energy management. The criterion of quality for an estimate of the effectiveness of the transition to the TOU-tariff, differential links and restrictions on control is written. The Hamilton function for the transport system was determined, on the basis of which the synthesis of an algorithm for step regulation of the conveyor belt speed was performed. To construct differential relations an analytical PDE model of the conveyor section was used, taking into account the transport delay of the material. The efficiency of the transition was assessed and qualitative comparative analysis of TOU-tariffs was carried out based on the speed regulation algorithm. It is shown that for the effective use of the energy management methodology, a combined control system for the flow parameters of the transport conveyor is required.

Keywords — distributed transport system, TOU-tariff, transport delay, the uneven distribution of material.

I. INTRODUCTION

The use of energy management methodology is one of the ways to reduce unit cost on material transporting in the mining industry. Despite the fact that conveyor transport is the most economical type of material transportation, the cost of material transportation is more than 20% of the total cost of material extraction [1] with the recommended standard factor of loading the conveyor section with material equal to 0.7 [2]. With a decrease in the coefficient of loading the conveyor section with the material, the cost of transportation costs increases nonlinearly and can become the main component in the cost of extracting material [3], [4]. The high share of transportation costs and, accordingly, energy costs in the cost of extracting material is one of the reasons for applying the energy management methodology [5] to reduce the cost of extracting material.

The essence of the approach based on the energy management methodology lies in the use of a tariff plan, within which the cost of electricity depends on the time of day. This requires the development of such algorithms for controlling the flow parameters of the transport system, which will make it possible to transfer the main energy consumption to periods with a low cost of electricity while limiting energy consumption during peak periods with a high cost of electricity. Such control of flow parameters can be achieved by regulation the speed of the belt [6]-[8], the intensity of the flow of the incoming material [9]-[11] to the input of the conveyor section from the accumulator hopper, or in a combined way.

To effectively control the consumption of electricity, a sufficient number of tariffs are proposed, among which the tariff with a fixed price during the day (FPT) should be distinguished; tariff with a differentiated price of electricity, which depends on the time of day (TOU) [12]; tariffs in which the price for electricity consumption is determined in real-time (RTT) [13], [14]. The analysis of the tariff structure for Great Britain, Ukraine and South Africa is presented in papers [15]-[17]. The overwhelming majority of works devoted to the design of systems for controlling the belt speed and the value of the flow rate from the accumulating bunker were carried out for the case of the FPT tariff, which assumes a fixed price of electricity. The effect of using TOU-tariff for an 8-km conveyor is considered in [18]. Indeed, it is reasonable to assume that the transition from FPT-tariff to TOU-tariff will provide additional cost savings for material transportation.

II. FORMAL PROBLEM STATEMENT

To assess the efficiency of the transition from FPT—tariff to TOU—tariff (FPT—TOU transition), let us introduce a tariff coefficient \( k_f(\theta) \) that determines the ratio of the electricity price for the TOU—tariff to the electricity price for the FPT—tariff at the moment of time \( t \). Then the value \( RC \) [21]

\[
RC = \left. \int_{0}^{t_f} k_f(\theta) N_e(\theta)d\theta \right/ \int_{0}^{t_f} N_e(\theta)d\theta
\]

corresponds to the efficiency of the FPT—TOU transition, calculated for the period \( t_f \) of using the TOU—tariff. The value \( RC < 1 \) corresponds to the gain from the FPT—TOU transition, and the value \( RC > 1 \) corresponds to the loss from the FPT—TOU transition. Statistical analysis of a sample of 12,056 industrial enterprises (44 industries) demonstrates that the FPT—TOU transition for industrial enterprises does not always lead to savings in energy costs [21]. This paper shows that the FPT—TOU transition for a period of \( t_f = 6 \) months brings more losses for the company than gains (\( RC < 1 \) for 57% and \( RC > 1 \) for 43%
respectively). As a result of the FPT–TOU transition, 80% of enterprises had \( 0.95 \leq RC \leq 1.05 \), 10.12% of enterprises had \( RC < 1 \) and 8.10% of enterprises had \( RC > 1 \). Thus, only every tenth enterprise benefits from the FPT–TOU transition.

The use of energy management methodology for conveyor transport has additional features. The transport conveyor is a dynamically distributed system. The length of the transport route of the longest conveyor systems reaches several tens of kilometres: Sasol–Shondoni Overland 20.5 km [22]; Western Sahara [23] 128 km with 11 section [23]. For long transport systems at a belt speed (meters/second), the value of the transport delay characterizing the time interval between the arrival of material at the input of the transport system and its output from the transport system is comparable to the period of change \( T_k \) in the tariff coefficient \( k_r(t) \) \((T_k = 24 \text{ hours})\).

Uneven distribution of material along the transport route also has a significant impact on the value of the coefficient \( RC \). The influence of the initial distribution of material along the transport system should also be noted. All of these factors reduce the likelihood of an FPT-YOU transition for the conveyor to benefit.

Thus, making a decision to use the energy management methodology is an urgent problem for the transport conveyor and requires additional analysis. In this regard, the main attention in this work will be paid to the analysis of the efficiency of the FPT-TOU transition, and, accordingly, to the choice of a specific TOU tariff. For a comparative analysis, let's use the tariff coefficient characterizing the structure of Eskom – TOU tariffs, Figure 1 [26]. TOU periods are represented by periods of time with peak consumption, standard and low energy consumption depending on the time of day and day of the week for high demand season (June-August), low demand season (September-May) and Nightsave Eskom-TOU periods [27, 28].

![Fig. 1. Tariff coefficient, characterizing the structure of Eskom – TOU periods](image)

When carrying out the analysis let's introduce the following assumptions: the period \( t_r \) for calculating the value of the transition efficiency \( RC \) is chosen to be much longer than the period for changing the tariff coefficient \( T_k \), in order to smooth out the influence of the initial conditions, \( t_r \gg T_k \); initially, the conveyor contains no material; the friction model in accordance with DIN 22101 is determined on the basis of the primary friction coefficient [29]; the total duration of the acceleration/deceleration periods of the belt is negligible with the characteristic time of the transport process \( t_r \); switching of speed modes occurs instantly, and the effects of the propagation of disturbances are not taken into account; to analyze the efficiency of the FPT-TOU transition, let us use the multistage speed control algorithm.

### III. CONVEYOR MODEL

To analyze the efficiency of the FPT – TOU transition based on the algorithm for multistage control of the belt speed, let us use the PDE – model of the conveyor [30]:

\[
\frac{\partial [\chi]_{0}(t,S)}{\partial t} + \frac{\partial [\chi]_{1}(t,S)}{\partial S} = \delta(S)\delta(t),
\]

\[
[\chi]_{0}(0,S) = \Psi(S), \quad [\chi]_{1}(t,S) = a(t)[\chi]_{0}(t,S),
\]

where \([\chi]_{0}(t,S) \leq [\chi]_{\text{max}}\), \([\chi]_{1}(t,S)\) are the linear density of distribution of material and material flow for \( t \in [0, T_d] \), \( S \in [0, S_d] \); \([\chi]_{\text{max}}\) is the maximum allowable material distribution density for the conveyor belt;

\( T_d \) is a characteristic time of the transportation process;

\( a(t) \) is belt speed;

\( \lambda_r(t) \) is material flow from the bunker to the input of the conveyor section;

\( \delta(S) \) and Heaviside function.

The traction force required to move the belt with the material at the specific mass of the belt and a linear load from the rotating parts in accordance with the model of primary resistance has the form [29]:

\[
T = C_f C_m \sum_{s} \int_{0}^{S_d} \left(2([\chi]_{0R} + [\chi]_{0C}) + [\chi]_{0}(t,S)dS, \right)
\]

where \( C_m = 9.81 \text{ (m/sec2)} \); \( f_C \) is the coefficient of resistance to belt indentation and rolling of driving rollers;

\( C \) is secondary resistance coefficient. Let us introduce the dimensionless parameters:

\[
\tau = \frac{t}{T_d}, \quad \xi = \frac{S}{S_d}, \quad \delta(\xi) = S_d \delta(S),
\]

\[
g(t) = \frac{a(t)T_d}{S_d}, \quad \psi(\xi) = \frac{\Psi(S)}{[\chi]_{\text{max}}},
\]

\[
\gamma(\tau) = \frac{\lambda_r(t)T_d}{S_d[\chi]_{\text{max}}}, \quad z(\tau) = k_1(T_d \tau),
\]

\[
\theta(\tau,\xi) = \frac{[\chi]_{0}(t,S)}{[\chi]_{\text{max}}}, \quad \theta_R = \frac{[\chi]_{0R}}{[\chi]_{\text{max}}}, \quad \theta_C = \frac{[\chi]_{0C}}{[\chi]_{\text{max}}},
\]

\[
n_e(\tau) = \frac{N_{E}(t)nT_d}{C_f C_m \sum_{s} S_d^2},
\]

where \( n_e \) is the efficiency. Taking into account the dimensionless parameters (3), let us represent the solution of equation (1) as follows:

\[
\theta(\tau,\xi) = \left(H(\xi) - H(\xi - G(\tau))\right) \gamma(\tau) + H(\xi - G(\tau)) \psi(\xi - G(\tau)).
\]
\[
\tau_\xi = G^{-1}(G(\tau) - \xi), \quad G(\tau) = \int_0^\tau g(\alpha) d\alpha,
\]
and define the expression for the dimensionless electrical power \(n_e(\tau)\), required to move the tape with the material with the total dimensionless mass \(m(\tau)\):

\[
n_e(\tau) = g(\tau) m(\tau),
\]

\[
m(\tau) = \int_0^1 (2\theta_{0R} + 2\theta_{0C} + \theta_0(\tau, \xi)) d\xi,
\]

where \(\Delta r_\xi(\tau)\) – transport delay of material receipt at the point of the transport route with the coordinate \(\xi\) at the moment in time \(\tau\). The obtained expressions are used to analyze the efficiency of the FPT–TOU transition, based on the algorithm of multistage regulation of the belt speed.

IV. SYNTHESIS OF AN ALGORITHM FOR MULTISTAGE CONTROL OF THE BELT SPEED BASED ON THE ENERGY MANAGEMENT METHODOLOGY

Let us formulate the problem of synthesizing an algorithm for the optimal multistage belt speed control: it is required to determine the speed modes of the conveyor belt and their switching points during a period of time \(\tau = [0, \tau_f]\) with the value of the dimensionless tariff coefficient

\[
z(\tau) = k_i \left(\frac{T_d}{\tau_0}\right)
\]

(Fig. 1) for a multistage belt speed control mode \(g(\tau) = u(\tau) = (u_1, u_2, \ldots, u_v)\),

\[
0 < u_1 < u_2 < \ldots < u_v < \infty, \quad u_j = \text{const}
\]

for the control quality criterion:

\[
\int_0^\tau z(\tau) g(\tau) m(\tau) d\tau \rightarrow \min, \quad z_{\min} \leq z(\tau) \leq z_{\max}
\]

(6)

with differential relations

\[
\frac{dm(\tau)}{d\tau} = \gamma_1(\tau) - \theta_1(1, \tau) = \gamma_1(\tau) - \gamma_1(\tau - \Delta t_1) \frac{u(\tau)}{u(\tau - \Delta t_1)}(7)
\]

\[
m(0) = 2(\theta_{0R} + \theta_{0C}) + \int_0^1 \psi(\xi) d\xi,
\]

and control restrictions

\[
\frac{\gamma_1(\tau)}{u(\tau)} \leq 1.
\]

The Hamiltonian and the conjugate system of equations for the synthesis of an algorithm for the optimal multistage control of the belt speed have the form:

\[
H = -z(\tau) u(\tau) m(\tau) + \psi_m \left(\gamma_1(\tau) - \gamma_1(\tau - \Delta t_1) \frac{u(\tau)}{u(\tau - \Delta t_1)}\right) \quad (9)
\]

\[
\frac{d\psi_m}{d\tau} = \frac{\partial H}{\partial m(\tau)} = z(\tau) u(\tau), \quad \psi_m(\tau_r) = 0. \quad (10)
\]

The solution to equation (7)–(10) determines the algorithm for the optimal multistage control of the belt speed.

V. ANALYSIS OF RESULTS

To analyze the efficacy of the FPT–TOU transition, let us take \(T_d = 1 \text{ hour}\), \(S_d = 20.5 \text{ (km)}\). Then, during the day, the time value changes within \(\tau \in [0; 24]\). The length \(S_d\) of the Sasol–Shondoni Overland conveyor was taken as a characteristic parameter [22]. In the range of speed change \(a_{\min} = 3.6 \text{ km/hour}, a_{\max} = 18 \text{ km/hour}\) let us define 11 modes of step speed regulation

\[
u_j = 0.176 + 0.07j, \quad u_{\min} = 0.176, \quad u_{\max} = 0.876 . \quad (11)
\]

Taking into account the assumption that there is no material on the conveyor belt at the initial time, it follows \(\psi(\xi) = 0\). Let’s take the value of the dimensionless specific mass of the belt \(\theta_{0C}\) and the linear load \(\theta_{0R}\) from the rotating parts \((\theta_{0R} + \theta_{0C}) = 0.2\), then

\[
m_{\min} = 0.4 \leq m(\tau) \leq 1.4 = m_{\max}
\]

(12)

\[
m(0) = 2(\theta_{0R} + \theta_{0C}) + \int_0^1 \psi(\xi) d\xi = 0.4.
\]

The control constraint (8) follows from the constraint on the maximum permissible load on the conveyor belt

\[
\frac{\dot{\lambda}_1(t)}{a(t)} \leq \left[\lambda\right]_{\text{max}},
\]

from where \(\gamma_1(\tau) \leq u(\tau) \leq 0.876\). The value of the analysis interval is assumed to be 30 days, which corresponds to the value \(\tau_f = 720\). The choice of the characteristic time value \(T_d\) allows you to conveniently display the change in parameters during the day \(\tau \in [0; 24]\) and the choice of the characteristic length value corresponds to the consideration of long transport conveyors (Sasol–Shondoni Overland [20] (20.5 km single flight overland conveyor with multiple horizontal curves). Then the control modes \(u(\tau)\) a speed of \(a_1 = 1\) (meter/second), \(a_1 = 5\) (meter/second), will correspond to dimensionless values of the belt speed \(u_{\min} = 0.176\) and \(u_{\max} = 0.876\). When analyzing the efficiency of choosing a TU-tariff, we will consider three options for a function that characterizes the dynamics of the incoming material flow

\[
\gamma_1(\tau) = 0.5 + \gamma_{10} \sin \left(2\pi \frac{\tau}{24}\right),
\]
with different values of the amplitude of oscillation \( \gamma_{10} = [0.0; 0.15; 0.3] \).

The synthesis of the step belt speed control algorithm for the given initial characteristic parameters of the system for the Nightsave Eskom - TOU periods is shown in Fig.2-4.

The synthesized algorithms for regulating the belt speed for Nightsave Eskom - TOU periods correspond to the values of the transition efficiency coefficient \( RC = [1.01; 1.0; 0.99] \), the amplitude set \( \gamma_{10} = [0.0; 0.15; 0.3] \). An increase in the amplitude of the input material flow \( \gamma_{10} \) leads to a decrease in the coefficient value \( RC \). The belt speed is determined based on the control quality criterion (6), differential relations(7) and the constraint (8). The value of the coefficient \( RC \) indicates the inexpediency of switching to the Nightsave Eskom – TOU periods tariff.

The synthesis of the control algorithm for low demand season – TOU period allows obtaining a lower transition efficiency coefficient \( RC = [0.974; 0.9622; 0.95] \) for the amplitude set \( \gamma_{10} = [0.0; 0.15; 0.3] \). For high demand season – TOU periods the transition efficiency coefficients \( RC = [1.79; 1.80; 1.803] \) for the amplitude set \( \gamma_{10} = [0.0; 0.15; 0.3] \) are higher. The share of high demand season – TOU periods is three months a year, the share of low demand season – TOU periods is 9 months a year.

Taking this into account and assuming that the function for the input material flow \( \gamma_{1} (\tau) \) is the same throughout the year, we get the aggregated value \( RC = [1.178; 1.171; 1.163] \) for the amplitude set \( \gamma_{10} = [0.0; 0.15; 0.3] \). The value of the aggregated coefficients high / low demand season – TOU periods coefficients are significantly higher than for Nightsave Eskom – TOU periods. A typical view of the belt speed control algorithm for high demand season – TOU periods is shown in Fig.5.

The structure of the speed control modes for high demand season – TOU periods is the same as for Nightsave Eskom – TOU periods. Such a control structure provides a high load of the conveyor section with the material. A high load factor is a consequence of the fact that the belt speed tends to the minimum value determined by inequality (8), and as a consequence, the material density at the input to the conveyor section tends to the limiting value. A high value of the input flow of material at the moments of time, which corresponds to a high price for electricity, leads to an increase in the speed of the belt, and, accordingly, to an increase in energy consumption. This circumstance explains the growth of the efficiency coefficient \( RC \) for high demand season – TOU periods. The fill level of the conveyor section for Nightsave Eskom – TOU periods is shown in Fig.6.

After filling the empty section with the material, the mass of material on the belt tends to the maximum value. When replacing the step law of regulation of the belt speed with a continuous law of regulation, the amount of material on the belt would correspond to the maximum value. A large range of changes in the value of the transport delay is determined by the range of changes in the belt speed (11) for the synthesized law of speed control in accordance with expression (4).
VI. CONCLUSION

The article discusses the possibility of applying the energy management methodology with step regulation of the belt speed. To analyze the efficiency of FPT–TOU transition, Eskom–TOU tariffs were considered: Nightsave Eskom–TOU periods; high demand season–TOU periods; low demand season–TOU periods. The analysis of the values of the coefficients $RC$ shows that the efficiency of the FPT–TOU transition is higher for transport systems with the highest amplitude of fluctuations of the incoming material flow. The values of the coefficients in many of the cases are in the range $0.95 \leq RC \leq 1.05$. To synthesize an algorithm for multistage belt speed control software has been developed that takes into account the transport delay when moving material along the transportation route and the initial distribution of the material. Since the minimum belt speed is determined by the size of the incoming material flow $\gamma_1(\tau)$, using only the optimal speed control system does not allow effective use of energy management methodology to reduce the cost of material transportation. A system for controlling the flow parameters of the transport conveyor is required, which allows regulating not only the belt speed but also the amount of material flow from the bunker at the conveyor input. With this regulation, it is possible to stop the conveyor or reduce the speed to the minimum allowable value during periods of high energy costs. This problem determines the prospect of further research on the possibility of applying the energy management methodology in order to reduce the cost of transporting material in conveyor systems.

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