METHODOLOGY FOR ENERGY-EFFICIENCY INVESTIGATION OF ELECTRICAL CONSUMERS

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Abstract: Uniform indications for electric consumers classifying are determined according to their technological signs and the physical forms of electrical energy conversion. Levels of consumption in electrical consumers are defined, on the basis of which 29 indexes for investigation, evaluation and comparison of the energy efficiency in electric drives are systematized. The indexes are distributed into 6 groups. Dependencies are defined and methods are developed for determination of the indexes system. An aggregate mathematical model for monitoring and evaluating the energy efficiency of grouped electric drives is synthesized. Case-study results for a typical belt-conveyor system in a thermo-electric power plant are obtained.

Keywords: energy efficiency, electrical consumers, electrical drives, methodology, methods

1. INTRODUCTION

The efficiency investigation and evaluation into electric power consumption in industry is a strategic issue, aimed at reducing the EU energy dependence and increasing the economy competitiveness [1]. In this connection, a number of studies and developments are done which are related to the electric drives (ED) – the most common consumers in this field.

A methodological model for energy-efficiency (EE) evaluation is synthesized in [2]. The conditions that are supposed to be considered in the further policy for efficient use of electrical energy are determined, including: initiating the exergy beginning in assessing the production and consumption technologies; approving uniform criteria, regulations and methods for electricity pricing as the generation, transmission, distribution, supplying, contracting, consumption and electricity payment to be connected in one node – the efficient electric power utilization; classifying the electric consumption not into branches, but bringing the forms of electric-energy transformation to a physical and technological base, and creating a unified procedure and tooling for automated EE investigation. A consumer's classification on a fundamentally new basis (in accordance with the physical forms of electrical energy conversion and towards their mutual connection) is proposed. According to this classification, levels for efficient electric power consumption are defined – physical (basis) level, optimum power consumption level, level of actual power consumption, level of the total electrical power losses, level of the electric power fed by the source and others [3, 4].

The specified levels create assumptions and they are a starting point for EE modeling. In this context, several generalized and specific analytical and grapho-analitical models for EE investigation are constructed and developed, as one of them is the generalized model for evaluating the EE of asynchronous ED presented in [5, 6]. In the basis of this model, an integral investigation technique lies which is characterized by its 29 informative

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indexes for EE assessment digested into 6 classification groups (groups A, B, C, D, E and F), an algorithm and a computer program for conducting automated investigations, available and functional technical means for obtaining experimental data on ED active and reactive power consumed. In addition, the model can be successfully applied in training of professionals and students through developed for this purpose teaching procedures [7, 8]. Simulation of induction motor (IM) duties with a view to estimate the electrical-energy utilization in ED has done in [9]. The derived grapho-analitical model provides accurate determination of the EE indexes system [5, 6], as an assessment of the optimum level, defined as an input index, can be made. Thus, the lack of information on optimum level which should be normally provided by the manufacturing companies is compensated. The practical applicability of the described model is ensured by published common databases containing performance characteristics of wide range of IM of different types and from different manufacturers [10, 11].

The models analyzed above refer to single, technologically unrelated ED. In order to cover the linked drives and combine them into technology groups, a model for monitoring and evaluating the EE of grouped ED has been developed in [12]. The model gives a possibility to determine the total EE with a generalized target function of the reduced relative electric-power consumption and it has the following advantages:

- Setting and evaluating the drives in groups, according to their functions and statistical indicators in each moment of time;
- Monitoring, evaluating the EE and controlling the quality of electric power demand towards previously defined minimum levels. The observed deviations are indicative of the analysis with a view to assess the degree of effective electrical energy utilization;
- Determining the relative power consumption as a weighted power value and considering the priority impacts of powerful consumers, whose regimes and design parameters have most influence on EE.

This development is an initial point for establishing systems for qualitatively new monitoring and electric-consumption control in industry but also in other manufacturing or non-productive enterprises.

Models for EE assessment in fuel transportation and preparation systems in coal-fired steam-power plants are synthesized in [13−15]. The models give an objective account of the production processes nature and specificity, including the qualitative indexes of used coal, presence of redundant ballast masses, leveling of coal-handling conveyors.

On the other hand, a number of studies are published concerning particular elements of ED but not drives as complete systems. These include researches and developments of new, more convenient and feasible methods for IM efficiency determination in field or laboratory conditions, as well as researches in effectiveness and energetic effects due to installing inverters or similar converting devices [16−24].

Based on the models in [2−6, 12], corresponding computer algorithms are developed and appropriate software tools for computing the system of EE indexes and relative electric-power consumption are developed [25]. The software in conjunction with adapted for the purpose widely-used measuring instruments [26] is considered when designing structures of automated systems for investigation and complex EE assessment of individual and grouped ED [27, 28]. To build the system described in [28] completely, additional mathematical models for aggregate computation of the EE indexes for grouped drives are synthesized; a standard file for inputting the entry information into the computer program '*Energy Efficiency'* is created [28]. The structure of the system is hardware and software provided. Series of investigations of typical industrial drives and systems are conducted by using the developed system, including combination lathes, belt conveyors, drum mills, fans, etc. [13, 15, 29−32]. The investigation results prove the efficiency and practical applicability of the integrated tooling and models for EE investigation of ED.

The above-analyzed developments have their disadvantages, which can be grouped in the following directions:

- It is found that EE practices are various, according to the specifics of the given processes, machines and units;
- Generally, the developments have not acquired a methodological character and solve particular problems without covering the efficient power consumption issue as a whole;
- Despite that the EE analysis of each ED (irrespective of its purpose or industry branch in which it operates) is to be based on the basis level of electrical consumption, this level is not grounded in sufficient degree.

In conclusion, the conducted analysis shows that there are real opportunities to reduce the complex of rules, methods, techniques and instruments (tooling) to a single methodological basis with a view to investigate and open new possibilities for improving the EE of ED. In this regard, the purpose of this article is set: *to ground a uniform integrated methodology for investigation and evaluation of the energy efficiency of electric drives.*

2. ELECTRICAL CONSUMERS CLASSIFICATIONS BY UNIFORM INDICATIONS

2.1. Technological indicators

It is the usual practice, the electrical consumers to be classified by branches (industry, agriculture, domestic sector etc.). Each branch, sub-branch and object has its own specificity that is important to be considered, but if the classification is formed on this principle, an indefinite multitude of indexes will exists and many of them will be duplicated. Thus, another classification scheme is rational – by technological indications. Two basic groups of electric consumers can be differentiated – technologically not connected and technologically connected consumers. The group's description and the typical consumers are presented in Table 1.

Table 1. Classification of electrical consumers according to their technological indicators.

<table>
<tr><th colspan="3">Description</th><th>Consumers</th></tr>
<tr><td>Group 1. Technologically not connected (‘free’ consumers)</td><td colspan="2">The group covers the domestic sector, tourism, administration centers, etc.</td><td>All domestic consumers, electrochemical appliances, microwave ovens, washing machines, electronic audio and video equipment, lighting equipment, air conditioner-humidifiers, etc.</td></tr>
<tr><td rowspan="2">Group 2. Technologically connected</td><td><u>Discrete electrified systems</u></td><td>The electric power consumption of machines, units, systems, workshops, etc. is described by the discrete production theory.</td><td>Consumers in mechanical engineering and others.</td></tr>
<tr><td><u>In-line electrified systems</u></td><td>The conditions for efficient electric consumption of machines, installations, systems, etc. derive from the in-line production theory.</td><td>Thermal and thermo-electric power plants and systems; consumers in chemical, food, wine and tobacco industries, agriculture, transport systems, etc.</td></tr>
</table>

2.2. Physical forms of electrical energy conversion

Each process, or activity, is described by the necessary (minimum) theoretical consumption level for running the process or doing the necessary quantity of work. This level is dictated by the corresponding physical laws and processes.

The quantity of electrical energy consumed, resulting from this physically predetermined level, is to be accepted for *an absolutely useful (efficient and unavoidable) consumption*. This means that each consumer has one basis level that represents its physical fundamental and is a starting point for determining the degree of efficient electric-energy utilization.

According to this basic energy consumption, new criteria, normative regulations and methods of electricity pricing should be approved, as generation, transmission, distribution, supplying, contracting, consumption and electricity payment will be connected in only node – the efficient use of electric energy.

Therefore, consumers' classification by the physical forms of electrical energy conversion is of primary importance. The physical forms of electrical energy conversion are three: conversion into mechanical, thermal and radiant energy (Table 2).

The technologically not connected and the technologically connected consumers redistribute towards each conversion form irrespective of their destinations. Levels of efficient electrical-energy consumption are to be defined according to the synthesized consumers' classifications.

Table 2. Classification of electrical consumers according to the physical forms of energy conversion.

Nr. crt.	Conversion forms	Consumers
1.	Electrical to mechanical energy	Electric motor machines and systems in all fields of economy and industry, pumps, fans, systems for ventilation, water-supply and irritation, domestic appliances.
2.	Electrical to thermal energy	Induction, convection and microwave heating in industry and domestic sector.
3.	Electrical to radiant energy	Lamps and radiant energy sources, irradiation and lighting systems.

3. LEVELS FOR EVALUATION OF THE EFFICIENCY IN ELECTRIC POWER CONSUMPTION

3.1. Physical (basis) level

3.1.1. In case of converting electrical energy into mechanical energy

This level refers to consumers that transform electrical energy into mechanical energy (Table 2). It covers the groups of the technologically not connected and the technologically connected consumers. Those are processes related to electric motor machines and systems where resisting moments in cutting, drilling, breaking, milling, mixing, separation, etc. are counteracted (mechanical engineering, electric-motor domestic appliances, electrical transport, building, etc.):

- Level in electric-motor machines and units. The level of energy consumed will be determined by the angular $\omega(t)$ or linear $v(t)$ speeds when doing technological operations, and by occurred resisting moments $M_s(t)$ and forces $F_s(t)$ in operating mechanisms [3, 4];
- Level in counteracting forces of gravity. Those are processes related to transportation of fluids and in-bulk materials. The physically necessary energy to provide the process of transportation is determined by the mass density ρ, the gravitational acceleration g, the transported load volumetric flow Q(t) and the height $H = h_2 - h_1$ for transportation [3, 4, 13, 29, 30].

3.1.2. In case of converting electrical energy into thermal energy

Those are processes related to heat treatment of materials and foods – direct and indirect (induction, convection) heating of solids and fluids. The energy absorbed by processed substances is useful. It can be determined by the substances thermal capacity C_T, the mass m and the wanted heating temperature t [3, 4].

3.1.3. In case of converting electrical energy into radiant energy

Here, the absorbed by receivers radiant energy W_α is effective, according to the receivers' spectral sensitivity $\alpha(\lambda,t)$ and the quantity of absorbed energy W_e which is converted into desired to the particular technological process form of energy – electrical energy, chemical energy, etc. [4].

The defined basis level of electrical energy consumed can be preliminarily obtained in conformity with production plans implementation and ensured manufacturing processes as the energy balances and measures for energy savings should be compiled and organized according to it.

3.2. Level of actual electric power consumption

This is the actual consumed electrical power in case of real operation and concrete parameters of the investigated production process, consumer or group of consumers.

3.3. Level of optimum electric power consumption

The optimum electric-energy consumption level can be reached only when the production activities are organized and the machines and systems are adjusted in such a way so that minimum relative electric-power consumption is observed [5, 13].

3.4. Level of the total power loss

The basis level dictates the quantity of energy that has been consumed in doing useful work only. The difference in the actual electric-power consumption and the energy determined by the basis level forms the total electrical power loss.

4. MODEL FOR ESTIMATION OF THE OPTIMUM LEVEL OF ELECTRIC DRIVES

The optimum drive's level can be assessed by specifying the most efficient operating conditions of its electric motor. Thus, let us compare the general views of the efficiency curves of a standard (class IE3) and an energy-efficient (class IE2 or IE1) electric motor, presented in Fig. 1 regarding the electrical power P_1 consumed from the power network. In operation, the ED motor working point not always corresponds to its maximum efficiency η_m as it may be before or after this maximum [33]. This forms three zones 'a', 'b' and 'c' which usually cover the actual motor loads P_{1i}. Zone A (points 1, 2, 3 and 4) is fixed by the acceptable efficiency drop $\eta_{a,eff}$, it is wider than the analogous one for standard motors (zone 'b'), and is characteristic of energy-efficient motors (see Figure 1). As seen from the figure, the motor efficiency starts rapidly decreasing outside areas 'a' and 'b' (under $\eta_{a,eff}$ and $\eta_{a,st}$) and therefore loads of this order are not desirable. The condition for determination of the limits of zones 'a' and 'b' (points 3, 4 and 10) can be defined by the admissible efficiency decrease:

$$\frac{\Delta\eta_i}{\Delta P^*_{fix}} = \tau_i \leq \tau_a = \frac{\Delta\eta_a}{\Delta P^*_{fix}} \tag{1}$$

where: ΔP^*_{fix} is the relative change in the motor load, $\Delta\eta_i$ is the corresponding i-th change in the motor efficiency, τ_i and τ_a are the i-th and the admissible value of the criterion for efficiency decrease, and $\Delta\eta_a$ is the admissible change in the motor efficiency.

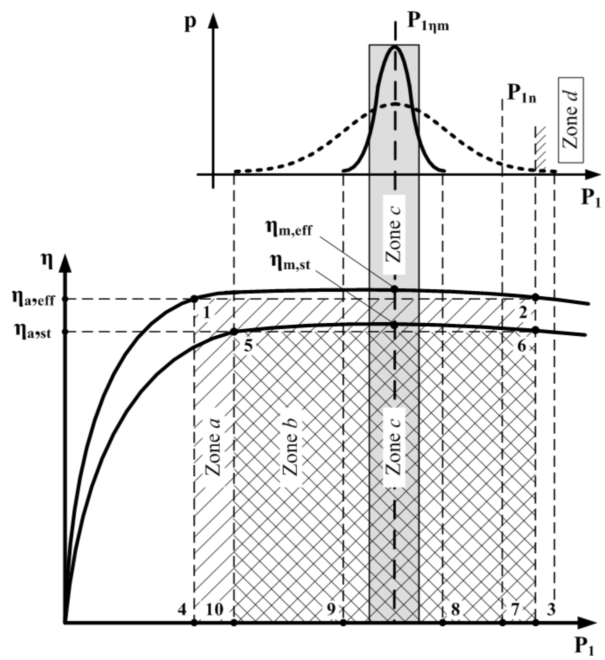

Fig. 1. Zones of efficient operation of electric motors compared to the probability distribution of the active power consumed.

For correct limit values determination, the relative change ΔP^*_{fix} need to be chosen the same within the studied range of loads:

$$\Delta P^*_{fix} = \frac{\eta_n}{P_{2n}}.\left(P_{1,k} - P_{1,k-1}\right) = const \tag{2}$$

where: η_n is the nominal efficiency, P_{2n} is the nominal shaft power, $P_{1,k}$ and $P_{1,k-1}$ are the values of the electric of power at the beginning and at the end of the change.

In order to achieve a rational solution, it is desirable the optimum ED level to be within the zone 'c' where the maximum electric motor efficiency is. This zone is surrounded by continuous line in Fig.1 and it usually varies from 70 to 80 percent of the full-load shaft power P_{2n}. The following system is used for determination of the zone limit values:

$$\begin{cases} \delta_c^r = P_{1\eta m} + \sigma_a . P_{1\eta m} \\ \delta_c^l = P_{1\eta m} - \sigma_a . P_{1\eta m} \end{cases} \tag{3}$$

where: δ_c^r and δ_c^1 are the right and the left limit value of the zone, $P_{1\eta м}$ is the power at maximum motor efficiency and σ_a is the admissible zone-width coefficient.

Typically, the drives working in steady-state operation consume active power that fluctuates around the mathematical expectation due to various random factors: environmental parameters (temperature, humidity, dust loading, etc.); non-uniformity of processed objects; technological factors and others (Figure 1). The total, aggregate effect of those factors is a random variable and the active power can have a different probability distribution $p(P_1)$ which, when the factors are many and have approximately equal influence, is normal. Thus, even when drive is set in its optimum working conditions, the operating point deviates from the maximum efficiency (for example, to points 8 and 9) as deviations' size depends on the dispersion parameters.

According to the defined zones 'a' and 'b' and in case of high dispersion, the ED motor load can decrease to the admissible values determined by points 4 and 10, and even lower. In this case however, according to the corresponding probability distribution, deviations are fixed in the opposite direction – of increasing of P_1, which reach the area "d" (see Figure 1), where operation should not be allowed due to motor overloading.

5. INDEXES FOR ENERGY-EFFICIENCY INVESTIGATION AND EVALUATION OF ELECTRIC DRIVES

A comparative diagram of EM consumption in optimum and non-optimum operation can be drawn on the basis of the evaluation levels (see Figure 2). After analyzing the diagram, and given that the basis level and energy do not depend on operating parameters (the area 1-2-3-4 is equal to the area 5-6-7-4), a complex system of informative indexes for investigation and evaluation of the EE of ED is worked out (Table 3). The indexes are divided into six groups – A, B, C, D, E and F. All the indexes related to the optimum ED 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 operation.

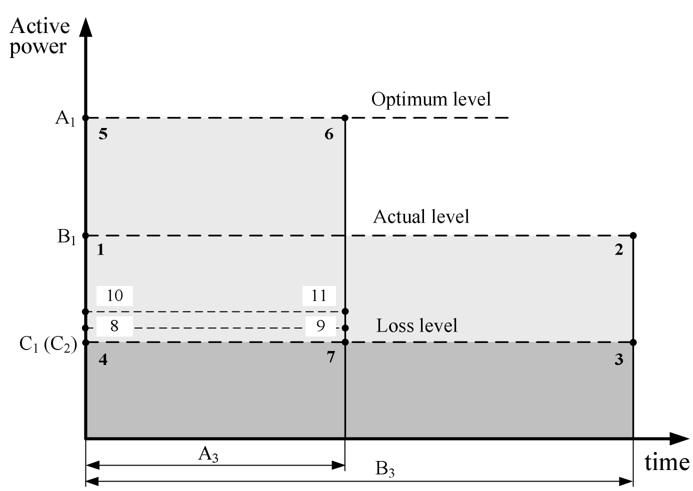

Fig. 2. Initial diagram for synthesizing the indexes for efficient consumption of electric drives.

The indexes A_6 – relative electric power consumption in optimum operation, B_7 – relative electric power consumption in actual operation, as well as D_1 – coefficient of overrun of total energy consumed and D_2 – coefficient of overrun of non-useful energy consumed.

Table 3. Characteristics and dependences for determination of the indexes for investigation and evaluation of the energy efficiency of electric drives.

Group	Symbol	Units	Description	Determination	
Group A	A_1	kW	Active power in optimum electric drive operation	By using the model in section 4	
	A_2	kVAR	Reactive power in optimum electric drive operation		
	A_3	min.	Optimum operating time	$A_3 = \frac{B_4}{A_1 - C_1}$	(4)
	A_4	kWh	Non-useful electric power consumption in optimum drive operation	$A_4 = C_1.A_3$	(5)
	A_5	kWh	Total electric power consumption in optimum operation	$A_5 = A_1.A_3$	(6)
	A_6	–	Relative electric power consumption in optimum operation	$A_6 = 1 + \frac{C_1}{A_1 - C_1}$	(7)
Group B	B_1	kW	Average active power in actual operation	$B_1 = \frac{1}{n}.\sum_{i=1}^{i=n} P_{act,i}$	(8)
	B_2	kVAR	Average reactive power in actual operation	$B_2 = \frac{1}{n}.\sum_{i=1}^{i=n} Q_{act,i}$	(9)
	B_3	min.	Actual operating time	$B_3 = n.\delta$	(10)
	B_4	kWh	Useful electric power consumption	$B_4 = (B_1 - C_1).B_3$	(11)
	B_5	kWh	Non-useful electric power consumption in actual drive operation	$B_5 = C_1.B_3$	(12)
	B_6	kWh	Total electric power consumption in actual operation	$B_6 = B_4 + B_5$	(13)
	B_7	–	Relative electric power consumption in actual operation	$B_7 = 1 + \frac{C_1}{B_1 - C_1}$	(14)
Group C	C_1	kW	Active power in no-load operation	By measurement	
	C_2	kW	Total power loss	$C_2 = B_5 - P_b.B_3$	(15)
Group D	D_1	–	Coefficient of overrun of total energy consumed	$D_1 = \frac{B_6}{A_5}$	(16)
	D_2	–	Coefficient of overrun of non-useful energy consumed	$D_2 = \frac{B_5}{A_4}$	(17)
	D_3	min.	Overrun of operating time	$D_3 = B_3 - A_3$	(18)
	D_4	kWh	Overrun of electric energy	$D_4 = B_6 - A_5$	(19)

Group E	E_1	%	Deviation from the maximum electric motor efficiency in optimum drive operation	$E_1 = \eta_{\mathbf{max}} - \eta_{op}$ (20)
	E_2	%	Deviation from the maximum electric motor efficiency in actual drive operation	$E_2 = \eta_{\mathbf{max}} - \eta_{act}$ (21)
	E_3	%	Maximum electric motor efficiency	On the basis of data from catalogues or other technical literature
	E_4	–	Deviation of the power factor from the desired value in optimum drive operation	$E_4 = E_6 - \frac{A_1}{\sqrt{A_1^2 + A_2^2}}$ (22)
	E_5	–	Deviation of the power factor from the desired value in actual drive operation	$E_5 = E_6 - \frac{B_1}{\sqrt{B_1^2 + B_2^2}}$ (23)
	E_6	–	Desired power factor	A set (input) value
Group F	F_1	kW	Standard deviation of the active power in actual operation	$F_1 = \sqrt{\frac{1}{(n-1)} . \sum_{i=1}^{i=n} (P_i - B_1)^2}$ (24)
	F_2	–	Coefficient of variation of the active power in actual operation	$F_2 = \frac{F_1}{B_1}$ (25)
	F_3	kVAR	Standard deviation of the reactive power in actual operation	$F_3 = \sqrt{\frac{1}{(n-1)} . \sum_{i=1}^{i=n} (Q_i - B_2)^2}$ (26)
	F_4	–	Coefficient of variation of the reactive power in actual drive operation	$F_4 = \frac{F_3}{B_2}$ (27)

Nomenclature:
n – the number of the measurements in averaging the drive active and reactive powers; $P_{act,i}$ – the i-th measured value of the drive active power in kW; $Q_{act,i}$ – the i-th measured value of the drive reactive power in kVAR; δ – the time interval between two consecutive measurements in minutes; P_b – the basis (useful) power in kW; η_{max} – the maximum electric motor efficiency in %; η_{op} and η_{act} – the motor efficiency in the optimum and actual drive operation in %.

In increasing ED load, additional power losses arise and the line 4-7, which assesses the total-loss level by the no-load active power C_1, starts shifting as shown in Figure 2. This line moves to 8-9 in actual drive operation; and it is 10-11 in optimum duty. In particular, if we consider the energy conversion processes in induction motors, these changes are due to increase in rotor and stator copper loss. When calculating the proposed indexes system, this problem can be solved by using the previously-determined total power loss C_2 (which takes into account the variable losses component) instead of the no-load active power C_1.

6. AGGREGATE MODEL FOR ENERGY-EFFICIENCY INVESTIGATION OF GROUPED ELECTRICAL CONSUMERS

The most industrial projects are characterized by a number of available electrical consumers which, according to their mutual connection, are divided into a certain number of technological groups. Within a specified period of time (typically one work shift), the drives of each technological group are mutually-linked through the pattern load charts similar to those presented in [12]. In a random minute, each consumer can be found to be turned-on or turned-off according to the particular chart. When turned-on, the power consumption efficiency can be determined with the relative consumption levels of each working consumer [2, 5].

The condition for minimizing the power consumption of the groups of consumers will be the aggregate reduced relative electric power consumption E^*_{agg} to approach its minimum possible level at each moment of time. In terms of these formulations, the model for EE monitoring and consumption minimization can be expressed by:

$$E^*_{agg,j} = \frac{1}{n} \cdot \left(\frac{\sum_{i=1}^{i=m_1} E^*_{1i} . P_{1i}}{\sum_{i=1}^{i=m_1} P_{1i}} + \frac{\sum_{i=1}^{i=m_2} E^*_{2i} . P_{2i}}{\sum_{i=1}^{1=m_2} P_{2i}} + \ldots + \frac{\sum_{i=1}^{i=m_k} E^*_{ki} . P_{ki}}{\sum_{i=1}^{i=m_k} P_{ki}} + \ldots + \frac{\sum_{i=1}^{i=m_n} E^*_{ni} . P_{ni}}{\sum_{i=1}^{i=m_k} P_{ni}} \right) \Rightarrow MIN \quad (28)$$

where $E^*_{agg,j}$ is the value of E^*_{agg} in the j-th moment of time; n is the number of the technological groups; m_1, m_2, m_k and m_n are the numbers of consumers in these groups; i is the serial number of the values of the relative-power consumption and the active electric power; E^*_{1i}, E^*_{2i}, E^*_{ki}, E^*_{ni} and P_{1i}, P_{2i}, P_{ki}, P_{ni} are the i-th relative electric-power consumptions and the i-th active powers of the consumers in the first, second, k-th and the n-th technological group.

In case of deviations from the minimum, energy losses are accumulated, which depend primarily on the actual relative consumption and the consumers' basis and optimum levels.

7. CASE STUDIES

7.1. Determination of the energy-efficiency zones of electric motors

Forty three generalized efficiency curves of IE2 and IE3 induction motors were studied. The curves were obtained using the computer program PSAT [11]. The motors' sizes are listed in Table 4. The coefficient σ_a is 0.1, the criterion τ_a is three percent and the relative change ΔP^*_{fix} is one percent. The obtained results are shown in Figure 3. In order to achieve a clear and qualitative analysis of the zones' widths, their limits are presented in relative units according to the determined maximum-efficiency power $P_{1\eta m}$ (see Table 4). The right limits of the zones 'a' and 'b' are adopted 1.2 times the nominal motor power due to lack of possibility for determining the points 2 and 6 in the model (see Figure 1). Similarly, modeling can be performed for the induction motors included in [11] or other appropriate databases.

Table 4. Data for the active power in hp at maximum efficiency of standard (a) and energy efficient (b) electric motors with various nominal shaft power P_{2n}.

P_{2n}, hp	a	b
5	4.55	3.55
7.5	5.85	5.25
10	7.40	7.00
15	10.8	10.5
20	14.4	14.0
25	18.25	17.5
30	21.9	21.0
40	31.2	28.4
50	41.0	34.5
60	52.8	42.0
75	70.5	54.0
100	93.0	76.0
125	116	97.5
150	134	128
200	178	170
250	218	210
300	261	252
350	305	287
400	344	332
450	392	369
500	420	410

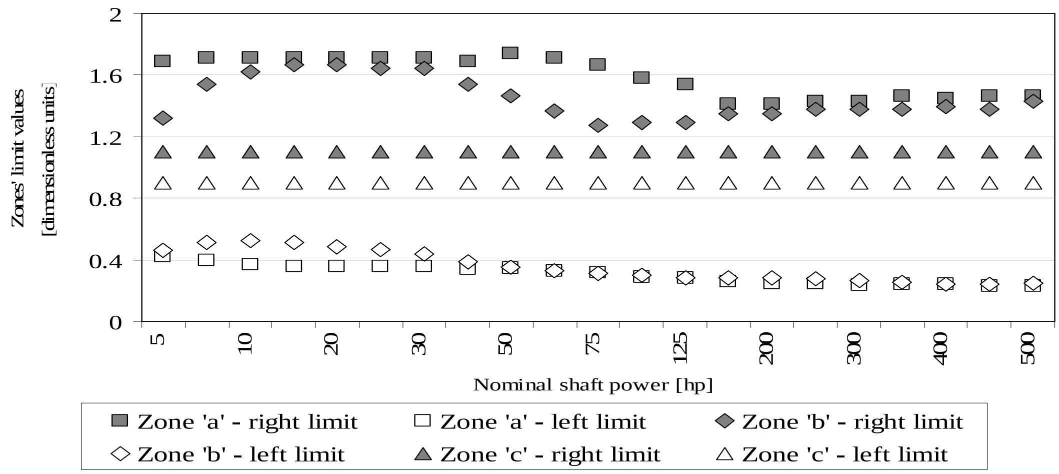

Fig. 3. Plot of the zones of the energy-efficient operations of electric motors with various nominal powers.

7.2. Determination of the energy-efficiency indexes

The object of this experiment was a typical system for transportation of coal in a thermo-electric power plant which consists of seven belt conveyors with a total installed capacity of 535 kW. Complete data on the configuration, operation, and technical characteristics of the object are presented in [13]. Digital electric meters, types EMPS T [26], were used for measuring the active and reactive power as the measured values were automatically recorded at each minute, and then processed by the developed software 'Energy Efficiency' [5, 25].

In the course of the measurements, the investigated system provided an average of about 6 feeds of coal per day as conveyors loading remained approximately constant for each feed. The investigation results, shown in Table 5, were obtained for a typical feeding during 35 minutes.

Table 5. Values of the indexes for evaluation of the energy efficiency of a coal-feeding system comprised of seven belt conveyors.

	1	2	3	4	5*	6	7*	System
A_1	63.883	93.696	135.56	64.716	−	25.970	−	−
A_2	28.785	55.057	72.433	32.814	−	13.876	−	−
A_3	3.947	4.458	22.463	24.210	−	20.458	−	−
A_4	2.117	5.291	23.515	7.371	−	7.188	−	−
A_5	4.203	6.961	50.751	26.113	−	8.855	−	−
A_6	2.015	4.169	1.863	1.393	−	5.313	−	−
B_1	33.824	72.573	84.600	32.501	36.711	23.938	16.726	299.92
B_2	26.447	56.744	68.882	24.376	17.780	13.566	19.039	226.48
B_3	76.000	74.000	75.000	79.000	79.000	35.000	35.000	43.000
B_4	2.086	1.670	27.236	18.742	0.000	1.667	0.000	26.398
B_5	40.761	87.840	78.514	24.053	48.337	12.298	9.757	188.541
B_6	42.847	89.510	105.75	42.794	48.337	13.964	9.757	214.94
B7	20.544	53.609	3.883	2.283	−	8.379	−	8.142
C_1	−	−	−	−	−	−	−	−
C_2	32.180	71.222	62.811	18.268	36.711	21.082	16.726	263.08
D_1	10.95	12.859	2.084	1.639	−	1.577	−	−
D_2	19.255	16.601	3.339	3.263	−	1.711	−	−
D_3	72.053	69.542	52.537	54.790	−	14.542	−	−
D_4	38.644	82.549	54.999	16.682	−	5.110	−	−
E_1	0.000	0.000	0.000	0.000	−	0.000	−	−

Table 5. Values of the indexes for evaluation of the energy efficiency of a coal-feeding system comprised of seven belt conveyors - continuation.

E_2	2.602	0.548	1.492	2.944	0.681	0.163	5.627	−
E_3	93.921	93.921	94.423	92.715	92.414	92.414	91.912	−
E_4	0.000	0.000	0.000	0.000	−	0.000	−	−
E_5	0.124	0.074	0.107	0.092	−	0.012	–	−
E_6	0.912	0.862	0.882	0.892	−	0.882	–	−
F_1	3.283	3.413	3.460	3.531	3.427	3.540	3.415	3.481
F_2	0.097	0.047	0.041	0.109	0.093	0.148	0.204	0.012
F_3	0.878	0.789	0.834	0.851	0.845	0.862	0.828	0.833
F_4	0.033	0.014	0.012	0.035	0.048	0.064	0.043	0.004

* Some of the indexes are not given since the load were been transported between points with equal altitudes and thus, the basis energy is zero.

7.3. Application of the aggregate model for grouped electrical consumers

Having the active-power and relative power consumption values, the aggregate model (28) was determined for each minute of a typical operation period of the transport system. The period was between the 112-th and 202-nd minute in the corresponding work shift. The results are graphically presented in Figure 4 as they are compared with the determined optimum consumption level. The occurred extreme points are due to non-simultaneous starting and stopping of the conveyors.

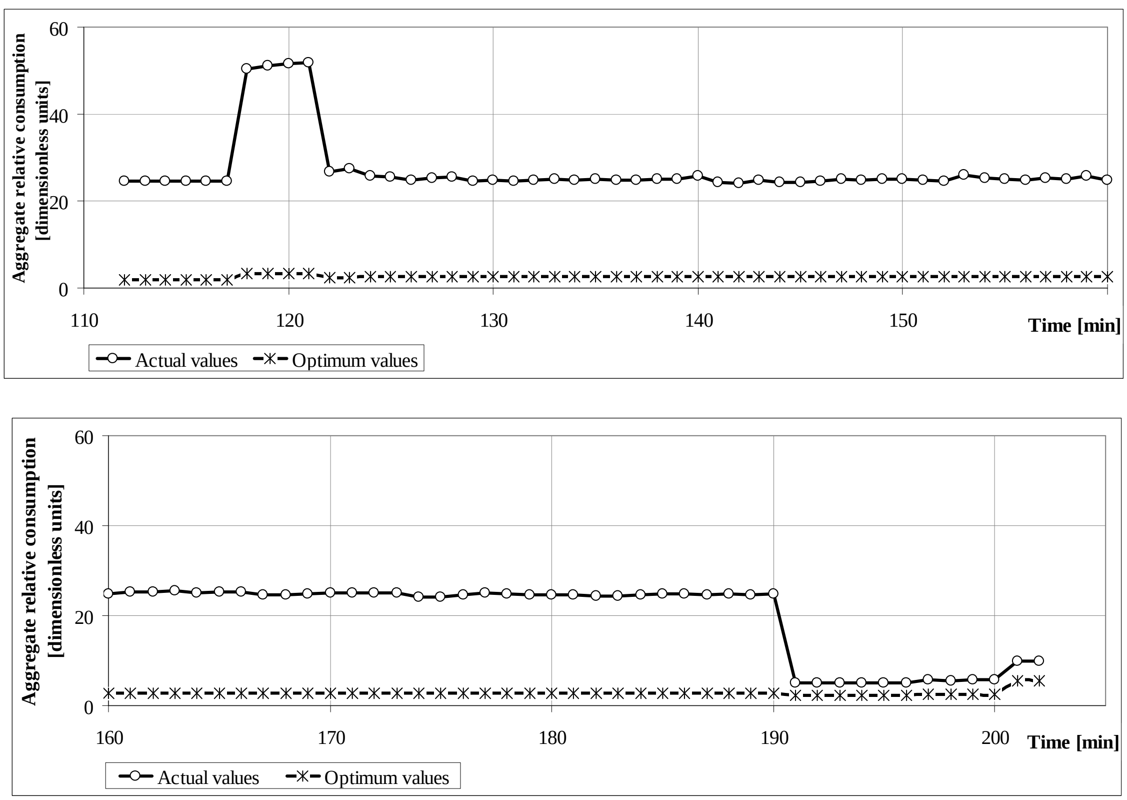

Fig. 4. Plot of the aggregate relative electric power consumption of a coal-feeding system.

8. CONCLUSIONS

1. Notwithstanding that power engineering is one of the sectors in which a public policy exists, and the legislation for solving energy-efficiency issues is ensured in principle, uniform criteria, regulations and methods of electricity pricing have not yet ratified, by which the generation, transmission, distribution, supply, contracting, consumption and payment to be linked into a single node, so that the interests and efforts of each

party to aim and ensure an efficient use of electric energy.

2. The results of this research show that, in energy-efficiency investigation, an objective necessity and prerequisites exist for putting the electric consumers, the corresponding laws and regulations, and the electric-power consumption management in each object, company, firm, dwelling or office – regardless of the nature of their processes and activities, into a single uniform methodological basis, as:

- According to the synthesis, consumers of electrical energy should be classified: into four groups (group 1 – conversion into mechanical energy; group 2 – conversion into thermal energy, group 3 – conversion into radiant energy) towards the physical forms of energy conversion; not by branches and production types, but according to the factors that determine their physical power consumption required for ensuring the technological processes and manufacturing programs.
- The physical (basis) level of consumption should be the instrument by which the power consumption to be modeled according to the consumers' groups and it should be adopted for a reference level for electrical consumption management in each process, site or enterprise. The physical level can be changed only by changing technologies, machines and units. The level of optimal power consumption also has a reference character. This is the theoretically-achievable level in a given piece of equipment and production technology. It is possible it to be determined by the developed grapho-analytical model using the machinery and equipment technical data and to be an integral part in the energy balances of industrial projects and firms. Estimation of effects of proposed measures for power savings should be carried out towards the optimum level and according to the developed technique and criteria D_1 and D_2 of the overrun of electrical energy.
- The synthesized set of 29 qualitative and quantitative indexes should be used for a thorough investigation, evaluation and comparison of the energy efficiency in electric drives. The indexes are divided into seven classification groups, as follows: group A – it consists of six indexes which characterize the optimum operation of drives, groups B and C – they estimate the actual and the no-load operation respectively, group D – it comprises four indexes and gives information about the overrun of electric energy and operating time, group E – it compares some actual driving motors operating characteristics, and group F – it fixes two statistical estimates in actual drive operation.
- The evaluation of the energy efficiency of electrical consumers, which are unified in separate technological groups, should be provided through the formulated mathematical model for monitoring, which determines the reduced and aggregate for these groups relative power consumption and enables a comprehensive analysis of the deviations from the minimum level. The model is a basis for building informative systems for qualitatively-new monitoring of the electric energy efficiency in each production object or enterprise with available grouped consumers.

3. The workability of the developed integral methodology is confirmed by:

- Conducting a complete investigation of a typical coal handling system. The aggregate model for grouped electric consumers was applied and the synthesized set of evaluation indexes was determined for each conveyor, and for the system as a whole. The high average values of the following indexes B7 – relative power consumption under actual operating conditions (8.14 units), and the coefficients D1 and D2 (5.82 and 8.83 units respectively), show a high degree of lack of organization in the investigated processes. A high average deviation (20.92 units) of the actual aggregate relative consumption from the desired optimum level was observed. The new data obtained indicates clearly the need for conducting energy efficiency investigations of coal handling systems and other similar transport systems.
- Applying the model for determination and analysis of the energy efficient operations of electric motors with using 42 efficiency curves of motors of two different minimum efficiency standards.

REFERENCES

[1] Action plan for energy efficiency: realising the potential, European Commission, 2006, <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2006:0545:FIN:EN:PDF> (23.02.2011).

[2] Andonov, K., Krasteva, A., Dinolov, O., Mihailov, L., Kirchev, V., Ermenkov, T., On the methodology and normative regulations of efficient electrical consumption, In: 12th International conference on machines, drives and power systems, Sofia, Bulgaria, 2008, p. 73–77.

[3] Andonov, K., Kirchev, V., Enimanev, K., Dinolov, O., Levels for monitoring the electric power consumption in industrial enterprises, In: 5th International scientific conference management and engineering,

Sozopol, Bulgaria, 2007, p. 384–389.
[4] Mihailov, L., Andonov, K., Botev, B., Dinolov, O., Krasteva, A., Levels for energy-efficiency investigation of electrical consumers, In: Proceedings of the University of Ruse, vol. 44, series 3.1, Ruse, Bulgaria, 2005, p. 177–185.
[5] Dinolov, O., Uniform model for energy efficiency evaluation of induction motor drives, Energetika, no 5, 2007, p. 37–43.
[6] Dinolov, O., General methods for energy-efficiency investigation and evaluation of induction motor drives, In: 12th International conference on machines, drives and power systems, Sofia, Bulgaria, 2008, p. 197–201.
[7] Dinolov, O., Andonov, K., Krasteva, A., Koev, K., Development of a unified training procedure on energy-efficiency investigation of induction motor drives, In: Year-book of the Technical University of Sofia, Bulgaria, vol. 59, 2009, p. 181–186.
[8] Dinolov, O., Development of a training procedure on energy efficiency in material handling machines, In: Proceedings of the University of Ruse, Bulgaria, vol. 49, series 3.1, 2010, p. 89–93.
[9] Dinolov, O., Modeling of energy-efficient operations in induction motors, Elektrotechnica & elektronica, Vol. 45, 2010, p. 26–29.
[10] Improving the Energy Efficiency of Pump Systems, U.S. Department of Energy, 2005, <http://www1.eere.energy.gov/industry/bestpractices/pdfs/psat_fs.pdf> (23.02.2011).
[11] Improve motor system efficiency for a broader range of motors with Motormaster - International, U.S. Department of Energy, 2005, <http://www1.eere.energy.gov/industry/bestpractices/pdfs/mmplus_international.pdf> (27.10.2010).
[12] Dinolov, O., Andonov, K., Evstatiev, B., Krasteva, A., Kirchev, V., Model for monitoring and evaluating the energy efficiency of grouped electric drives, Energetika, no 8, 2008, p. 26–31.
[13] Andonov, K., Dinolov, O., Kirchev, V., Nedev, G., Investigating the energy efficiency of a coal-feeding system, Energetika, no 8, 2007, p. 26–33.
[14] Dinolov, O., Specificity and factors in estimating the energy efficiency of thermo-electric power plants, In: Proceedings of the University of Ruse, Bulgaria, vol. 46, series 3.1, 2007, p. 23–27.
[15] Andonov, K., Dinolov, O., Kirchev, V., Nedev, G., Study of the energy efficiency of an integral system for coal preparation, Energetika, no 5, 2008, p. 14–24.
[16] Eltom, A., Demirbas, A., Motor system energy efficiency in the nylon industry: A comparison of PWM and square wave inverters, In: IEEE International electric machines and drives conference, Miami, United States, 2009, p. 508−513.
[17] Eromon, D., Differences of induction motor field efficiency measuring techniques, In: International mechanical engineering congress and exposition, Orlando, United States, 2005, p. 11−23.
[18] Grantham, C., McKinnon, D., A rapid method for load testing and efficiency measurement of three-phase induction motors, In: 11th International conference on electrical machines and systems, Wuhan, China, 2008, p. 160−165.
[19] Sun, P., Lai, J., Qian, H., Yu, W., Smith, C., Bates, J., Efficiency evaluation of a 55kW soft-switching module based inverter for high temperature hybrid electric vehicle drives application, In: 25th Annual IEEE applied power electronics conference and exposition, Palm Springs, United States, 2010, p. 474−479.
[20] Hothongkham, P., Kinnares, V., Investigation into harmonic losses in a PWM multilevel cascaded H-bridge inverter fed induction motor, In: 7th International conference on power electronics and drive systems, Bangkok, Thailand, 2007, p. 1043−1048.
[21] Ramos, M.C.E.S., Tatizawa, H., Burani, G., Ramos, M.C.G., Methodology for assessment and optimization of induction electric motors aiming energy conservation, aided by computer simulation, WSEAS Trans. Syst., No 8, 2009, p. 410−419.
[22] McKinnon, D.J., Grantham, C., On-site efficiency evaluation of three-phase induction motors using synthetic loading methods, In: Second international conference on power electronics, machines and drives, vol. 1, Edinburgh, United Kingdom, 2004, p. 291−296.
[23] Grantham, C., Tabatabaei-Yazdi, H., Rahman, M.F., Novel method for rapid efficiency measurement of three phase induction motors, IEEE Trans Energy Convers, nol. 14, 1999, p. 1236−1240.
[24] Phumiphak, P., Chat-Uthai, C., Nonintrusive method for estimating field efficiency of inverter- fed induction motor using measured values, In: IEEE International conference on sustainable energy technologies, Singapore, Singapore, 2008, p. 580−583.
[25] Dinolov, O., Andonov, K., Evstatiev, B., Kirchev, V., Software instruments for automated investigation of the energy efficiency in electrical drives, In: International scientific conference UniTex, vol. 1, Gabrovo, Bulgaria, 2008, p. 104–108.
[26] Three phase industrial meters, <http://www.mps.bg/documents/Three_phase_industrial_meters.pdf> (23.02.2011).

[27] Andonov, K., Dinolov, O., Mihailov, L., Botev, B., Krasteva, A., Automated technical system for investigating the energy efficiency of electrical consumers, In: Proceedings of the University of Ruse, vol. 44, series 3.1, Ruse, Bulgaria, 2005, p. 9–14.
[28] Dinolov, O., Andonov, K., Synthesizing the structure of an automated system for energy-efficiency evaluation in electric-motor drives, Elektrotechnica & elektronica, vol. 44, 2009, p. 55–61.
[29] Andonov, K., Dinolov, O., Koev, K., Nedev, G., Kirchev, V., Study of the energy efficiency of a draught fan system in a coal-fired thermal power station, Energetika, no 6-7, 2009, p. 40–45.
[30] Dinolov, O., Nedev, G., Kirchev, V., Andonov, K., Research on the energy efficiency of a coal-pulverization system with intermediate hopper, In: Proceedings of the University of Ruse, Bulgaria, vol. 46, series 3.1, 2007, p. 16–22.
[31] Kolev, G., Petkov, N., Dinolov, O., Energy-efficiency investigation and evaluation of a belt-conveyor, In: International proceedings for under- and post-graduate students, Ruse, Bulgaria, 2007, p. 6–12.
[32] Dinolov, O., Kolev, G., Petkov, N., Investigating the electric power consumption of combination lathes, In: Student's scientific proceedings, Ruse, Bulgaria, 2008, p. 63–67.
[33] Kirchev, V., Dinolov, O., Comparative study on the possibilities for increasing the energy efficiency in the induction motor drives, Energetika, vol. 1, 2008, p. 35–43.