RESULTS FROM THE APPLICATION OF A MODEL FOR ENERGY-EFFICIENCY INVESTIGATION OF MECHANICAL HANDLING MACHINES AND SYSTEMS (PART 1)

DINOLOV OGNYAN[1*], MANOLOVA BORYANA[1], LIUDMIL MIHAILOV[1], KONDYU ANDONOV[1]

[1]*Dept. of Electric Power Engineering, University of Ruse 'Angel Kanchev', 8 Studentska St, Ruse, 7017, Bulgaria*

Abstract: The aim of this research is to ascertain the functionality and practical applicability of a developed generalized model for investigation of the energy efficiency of mechanical handling machines and systems in its specific application for the continuous-transport individual machines and systems. A typical industrial system for transportation and fragmentation of rock materials is chosen as an investigation object. The investigation procedure is entirely based on the model being validated. The obtained results demonstrate the presence of possibilities for practical application of the model and reveal a low energy-efficiency level. If the belt conveyors' load is optimal, the electric energy consumption of the site can be decreased by 45 % as the potential energy losses can be reduced to 0.66 % in case of reconstruction.

Keywords: energy efficiency, mechanical handling machines and systems, electric drives, models for investigation

1. INTRODUCTION

A generalized model for investigating the energy efficiency of electrically-driven mechanical handling machines and systems is developed [1]. The model allows a comprehensive evaluation and a baseline comparison of the energy efficiency both of the participating electric drives and of the technological scheme, regardless of their field of application. Given its aggregate and theoretical nature, the functionality of the model and the possibilities of application in practice should be gradually studied, proved and justified. The studies should be directed as to the complete continuous-transport systems, as well as to the various types of individual mechanical handling machines, which in turn, are divided into *machines for continuous transport* and *machines with a cyclic operation* according to the approved classification [2].

The aim of this study is to ascertain the functionality and practical applicability of the generalized model, synthesized in [1], for investigation of the energy efficiency of mechanical handling machines and systems in its specific application for the continuous-transport individual machines and systems.

2. OBJECT OF INVESTIGATION

A typical industrial system for transportation and fragmentation of rock materials is chosen as an investigation object. The complete flow diagram of the system is shown in Figure 1 where the losses of high due to the presence of support elements and load passages, the out-of-levelling's of the transport machines, and the total out-of-levelling of the system are plotted as well.

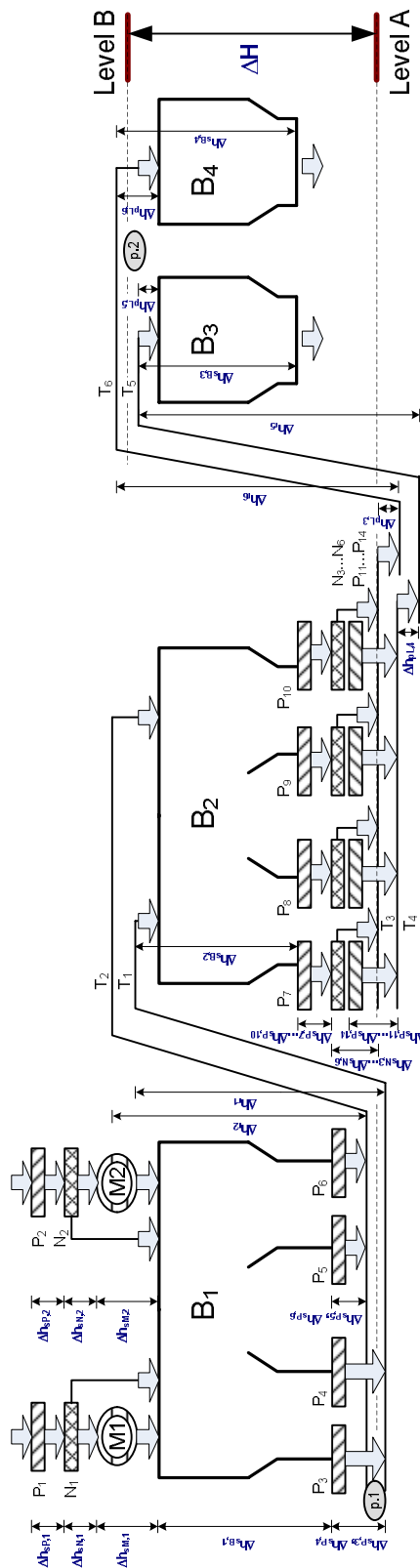---

[*] Corresponding author, email: odinolov@uni-ruse.bg

Fig. 1. System for transportation and processing of rock materials.

The system supply is conducted by the feeders P_1 and P_2, and the screens N_1 and N_2, where, being divided into two, one part of the flow goes directly into the primary bunkers B_1 and B_2, and the other part is fed to them through the mills M_1 and M_2 that crush the pieces to the required particle size. The load is fed into the intermediate bunker B_2 by the feeders $P_3…P_6$ and the belt conveyors T_1 and T_2. Separation of the material takes place at the exit of the bunker through a system of feeders $P_7…P_{14}$ and screens $N_3...N_6$, then, using the conveyors $T_3...T_6$, the separated material is transported and poured into two end bunkers B_3 and B_4, which contain rock materials of different particle size.

In this particular case, in determining the quantities and indices according to the model [1], the section between points 1 and 2 of the scheme is considered as a system for continuous transport because the loads' transportation is performed between these points.

3. METHODS OF INVESTIGATION

3.1. Transport machines
The investigation and the evaluation of the energy efficiency of the transport machines in the system are performed using the model for investigating, evaluating and comparing the energy efficiency of mechanical handling machines and systems [1].

3.2. Electrically-driven auxiliary elements
The investigation of the auxiliary elements powered by electric energy (the mills, the screens and the feeders) is performed with the aid of the generalized model [3] and the automated system [4] for evaluation of the induction-motor-drives energy efficiency.

Based on levels of electrical energy consumption, the model [4] provides an assessment with the aid of 29 indexes for investigation, evaluation and comparison of the energy efficiency in electric drives. A detailed indices description is given in Table 1. The indexes are distributed into 6 groups. All the indexes related to the optimum operation are put into group **A**. Similar distribution is done for groups **B** and **C** but according to those indexes relevant to the actual and no-load operation respectively. Group **D** gives information on the overrun of electrical energy and operating time, group **E** – on deviations of some quantities of specific values. The last group **F** fixes statistical estimates characterizing the actual drive operation. The indices A_1 - active power in optimum operation of the machine (system); A_2 - reactive power in optimum operation of the machine (system); and E_6 - desired (optimum) power factor, are input indices. Based on their values, the all other indices of the model can be calculated.
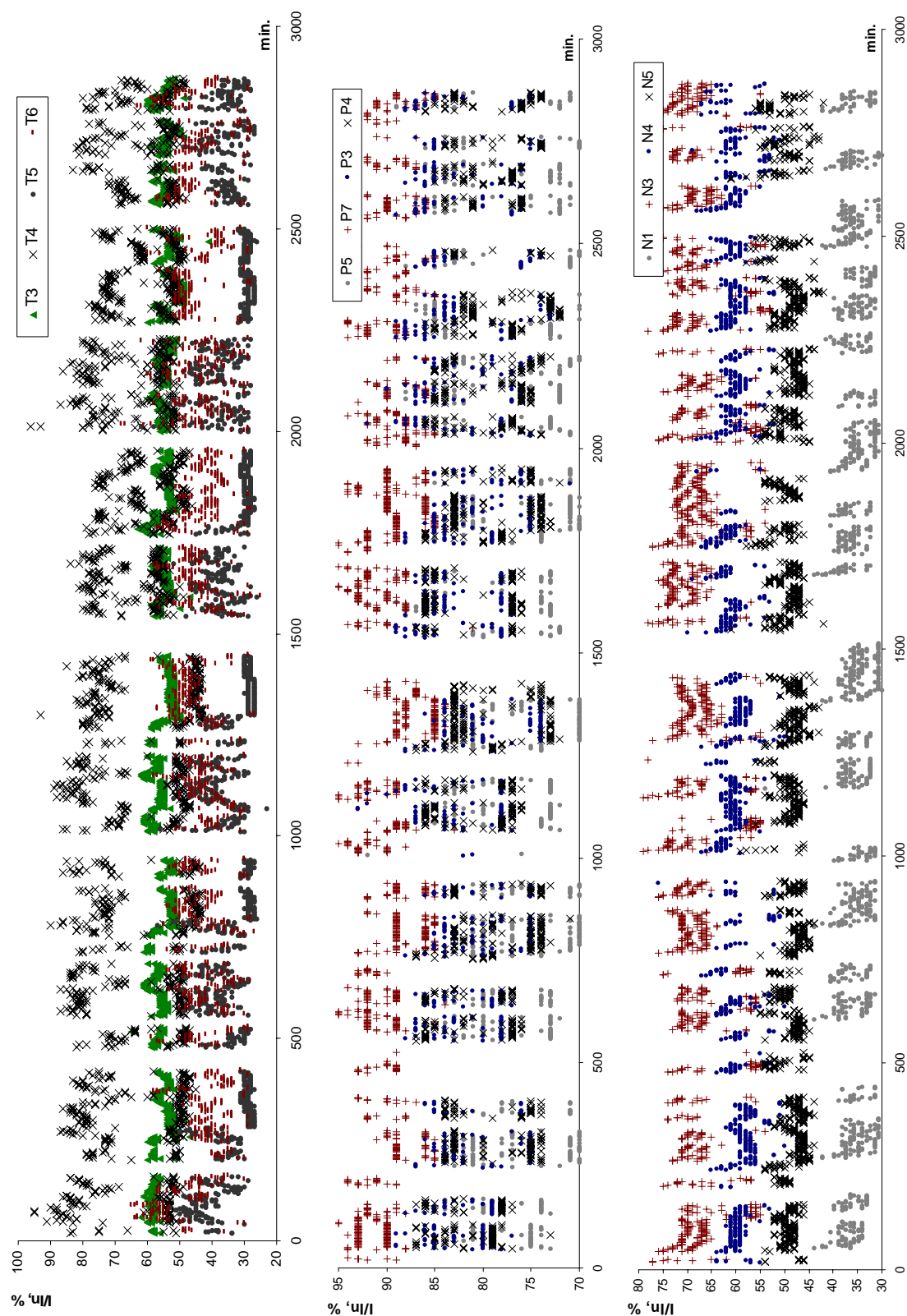
Fig. 2. Graphical interpretation of data of the electric loads for a representative part of the investigated machines.

The system [4] is for an automated energy-efficiency investigation and complete assessment in single as well as in grouped electric-motor drives. It uses mathematical models for total computing of the energy-efficiency indexes described above, and has an option for evaluating jointly working (grouped) electric-motor drives. The system' structural design is hardware and software ensured with two computer programs, a portable computer and a digital electricity meter with corresponding software. The system's working capacity and practical applicability are tested and proved by conducting investigations of objects in operation.

The software *EffSyst v.1.0* [5] is used in simulation mode. The net-losses level is estimated by the index C_1 - active power in no-load operation.

3.3. Determination of the input indices
The data for the electric loads (Figure 2), as well as the duration of operation of the consumers, are taken from the monitoring system of the site. The optimum-level indices A_1 and A_2 are obtained according to the model for determining the energy efficient operations of induction motors [6], and the index E_6 is set in the optimum operation and is evaluated using the aggregate operating characteristics of the software *PSAT 2008* [7].

4. EXPERIMENTAL RESULTS

The results of the investigation are summarized and shown in Table 1. All indices for each machine and for the examined complete system, including the indices of the newly-synthesized group H, are determined. The actual relative electric-power consumption B_7 of the individual machines ranges from 1.35 to 26.2 relative units with an average value of 6.93 units, as the aggregate relative consumption of the whole system is almost three relative units.

Table 1[a]. Data for the indices for energy efficiency evaluation of the electric drives of a system for transportation and processing of rock materials (Part 1).

Index	Dimension	P_1	P_2	P_3	P_4	P_5	P_6	P_7*	P_8*	P_9
A_1	kW	36.76	36.76	36.76	36.76	36.76	36.76	25.00	25.00	22.97
A_2	kVAr	26.61	26.61	26.61	26.61	26.61	26.61	18.15	18.15	17.23
A_3	min	155	202	967	646	592	789	984.0	1173	998
A_4	kWh	11.01	18.07	515.8	344.4	295.7	432.2	391.0	465.9	350.2
A_5	kWh	94.88	123.6	592.2	395.5	363.0	483.5	410.0	488.6	382.0
A_6	–	1.131	1.171	7.748	7.748	5.399	9.420	21.59	21.59	12.00
B_1	kW	8.424	10.62	35.83	34.55	33.28	35.40	24.79	24.97	22.64
B_2	kVAr	19.30	19.40	25.94	25.01	24.96	25.63	17.95	18.14	16.98
B_3	min	1210	1208	1203	1209	1212	1211	1202	1207	1207
B_4	kWh	83.87	105.6	76.43	51.04	67.23	51.33	18.99	22.63	31.85
B_5	kWh	86.01	108.1	641.9	645.1	605.0	663.1	477.6	479.6	423.6
B_6	kWh	169.9	213.7	718.3	696.1	672.2	714.5	496.6	502.3	455.5
B_7	–	2.025	2.024	9.398	13.64	9.999	13.92	26.15	22.19	14.30
C_1	kW	4.265	5.371	32.01	32.01	29.95	32.86	23.84	23.84	21.06
C_2	kW	–	–	–	–	–	–	–	–	–
D_1	–	1.790	1.728	1.213	1.760	1.852	1.478	1.211	1.028	1.192
D_2	–	7.812	5.985	1.244	1.873	2.046	1.534	1.222	1.029	1.210
D_3	min	1055	1006	236	563	620	422	218.0	34.40	209
D_4	kWh	75.00	90.07	126.1	300.6	309.2	231.0	86.62	13.67	73.44
E_1	%	0	0	0	0	0	0	0	0	0
E_2	%	7.654	6.384	0	0	0.024	0	0	0	0
E_3	%	92.92	92.92	92.92	92.92	92.92	92.92	92.92	92.92	92.92
E_4	–	0	0	0	0	0	0	0	0	0
E_5	–	0.41	0.33	0	0	0.01	0	0	0	0
E_6	–	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.81	0.80
F_1	kW	3.416	5.163	1.074	1.380	6.315	4.950	0.990	1.376	1.040
F_2	–	0.406	0.487	0.035	0.042	0.194	0.140	0.041	0.055	0.046
F_3	kVAr	5.871	7.078	0.583	0.749	3.552	2.688	0.538	0.747	0.585
F_4	–	0.305	0.365	0.023	0.030	0.143	0.105	0.030	0.041	0.035

Table 1[b]. Data for the indices for energy efficiency evaluation of the electric drives of a system for transportation and processing of rock materials (Part 2).

Index	Dimension	P_{10}*	P_{11}	P_{12}	P_{13}	P_{14}	N_1	N_2	N_3	N_4
A_1	kW	25.00	10.11	10.11	10.11	10.11	41.35	41.35	10.12	10.12
A_2	kVAr	18.15	8.376	8.376	8.376	8.376	29.94	29.94	8.644	8.644
A_3	min	1069	45.46	268.7	635.8	465.7	61.93	56.46	573.8	288.1
A_4	kWh	412.7	0.877	20.61	60.76	48.15	2.934	2.592	47.23	20.97
A_5	kWh	445.3	7.659	45.26	107.1	78.46	42.68	38.91	96.67	48.54
A_6	–	13.64	1.129	1.836	2.311	2.588	1.074	1.071	1.955	1.761
B_1	kW	24.79	1.494	5.821	8.036	7.716	4.822	4.561	7.402	5.734
B_2	kVAr	17.95	6.044	6.449	7.304	7.224	21.38	20.22	7.134	6.527
B_3	min	1207	1211	1215	1208	1202	1205	1206	1204	1210
B_4	kWh	32.65	6.782	24.64	46.35	30.31	39.75	36.32	49.44	27.57
B_5	kWh	466.0	23.37	93.23	115.4	124.3	57.10	55.36	99.09	88.07
B_6	kWh	498.7	30.15	117.9	161.8	154.6	96.84	91.68	148.5	115.6
B_7	–	15.27	4.446	4.783	3.491	5.103	2.437	2.524	3.004	4.195
C_1	kW	23.17	1.158	4.604	5.734	6.203	2.843	2.754	4.938	4.367
C_2	kW	–	–	–	–	–	–	–	–	–
D_1	–	1.120	3.937	2.604	1.511	1.97	2.269	2.356	1.537	2.382
D_2	–	1.129	26.64	4.523	1.902	2.581	19.46	21.36	2.098	4.205
D_3	min	138.3	1166	946	572	736	1143	1150	630	922
D_4	kWh	53.39	22.50	72.62	54.69	76.12	54.16	52.76	51.86	67.10
E_1	%	0	0	0	0	0	0	0	0	0
E_2	%	0	8.635	1.535	0.266	0.368	9.155	9.388	0.468	1.65
E_3	%	92.92	92.92	92.92	92.92	92.92	92.92	92.92	92.92	92.92
E_4	–	0	0	0	0	0	0	0	0	0
E_5	–	0	0.53	0.10	0.03	0.04	0.59	0.59	0.04	0.10
E_6	–	0.81	0.77	0.77	0.77	0.77	0.81	0.81	0.76	0.76
F_1	kW	0.941	0.051	0.727	1.501	2.674	1.146	1.157	2.366	0.836
F_2	–	0.038	0.034	0.125	0.187	0.347	0.238	0.254	0.32	0.146
F_3	kVAr	0.511	0.154	0.604	1.023	1.878	3.812	3.848	1.710	0.714
F_4	–	0.029	0.026	0.094	0.140	0.260	0.179	0.191	0.240	0.110

* For these machines the indices A_1 and A_2 are set at the nominal motor operation because the losses level exceeds the loads in the 'c' zone of the model in [6].

Table 1[c]. Data for the indices for energy efficiency evaluation of the electric drives of a system for transportation and processing of rock materials (Part 3).

Index	N_5	N_6	T_1	T_2	T_3	T_4	T_5	T_6	M_1	M_2	SYSTEM**
A_1	10.12	10.12	121.3	121.3	–	–	68.92	68.92	295.7	295.7	1454
A_2	8.644	8.644	84.67	84.67	–	–	48.11	48.11	191.0	191.0	1007
A_3	156	974	190	181	–	–	151	404	307	410	289.1
A_4	6.914	130.5	94.05	76.43	–	–	7.237	48.88	134.7	399.0	2031
A_5	26.23	164.1	384.7	365.6	–	–	173.1	463.8	1511	2022	7007
A_6	1.358	4.878	1.324	1.264	–	–	1.044	1.118	1.098	1.246	1.408
B_1	3.618	9.704	43.96	39.66	11.96	14.99	11.06	27.70	94.72	139.0	670.3
B_2	6.103	8.038	66.75	60.22	12.20	13.21	37.91	35.99	136.5	141.8	786.9
B_3	1215	1213	1219	1213	1210	1209	1217	1218	1208	1207	1200
B_4	19.32	33.6	290.7	289.2	0	0	165.8	414.9	1377	1622	4976
B_5	53.95	162.5	602.5	512.6	241.2	302.0	58.46	147.5	530.4	1174	8430
B_6	73.26	196.1	893.1	801.8	241.2	302.0	224.3	562.4	1907	2796	13406

continued from Table 1ᶜ

B_7	3.792	5.829	3.073	2.772	–	–	1.353	1.355	1.385	1.724	2.694
C_1	2.664	8.036	–	–	–	–	–	–	26.34	58.36	421.5
C_2	–	–	29.65	25.35	11.96	14.99	2.882	7.264	–	–	
D_1	2.793	1.195	2.322	2.193	–	–	1.296	1.213	1.262	1.383	1.913
D_2	7.803	1.245	6.406	6.707	–	–	8.078	3.017	3.939	2.942	4.150
D_3	1059	239	1029	1032	–	–	1066	814	901	797	910.9
D_4	47.03	31.99	508.4	436.1	–	–	51.22	98.58	395.7	775.0	6399
E_1	0.052	0	0	0	–	–	0	0	0	0	–
E_2	5.050	0	4.964	5.644	1.323	0.439	8.599	4.19	5.739	2.889	–
E_3	92.92	92.92	92.92	92.92	92.92	92.92	92.92	92.92	92.41	92.41	–
E_4	0	0	0	0	–	–	0	0	0	0	–
E_5	0.25	0	0.27	0.27	–	–	0.54	0.21	0.27	0.14	–
E_6	0.76	0.76	0.82	0.82	–	–	0.82	0.82	0.84	0.84	–
F_1	0.271	3.275	6.455	14.22	0.573	4.311	4.893	10.87	55.16	75.26	–
F_2	0.075	0.338	0.147	0.359	0.048	0.288	0.443	0.393	0.583	0.542	–
F_3	0.343	2.035	7.351	16.20	0.439	2.852	12.58	10.59	59.63	57.58	–
F_4	0.056	0.254	0.110	0.269	0.036	0.216	0.332	0.295	0.437	0.407	–
H_1	–	–	–	–	–	–	–	–	–	–	1,621

Nomenclature: A_1 - active power in optimum operation of the machine (system); A_2 - reactive power in optimum operation of the machine (system); A_3 - optimum operating time; A_4 - non-useful electric power consumption in optimum operation; A_5 - total electric power consumption in optimum operation; A_6 - relative electric power consumption in optimum operation; B_1 - average active power in actual operation; B_2 - average reactive power in actual operation; B_3 - actual operating time; B_4 - useful electric power consumption; B_5 - non-useful electric power consumption in actual operation; B_6 - total electric power consumption in actual operation; B_7 - relative electric power consumption in actual operation; C_1 - active power in no-load operation; C_2 – total power loss; D_1 - coefficient of overrun of total energy consumed; D_2 - coefficient of overrun of non-useful energy consumed; D_3 - overrun of operating time; D_4 - overrun of electric energy; E_1 - deviation from the maximum electric motor efficiency in optimum operation; E_2 - deviation from the maximum electric motor efficiency in actual operation; E_3 - maximum electric motor efficiency; E_4 - deviation of the power factor from the desired value in optimum operation; E_5 - deviation of the power factor from the desired value in actual operation; E_6 - desired (optimum) power factor; F_1 - standard deviation of the active power in actual operation; F_2 - coefficient of variation of the active power in actual operation; F_3 - standard deviation of the reactive power in actual operation; F_4 - coefficient of variation of the reactive power in actual machine operation; H_1 - relative load lift.

** The machines T_3 and T_4 are not involved in calculations due to the lack of out-of-levelling.

The total overrun of electric energy D_4 due to lack of loading reaches 4155 kWh as it is the highest with the machines T_1 and M_2. This can be explained by the relatively large consumed power and losses level. The relative consumption A_6 in optimum operation moves from 1.04 to 21.6 while the average decrease towards the actual operation is about two relative units. The resulting low levels of the statistical indices F_1...F_4 justify the high fidelity of the results within the actual technological conditions.
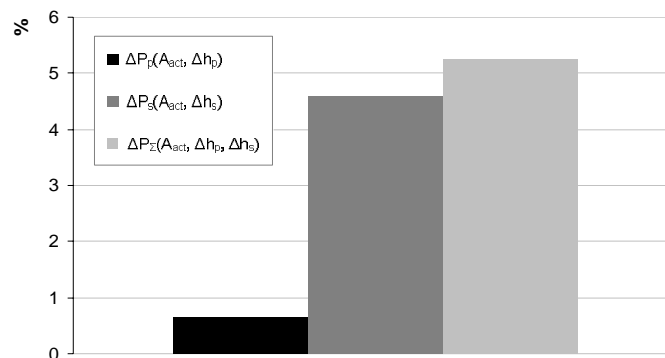

Fig. 3. Power losses in relative units towards the total consumed electrical power of the transport system.

The power losses ΔP_p (A_{act}, Δh_p), ΔP_s (A_{act}, Δh_s) and ΔP_Σ (A_{act}, Δh_p, Δh_s) due to loss of potential energy are determined based on the recorded geometrical characteristics of the complex system. The results are presented graphically in Fig. 3. The low power ratios can be explained by the higher losses of electric power, especially in the feeders of the system.

The relative load lift H_l exceeds 1.5 relative units (Table 1). The high value is due to the irregularly-selected terrain for the industrial-plant construction without a full usage of the gravity forces. The presence of intermediate bunkers, which creates certain operational conveniences and the related with them regulating masses, also increases the above-mentioned energy proportion.

5. CONCLUSIONS

The conducted investigation of the chosen industrial object and the results obtained prove the presence of practical possibilities for application of the generalized model [1] for investigating the energy efficiency of mechanical handling machines – individually and as a complex systems for continuous transport. The studies regarding the model applicability should be expanded in the area of mechanical handling machines and systems with a cyclic operation.

The investigation of the industrial system for rock-materials transportation through the generalized model [1] is carried out by 33 indices. The obtained results of the investigation indicate a low energy-efficiency level for the object. If the belt conveyors' load is optimal, the electric energy consumption of the site can be decreased by 45 %.

The determined low energy-efficiency levels of the investigated system reveal the need and the relevance of conducting further practical studies on the systems for transporting and grinding rock materials, as well as on the other similar systems for transportation of bulk loads.

The results of the model [1] validation can be used in:
- The construction of mechanical handling machines for systems for continuous transport;
- The design of new, reconstruction and modernization of existing mechanical handling machines and continuous-transport systems;
- The synthesis of a set of indices and the structure of acting systems for controlling the electric energy consumption of the machines and systems for continuous transport.

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