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ENSURING MAXIMUM ENERGY EFFICIENCY OF WORKING PLACES ON THE BASIS OF SYSTEM ENERGY AUDIT

A method for ensuring the maximum energy efficiency of working places on the basis of system energy audit is proposed. The method is based on the use of certain complete sets of ways to obtain the necessary functional properties of working places and structures of ways to ensure energy efficiency of processes. The expediency of the use of general models for integrated structural-parametric optimization of systems and linearized models of energy supply and consumption processes is shown. A complete set of structures of possible solutions has been developed for every path on ensuring the necessary functions of the working place. It is shown that the formation of a complete set (within the accepted classification) of possible structural solutions can be achieved by topological product of complete sets of ways to obtain the desired functional properties of jobs and structures of ways to ensure energy efficiency processes. For each structurally excellent path, a relationship system is proposed according to which the search for reserves of energy saving and energy efficiency can be carried out within the limits of blocking circuits.

Keywords: Limiting energy efficiency working places, full set, functional properties, structures of methods, integrated optimization, linearized models.

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ЗАБЕЗПЕЧЕННЯ ГРАНИЧНОЇ ЕНЕРГОЕФЕКТИВНОСТІ РОБОЧИХ МІСЦЬ НА ОСНОВІ СИСТЕМНОГО ЕНЕРГОАУДИТУ

Запропоновано метод забезпечення граничної енергоефективності робочих місць на основі системного енергоаудиту. Метод базується на використанні визначених повних множин шляхів отримання потрібних функціональних властивостей робочих місць і структур способів забезпечення енергоефективності процесів. Показана доцільність застосування при цьому загальних моделей комплексної структурно-параметричної оптимізації систем та лінеаризованих моделей процесів подачі та споживання енергії. Розроблена повна множина структур можливих рішень на кожному шляху забезпечення необхідних функцій робочого місця. Показано, що формування повної множини (у межах прийнятої класифікації) можливих структурних рішень може бути забезпечене шляхом топологічного добутку повних множин шляхів отримання потрібних функціональних властивостей робочих місць і структур способів забезпечення енергоефективності процесів. Для кожного структурно відмінного шляху запропонована система залежностей, по якій у межах блокуючих контурів може здійснюватись пошук резервів енергозбереження та підвищення енергоефективності.

Ключові слова: гранична енергоефективність, робочі місця, повна множина, функціональні властивості, структури способів, комплексна оптимізація, лінеаризовані моделі.

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ОБЕСПЕЧЕНИЕ ГРАНИЧНОЙ ЭНЕРГОЭФФЕКТИВНОСТИ РАБОЧИХ МЕСТ НА ОСНОВЕ СИСТЕМНОГО ЭНЕРГОАУДИТА

Предложен метод обеспечения предельной энергоэффективности рабочих мест на основе системного энергоаудита. Метод основан на использовании определенных полных множеств путей получения нужных функциональных свойств рабочих мест и структур способов обеспечения энергоэффективности процессов. Показана целесообразность применения при этом общих моделей комплексной структурно-параметрической оптимизации систем и линеаризованных моделей процессов подачи и потребления энергии. Разработана полная множество структур возможных решений на каждом пути обеспечения необходимых функций рабочего места. Показано, что формирование полного множества (в рамках принятой классификации) возможных структурных решений может быть обеспечено путем топологического произведения полных множеств путей получения нужных функциональных свойств рабочих мест и структур способов обеспечения энергоэффективности процессов. Для каждого структурно отличного пути предложена система зависимостей, по которой в пределах блокирующих контуров может осуществляться поиск резервов энергосбережения и повышения энергоэффективности.

Ключевые слова: предельная энергоэффективность, рабочие места, полная множество, функциональные свойства, структуры способов, комплексная оптимизация, линеаризованные модели.

1 Introduction. Energy efficiency of products is an important factor of their competitiveness. It is provided at every working place. Obviously, the overall energy efficiency for each process variant will be the higher, the higher the energy efficiency in all actions.

Because of this, great attention is paid to energy efficiency of serial production which types include the production of vehicles, agricultural machinery, etc. The goal is to ensure the highest possible energy efficiency in every working place. One way to achieve this is system auditing. It requires a certain technique, which should provide theoretically and practically acceptable results. But up to this day, there are no approaches to the development of a general energy audit method, which would allow us to obtain extremely high energy efficiency of the process at each working place.

2 Literature review. The issues of ensuring high energy efficiency of processes and energy saving are dealt with in many publications concerning both industrial policy in general [1] and certain aspects [2-12]. In particular, the work [2] addressed the issues of formation and selection activities in regional energy saving programs in engineering and construction. The paper [3] outlines the application of project management methodology to improve the energy efficiency of innovative technical systems of the new type. The work [4] is devoted to the system classification of construction and machine-building innovations intended for use in calculating energy efficiency indicators. Methods of applying the principles of variability, transformability, redundancy, and integrated optimization in solving energy saving and energy efficiency problems are described in [5].

A significant contribution to the development of the energy saving and energy efficiency theory was the paper [6] where the synthesis of the full set of general structures for ways to improve energy efficiency of production has been performed, and the paper [7] where general models for the energy use and conservation in industrial enterprises have been proposed. Some energy saving issues with the use of artificial intelligence and variative systems are considered in [8, 9]. System solution of energy saving tasks at industrial enterprises is proposed in the paper [10].

The work [11] is devoted to ensuring the highest possible economic effectiveness of regional energy saving programs at the stage of making project decision. Adaptive approach to regulation of the "effect / cost" ratio in consumers and enterprises producing energy-saving equipment for railways was described in the paper [12].

3. The aim and objectives of research. The purpose of this study is the theoretical justification and development of a method for ensuring the ultimate energy efficiency of jobs in production systems based on system energy audit. To achieve this goal it is necessary to perform the following tasks:

1. Identifying many ways to obtain the desired functional properties of jobs.
2. Synthesis of structures of ways to ensure high energy efficiency of workplaces.
3. Development of a system energy audit algorithm based on the use of a general model of target transformations that occur during the interaction of the transforming system and the transformed one.

4. Presentation of the main material.

Despite a significant number of publications devoted to solving the energy efficiency and energy saving issues, the problem of ensuring the maximum energy efficiency of working places on the basis of system energy audit has not yet been set, and a general algorithm for its solution has not been proposed. The main reason for this situation is that the published works did not form a common set of possible structural solutions, without which it is not possible to formulate and to propose the specified algorithm.

The purpose of this study**:** development of a method for ensuring the maximum energy efficiency of working places based on energy audit system using full sets of ways to obtain the desired functional properties of working places and structures of ways to ensure energy efficiency of processes.

Ensuring limiting efficiency of any process as a system can be achieved in solving the problem of integrated structural and parametric optimization [13]. A peculiarity of such a formulation of the problem is the need to search for complete sets of possible structural solutions, among which one or several optimal solutions are determined by the optimality criterion, what corresponds for each case to the parametric optimization of the system. Upon that, the search for this solution is carried out using discrete-continuous 3D-models of clusters of blocking circuits that form the areas of permissible parametric solutions within each path to ensure the required properties of working places.

The paths for ensuring the required properties of the systems are defined in [14]. Proceeding from them, it is possible to form a matrix of possible structural solutions for ways of ensuring the required properties of working places, which should be considered during a system energy audit. It may have the following form:

$$
\mathrm{M_{sh}} = \begin{vmatrix}
0 & 0 & 0 & 0 & 0 & 0 & F \\
0 & 0 & 0 & 0 & 0 & T & F \\
0 & 0 & 0 & 0 & N & T & F \\
0 & 0 & 0 & M & N & T & F \\
\mathrm{D} & P & I & S & N & T & F \\
\mathrm{D} & P & I & S & N & T & F \\
\mathrm{D} & \mathrm{P} & I & S & T & N & F
\end{vmatrix},
$$

where the following designation of the phase cycles of a life cycle for working place technical means are taken: F - functioning; T - retraining; N - changeover; M - modernization; P - designing; I - manufacturing; C - testing and certification; D - research within the framework of a type of technical means; D^* - research on the creation of new types of technical means for a working place.

Using the data given in [6], it is possible to form a vertical vector of possible ways for energy efficiency improvements. Within the framework of the notations approved in the specified work, this vector can be written as follows:

$$
\begin{gathered}
\mathbf{r} = \{I_s \times N,\ U_m \times N,\ S_m \times N,\ I_s \times h,\ U_m \times h,\ S_m \times h, \\
I_s \times O_d,\ U_m \times O_d,\ S_m \times O_d,\ I_s \times V_d,\ U_m \times V_d,\ C_m \times B_d, \\
I_s \times P_r,\ U_m \times P_r,\ S_m \times P_r,\ D_o \times N^*,\ U_v \times N^*, \\
R_d \times N^*,\ P_r \times h^*,\ U_v \times h^*, R_d \times h^*,\ D_s \times O_d^*,\ U_v \times O_d^*, \\
R_d \times O_d^*,\ D_s \times V_d^*,\ U_v \times V_d^*,\ R_d \times V_d^*,\ D_s \times P_r^*, \\
U_v \times P_r^*,\ R_d \times P_r^*\}, \qquad (1)
\end{gathered}
$$

where the set of functions, the duration of which affects the energy consumption, are as follows: O_d - main actions, V_d - auxiliary actions, P_r - downtimes; the set of techniques that can reduce power consumption, reducing the cycle length: I_s - exception, U_m - decrease; S_m - combination; index * means a symmetric set of techniques aimed at energy self-sufficiency of the system, for the energy-conversion efficiency: D_o - addition, U_v - increase, R_d - separation.

Having formed the specified components of the set by their topological multiplication, we can obtain a complete (within the accepted classification) set (matrix) $\mathrm{M_r}$ of possible solutions:

$$
\mathrm{M_r} = \mathrm{M_{sh}} \times \mathrm{r^t}, \qquad (2)
$$

where superscript **t** indicates transposition.

It is necessary to carry out parametric optimization for each element of the set $\mathrm{M_r}$ as for one of the possible structural solutions.

The problem of integrated parametric optimization of a working place as a system can be formalized on the basis of a universal relationship system [14]:

$$
W1(Z), W2(Z), ..., Wn(Z), \qquad (3)
$$

$$\begin{cases} \vec{w}(t,\vec{z}_k,\vec{u}_k) \Rightarrow \vec{w}(t)_{opt}, \\ u_k = \sum_{\xi}^{l} f_k(\delta_\xi u^*_{o\xi}), \\ \vec{z} = \Phi_c(t,\vec{y},\vec{u}), \\ u_o = \sum_{\eta}^{m} f_o(\delta_\eta u^*_{n\eta}), \\ u_n = \sum_{\tau}^{n} f_n(\delta_\tau u^*_\tau), \\ \delta_g(t) \in \{0,1\}, \\ g \in \{\xi,\eta,\tau\}, \\ Al_i^-(|S_\Sigma|,\vec{\Pi},t) \le Al_i(|S_\Sigma|,\vec{\Pi},t) \le Al_i^+(|S_\Sigma|,\vec{\Pi},t), \\ i \in \{1,l\}; \\ F_j^-(|S_\Sigma|,\vec{\Pi},t) \le \Phi_j(|S_\Sigma|,\vec{\Pi},t) \le F_j^+(|S_\Sigma|,\vec{\Pi},t), \\ j \in \{1,m\}; \\ \vec{\Pi}^-_{ijk} \le \vec{\Pi}_{ijk} \le \vec{\Pi}^+_{ijk}, \\ k \in \{1,n\}, \\ \vec{\Pi} \in \{\vec{x},\vec{y},\vec{z}\}, \end{cases} \qquad (4)$$

where W – the optimality criterion vector; t - time; x_1, x_2, x_n ; y_1, y_2, y_m; z_1, z_2, z_k; $u_N, N \in \{k,o,n\}$ - parameters and actions which perform control at the super-system, system and subsystem levels, respectively; δ_g - the sequence of introduction of control actions; Al sign means the algorithm of the procedure provided by the theory of deductive systems for determining the values of algorithmic constraints and tolerances on them; F, f_n - functional relationships; $|S_\Sigma|$ - structure; $\vec{\Pi}$ - vector of parameters; subscripts mean the following: k - supersystem; o - system; n – subsystem; i - hierarchy level; j - number of functional constraints; p - relation to the parameter; *opt* - optimal value; superscripts "-" and "+" mean, respectively, the lower and upper tolerances.

The vector $W1(Z), W2(Z)...Wn(Z)$ is used as an optimality criterion which in this case should reflect the value of the energy efficiency indicator.

Energy efficiency (E_f) of the production is estimated by the amount of energy (Q_e) spent on the achievement of the target on the planned volume of transformation (A_f) compared to the ideal value of this indicator.

$$E_f = \frac{Q_e}{A_f} \quad . \qquad (5)$$

Based on (4), the concretized relationship for the calculation of specific energy consumption characterizing the energy efficiency of the system can be represented in the form:

$$E_f = \int_0^{T_{ц}} N * dt / A_f = \sum_{i=1}^{n} (Ni * Ti * hi) / \sum_{i=1}^{m} A_i, \qquad (6)$$

where: N, Ni, Ti, hi, Ai. - design and real power input averaged within the phase cycle, power usage time (phase cycle duration), total energy loss ratio (the value inverse to efficiency coefficient h^* of the energy-consuming element of the system) at the i-th transformation, and the volume of the executed i-th transformations, respectively; n, m - the number of the energy-consuming (supplying) elements of the system and transformations.

The dependence for calculating the growth (increase) in energy efficiency can be found by calculating the differential of the variable components from formula (5), taking into account that the integral energy saving model (reduction of energy consumption) has the form:

$$-\Delta E = \int_0^{T_n} \frac{dE_3}{dt}(t)\,dt; \qquad (7)$$

$$\mathrm{dE_f} = = 2\sum_{i=1}^{n} (Ni*Ti*hj)\,dA\phi / [\sum_{i=1}^{m} (Ai)]^2 + \sum_{i=1}^{n} (dNi*Ti*hi + dTi*Ni*hi + \ldots$$
$$\ldots + dhi*Ni*Ti) / \sum_{i=1}^{m} Ai. \qquad (8)$$

For a systematic search for energy saving and energy efficiency reserves, we can get a non-concretized model of total energy consumption by assigning its energy consumption values to each type of function, in the form:

$$E_i = \sum_{j=1}^{k} E_{jo}(t) + \sum_{j=1}^{k} E_{ju}(t) + \sum_{j=1}^{k} E_{jd}(t)\,, \qquad (9)$$

where E_i , $i \in \{o, u, d\}$ - energy costs for implementation of core (o), management (u) and support (d) functions (including preparatory), respectively; n, m, k is the number of subsystems that implement these functions;

Relationships (3) are constructed by parameterizing the elements and relationships of the structural model, including limiting ones, and the subsequent step-by-step concretization.

Models of the first level of concretization unfolded along the time coordinate in accordance with the typical linearized energy consumption schedules are shown in Figures 1 and 2 for an enterprise as a whole and for its management and control subsystem [7].

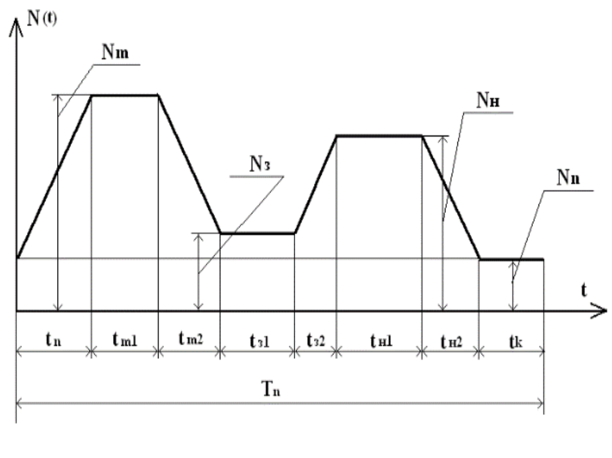

Fig. 1 – Typical Power Supply Schedule

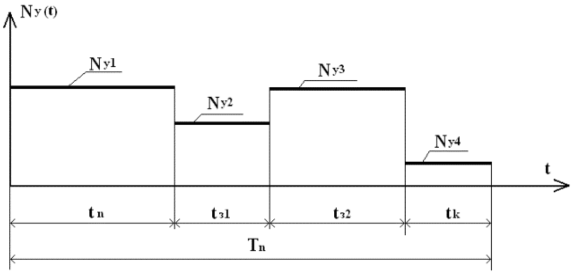

Fig. 2 – Typical Power Consumption Schedule for management and control needs

As a first approximation, the models can be represented by the following relationships at the time point: $t = T p$:

$$\sum_{j=1}^{k} E_K(T_n) = N_{Y1}\cdot(t_{З1}-t_n)+N_{Y2}\cdot(t_{З2}-t_{З1})+$$
$$+N_{Y3}\cdot(t_{З3}-t_{З2})+N_{Ym}\cdot(T_n-t_k). \qquad (10)$$

$$\sum_{j=1}^{k} E_i(T_n) = \sum_{j=1}^{k} E_k(T_n) - \sum_{j=1}^{k} E_y(T_n), \qquad (11)$$

where N_j , t_j, $j \in \{n, m_1, m_2, s_1, s_2, n_1, n_2, k\}$ - power consumption and time points corresponding to the beginning of work, the end of reaching the maximum production capacity period, the beginning of the first production capacity decline, the power consumption by the end of the first production capacity decline, the beginning of the second rise, the power consumption by the end of the second rise, the beginning of the second production capacity decline, and by the end of the second production capacity decline, respectively; T_p - the planned period of time.

When developing the relationships (9) we used the averaged specific utility (non-production) costs N_k (T_p), i.e. we accepted that $N_k(Tn) = const$. We could enter the following relative indicators to further specify these relationships,:

- energy:

$$\eta_{nm} = \frac{N_n}{N_m};\ \eta_{зm} = \frac{N_з}{N_m};\ \eta_{нm} = \frac{N_н}{N_m};\ \eta_{nз} = \frac{N_n}{N_з};$$

$$\eta_{ук} = \frac{N_{y1}}{N_к(T_n)};\ \eta_{y21} = \frac{N_{y2}}{N_{y1}};\ \eta_{yз1} = \frac{N_{yз}}{N_{y1}};$$

- time:

$$\xi_{nm} = \frac{t_{m1}-t_n}{T_n};\ \xi_{mm} = \frac{t_{m2}-t_{m1}}{T_n};\ \xi_{зm} = \frac{t_{з1}-t_{m2}}{T_n};$$

$$\xi_{mн} = \frac{t_{н1}-t_{m2}}{T_n};\ \xi_{нз} = \frac{t_{н1}-t_{з2}}{T_n};\ \xi_{нн} = \frac{t_{н2}-t_{н1}}{T_n};$$

$$\xi_{кн} = \frac{t_к-t_{н2}}{T_n};$$

$$\xi_{зn} = \frac{t_{з1}-t_n}{T_n};\ \xi_{зз} = \frac{t_{з2}-t_{з1}}{T_n};\ \xi_{Tз} = \frac{T_n-t_{з2}}{T_n};$$

$$\xi_{y1} = \frac{t_{з1}-t_n}{T_n};$$

$$\xi_{y2} = \frac{t_{з2}-t_{з1}}{T_n};\ \xi_{y3} = \frac{t_к-t_{з2}}{T_n};\ \xi_{yn} = \frac{T_n-t_k}{T_n}.$$

Taking into account the presence of additive structures, the optimization procedure should be reasonably performed using discrete-continuous 3D models of clusters with blocking circuits that form the areas of permissible parametric solutions within each path to ensure the required properties of working places. This takes into account physical, technical, economic, organizational and time constraints, the totality of which provides data for the formation of blocking circuits. The scheme of the method for a multioperational process is illustrated in Figure 3 [14], where a cluster of blocking circuits in the coordinates of the processing modes (with speed ***n*** and feed ***s)*** is formed.

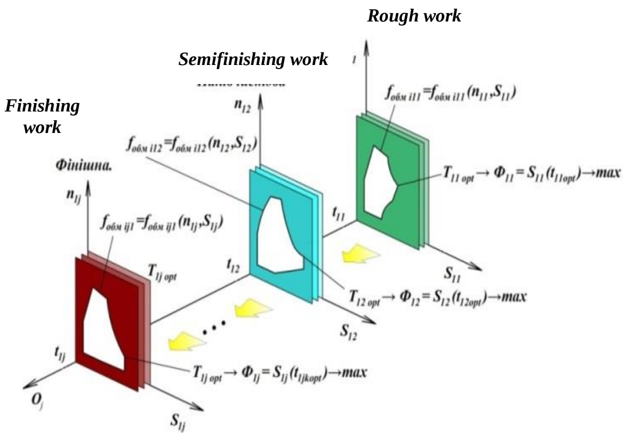

Fig. 3 – Discrete-continuous model of blocking circuit clusters

From the figure shown it is follows the possibility to choose the most effective solution for the presented cluster. Within the full set of clusters corresponding to the full set M_r of the structural solutions that should be considered in a systemic energy audit, there is the ability to determine a globally effective solution by performing a comparative procedure.

Conclusions. The full set $M_R = M_{sh}\ x\ \boldsymbol{r}^t$ was received for the structures of possible decisions on each way of ensuring the necessary functions of a working place.

For each structurally different path a relationship system is proposed, which can be used to find reserves of energy saving and energy efficiency within the limits of blocking circuits. The resulting linearized relationships for calculating the energy efficiency criterion have been obtained. These relationships can be simplified by taking into account the specifics and types of working places.

Ensuring maximum energy efficiency of working places based on system energy audit can be achieved by formalized setting up and solution of the problem of integrated structural-parametric optimization of processes and technical means using complex optimality criteria and taking into account existing constraints. The formation of complete (within the accepted classification) possible structural decisions can be achieved by the use of topological product of complete sets of ways to obtain the desired functional properties of working places and structures of ways to ensure energy efficiency of processes. Linearized models of energy supply and consumption processes can be used for parametric optimization. It is advisable to search for the optimal solution by using discrete-continuous 3D-models of clusters with blocking circuits which form the field of permissible parametric solutions within each path to ensure the required properties of working places. To perform energy audit of a system, it is advisable to create databases specialized for various kinds and types of working places.

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