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Analysis and Optimization of Electric Motor Power for Rubber Belt Conveyors

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Abstract

This paper investigates the optimization process of the electric motor power of one of the rubber belt conveyors, internally designated by the combine as 3A1 and 3A2, using the MATLAB software package for simulation and analysis of optimal parameters. For this purpose, the basic technical data of the conveyors including the belt speed, the peripheral force and the current energy consumption of the electric motor with a power of 250 KW have been collected. In the optimization process, different scenarios for the change of the peripheral force at a certain speed, the power of the electric motor for moving the conveyor, the total effective power of the drum bearing, the power of the conveyor on the shaft of the drive drum were considered, while graphical analyzes and simulations were used in order to identify the optimal values for maximum efficiency.

Discipline: Mechanical and Industrial Engineering & Management.

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1 Introduction

In the industrial processes, the transporters with rubber belt conveyors play an important role in the transfer of materials over long distances, especially in open and closed pits. One of the most important factors for the efficient operation of these systems is the power of the electric motor.[1,2,3] Optimizing the power of the electric motor is important for reducing operating costs and increasing energy efficiency, which is of paramount importance for factories operating with large transportation systems [11,16]. Through precise analysis and application of optimization techniques [5,12,13,15,17], it is possible to achieve significant energy savings and improved system performance that directly affects the overall productivity and cost-effectiveness of the process. The rubber belt conveyors designated as 3A1 and 3A2 are part of a larger transport system in the open pit coal at the Factory Oslomej-Kicevo in the Republic of North Macedonia, so their optimization can serve as an example for improving the entire network of conveyors in the factory [18,19]. In this case, analyzing one conveyor provides a methodology for improving all conveyors with similar characteristics.

2 Rubber Belt Conveyors 3A1 and 3A2

Conveyors with rubber bands internally designated as 3A1 and 3A2 are installed between the landfill and the bunker of the thermal power plant in the Oslomej-Kicevo open pit, where they are also known as "Supported bridge". The highest point of the conveyor belts 3A1 and 3A2 reaches 44 meters and then the coal is directed to other additional straight conveyors to fill the bunkers with coal. [19]

2.1 Technical Characteristics of Conveyors

In this study, technical information of conveyors includes

- Length of the strip L=208 m
- Bandwidth B=1200 mm
- Belt capacity Q=1000 t/h
- Speed of movement of the tape v= 4.20 m/s
- Electric motor power P=250 kW
- Voltage U=0.4 kV
- Granulation (a=30 mm) in small pieces
- Material transported Bulk density coal $\gamma_m=0{,}85\left[\frac{t}{m^3}\right]$
- Conveyor height H=44 m

2.2 Analysis of the Power of the Electric Motor

The power of the conveyor in [kW] at the shaft from the drive drum without the additional resistances is calculated using the expression [7]

$$P_0=\frac{F_p\cdot v}{1000}$$

F_p [N] - the peripheral force of the drive drum and
v = 4.20 m/s – speed of movement of the rubber band.
The peripheral force [7,8] of the driving drum is calculated by the expression:

$$F_p=c\cdot t\cdot L\cdot(q_m+2q_{tapeweight}+q_r)\cdot\cos\beta_p\pm q_m\cdot H \quad [N]$$

where parameters are known:

L=208 m, length of the rubber band
H=44 m, the highest point of the conveyor

Table 1: Values of the coefficient c

L(m)	Under 4	4	5	6	8	10	12,5	16	20	25	32	40
c	9	7,6	6,6	5,9	5,1	4,5	4,0	3,6	3,2	2,9	2,6	2,4
L(m)	50	63	80	125	160	200	250	320	400	500	630	800
c	2,2	2,0	1,85	1,64	1,53	1,45	1,37	1,29	1,23	1,19	1,15	1,12
L(m)	1000	1250										
c	1,10	1,08										

Table 1 gives the values of coefficient c as a function of the length of the conveyor for L=208m [8,9].

The coefficient c=1.41 is determined by interpolation and is a resistance factor that takes into account the bending resistance of the tape around the drum, the friction in the roller bearings and the drum bearings.

The coefficient of friction t in the bearings of the rollers and drums for an ambient temperature of 20°, the value of this coefficient is read from Table 2. [8,9]

Table 2: The friction coefficient t of the rollers and drums for an ambient temperature of 20^o

Operation conditions, drive condition type of support	t^{20} [°C]
Good stable equipment with low-friction rolling bearings	0.016......0.018
Average equipment with average working conditions	0.018......0.020
Hard-working conditions, poor maintenance, dirt	0.020...0.025
Equipment with sliding bearings	0.050

Depending on the condition of the drive, operating conditions, type of support and stable equipment with low bearing friction t_{20}=(0.018......0.020), the maximum value is taken t_{20}=0.020.

For this factor, when the working environment changes, then x, y, z_T are determined and then calculated according to

$$t=t_{20}\cdot x\cdot y\cdot z_T=0.020,\cdot 0.9,\cdot 1.0,\cdot 1.0$$

$$t=0.018$$

x=0.9 – correction factor depending on the speed of movement. The values for this factor are given in Table 3 and are valid for v= 4.20 m/s. [8,9]

Table 3: Speed factor x.

Rubber band speed v [m/s]	Above 6	5	4	under 3
Factor x	1.1	1.0	0.9	0.85

y=1.0 – correction factor as a function of the diameter of the roller.

Table 4 gives the value of coefficient y and for our problem d_v =89...194 (mm) is relevant. [8,9].

Table 4: Values of the coefficient of the diameter y

Diameter of the roller d_v [mm]	Factor, y
89 ... 194	1.0
Above 194	1.1

z_T – the correction factor as a function of temperature is calculated according to the expression:

$$z_T=\frac{1}{6}C_t+\frac{5}{6}=\frac{1}{6}1.0+\frac{5}{6}=1.0$$

C_t=1.0 – correction factor of the working temperature. Values of the coefficient C_t are given in Table 5 and are authoritative for an ambient temperature of 20°. [8,9]

Table 5: Values of the coefficient C_t

Ambient temperature, °C	+20	+10	0	-10	-20	-25	-30
factor, C_t	1.0	1.1	1.4	2.0	2.7	3.2	3.8

Line weight of the material being transported

$$q_m=\frac{Q_{mt}\cdot g}{3.6\cdot v}=\frac{1000\cdot 9,81}{3.6\cdot 4.20}=648.809\ \left[\frac{N}{m}\right]$$

Mass transport capacity

$$Q_{mt}=3600A\cdot v\cdot \gamma_m\ \left[\frac{t}{h}\right]$$

In our case, it is [18]

$$Q=Q_{mt}=1000\left[\frac{t}{h}\right]$$

Tape line weight

$$q_{tape\ weight}=\left(m_{basics}+m_{the\ linings}\right)\cdot B\cdot g=(7.35+10.175)\cdot 1.2\cdot 9.81==206.304\left[\frac{N}{m}\right]$$

The number of layers should not be less than 3 for strips with a width of up to 1400 (mm) and five layers for rubber strips with a width greater than 1400 (mm). Based on these data the relevant number of layers of the rubber band is z=5 layers of type EP 315. [7]

The mass of the textile base is taken from Table 6 for rubber tape type EP 315 and z=5 layers, and its value is

$$m_{basics}=7.35\ \left[\frac{kg}{m^2}\right]$$

It is recommended that the thicknesses of the coal strip layers be:

Top layer:

$$\delta_1=6\ (mm)$$

Bottom layer:

$$\delta_2=3\ (mm)$$

About the thicknesses of the layers

$$\frac{\delta_1}{\delta_2}=\frac{6}{3}$$

and quality N for normal quality for the rubber band from Table 6 is taken: [8,9]

$$m_{the\ linings}=10.170\ \left[\frac{kg}{m^2}\right]$$

Table 6: Mass of rubber linings depending on the quality $m_{the\ linings}\left[\frac{kg}{m^2}\right]$

Thickness of layers $\frac{\delta_1}{\delta_2}$ [mm]	The quality of the rubber coating				
	M	N	VO	NZ	G
2/1=3	3.360	3.390	3.990	3.870	4.170
2/2=4	4.480	4.520	5.320	5.160	5.560
3/1=4	4.480	5.520	5.320	5.160	5.560
3/2=5	5600	5.650	6.650	6.450	6.950
4/2=6	6720	6.780	7.980	7.740	8.340
4/3=7	7840	7.910	9.310	9.030	9.730
5/2=7	7840	7.910	9.310	9.030	9.730
5/3=8	8960	9.040	10.640	10.320	11.120
5/4=9	10.080	10.170	11.970	11.610	12.510
6/2=8	8.980	9.040	10.640	10.320	11.120
6/3=9	10.080	10.170	11.970	11.610	12.510
6/4=10	11.200	11.300	13.300	12.900	13.900
8/3=11	12.320	12.430	14.630	14.190	15.290
8/4=12	13.440	13.560	15.960	15.480	16.680

The linear weight of all the rollers is determined by

$$q_r = q_{bearing\ rollers} + q_{return\ rollers} = (148,75+48,76) = 197.51\ \left[\frac{N}{m}\right]$$

The linear weight of the bearing rollers,

$$q_{bearing\ rollers} = \frac{G_{bearing\ rollers} N_{bearing\ rollers}}{L} = \frac{372,78 \cdot 83}{208} = 148.75\ \left[\frac{N}{m}\right]$$

The weight of the set of cutting rollers is determined by

$$G_{bearing\ rollers} = m_{bearing\ rollers} \cdot g = 38 \cdot 9.81 = 372.78\ [N]$$

The mass of the set of bearing rollers regardless of their type as a function of the diameter $d_{bearing\ rollers}$ and the width of the rubber band B and the form of installation in the line (set) is determined from Table 7. [8,9,10]

Table 7: Approximate mass of the bearing and return rollers in [kg].

Diameter of the bearing rollers	Carrier type rollers	300	400	500	650	800	1000	1200	1400	1600	1800	2000
38	Flat	1.2	1.4	1.6	1.9	2.3						
	Two parts	1.5	1.7	1.9	2.3	2.7						
	Three parts	1.8	2.0	2.2	2.6	3.1						
51	Flat	1.7	1.9	2.1	2.7	3.3						
	Two parts	2.0	2.3	2.6	3.1	3.7						
	Three parts	2.5	2.7	3.1	3.5	4.1						
63	Flat	2.2	2.6	3.0	3.7	4.4	5.4					
	Two parts	3.0	3.4	3.8	4.5	5.2	6.2					
	Three parts	3.8	4.6	4.6	5.9	6.0	7.0					
89	Flat		4.1	5.0	6.4	7.8	9.4	11.2	13.0			
	Two parts		5.5	6.5	7.8	9.3	10.5	12.4	14.5			
	Three parts		7.0	7.9	9.3	10.7	12.5	14.1	15.9			
108	Flat			8.6	10.0	11.4	13.5	15.6	17.7	20.1		
	Two parts			10.9	12.3	13.7	15.8	17.9	19.9	22.3		
	Three parts			13.1	14.5	15.9	18.0	20.1	22.2	24.6		
133	Flat					14.8	18.4	22.0	25.6	29.2		
	Two parts					17.4	21.3	24.9	28.2	32.1		
	Three parts					20.0	24.2	27.8	31.4	35.0		
159	Flat							28.8	32.3	35.7	39.3	42.8
	Two parts							33.4	36.9	40.4	43.9	47.4
	Three parts							38.0	41.5	45.0	48.5	52.0

For the diameter of the bearing roller $d_{bearing\ rollers}$=159 [mm], the width of the strip B=1200 [mm] and the trough shape of the profile with three rollers, from Table 7, the average mass of the set (line) of the bearing rollers is

$$m_{bearing\ rollers}=38\ [kg].$$

The linear weight of the return rollers is expressed as

$$q_{return\ rollers}=\frac{G_{return\ rollers}N_{return\ rollers}}{L}=\frac{215{,}82\cdot 47}{208}=48{,}76\left[\frac{N}{m}\right]$$

The weight of the set of return rollers is determined by

$$G_{return\ rollers}=m_{return\ rollers}\cdot g=22.0\cdot 9.81=215.82\ [N]$$

For the return roller diameter $d_{return\ rollers}$=133 [mm], belt width B=1200 [mm] and form with one horizontal roller, the average mass of the set is taken from Table 7 (line) of return rollers:

$$m_{returns\ rollers}=22.0\ [kg]$$

For the width of the rubber band B=1200 [mm], the diameter of the bearing and return rollers is obtained from Table 8. [8,9]

- The diameter of the guide rollers $d_{bearing\ rollers}$=159 [mm]
- The Diameter of return rollers $d_{return\ rollers}$=133 [mm]

Table 8: Values of the diameters of the rollers as a function of the width of the rubber band

Width of rubber band B (mm)	400,500, 650,800	1000, 1200	1400,1600,1800	2000
The diameter of the rollers $d_{bearing\ rollers}$ [mm]	88.9	108	133	159
	108	133	159	193.7
	133	159		

For coal, the bulk weight is taken to be $\gamma_m=0.85\left[\frac{t}{m^3}\right]$. [7]

For bulk material $\gamma_m=0.85\left[\frac{t}{m^3}\right]$, the distance of the bearing rollers is determined:

$$l_{bearing\ rollers}=1750+0.625\cdot B=1750+0.625\cdot 1200=2500\ [mm]$$

The distance of the return rollers is determined according to

$$l_{return\ rollers}=2\cdot l_{bearing\ rollers}=2\cdot 2500\ [mm]=5000\ [mm]$$

The number of lines (sets) of the bearing rollers is expressed as

$$N_{bearing\ rollers}=\frac{L}{l_{bearing\ rollers}}=\frac{208}{2.5}\approx 83\ \text{lines(sets)}$$

The number of lines (sets) of return rollers is expressed as

$$N_{return\ rollers}=\frac{L}{l_{return\ rollers}}=\frac{208}{5}\approx 42\ \text{lines(sets)}$$

For the height and length of the conveyors: H= 44 (m) and L=208 (m), the exact angle of inclination of the conveyor is determined by [20]

$$\beta_{slope}=\arcsin\left[\frac{44}{208}\right]=\arcsin[0.211]=12.18°$$

By substituting these values, the peripheral force of the drive drum is obtained:

$$F_p=c\cdot t\cdot L\cdot(q_m+2q_{tapeweight}+q_r)\cdot\cos\beta_{slope}\pm q_m\cdot H\ \ [N]$$

$$F_p=1.41\cdot 0.018\cdot 208(648.809+2\cdot 206.304+197.51)\cdot 0.99+648.809\cdot 44$$

$$F_p=35127\ [N]$$

For the power P_0 with a direct substitution of the calculated force is obtained

$$P_0=\frac{F_p\cdot v}{1000}=\frac{35127\cdot 4,20}{1000}\approx 148\ [kW]$$

The power to overcome the additional resistances that occur in cleaning agents is:

$$P_{cleaner}=1.6\cdot B\cdot v\cdot n=1.6\cdot 1.2\cdot 4.20\cdot 1=8064[W]=8.064\ [kW]$$

B=1.2 [m] – width of the rubber band,
n=1 [cleaner] – number of rubber band cleaning devices.

The required power to overcome the resistances due to friction in the side balancers of the tape is

$$P_b=0,08\cdot l_b$$

l_b – length of the balancer and is assumed to be equal:

$$l_b=5\ [m]$$
$$P_b=0.08\cdot l_b=0.08\cdot 5=0.4\ [kW]$$

The total effective power of the drum bearing is

$$P_e=P_0+P_{cleaner}+P_b=(148+8.064+0.4)=156.464\ [kW]$$

The power of the electric motor for moving the conveyor,

$$P_{el}=\frac{P_e}{\eta}=\frac{156.464}{0.85}=184.07\ [kW]$$

η – coefficient of utilization (from the electric motor to the drive drum).

3 Graphical Presentations of the Results Obtained using the MATLAB R2016a Application

We optimize the expression: [6,8]

$$P_0 = \frac{F_p \cdot v}{1000}$$

After running the code in MATLAB:

```
% Given constant velocity
v = 4.2; % m/s

% Define the function to minimize
P0 = @(Fp) (Fp * v) / 1000;

% Set an initial guess for F_p
Fp_initial = 35127; % N

% Define bounds for F_p (for example, from 10000 N to 50000 N)
Fp_min = 10000; % N
Fp_max = 50000; % N

% Use fmincon to minimize P_0 within the bounds
options = optimoptions('fmincon', 'Display', 'iter');
[Fp_opt, P0_opt] = fmincon(P0, Fp_initial, [], [], [], [], Fp_min, Fp_max, [], options);

% Display the results
disp(['Optimal F_p: ', num2str(Fp_opt), ' N']);
disp(['Minimum P_0: ', num2str(P0_opt), ' kW']);

% Plot the result
Fp_range = linspace(Fp_min, Fp_max, 100);
P0_values = (Fp_range * v) / 1000;

figure;
plot(Fp_range, P0_values, '-b', 'LineWidth', 2);
hold on;
plot(Fp_opt, P0_opt, 'ro', 'MarkerSize', 8, 'MarkerFaceColor', 'r');
xlabel('Force (N)');
ylabel('Power (kW)');
title('Optimized Power vs Force');
grid on;
legend('Power vs Force', 'Optimal F_p');
```

The software will give the optimal value of F_p and P_0 and also generate a graph showing the relationship between force and power for a certain speed with the optimal point marked as in Figure 1.

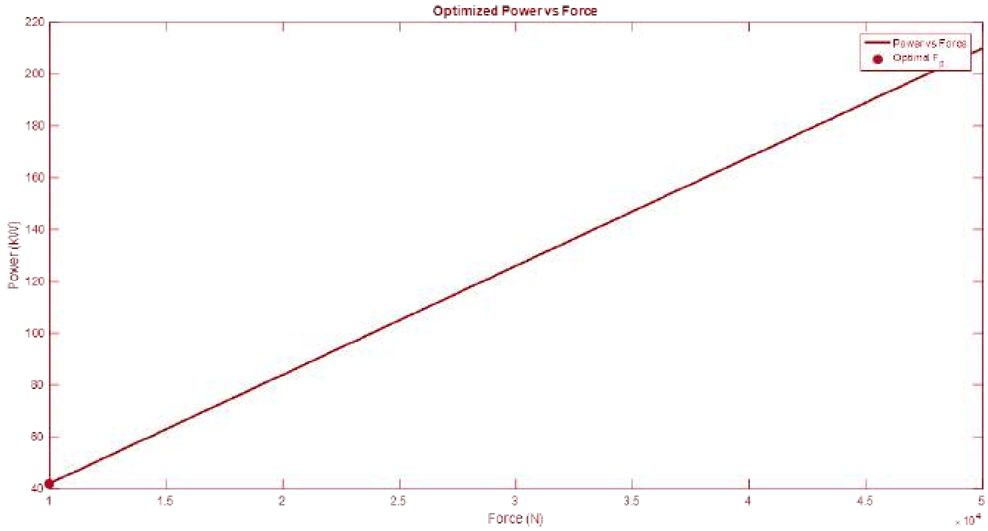

Figure 1: Drive drum shaft conveyor power for a given web speed and different drive drum peripheral force

Figure 1, the graph shows how P_0 в varies as a function of F_p while the optimum point is marked in red. The graph shows that as the force F_p , increases, the power P_0 also increases. In the lower left part of the graph, where F_p is relatively low, and the power is minimal. However, in the upper right corner, where the force is high, the power reaches its maximum. This trend shows that with more force, significantly more power can be obtained.

The local minimum that satisfies the constraints is given in Figure 2.

Iter	F-count	f(x)	Feasibility	First-order optimality	Norm of step
0	2	1.475334e+02	0.000e+00	4.200e-03	
1	4	1.475334e+02	0.000e+00	4.200e-03	4.200e-03
2	6	1.475333e+02	0.000e+00	4.200e-03	2.100e-02
3	8	1.475329e+02	0.000e+00	4.200e-03	1.050e-01
4	10	1.475306e+02	0.000e+00	4.200e-03	5.250e-01
5	12	1.475196e+02	0.000e+00	4.200e-03	2.625e+00
6	14	1.474645e+02	0.000e+00	4.200e-03	1.313e+01
7	16	1.471889e+02	0.000e+00	4.200e-03	6.563e+01
8	18	1.458107e+02	0.000e+00	4.200e-03	3.281e+02
9	20	1.389201e+02	0.000e+00	4.200e-03	1.641e+03
10	22	1.044672e+02	0.000e+00	4.200e-03	8.203e+03
11	24	4.231234e+01	0.000e+00	4.200e-03	1.480e+04
12	26	4.200156e+01	0.000e+00	3.733e-03	7.399e+01
13	29	4.200078e+01	0.000e+00	1.866e-03	1.850e-01
14	31	4.200117e+01	0.000e+00	1.172e-03	9.223e-02
15	33	4.200020e+01	0.000e+00	2.000e-04	2.315e-01
16	35	4.200000e+01	0.000e+00	2.000e-06	4.714e-02
17	37	4.200000e+01	0.000e+00	2.000e-08	4.715e-04

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in feasible directions, to within the default value of the optimality tolerance, and constraints are satisfied to within the default value of the constraint tolerance.

<stopping criteria details>

Optimal F_p: 10000 N
Minimum P_0: 42 kW
\>>

Figure 2: The number of steps (iterations) until reaching the optimal minimum

The optimization algorithm is finished after reaching a local minimum for

$$F_p=10000\ [N]$$

The objective function stabilized around the value of:

$$P_0=42\ [kW]$$

By optimizing the power of the electric motor for moving the conveyor: [6,8]

$$P_{el}=\frac{P_e}{\eta}$$

With a given total effective power:

$$P_e=156{,}464[kW]$$

is optimized η – the coefficient of utilization is optimized to minimize the output electrical energy P_{el}.

Running the code in MATLAB:

```
% Given input power
P_e = 156464; % Input power in watts

% Define the objective function to minimize P_el by varying eta
P_el = @(eta) P_e / eta;

% Set an initial guess for eta
eta_initial = 0.85;

% Define bounds for eta (for example, from 0.5 to 1)
eta_min = 0.5;
eta_max = 1;

% Use fmincon to minimize P_el within the bounds
options = optimoptions('fmincon', 'Display', 'iter');
[eta_opt, P_el_opt] = fmincon(P_el, eta_initial, [], [], [], [], eta_min, eta_max, [], options);

% Display the results
fprintf('Optimal efficiency (eta): %.4f\n', eta_opt);
fprintf('Minimum Electrical Power Output (P_el): %.2f W\n', P_el_opt);

% Plot the result
eta_range = linspace(eta_min, eta_max, 100);
P_el_values = P_e ./ eta_range;

figure;
```

```
plot(eta_range, P_el_values, '-b', 'LineWidth', 2);
hold on;
plot(eta_opt, P_el_opt, 'ro', 'MarkerSize', 8, 'MarkerFaceColor', 'r');
xlabel('Efficiency (η)');
ylabel('Electrical Power Output (P_{el}) (W)');
title('Optimized Electrical Power Output vs Efficiency');
grid on;
legend('P_{el} vs η', 'Optimal η');
```

The optimization algorithm terminates after a local minimum is reached for the optimal value of the utilization coefficient:

$$\eta=1.0$$

The local minimum for electric power P_{el}, is obtained (Figure 3) with value:

$$P_{el}=156464.00 \text{ [W]}$$

```
                                            First-order      Norm of
 Iter F-count            f(x)  Feasibility   optimality         step
    0       2    1.840753e+05    0.000e+00    3.702e+04
    1       4    1.565814e+05    0.000e+00    2.284e+04    1.493e-01
    2       6    1.564966e+05    0.000e+00    4.749e+01    5.415e-04
    3       8    1.564642e+05    0.000e+00    2.968e-01    2.075e-04
    4      10    1.564640e+05    0.000e+00    5.914e-03    1.037e-06

Local minimum found that satisfies the constraints.

Optimization completed because the objective function is non-decreasing in
feasible directions, to within the default value of the optimality tolerance,
and constraints are satisfied to within the default value of the constraint tolerance.

<stopping criteria details>

Optimal efficiency (eta): 1.0000
Minimum Electrical Power Output (P_el): 156464.00 W
```

Figure 3: The number of steps (iterations) until reaching the optimal minimum

Figure 4 shows how P_{el} varies depending on the utilization coefficient η.

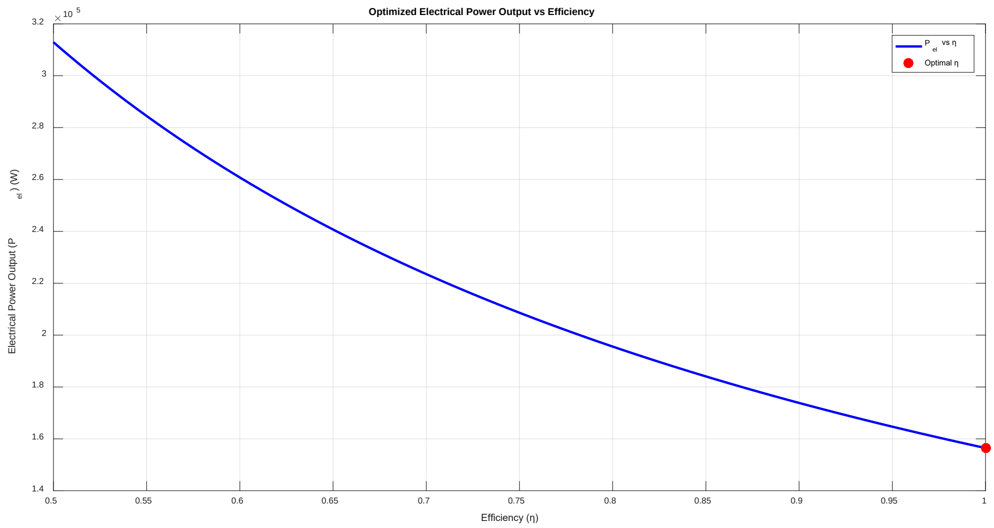

Figure 4: Power of the electric motor of the conveyor in the case of different values of the utilization coefficient and the total effective power of the drum shaft

Figure 4 shows that by increasing the utilization ratio (efficiency) of the system, the electrical power required to maintain the same mechanical power decreases significantly. The best efficiency is ideally closer to 1, as it will require less electrical power.

4 Conclusion

In this research, analysis and optimization of the conveyors with rubber belts 3A1 and 3A2 in the open coal mine in Oslomej - Kichevo have been carried out. In this paper, there is a combination of the calculation of the peripheral force and the power of the electric motor with the classical analytical formulas, with the optimization of the conveyor components using a modern MATLAB software tool. For this purpose, MATLAB was successfully applied for the optimization of the components of the conveyor system with a rubber belt, with a special focus on the analysis of the power of the electric motor. Through the analysis of various parameters such as the speed of the conveyor belt and the peripheral force, a model has been developed that enables the efficient analysis of the required power for the operation of the system. This optimization leads to a reduction of unnecessary energy losses and allows better sizing of the motors used.

The first code in MATLAB analyzes the dependence between force and mechanical power at a given constant belt speed, thereby determining the optimal force that minimizes mechanical power, which is key to optimizing energy resources and conveyor efficiency.

The second code focuses on the minimization of the electrical power depending on the utilization coefficient (efficiency) η of the system, thus determining the optimal efficiency that leads to the minimum delivered electrical power. The results of this analysis show how efficiency affects the performance of the system, in order to achieve better functioning.

The results of this optimization can be used to better dimension the transportation system in order to achieve greater energy efficiency, which will ultimately result in lower operating costs and a longer lifetime of system components.

With proper optimization of components, one can expect in addition to greater energy efficiency and long-term stability as well as reliable operation of rubber belt conveyor systems, which is key to sustainable development in any industry.

5 Availability of Data and Material

Data can be made available by contacting the corresponding author.

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