Agronomy Research **14**(5), 1619–1625, 2016

Basic theory and methods for managing energy efficiency in consumer systems

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Abstract. In this article, we present a scientifically proven methodology for monitoring and controlling of industrial energy efficiency in consumer power systems (CPS) – an original method of finite relations (MFR), which uses relative energy intensity resulting from energy use in the technology of the enterprise as the main indicator of innovative energy efficiency. The differentiation algorithm and control of energy consumption are based on the effectiveness of energy use in power technology processes which ensure delivery of technologically expected results. The main provisions of the method are confirmed by experiments and tested under production conditions. The research results correspond to the basic principles of the global energy efficiency practices (integrated approach to the design and the principle of sustainable development), but yielded a number of more specific solutions.

Key words: energy saving, power consumption of production, criteria of energy efficiency, consumer power system.

INTRODUCTION

The quest for energy conservation by individual countries and on a global scale, due to a variety of obvious reasons, has a fairly long history, and the analysis of this quest allows you to make some conclusions. In particular, in production, which is almost the revealing (Stasinopoulos et al., 2012) point of the prospect of energy consumers' systematic approach to the design and engineering of sustainable development. Such recommendations are convincing and effective because of a large number of separate illustrated practical examples. However, their implementation requires in each case integrated energy to generalize the method of calculation, control and monitoring performance, providing energy-saving properties of the complex. This goal is the subject of this article. It should also be borne in mind that energy efficiency is closely related to the competitiveness of production enterprises, thus, to improve their economic situation. To find answers to the question 'Why the real engineering as a product of the exact sciences does not offer appropriate solutions for energy savings?' it is important to determine the prospects for the development of energy conservation. One possible answer lies in the fact that engineering knowledge is created mainly by studying the device of power equipment and its performance for a particular use. With such knowledge, the energy (Q) (the main carrier of action) and power (P) (indicator mode motion energy) are significantly fragmented, as their practical connection with total consumption is a much more complex mathematical operation of integration of functions, which is not always feasible.

MATERIALS AND METHODS

Cash-measuring finite ratio method (MFR) is based (Karpov & Yuldashev, 2010) on the ability to measure power at any function of power and allows circumventing this difficulty with the in-depth knowledge of experts. The ratio of energy input to a technical element (Q_S) and the output energy of the element (Q_e) forms the performance indicator (Q_E) of the energy passing through the element.

$$Q_E = \frac{Q_S}{Q_e} \qquad (1)$$

Versatility and availability of the values of this indicator made it possible to obtain a numerical estimate of the energy of not only individual technical elements and engineering systems.

From the standpoint of energy efficiency, it is most relevant to consider energy companies and products acceding the market competition. Expediency is not explained by the fact that the definition of the energy intensity of production is not available, and that the ability to manage power consumption at present is intuitive and heuristic even for experts, and not provided with a special methodology. The task of energy product management (minimization) led to the solution for the energy companies (Karpov et al., 2014) as energetic consumption systems (ECS), creating a well-defined structure of the energy intensity of production and the method of finite relations, and allowing us to analyse the structure and justify optimization of management solutions. Functional diagram of the ECS generally shown in Fig. 1.

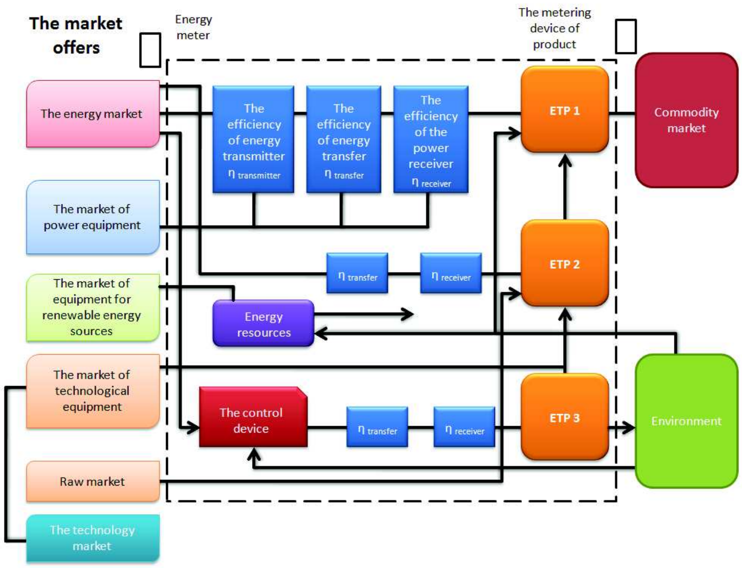


Figure 1. Block diagram of the ECS.

The generality of the scheme for the energy of different companies is reflected by the presence and the ability to measure all kinds of energy input, the presence of power lines supplying power directly to the receivers, as well as by specification of the bilateral market restrictions in the form of market quotations on the left side (with the payment of expenses) and the consumer market for the implementation of the Right product (with the refund in the form of income) on the right side. Basically, new circuit elements are power technology processes (ETP). The diagram shows three kinds of ETP, reflecting all of their real-life variety. Each ETP is accompanied by information about what type of energy is used, which object is the energy impact, a result of figure *R* to be obtained on production technology. Of particular importance in the scheme of introducing the ETP of ECS is the fact that they allow to calculate the minimum energy Q_{min} consumption for processing the results of *R*, which makes the formulation of the problem to optimize the energy efficiency more correct.

$$Q_{R\,i}^{spec} = Q_i^{spec} \cdot R_i \tag{2}$$

$$Q_{min} = \sum_{1}^{n} Q_{R\,i}^{spec} \tag{3}$$

where Q_i^{spec} – grounded theoretical energy density is determined in general physical constants, regulatory or experimental data.

In addition, calculations for higher ETP require the knowledge of experts – power engineering on the physical laws of the impact of energy on different media. According to a scientific school that developed at the emergence of the theory of energy saving, AEDs contain an empirical examination of the ETP, which aims to determine the effect of experimental energy losses on energy consumption results of ETP. The estimated value of energy losses on each item and each energy line of ECS is determine from and justified based on the values of energy consumption and according to the structure of the energy intensity of production, taking into account the financial costs and urgent, medium- and long-term measures to reduce the energy intensity of production.

The methods developed make it possible to calculate the impact of energy savings in the economic performance of the company (Kabanen & Karpov, 2014). Our studies have shown that the practical use of this feature provides a basis for the transfer of activities of energy companies only in the professional section of effective energy management; energy efficiency increases because of the yield of the company. It is also established that, presumably, involved commercialized energy gets its own economic indicator - the private rate of return (α_E):

$$\alpha_E = \frac{P_p}{\mathrm{C_T} \cdot Q_{el}} = \frac{Q_{el}^{market}}{Q_{el}} \tag{4}$$

where P_p – price of products; $\mathrm{C_T}$ – energy tariff; Q_{el} – power consumption of enterprise; Q_{el}^{market} – energy intensity of production of a market.

The positive effect of energy savings on the economic condition of the company strengthens the confidence in success and solves the problem of sustainable development, which is largely constrained to the high cost of elimination of environmental damage.

In theory formed the basis of energy-saving consumer energy systems put the main, but not deeply studied the theorem of calculus (Fermat's , Rolle's, Lagrange's, Cauchy's), numerical integration of functions of one variable, the average power is determined by the energy value or the increment. Largely, the provisions of the new applications of the theory of energy saving may be differential inequalities in integral calculus.

RESULTS AND DISCUSSION

To illustrate the validity of the use of the theory described in a practical energy saving data, we provide an empirical examination of a single electronic trading platform – water heating in electric heater. According to the classification adopted in the framework of the ECS, heating process can be attributed to the ETP2 (sub-processes). In this process, electric energy is converted into heat by means of a tubular electric heater (heater), which then has an impact on the volume of the energy of the heated fluid to raise its temperature to a value predetermined by the technology.

The object of examination is a water heater type EVBO-20 / 1.25, intended for heating water. The main parameters of the heater: the volume of heated water is 20 litres; rated power heater – P_s = 1.25 kW.

Based on the passport data of the heater, we selected baseline conditions for studies – the initial water temperature $T_{initial}$ = 20 °C and the required heating temperature T_{final} = 60 °C.

Preliminary analysis of the ETP test allowed to determine the theoretical amount of energy required to produce a given technological outcome (increase in temperature from the initial to the final), by the transition from the general formula (2) to the private characteristic of the process:

$$Q_R^{spec} = c \cdot m \cdot \left(T_{final} - T_{initial}\right) = Q^{spec} \cdot R\,, \tag{5}$$

where *m* – mass of water; kg; *c* – the specific heat of water kJ (kg °C)$^{-1}$.

In this example, Q^{spec} is determined based on the physical quantities in the calculation constant. For the test, a theoretical heating energy consumption was $Q_R^{spec} =$ 3,352 kJ.

Theoretical time to achieve results t^{spec} can be determined by a calculation using the formula:

$$t^{spec} = \frac{Q_R^{spec}}{P_s}; \tag{6}$$

if t^{spec} = 2,682 c.

An empirical assessment of the impact of energy loss results – ETP is based on determining the relative power consumption of the process (Q_E). For this indicator, we carried out, according to MFR, simultaneous measuring and recording of the amount of electrical energy consumption (Q_s) and temperature (*T*), which characterizes the integral impact of energy on the environment:

$$Q_E = \frac{Q_s}{Q_R^{spec}} = \frac{\int P_\varphi(t)dt}{Q^{spec} \cdot (T_{final} - T_{initial})}. \quad (7)$$

Maximum efficiency of the process is characterized by a lack of energy loss ($\Delta Q = 0$), in this case, all consumed energy is spent to achieve the result of the process ($Q_s = Q_R^{spec}$) and $Q_E = 1$ if $\Delta Q = 0$.

The controlled experimental studies of the process implemented in the course of the examination allowed to determine the loss of energy (ΔQ) and assess the impact of this on the relative energy content (Q_E) with appropriate operational and regulatory constraints:

Experiment №1. The definition of 'congenital' energy efficiency of equipment due to the level of engineering in the design phase (U = 220 V, $T_{ambient}$ = 22 °C);

Experiment №2. Investigation of the effect of ambient temperature from the decrease of energy in equipment (U = 220 V, $T_{ambient}$ =1 °C). The selected ambient temperature, according to the passport data of the test heater, is the minimum acceptable for its operation;

Experiment № 3. Investigation of the impact of reducing the voltage on the energy loss (U = 198 V, $T_{ambient}$ = 22 °C). The values of the steady voltage deviation in accordance with GOST 32144-2013 should not exceed ± 10% of nominal;

Based on the performance indicators derived from the research, we developed measures for managing energy efficiency in the process – the application of thermal insulation to reduce heat loss through the surface of the tank heater.

Experiment № 4. Analysis of the application of thermal insulation to reduce heat loss through the surface of the tank heater. (U = 220 V, $T_{ambient}$ = 22 °C). For this, we chose insulation with a thermal conductivity λ = 0.038 W (m °C)$^{-1}$.

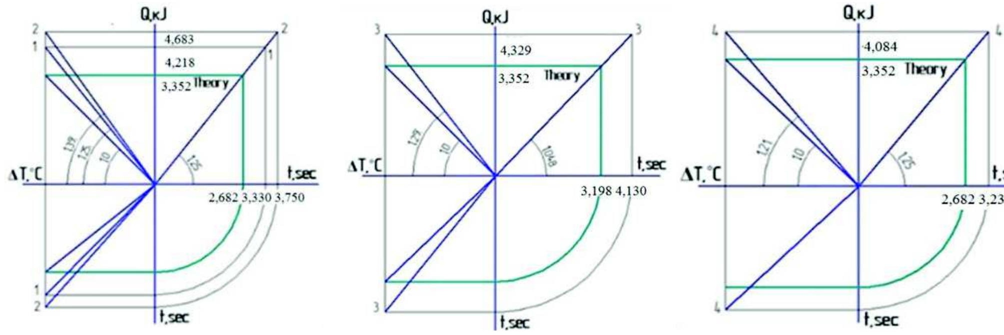
The results of experimental studies allow speaking with confidence about the universality of the finite relations, as well as its applicability in practical energy saving at all stages of the life cycle of the ECS.

Table 1. Main results of experiments

Experiment №	U, V	$Q_н$, kJ	$Q_к$, kJ	ΔQ, kJ	t, sec	P_φ, kW	$Q_э$
1 ($T_{ambient}$ = 22 °C)	220	4,218	3,352	866	3,330	1,248	1,258
2 ($T_{ambient}$ = 1 °C)	220	4,687	3,352	1,335	3,750	1,251	1,398
3 (U = 198V)	198	4,329	3,352	977	4,130	1,048	1,292
4 (thermal insulation)	220	4,084	3,352	732	3,230	1,254	1,218

The total number of sources for further analysis of the process variables is three (electricity consumption Q_s, the result of ΔT, and the process t), so their values are conveniently displayed in the form of points in a plane coordinate system, forming the original idea, which is proposed to call the universal energy diagram (Fig. 2).

On one chart, few circuits may be delayed, illustrating the various experimental conditions, however, the comparison will always be carried out with a theoretical outline, reflecting the highest energy efficiency (see Fig. 2, the circuit 'Theory').



a) b) c)

Figure 2. Energy diagram of the heating process: a) experiments №1 and №2, b) experiment №3, b) experiment №4.

Analysis of the results of empirical examination revealed common patterns of change in the efficiency of heating due to the effect of energy loss, and to carry out verification, we transformed them into the form of a numerical estimate of the relative energy consumption and energy saving measures.

The results of experimental studies allow speaking with confidence about the applicability of the method of finite relations in practical energy saving, as well as its universality. Subject to all major trading and enterprise information-measuring systems that implement the proposed method, it is possible to create a global system for monitoring energy efficiency in terms of the relative energy consumption. Such a system will ensure continuous monitoring of the use of resources to determine the optimal strategy for managing power consumption of products. Thus, experts of energy service businesses are able to affect the stability of the technical and economic spheres of production by means of operational performance.

A similar examination was carried out to change the electrical energy into mechanical energy – induction motor (IM).

To control the energy efficiency of IM, according to MFR, you must conduct periodic systematic measurement of relative energy intensity of his work during the whole period of operation.

In reference books and catalogues of manufacturers, the value of the energy characteristics of induction motors (IM) (η and $cos\varphi$) are given at partial load (25; 50; 75; 100 and 125% of rated power). However, in the real world, there is a difference in the energy performance of new blood pressure on the passport, which can be evaluated numerically in terms of the relative energy consumption.

The main characteristics of the studied blood pressure passport are type-AO2-51-4S2; Power – 7.5 kW.

For experimental studies to determine the relative power consumption of AD and DC motors, we developed a universal test bench, equipped with an electromagnetic brake that simulates the load on the motor shaft. For the measurement, recording and archiving of operating parameters of the IM, the stand is equipped with information-measuring system (IMS), which allows you to receive energy efficiency index of algorithms CIE (Table 2).

Table 2. Relative energy intensity of the work of IM stated in the passport and the results of experimental studies

Load factor of IM	Relative energy intensity IM, Q_E	
	Q_E^{namepl}	Q_E^{exp}
0.25	2.1	2.77
0.50	1.46	1.77
0.75	1.33	1.50
1.00	**1.29**	**1.44**
1.25	1.31	1.48

The results of experimental studies demonstrate the applicability of the method of finite relations to determine the energy efficiency of IM. Analysis of the results of calculations and experimental data leads to the conclusion that the blood pressure has a minimum relative power consumption at a rated load of operation $Q_E^{pasport} = 1.29$ and $Q_E^{exp} = 1.44$. By reducing the load factor below 0.75, there is a significant deterioration of the energy characteristics and an increase in relative energy intensity of the work of IM.

CONCLUSIONS

Using this method in practical energy saving will enable to assess the state of electric energy and to develop measures to manage energy efficiency, using known methods and means (regulation, control modes, etc.). Or replace them with new ones with improved power parameters. Thus, experts of energy service businesses are able to affect the stability of the technical and economic spheres of production by means of operational performance.

The development presented in the article should ensure the acceleration of the progressive development of energy consumers. As a rule, producers have one significant unconventional energy resource (energetic discharges, local wind energy, solar radiation, water flows, available biomass energy). The effectiveness of the use of this resource will be greatly enhanced by the reduction in the state of power of the consumer system.

It should also provide a solution to energy problems by using specially trained personnel. The methods outlined in this article can be used to develop educational programs of multi-level education, which provide consistent knowledge to the audience about the controlled system.

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