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A Method of Effective Planning and Control of Industrial Facility Energy Consumption

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Abstract**—**A method of effective planning and control of industrial facility energy consumption is offered. The method allows optimally arranging the management and full control of complex production facilities in accordance with the criteria of minimal technical and economic losses at the forecasting control. The method is based on the optimal construction of the power efficiency characteristics with the prescribed accuracy. The problem of optimal designing of the forecasting model is solved on the basis of three criteria: maximizing the weighted sum of the points of forecasting with the prescribed accuracy; the solving of the problem by the standard principles at the incomplete statistic data on the basis of minimization of the regularized function; minimizing the technical and economic losses due to the forecasting errors.

Keywords**—**Energy consumption, energy efficiency, energy management system, forecasting model, power efficiency characteristics.

I. Introduction

AT the current time the increase of power consumption efficiency is the essential trend in the household policy of the industrial facilities in the Russian Federation. However, the systematic power efficiency effect is not achieved on the big number of facilities. The point is that for solving the current problem it is not enough to rest only on the data from the separate, not associated with each other power-saving measures.

As seen from the experience of the industrially-advanced countries and large iron and steel enterprises of the Russian Federation, the systematic effect of power-saving measures can be achieved only through the introduction of the unified integral power consuming managements, encompassing all departments of facilities [1]-[7]. That said, in the systematic point of view, the solving of the problem of industrial activities management must be carried out optimally in accordance with the criteria of technical-economic and production efficiency.

Taking into account the said above, this article offers method of effective planning and control of industrial facility energy consumption. The method allows to efficiently arrange the management of the complex industrial objects in accordance with the mentioned criteria.

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II. The General Structure of Automated Information System (AIS) for Energy Management

The structural scheme of automated system of energy management is shown on the Fig. 1.

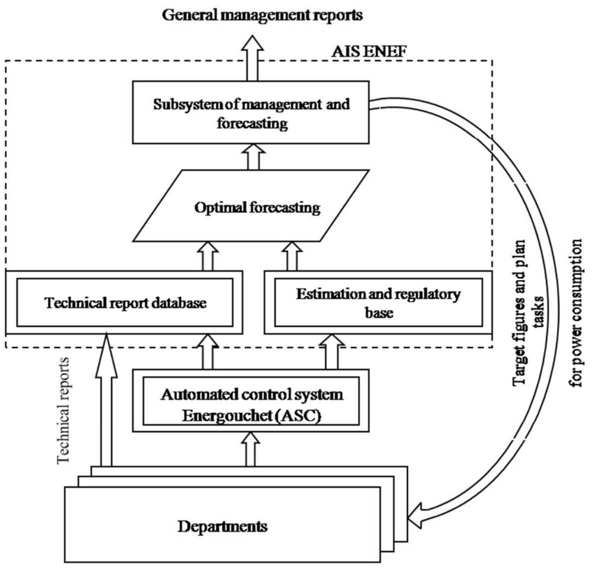

Fig. 1 The structural scheme of facilities automated energy management system

On the basis of the ASC Energouchet and technical reports of the represented departments, the information database for power resources efficient consumption reports are formed for the requested time period (day, month, year). With the help of information, given in the technical reports, the current power efficiency management for energy resources consumption by different departments is carried out. The data from estimation and regulatory base is employed as well. The current information, contained in the technical reports, goes through factorial analysis, upon that the new factors that drastically influence the power consumption efficiency, are revealed. The revealed factors and relations are used for optimal construction and designing of the current energy properties of power consumers with due account for production and technical-economic indexes [8]. On the basis of the received characteristics the adjustment of estimation and regulatory energy base is carried out. With the use of adjusted estimation and regulatory base for the next period of time the target figures and plan tasks are calculated for every department. For every stage of managements and the formation of plan tasks the energy efficiency examination is implemented. The aim of the examination is the detection of "problematic" areas of energy resources consumption and determination of the power consumption reduction resource. The required adjustment measures are taken for the patching of so called "problematic" examination areas with the help of factorial analysis. The fulfillment of the given measures should reduce the power consumption rate of the departments.

III. A Method of Effective Planning and Control of Industrial Facility Energy Consumption

The power efficiency, AIS, is based on the current factorial analysis of the statistics of an industrial facility power resources consumption and formation of the optimal forecasting management by the departments.

The production equipment power efficiency is defined on the basis of power efficiency characteristic. As for the analytical representation, the analytical characteristics shall be seen as the combination of the basic mathematical relation and the conditional corrections:

$$W_{ER} = f(P_{PR},\ Q_{PR},...) + \sum_i c_i \Delta x_i \tag{1}$$

here the basic relation $f(P_{PR},\ Q_{PR},...)$ reflects the consumption of energy resources, depending directly on the production output. The corrections $\{c_i \Delta x_i\}$ reflect the deviation of conditional parameters values Δx_i from the basic values by the resource consumption values.

The relations of the type (1) can be constructed with the use of the known principles on the basis of the processing of the statistical information for the results of conditional tests and operation data. This article offers the new committee approach principle, based on the optimal construction of the energy properties (1) with prescribed accuracy in accordance with the minimizing the technical-economic losses at the forecasting management.

Let us consider the principle for constructing the optimal forecast model of energy resources consumption. Factual power consumption relation shall be represented in the generalized form:

$$y = f[\mathbf{a}](\mathbf{x}) \tag{2}$$

where y is the volume of energy resources consumption, $\mathbf{x}$ is the vector of technological factors; $\mathbf{a}$ is the vector of structural parameters of forecasting model.

The forecasting error for k monitoring is defined as the difference between the factual value of power resources consumption volume and forecast value for the given observation:

$$e_k = y_k - f[\mathbf{a}](\mathbf{x_k}),\ k \in I_N \tag{3}$$

where k is the index of statistical monitoring, which adopts the value from the index set I_N , e_k is the forecasting error for k statistic monitoring, y_k is the factual value of power resources consumption volume for k statistic monitoring, $f[\mathbf{a}](\mathbf{x_k})$ is the forecast value for the given observation for k statistic monitoring.

Here we set the limit for the value of the forecasting error:

$$|e_k| \le e_{acc},\ k \in I_N \tag{4}$$

where e_{acc} is acceptable forecast error value.

The statistics indexing shall be carried out in reverse reading time λ, which is counted in accordance with the scheme, shown on Fig. 2.

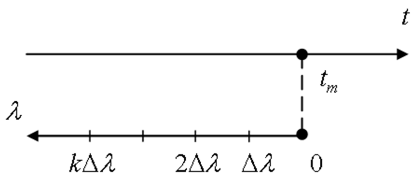

Fig. 2 The statistics indexing: λ is reversed time reading, k is the statistical monitoring index, t is clockwise reading, t_m is the current period of time, the starting of reverse time reading

Let us consider that at the reverse time reading the data is getting outdated. The aging of data coefficient for k statistical monitoring shall be defined by the exponentially vanishing relation:

$$\alpha_k = e^{-\frac{k\Delta\lambda}{\tau_C}}, \tag{5}$$

where α_k is the data aging coefficient, τ_C is data aging response time.

The current problem is to define the forecasting model (2) on the basis of optimal selection of structural parameters vector $\mathbf{a}$ in accordance with the criteria of maximizing the weighted number of the fulfilled inequalities (4):

$$\max_{\{\mathbf{a}\}} \sum_k \alpha_k \mu_k , \tag{6}$$

where μ_k is the characteristic function of k inequality,

$$\mu_k = \begin{cases} 1, \text{ if } k \text{ inequality holds,} \\ 0, \text{ if } k \text{ inequality is ruled out.} \end{cases}$$

The solution of the stated problem is shown in [9]. The specifics of the solution are based on the fact, that in general it has contradictory statement and not all the inequalities shall be solved in the proposed solution. Non-solution for the inequality shows that this statistical point is let out from the solution of the problem, and is not described by the relation (3). It can be possible in two cases: the statistical point is irregular and is defined as the statistical error, or the relation

(2) inaccurately defines the actual characteristics of the production facility and requires the certain modification. This article offers the application of the committee approach on the basis of the flexible adaptable solutions.

The contradictory inequality systems are characterized by the set of the highly compatible subsystems, which define the corresponding set of the respective partial solutions:

$$\{\mathbf{a}_\sigma : \beta_\sigma;\ \sigma \in \Sigma_{com}\}\ ,\beta_\sigma = \sum_{k \in I_\sigma} \alpha_k \tag{7}$$

where $\mathbf{a}_\sigma$ is the partial solution, β_σ is the influence of the partial solution, Σ_{com} is the set of values of the highly compatible inequalities subsystems (4), I_σ is the set of inequality indexes values, included into the highly compatible subsystem with index σ .

The forecast value of the resource consumption is calculated according to:

$$y^* = \sum_{\sigma \in \Sigma_{com}} \beta_\sigma f[\mathbf{a}_\sigma](\mathbf{x}) \tag{8}$$

where y^* is the forecasting values of the resource consumption.

The appearance of the highly compatible subsystems reveals the hidden factors, influencing the production facility's power consumption. This question suggests the additional researches on the basis of the energy consumption observations.

For the research of the features of the appearing statistical points, it is necessary to carry out the power-consuming properties inspection of production facility. The power-consuming properties inspection of the production facility is an expensive arrangement. The natural criteria for cost reduction of power-consuming properties inspection is the reduction of its number. This problem is equivalent to the problem of the maximizing criterion (6), which can be interpreted as the discovering the highly compatible subsystems of regular statistic points.

In general, it is possible that the volume of production facilities operation statistic data can be not enough for the errorless construction of the empirical forecast model. The standard evaluation model of energy resources consumption shall be used for the regularization of the problem statement at the incomplete statistical data volume. The model is constructed on the basis of the standard principles for evaluating the operating procedures power resources consumption rate, the standard operating energy efficiency characteristics, operating conditions maps and so on.

As the criterion for the regularization of problem statement we shall use the squares sum of deviation of factual power resources volume value from the standard values:

$$R = \sum_k |y_k - \varphi_n(\mathbf{x})|^2 \tag{9}$$

where R is the regularization criterion, $\varphi_n(\mathbf{x})$ is the standard power efficiency characteristics of production facility.

The problem of defining the structural parameters $\mathbf{a}$ of forecasting model with account for the regularization criteria (9) resolves itself into minimizing the function:

$$\min_{\{\mathbf{a}\}} E^2 = \sum_k |y_k - \varphi_n(\mathbf{x})|^2\ , \tag{10}$$

The forecasting model is used for the forecasting of the power resources consumption rate in an evaluation period on the basis of production objective for industrial facility. The given forecast is used for the managing of power resources consumption as well as for the requisition of recourses purchase. In any case the forecast error causes technical and economic losses, which is necessary to minimize.

On Fig. 3, we can see the penalty scheme, that is applied in relation to the error of the power resources consumption cost forecast [10].

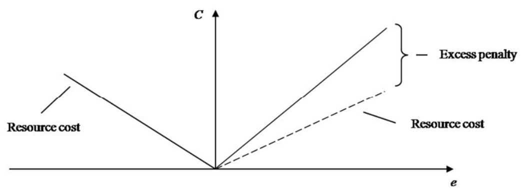

Fig. 3 Error cost

For instance, penalty can be defined on the basis of the following consideration. If the forecasting model gives largely positive estimation, then the forecast on the basis of such model gives low estimation. In such case the requisition of a facility for a limited resource shall be deemed as low estimation, thus the facility is required to ask for over limited supply of resource at a higher price. If the forecast is over evaluated, then the supply of the resource will be excessive, thus meaning that the facility will have to pay more.

The total penalty for inaccurate forecast:

$$C = \sum_k c_r \cdot |e_k^-| + \sum_k c_p \cdot |e_k^+| \tag{11}$$

where c_r, c_p are the cost of resources and penalty respectively, e_k^- , e_k^+ are the negative and positive error values.

On the whole the problem of optimal construction of forecasting model is solved on the basis of three criteria:

1) Maximizing the weighted sum of the points of forecasting with the prescribed accuracy (6);
2) Solving of the problem by the standard principles at the incomplete statistic data on the basis of minimization of the regularized function;
3) Minimizing technical and economic losses from forecasting errors (11).

The solution of the given problem comes down to the solving of the multiextremal problem of mathematical programming with nondifferentiable criteria. Furthermore, we take the following quadratic penalty function as an example for problem solution:

$$S = 0,5 \cdot \sum_k s_r^2 \alpha_k \cdot \left| e_k^- \right|^2 + 0,5 \cdot \sum_k s_p^2 \alpha_k \cdot \left| e_k^+ \right|^2 + \\ + \gamma_R \sum_k \left| y_k - \varphi_n(\mathbf{x}) \right|^2 \tag{12}$$

where γ_R is the regularization coefficient, the parameters s_r, s_p are selected upon the minimal technical-economic criteria.

IV. Approval of the Effective Energy Consumption Planning and Control Method for the Industrial Facility

The offered method was tested based on the actual data of production output and energy consumption by power plants of the iron and steel facility.

Table I contains input data on energy consumption for production of the following types of products by the power plants: electric energy, heat with steam and heat with hot water over November 2013 – August 2014.

TABLE I
Input Data on Energy Consumption by the Power Plants

Month	Electric energy		Heat with steam		Heat with hot water	
	P, MWh	W^{act}, MWh	P, Gcal	W^{act}, MWh	P, Gcal	W^{act}, MWh
Nov-13	416561	22079	406872	7013	380738	12657
Dec-13	460493	24051	443561	7498	447201	13930
Jan-14	453672	23407	440507	7253	461279	14434
Feb-14	428122	22613	410554	6997	386365	12621
Mar-14	419761	22556	391186	6968	329861	12136
Apr-14	410798	22691	359543	6262	255516	9383
May-14	405675	24420	333301	5940	97726	3549
Jun-14	397200	24671	347510	6220	89643	3401
Jul-14	410815	25351	343857	6074	97893	3792
Aug-14	419417	25538	360796	6500	79078	3941

Table I contains the following abbreviations: P production; W^{act} – actual values of energy consumption demanded for production.

Coefficients a_i were determined in accordance with the offered method; then total energy consumption was forecasted based on them. Numerical values of a_i coefficients for winter and summer periods are given in Table II.

Fig. 4 shows forecasted and actual values of total energy consumption of the power plants of the iron and steel facility. Temporal changes of energy consumption by the facility are mainly determined by the change of the production output. Seasonality should be taken into account when determining the dependency between the specific energy consumption and the production output by the production area.

Using the offered method one can improve accuracy of energy consumption forecasting for the group of power plants up to 1%.

TABLE II
Values of Coefficients

Coefficient	Winter period	Summer period
a0	1,68E+01	1,63E+01
a1	1,40E-09	2,47E-09
a2	-2,23E-07	8,23E-07
a3	-2,37E-07	2,32E-07
a4	1,77E-09	1,41E-09
a5	9,77E-07	3,26E-07
a6	2,91E-07	7,56E-07
a7	1,91E-09	2,18E-09
a8	7,11E-07	8,49E-07

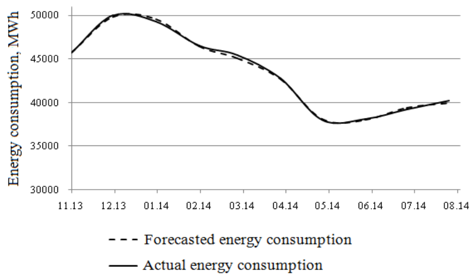

Fig. 4 Forecasted and actual values of total energy consumption

V. The Features of Energy Efficiency Automated Information System (AIS ENEF)

Developed program AIS ENEF provides the following functions:

– forecasting of the power resources consumption at the planned values of products output and the set values of the basic technological factors;
– determining the current indexes of departments power intensity;
– determining the values of excess energy consumption flow and the cause the leads to it;
– estimation of the reduction reserves for the power consumption.

The program has the following options:

– the analysis of the power consumption rate;
– implementation of the report informational database and its review;
– power-saving measures database for the reduction of production energy intensity for each department individually.

The calculation of the fuel gases (or electric energy) consumption rate value is carried out separately for each workshop on the basis of the multifactorial regression analysis (Fig. 5).

In the upper part of the window is the dropdown list with the workshops name, for which the calculation should be done. Below you can find additional dropdown list, which enables us to choose the type of resource. This action gives you the possibility to calculate not only the fuel consumption rate on the basis of multifactorial regression analysis, but also its component, such as natural gas, blast furnace gas, coke oven gas. Further on, in the table you can find the list of factors of a specific workshop and the particular resource that is being consumed at the time given; the values of regression coefficients and factor values. This being said, the factor values can be edited. For this purpose it is necessary to choose the option "Mode → Editing" from general settings menu. Additionally, the button "Factor model" in the given window, at the clicking of which the new window appears. You can see it on Fig. 6.

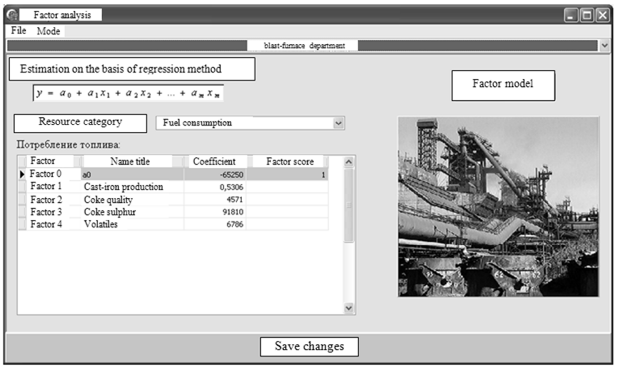

Fig. 5 Factor analysis

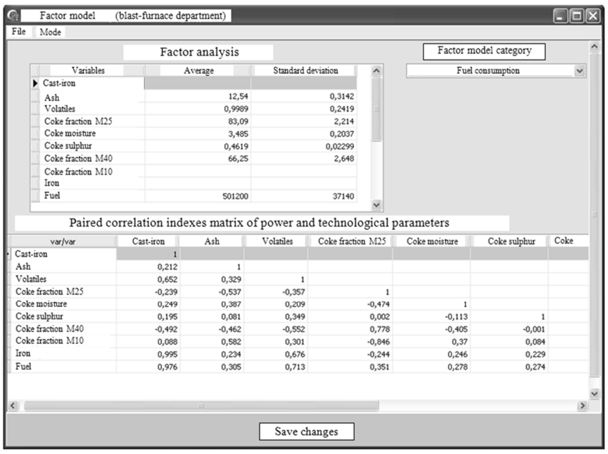

Fig. 6 Factor model

The window (Fig. 6) is intended for the activation of the factor workshop model that is chosen in the window "Factor analysis" (Fig. 5). Here you can find two tables. The upper table is employed for activation of given workshop's factors of mean and standard deviation values. The table below is employed for activation of the paired correlation indexes matrix of power and technological parameters. Additionally this window has the dropout list of "The factor model type", that enables you to review not only the factor model of fuel consumption for particular workshop in general, but the factor models of the particular fuel components consumption such as natural gas, coke oven gas and blast furnace gas.

As opposed to the common revenue metering on the production facility's inputs the offered system is based on the definition of the energy characteristics of particular workshops and production areas. In this case it enables you to carry out the prices forecasting of the power resources consumption, revealing the points of excessive power resources consumption, finding out its causes, estimate the production's power intensity reduction reserves on the basis of the necessary power-saving measures.

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