MODEL FOR ENERGY-EFFICIENCY AUDIT AND MONITORING OF THE COAL PROCESSING SYSTEMS IN THE FOSSIL-FUEL POWER PLANTS

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Abstract: Based on interpretation of existing developments, an aggregate model for energy audit and monitoring of the electric-energy efficiency in the coal processing systems in the fossil-fuel power plants is developed. The model takes into account the nominal power capacities of the available drives, by which the usability of the installed power capacity is considered and the interdependence between the power consumed and the relative consumption is avoided in determining the aggregate relative electric-power consumption. The model is justified by conducting an energy audit of a typical coal processing systems in operation. The results of this research can be a basis for the development of models of systems and systems for qualitatively new monitoring of the overall electric-energy efficiency in the fossil-fuel power plants.

Keywords: energy audit, electric-energy efficiency, monitoring, fossil-fuel power plants, energy-efficiency control, energy management, models for audit

1. INTRODUCTION

Conducted studies [1] indicate that, at present, the potential for improving the energy efficiency (EE) in steam power plants is high. The research in this area is particularly well represented in India [2], where the majority of electric power generation is provided by these plants.

The analysis of the developments in the field of the constructional and regime parameters of the steam generators, including their electric-drives systems, shows that, on the whole, the EE optimization is targeted at different directions as different available options are used. Results are achieved by reducing the excess air for pneumatic transport, lowering the temperature of the flue gases, a forced cooling of the water vapour [1], optimizing the construction of the heat exchangers [3] and of the hoppers for coal and coal powder [4], air slag cooling with increasing the steam-generators' efficiency factor with more than 0.5% [5], as well as by improving the performance of the turbo alternators which, according to some authors [6], are among the most ineffective elements of the steam power plants. Different systems for control of the current processes are also available [7, 8].

After the feed-pump systems, the fuel-preparation systems in the steam power plants are found to be one of the most powerful ones as, for a typical fossil-fuel power plant, their installed capacity averaged 15 % of the total installed capacity of the other systems supplied at a middle voltage [9]. Given the topicality of the issue, a number of implemented optimization tasks and models for improving the EE of the considered objects are referred in literature. In [10], a modernization of three fossil-fuel power plants is described: replacing the existing pulverizes with those with higher productivity and with the ability to work with coal with a wider range of variation of the

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quality parameters; increasing the number of outgoing coal-powder conduits of the pulverizes, in order to reduce the hydraulic resistance caused in splitting the fuel flow; installation of additional hot-air fans to the pulverizes; modification of the burners resulting in better mixing of the coal powder in low loads of the steam generator; using two hoppers for supplying raw coal to one pulverized with a view to mix coal with different quality parameters. The modernization has led to reduction of the harmful emissions and the self-consumption of the steam generators. In another development [11], an improvement of the efficiency of such generator with 2...3 % is realized for a main plant in Russia just by optimization of the plant's coal processing systems.

Energy auditing of the coal processing systems in Bulgaria is regulated by a corresponding legislation [12]. In this regard, some case studies [13] are conducted and some generalized developments [14, 15, 16] are proposed, the core of which is the methodology [15] for investigation and evaluation of the EE of the aggregate systems for preliminary transport and processing of coal. Similar generalized developments are not proposed by other authors. Disadvantages of the methodology are the lack of possibilities for evaluating the EE of a group of pulverizes operating in parallel, and its unsubstantiated performance and applicability for the coal processing systems implemented with medium and high speed mills.

The **aim of this study** is to justify a comprehensive model for energy audit and monitoring of the electric-energy efficiency of the coal processing systems in the fossil-fuel power plants.

2. MODEL ELABORATION

The model block diagram is shown in Figure 1. The main and supplementary evaluation indices, blocks 3 and 4 respectively, can be determined according to the generalized model and methodology for EE evaluation in electric drives [17] and the model for computer-aided investigation of the effectiveness of the complex coal processing systems [15]. A description of the indices is given in Table 1. The energy $W_{\Delta\Psi}$ in the corresponding formula from Table 1 can be determined through the relative moisture content of coal (coal powder) by the following dependence [15]:

$$W_{\Delta\Psi}(m_c, \Psi_1, \Psi_2) = \frac{1}{3.6.10^5}.m_c.(\Psi_1 - \Psi_2).W_{eva}^* \text{, kWh,} \tag{1}$$

where ψ_1 и ψ_2 are the relative moisture contents of the raw coal prior to the mill and of the coal powder after it, respectively, %; m_c - the mass of the processed coal, kg; W^*_{eva} - the specific heat of evaporation of the moisture in coal, kJ/kg.

In case that the coal processing system is implemented without intermediate powder hopper, the mills are few in number and are characterized by an operation in parallel. The case of simultaneous supply of one or more intermediate powder hoppers by several parallel operating pulverizes (ball mills) is also possible. For such conditions, it is feasible the target model [17] for EE evaluation of grouped drives (Block 6) to be applied. The interdependence between power consumed and the relative consumption, as well as the disregarding the available capacity usability can be considered as disadvantages of this development leading to insufficient informativeness. Here, these disadvantages are eliminated by interpretation of the model taking into account the nominal power capacity of the available drives. Thus, the following expressions to determine the aggregate relative power consumption E^*_{agg} of the coal processing systems can be written:

- coal processing system with intermediate powder hopper:

$$E_{agg}^* = \frac{1}{2}\left(\frac{E_{11}^* P_{n11} + E_{12}^* P_{n12} + ... + E_{1i}^* P_{n1i} + ... + E_{1m_1}^* P_{n1m_1}}{P_{n11} + P_{n12} + ... + P_{n1i} + ... + P_{n1m_1}} + \right.$$
$$\left. + \frac{E_{21}^* P_{n21} + E_{22}^* P_{n22} + ... + E_{2i}^* P_{n2i} + ... + E_{2m_2}^* P_{n2m_2}}{P_{n21} + P_{n22} + ... + P_{n2i} + ... + P_{n2m_2}} \right) \Rightarrow \text{MIN} \tag{2}$$

- coal processing system without intermediate powder hopper:

$$E_{agg}^{*} = \frac{E_{11}^{*}.P_{n11} + E_{12}^{*}.P_{n12} + ... + E_{1i}^{*}.P_{n1i} + ...E_{1m_l}^{*}.P_{n1m_l}}{P_{n11} + P_{n12} + ... + P_{n1i} + ...P_{n1m_l}} \Rightarrow MIN \qquad (3)$$

where $E*_{11}$, $E*_{12} + ... + E*_{1i} + ... + E*_{1m1}$ are the relative consumptions of the mills (low-, medium- and high-speed mills) of the coal processing system; $P*_{n11}$, $P*_{n12} + ... + P*_{n1i} + ... + P*_{n1m1}$ are the nominal powers of the mill' motors, kW; $E*_{21}$, $E*_{22} + ... + E*_{2i} + ... + E*_{2m2}$, $P*_{21}$, $P*_{22} + ... + P*_{2i} + ... + P*_{2m2}$, $P*_{n21}$, $P*_{n22} + ... + P*_{n2i} + ... + P*_{n2m2}$ are the same quantities but for the mill fans; m_1 and m_2 are the numbers of the mills and mill fans, respectively.
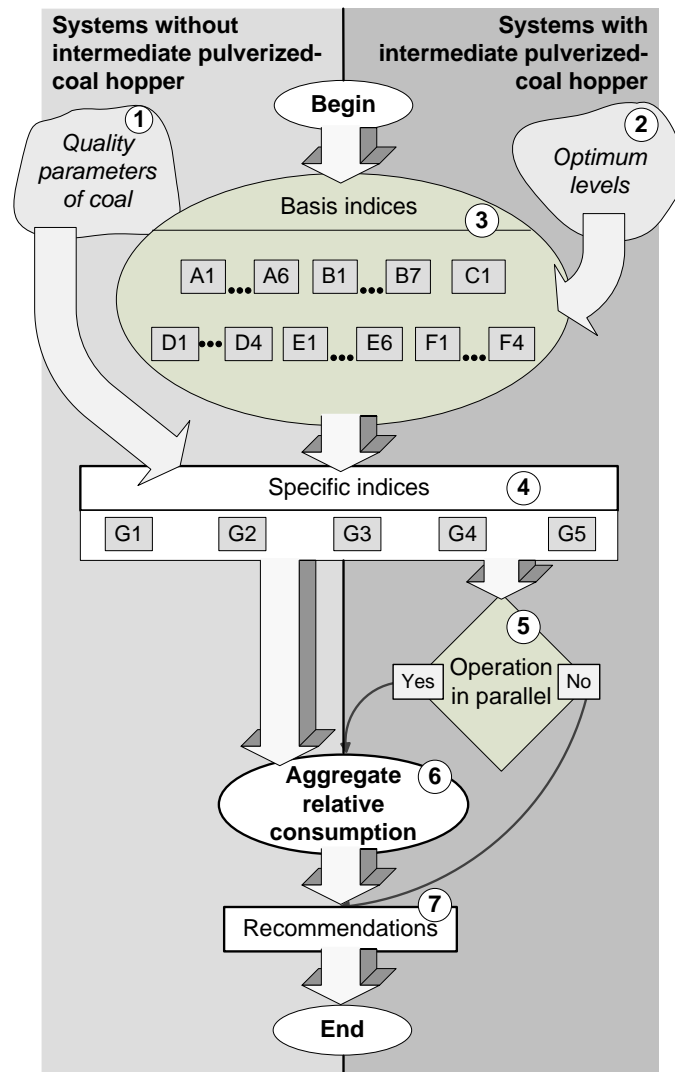

Fig. 1. Block diagram of a model for energy audit and monitoring of the coal processing systems in the fossil-fuel power plants.

The dependences (2) and (3) allow not only an evaluation of the losses due to low load levels and structural imperfections, but also EE optimization by replacing oversized motors.

The necessary input information of the developed model (blocks 1 and 2, Figure 1) includes data on the quality parameters of the fuel used and on the optimal active and reactive power levels that can be fixed by applying the graphically-analytical model for the determination of the energy-efficient modes of operation of the mill-driving electric motors [17].

Table 1. Indices for energy-efficiency audit and monitoring of the coal processing systems in fossil-fuel power plants [15, 17].

Group	Symbol	Units	Description	Determination
Group A	A_1	kW	Active power in the optimum operation of the coal pulveriser/mill fan	By using the model in [17]
	A_2	kVAr	Reactive power in the optimum operation of the coal pulveriser/mill fan	
	A_3	h	Optimum operating time	$A_3 = \dfrac{B_4}{A_1 - C_1}$
	A_4	kWh	Non-useful electric power consumption in optimum operation	$A_4 = C_1.A_3$
	A_5	kWh	Total electric power consumption in optimum operation	$A_5 = A_1.A_3$
	A_6	–	Relative electric power consumption in optimum operation	$A_6 = 1 + \dfrac{C_1}{A_1 - C_1}$
Group B	B_1	kW	Average active power in actual operation	$B_1 = \dfrac{1}{n}.\sum\limits_{i=1}^{i=n} P_{act,i}$
	B_2	kVAr	Average reactive power in actual operation	$B_2 = \dfrac{1}{n}.\sum\limits_{i=1}^{i=n} Q_{act,i}$
	B_3	h	Actual operating time	$B_3 = n.\delta$
	B_4	kWh	Useful electric power consumption	$B_4 = (B_1 - C_1).B_3$
	B_5	kWh	Non-useful electric power consumption in actual operation	$B_5 = C_1.B_3$
	B_6	kWh	Total electric power consumption in actual operation	$B_6 = B_4 + B_5$
	B_7	–	Relative electric power consumption in actual operation	$B_7 = 1 + \dfrac{C_1}{B_1 - C_1}$
Group C	C_1	kW	Active power in no-load operation	By measurement
Group D	D_1	–	Coefficient of overrun of total energy consumed	$D_1 = \dfrac{B_6}{A_5}$
	D_2	–	Coefficient of overrun of non-useful energy consumed	$D_2 = \dfrac{B_5}{A_4}$
	D_3	h	Overrun of operating time	$D_3 = B_3 - A_3$
	D_4	kWh	Overrun of electric energy	$D_4 = B_6 - A_5$
Group E	E_1	%	Deviation from the maximum electric motor efficiency in optimum operation	$E_1 = \eta_{max} - \eta_{op}$
	E_2	%	Deviation from the maximum electric motor efficiency in actual operation	$E_2 = \eta_{max} - \eta_{act}$

	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 operation	$E_4 = E_6 - \dfrac{A_1}{\sqrt{A_1^2 + A_2^2}}$
	E_5	–	Deviation of the power factor from the desired value in actual operation	$E_5 = E_6 - \dfrac{B_1}{\sqrt{B_1^2 + B_2^2}}$
	E_6	–	Desired power factor	A set (input) value
Group F	F_1	kW	Standard deviation of the active power in actual operation	$F_1 = \sqrt{\dfrac{1}{(n-1)} \cdot \sum\limits_{i=1}^{i=n} (P_i - B_1)^2}$
	F_2	–	Coefficient of variation of the active power in actual operation	$F_2 = \dfrac{F_1}{B_1}$
	F_3	kVAr	Standard deviation of the reactive power in actual operation	$F_3 = \sqrt{\dfrac{1}{(n-1)} \cdot \sum\limits_{i=1}^{i=n} (Q_i - B_2)^2}$
	F_4	–	Coefficient of variation of the reactive power in actual operation	$F_4 = \dfrac{F_3}{B_2}$
Group G	G_1	kWh/t	Specific electric energy consumption for processing (moisture evaporation, milling) of a unit of mass of coal	$G_1 = \dfrac{B_6}{m_c} \cdot 10^3 = G_2 + G_3$
	G_2	kWh/t	Specific electric energy consumption for processing of the useful mass of coal	$G_2 = 10^{-2}(100 - \varepsilon + \psi_1)G_1$
	G_3	kWh/t	Specific electric energy consumption for processing of the ballast (the non-useful mass) of coal	$G_3 = 10^{-2} \cdot (\varepsilon + \psi_1)G_1$
	G_4	kWh/MWh	Specific electric energy consumption towards the heat of combustion of coal	$G_4 = \dfrac{3.6 \cdot 10^6}{Q_L} \cdot \dfrac{W_{el.p} + W_{\Delta\Psi}}{m_c}$
	G_5	–	Coefficient of deviation of the coal ballast from practically minimum ballast	$G_5 = \dfrac{\varepsilon + \psi_1}{\varepsilon_{min} + \psi_{1.min}}$

Nomenclature: n – the number of the measurements in averaging the active and reactive powers of the coal pulveriser/mill fan; $P_{act,i}$ – the i-th measured value of the active power of the pulveriser/mill fan in kW; $Q_{act,i}$ – the i-th measured value of the reactive power in kVAr; δ – the time interval between two consecutive measurements in hours; η_{max} – the maximum electric motor efficiency in %; η_{op} and η_{act} – the motor efficiency in the optimum and actual operation in %; Q_L – lower heating value, kJ/kg; $W_{el.p}$ – the electric energy consumed by the pulveriser (pulveriser and mill fan) for milling and transportation of coal, kWh; $W_{\Delta\psi}$ – the thermal energy consumed for evaporation of a part of the moisture in the coal that incomes in the pulveriser, kWh; ε, ε_{min} and $\psi_{1.min}$ – the actual ash content and the minimum contents of ash and moisture in coal, respectively, % (the minimum values are determined by statistical data on the quality characteristics of the used coal).

3. OBJECT OF AUDIT

A coal processing system of a steam generator type Еп-670-140 in a fossil-fuel power plant is singled out as a research object. At the time of the audit, the quality parameters of coal have the values shown in Table 2.

The system is characteristic in technical parameters and installed capacities for most of the existing steam generators at the plant. It consists of eight identical pulverisers implemented by high-speed impact mills (HSIM)

and arranged two to each of the four sides of the combustion chamber. At the time of the study, six of them worked at an output of 60 t/h each as two of the pulverisers were in reserve. This is the normal mode for the power unit.

Table 2. Data on the quality parameters of coal in a fossil-fuel power plant.

Ash content	Moisture content	Sulphur content	Xylitol content	Lower heating value
%	%	%	%	kcal/kg
17.0	56.8	2.21	4.50	1440

The flow diagram of one of the composite pulverisers' systems is shown in Figure 2, and the technical characteristics of their main elements are listed in Table 3.
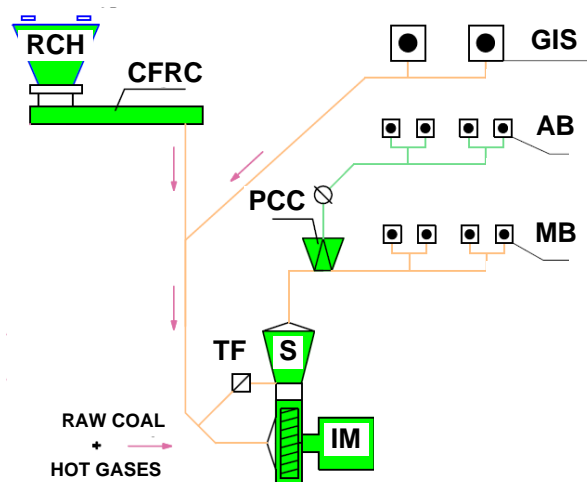

Fig. 2. Flow diagram of a pulveriser system in fossil-fuel power plant:
RCH - raw coal hopper; CFRC – combined feeder for raw coal; S – separator; TF – throttling flaps; PCC – pulverized-coal concentrator; GIS - gas-intake shaft; AB - auxiliary burners; MB – main burners; IM – high speed impact mill.

Table 3. Technical data and parameters of a pulveriser system in a fossil-fuel power plant.

--	Mill	Dispenser	Feeder
Type	MB 3300/800	Chain	Chain
Output, kg/s	19.44	3.89-19.44	3.89-19.44
Type of the induction motor (IM)	АКНЗ-2-I6-57-I2 УЗ	AD-180M-4	MOM-225M-8
Nominal power if the IM, kW	800	15	22
Nominal voltage of the IM, kV	6.3	0.4	0.4
Nominal current of the IM, A	102	30	45
Nominal cosφ of the IM	0.8	0.87	0.91
Efficiency of the IM, %	94.3	87.5	89.8

The fuel enters the raw coal hopper (RCH) after pre-treatment. Coal is scooped from the RCH by a raw coal dispenser (RCD), and then it enters the raw coal feeder (RCF) and turn to gas-intake shafts (GIS). Given the proportional change in the rotational speed of the RCD to RCF, these facilities are combined and considered as combined feeders for raw coal (CFRC). The humidity in coal starts to be detracted in the GIS with the aid of hot gases drawn from the upper part of the combustion chamber. The so prepared fuel enters the impact mill (IM), whereby it is ground to powder and, together with the hot gases, is directed into the combustion chamber. After IM, the powder-gas mixture passes through the separator (S), wherein the coarse particles are returned for regrinding in IM. After the separator, the coal powder passes through a pulverized-coal concentrator (PCC), where a distribution of the mixture between the main (MB) and the auxiliary (AB) burners is provided. Flaps 'air-mixture', through which the powder-gas mixture is additionally distributed between MB and AB, are installed prior the AB.

4. RESULTS

The used measurement system for determining the electric loads is presented in section 7.2 of [17]. The mass of coal was measured using the plant's monitoring system. The obtained results are shown in Figure 3...Figure 6 and Table 4. It can be seen that the audited HSIM work in similar loads. Their electric loads are well grouped around their average values and have low levels of dispersion. The standard deviations for the active powers of the individual mills currently vary from 12.15 to 16.34 kW, and for the reactive powers - from 9.13 to 12.25 kVAr, as the generalized standard deviation, calculated on the basis of all available data, is 14.52 kW for the active power and 10.89 kVAr for the reactive, at ranges 43.6 kW and 33.4 kVAr and intervals of variation (654.7 ... 698.3) kW and (490.4 ... 523.8) kVAr, respectively.
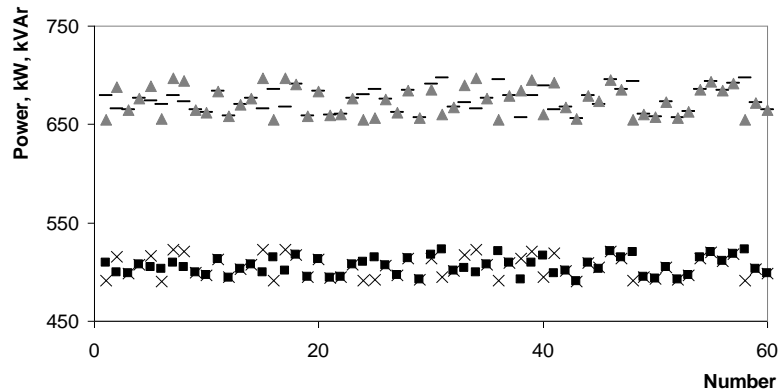

Fig. 3. Distribution of the electric loads of high-speed impact mill №1 and high-speed impact mill №2: ▬ ▲ active powers; ✕ ■ reactive powers.
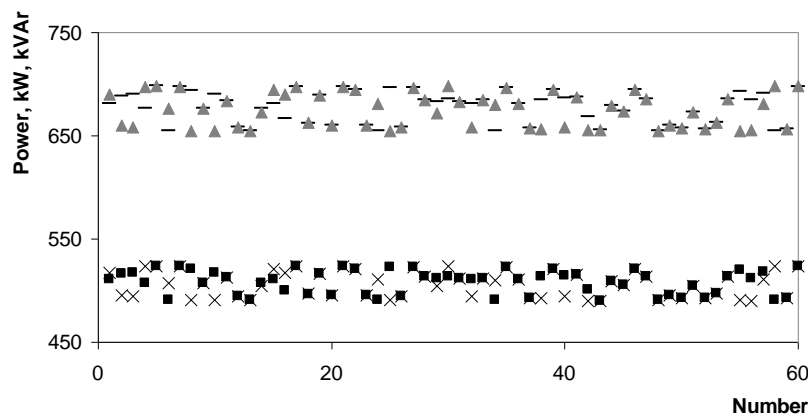

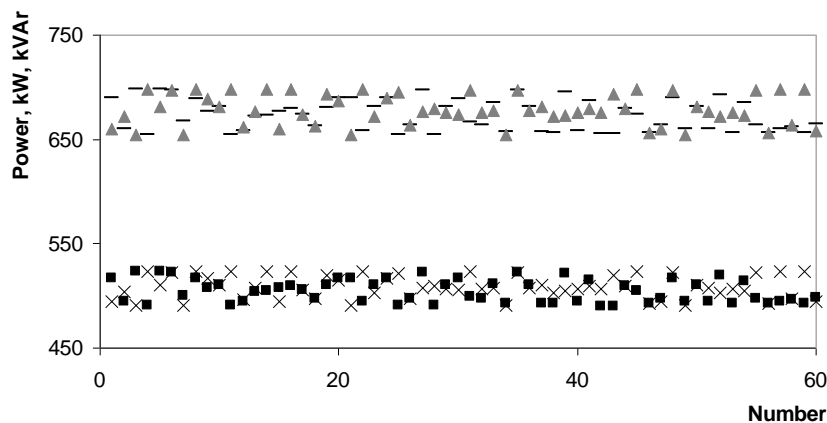Fig. 4. Distribution of the electric loads of high-speed impact mill №3 and high-speed impact mill №4.

Fig. 5. Distribution of the electric loads of high-speed impact mill №5 and high-speed impact mill №6.

Table 4. Values of the audit indices for the energy efficiency of six high-speed impact mills.

	M1	M2	M3	M4	M5	M6
A_1	848.3	848.3	848.3	848.3	848.3	848.3
A_2	636.2	636.2	636.2	636.2	636.2	636.2
A_3	44.33	44.34	44.61	44.37	44.17	44.67
A_4	134.8	134.7	135.7	134.9	134.3	135.8
A_5	626.6	626.8	630.7	627.4	624.5	631.6
A_6	1.274	1.274	1.274	1.274	1.274	1.274
B_1	674.3	674.4	677.5	674.9	672.6	678.2
B_2	505.7	505.0	508.1	506.2	504.4	508.6
B_3	60.00	60.00	60.00	60.00	60.00	60.00
B_4	491.8	492.0	494.9	492.4	490.2	495.7
B_5	182.5	182.3	182.6	182.4	182.4	182.5
B_6	674.3	674.4	677.5	674.9	672.6	678.2
B_7	1.371	1.371	1.369	1.370	1.372	1.368
C_1	182.5	182.3	182.6	182.4	182.4	182.5
D_1	1.076	1.076	1.074	1.076	1.077	1.074
D_2	1.354	1.353	1.345	1.352	1.358	1.343
D_3	15.67	15.66	15.38	15.62	15.82	15.32
D_4	47.69	47.60	46.82	47.50	48.11	46.61
E_1	0.100	0.100	0.100	0.100	0.100	0.100
E_2	0.500	0.700	0.500	0.900	1.100	0.700
E_3	94.30	94.30	94.30	94.30	94.30	94.30
E_4	0	0	0	0	0	0
E_5	0.070	0.080	0.060	0.080	0.090	0.060
E_6	0.800	0.800	0.800	0.800	0.800	0.800
F_1	1.560	1.896	1.960	2.128	1.882	1.901
F_2	0.002	0.003	0.003	0.003	0.003	0.028
F_3	1.170	1.424	1.460	1.596	1.407	1.426
F_4	0.002	0.003	0.003	0.003	0.003	0.003
G_1	11.24	11.24	11.29	11.25	11.21	11.30
G_2	2.944	2.945	2.958	2.947	2.937	2.961
G_3	8.294	8.295	8.333	8.301	8.273	8.342
G_4	243.7	243.7	243.8	243.7	243.7	243.8
G_5	1.190	1.190	1.190	1.190	1.190	1.190

The usefully B_4 and the non-usefully B_5 consumed energy in actual operation moves within the intervals from 490.2 to 495.7 kWh and from 182.3 to 182.6 kWh, accordingly, at average levels of 492.9 kWh and 182.5 kWh. The standard deviations are 2.068 kW and 0.105 kVAr. The relative consumptions A_6 and B_7 also vary in low ranges and have average levels of 1.274 and 1.370 relative units. Low levels of variation are also characteristic of the overrun coefficients D_1 and D_2, as well as of the specific electric-power consumptions G_1, G_2, G_3 and G_4. Their mean values are 1.076 units, 1.351 units, 11.26 kWh/t, 2.949 kWh/t, 8.306 kWh/t and 243.7 kWh/MWh, respectively. The average overrun of consumed energy D_4 is 47.39 kWh, while the average aggregate relative electric-power consumption E^*_{agg} is 1.369 relative units.

4.1. Discussion

Based on the data presented, it is found that the actual relative consumption is close to the optimum one as the difference is about 7.5 %. This indicates that there are certain reserves for EE increase. The corresponding measures should be aimed primarily at improving the service conditions at the expense of potential design improvements since the coefficient D_2 is 25% higher than the coefficient D_1. The fuel base of the plant has

relatively unfavourable parameters. This is established taking into account the level of the ballast coefficient G_5 which is 1.06 times higher than the levels found in previous relevant studies [15].
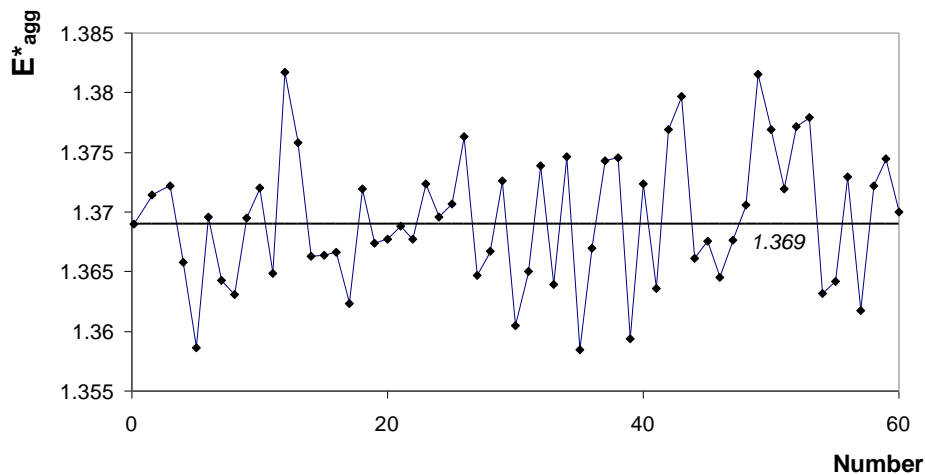

Fig. 6. Diagram of the aggregate relative consumption of a coal processing system in a fossil-fuel power plant.

The results confirm the significant benefits in energy terms of the pulveriser systems with HSIM as compared with the systems with low-speed ball mills (LSBM), for which it is found [15] that the average relative consumption is about 60 relative units. While in design and constructional respect, HSIM are efficient enough ($D_1 \approx 1$), the same cannot be said for LSBM where D_1 reaches approximately 20 units [15].

4.2. Recommendations
Due to the high operational capacity and usability, a recommendation can be made to increase the audited system load with approximately 10 %, despite the small differences between the consumptions B_7 and A_6. This recommendation is justified given the fact that, at an average production cost of electricity 44.35 Euro/MWh [13], the monthly overrun of energy due to non-optimum loading is approximately 204.7 MWh while the loss of money in a month reached around 9,080 Euro.

5. CONCLUSIONS

(1) Based on the methodology adopted, a model for energy audit in the coal processing pulveriser systems in the fossil-fuel power plants is developed. The model is generalized in nature and allows evaluation of the losses due to lack of loading and design imperfections of the electric-power consumers, as well as energy-efficiency optimization by setting optimum operating conditions and replacing oversized motors. The model can be also used for energy-efficiency control and monitoring.

(2) The development is justified by conducting systematic studies of a typical coal processing system in operation. Overall, the results indicate acceptable levels of efficiency. The relative consumption of each investigated mill fluctuates around 1.37 relative units. However, savings in the amount of about 108,625 Euro for a period of one year can be achieved in case of achievement of optimum consumers loading.

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