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Methods for assessing the technical compatibility of heterogeneous elements within a technical system

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The article provides methods for assessing the compatibility of elements in the design of complex technical systems. The compatibility of the elements is considered as the main indicator that determines the quality of systems including heterogeneous elements. The presented methods make it possible at the design stage to choose a technical solution that is most suitable for the project objectives, taking into account the operating conditions of the system. The methods make it possible to evaluate compatibility by a single and complex indicator. The choice of indicator depends on the purpose of the assessment. An example of methods implementation in the design of systems including an electric drive and pipeline shutoff valves is considered. It has been experimentally proved that in systems with low values of the compatibility level, the actual power characteristics exceed the required values, which leads to additional voltages in the system elements and their breakdowns. The results of the assessment of typical systems allowed to identify the shortcomings of existing structures and propose alternative solutions to problems. The compatibility of elements within the framework of a technical system makes it possible to increase the functional efficiency of systems with minimum weight and size and power characteristics, to optimize the price-quality ratio, and to increase the competitiveness of the final product.

***Key words*:** technical system; compatibility; electric drive; shutoff valves; technical efficiency; quality; competitiveness

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Introduction. Modern industry is characterized by a variety of technological processes for the implementation of which thousands of different machines and mechanisms have been created. One of the most common mechanisms is an electric drive (ED) – a controlled electromechanical system that converts electrical energy into mechanical energy. The main technical requirements for this type of system are reliability, accuracy, speed and compatibility [4, 8]. According to the authors, it is compatibility that is the determining indicator of the quality of this type of product.

The concept of compatibility for ED has a complex hierarchical structure. Compatibility requirements must be fulfilled both in relation to the simplest elements of the electronic drive (electric motor, conversion, control and transmission device), which as a result will ensure the coordination of the torque and speed of the engine with the efforts and speed of the technological machine executive body, and in relation to the complex technical systems (TS), including in their structure a subsystem of ED to provide a set of properties that determine their functional purpose [9, 10].

Ensuring compatibility requirements at the design stages and in production allows to improve the quality and competitiveness of the product type under consideration by reducing the weight and size parameters, increasing the reliability, efficiency and durability of electronic devices [13].

When examining the issues of ensuring and evaluating compatibility using the example of electric actuators for pipeline shutoff valves (PSV), the following results were obtained:

• a method for assessing the compatibility indicator to determine the conformity of ED to the functional purpose has been developed;

• a method for evaluating the compatibility of ED with heterogeneous elements is proposed, taking into account real operating conditions, as a tool for analyzing the technical perfection of complex TS and eliminating the formation of emergent properties.

A method for evaluating the compatibility indicator at the ED design stage. Evaluation of the conformity of ED to the functional purpose is the first step in the development of a new design. The purpose of creating the ED is to ensure the law of motion and the required power characteristics (forces, torques) of the executive body [6]. Based on this goal, the assessment of the compati-

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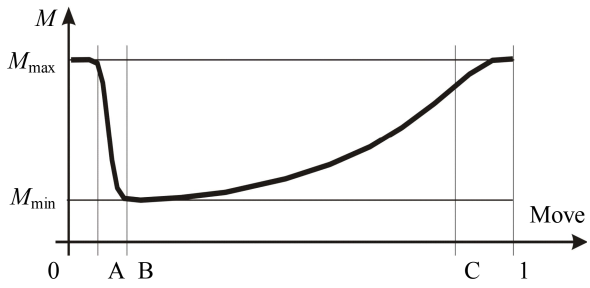

Fig.1. Torque change graph on the spindle PSV depending on the stroke of the locking element

bility indicator at the design stage should be reduced to comparing the obtained characteristics with the given values.

The graph of the torque change during the PSV execution of the OPEN-CLOSED working cycle (the movement of the locking member from point 0 is "open" to point 1 is "closed") is shown in Fig.1.

Section O-A corresponds to the breakdown of the valve body of the valve from the extreme position. This process requires the maximum torque (M_{max}) of the electric drive. Then the moment drops sharply, since the closure is already moving, but has not yet come into contact with the medium (section A-B).

With an increase in the area of contact with the medium, the torque gradually increases, which can be represented by the dependence

$$M_{\text{PSV}} = f(PS), \tag{1}$$

where P – pipe pressure; S – contact area.

At point 1, the torque reaches its maximum value again, since to eliminate leaks, a "boost" of the locking element is necessary to ensure the required tightness with the seat [8].

The graph in Fig. 1. represents the output characteristic of the locking element and is the initial characteristic for the design of ED. If during the design it will be possible to ensure the exact coincidence of the characteristics (this case is ideal), then the energy of the ED will be spent rationally and it will have a minimum power and mass [14]. Thus, the main task in the design is the maximum approximation of these characteristics.

For ED, this task can be implemented in two ways:

• through the use of an electromechanically controlled electric motor; this option has several drawbacks: the cost of the electric drive and its mass increase, and the scope of the mechanism is sharply narrowed, since in severe climatic conditions the use of this design is impossible;

• by developing the kinematics of the transmission unit, bringing together the characteristics of the electric drive and the actuator when using an asynchronous electric motor.

The desire to provide the required output characteristics has led to the creation of a multitude of ED design solutions for PVS:

• single-speed electric drive with a constant gear ratio throughout the entire open-close cycle (Fig.2);

• two-speed electric drive with a step gear ratio; a change in the gear ratio is provided by turning the friction clutch on and off (Fig.3);

• rocker drive with a smooth change in gear ratio (developed by Tula State University) (Fig.4).

The assessment of these designs in terms of compatibility will be executed. One of the options for evaluating the compatibility index of ED with PSV can be a comparison of the speed characteristics of PSV when it is controled by the estimated samples of ED with basic characteristics.

In this case, the evaluation algorithm will include the following steps:

• determination of the main kinematic dependences of the electron beam and the construction of graphs of PVS speed change;

• determination of the basic characteristics of the change in speed PVS;

• calculation of compatibility coefficient

$$S_i = \sum \Delta V_i^2 , \tag{2}$$

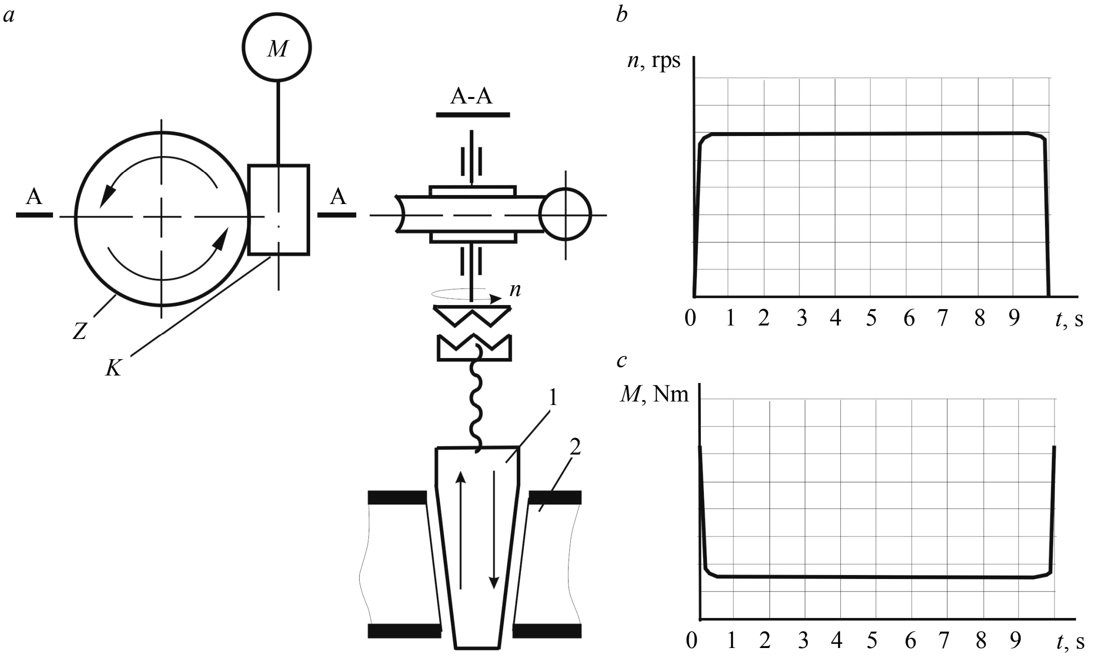

Fig.2. Single-speed electric drive: *a* – simplified kinematic scheme (*M* – electric motor; *K* – worm; Z is the screw wheel; 1 – valve; 2 – pipeline); *b* – graph of changes in the frequency of rotation of the output shaft; *c* – graph of the change in torque on the output shaft of the electric drive

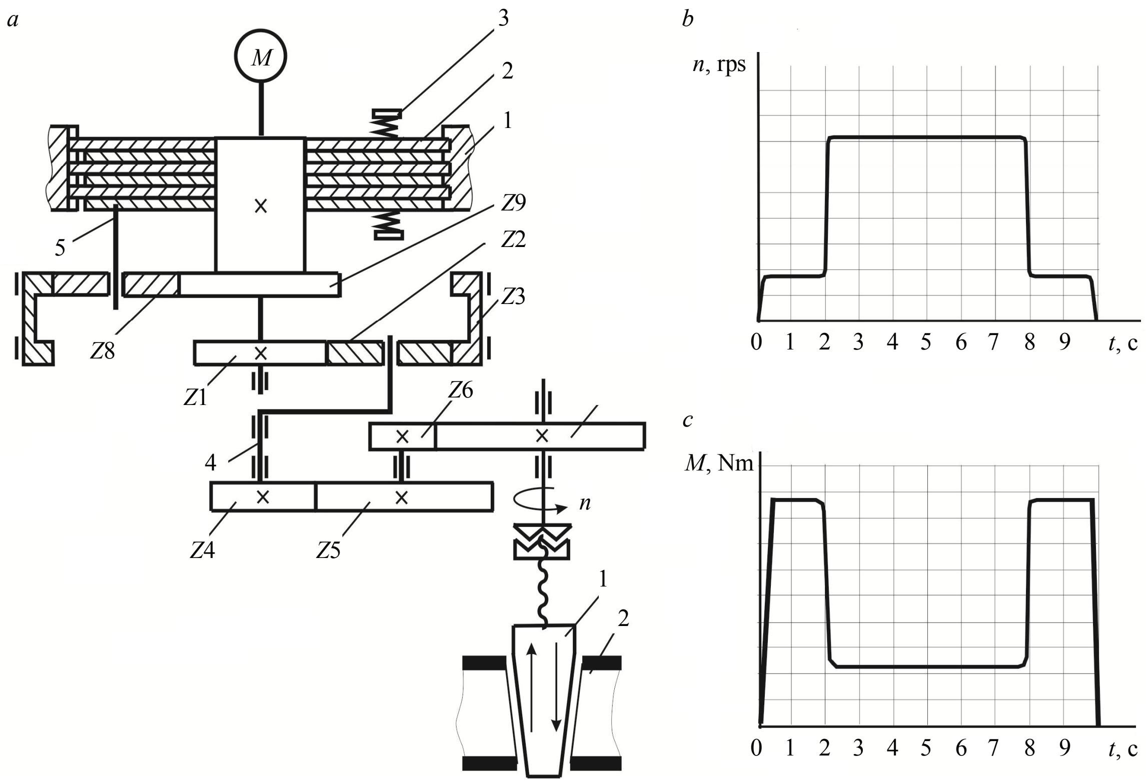

Fig.3. Two-speed electric drive: *a* – simplified kinematic diagram (*M* – engine; 1 – case; 2 – clutch of maximum torque; 3 – spring mechanism; 4, 5 – carrier; 6 – valve; 7 – pipeline; *Z* – gears); *b* – graph of changes in the frequency of output shaft rotation; *c* – graph of the change in torque on the output shaft of the electric drive

where ΔV_i – speed deviation, which is determined by the dependence

$$\Delta V = V_i - V_b, \qquad (3)$$

V_i – the value of speed at the *i*th point in time when PSV works with the evaluated object; V_b – basic value of speed at the *i*th point in time.

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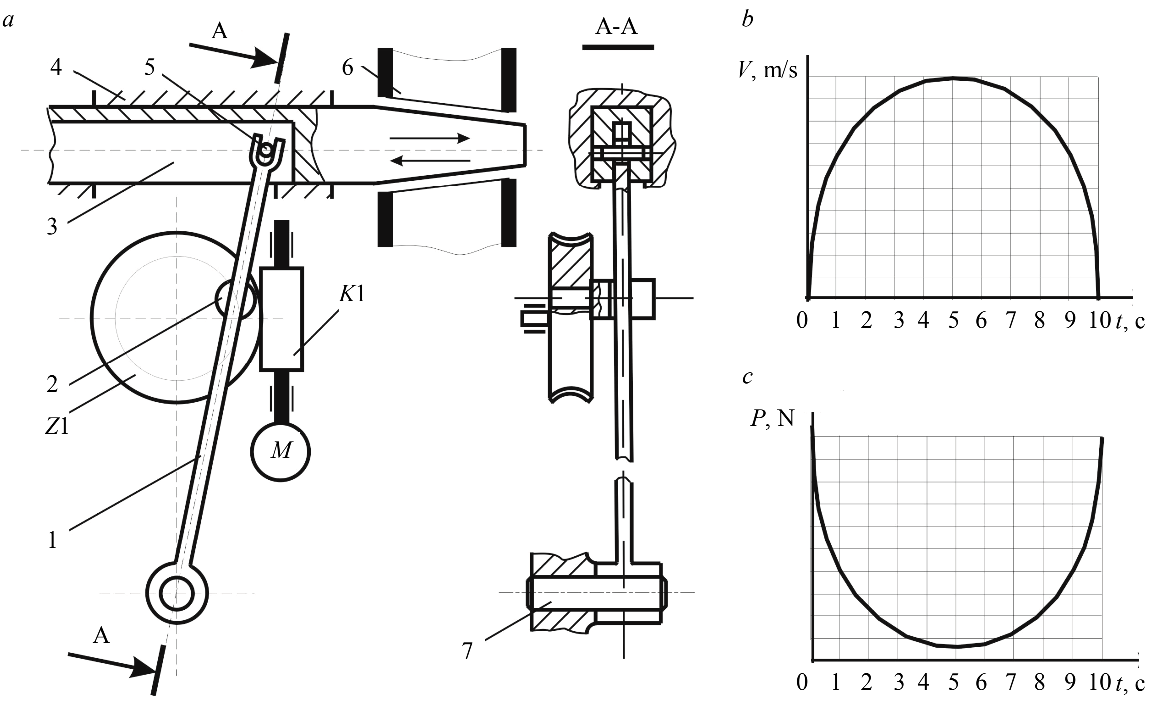

Fig.4. Rocker drive: *a* – simplified kinematic diagram (1 – rocker; 2 – rock rocker; 3 – housing gate valves; 4 – electric drive housing; 5 – rod, 6 – pipeline; *M* – motor; *Z*1 – a worm wheel; *K*1 – worm); *b* – speed changes graph; *c* – force change graph

Sum of squares ΔV_i^2 is selected to eliminate the effects of positive and negative values ΔV_i. The sum ΔV_i^2 tendency to zero value will characterize the high compatibility of the speed characteristic with the base value. Thus, the design with the minimum coefficient S_i value will be recognized as the best design in terms of compatibility.

The essence of the proposed methodology is illustrated in the graph (Fig. 5), where a parabolic function is adopted as the basic characteristic for assessing the compatibility coefficient, since such a characteristic provides minimal acceleration and the greatest smoothness of movement.

To conduct the assessment, the following conditions must be met:

• the number of measurements for each sample to be evaluated should be the same;

• evaluated objects must be placed in the same conditions, which can be represented by following dependencies:

$$t_{\max b} = t_{\max i}, \tag{4}$$

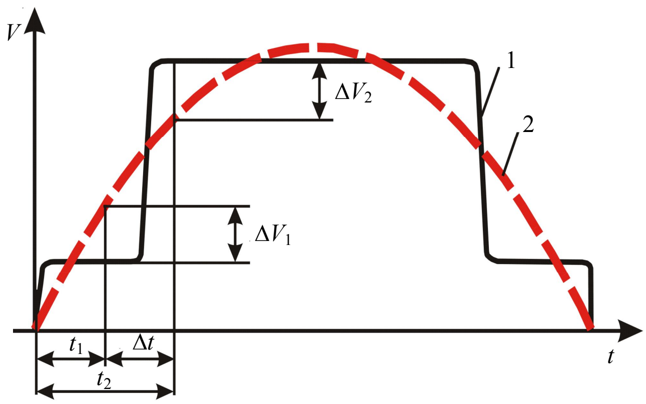

Fig.5. Graphical interpretation of an indicator score compatibility
1 – graph of the change in speed when combining PSV with the evaluated sample of ED; 2 – basic graph of the change in PSV speed

$$\int_0^{t_{\max}} V_i(t)dt = \int_0^{t_{\max}} V_{i\text{б}}(t)dt\,, \tag{5}$$

where $t_{\max b}$, $t_{\max i}$ – performing runtime; V_i, V_{ib} – the speed of movement of the locking element when managing the estimated and basic samples, respectively, at the *i*th time.

Basic values of speed when using a parabolic function can be determined by the formula

$$V_\text{b} = at^2 + bt + \text{c}, \tag{6}$$

where V_b – PSV base speed; *a*, *b*, *c* – constant values; *t* – time value.

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The constant values (a, b, c) can be determined by solving the system of equations:

$$0 = a0^2 + b0 + c; \tag{7}$$

$$0 = at_{\max}{}^2 + bt_{\max} + c; \tag{8}$$

$$t_{\max b} = t_{\max s} = t_{\max t} = t_{\max r} = t_{\max}; \tag{9}$$

$$\int_0^{t_{\max}} V_s(t)dt = \int_0^{t_{\max}} V_t(t)dt = \int_0^{t_{\max}} V_r(t)dt = \int_0^{t_{\max}} V_b(t)dt\,, \tag{10}$$

where V_s – function of changing the speed of a single-speed electric drive; V_t – function of changing the speed of a two-speed electric drive; V_r – function of changing the speed of the rocker drive; V_b – basic speed change function.

The first equation describes the basic characteristic of speed at the initial moment of time, when time and speed take zero values $t_0 = 0$ и $V_{b0} = 0$. In this case, equation (6) takes the form (7).

The second equation describes the basic characteristic of speed at a finite moment in time and corresponds to a stop of the system when time reaches its maximum value and the speed is equal to zero again: $t = t_{\max}$ и $V_{bn} = 0$. At this moment, equation (6) takes the form of (8).

Method implementation example. The graphical results of evaluating the compatibility index for three EDs: single-speed (Fig.6, *a*), two-speed (Fig.6, *b*) and rocker EP (Fig.6, *c*) are presented. Based on the presented graphs (Fig.6), the closest coincidence of the speed characteristics with the base one can be obtained when using a rocker ED as a control device. This is due to the smooth change in the characteristics of this design compared to a two-speed and single-speed ED. The value of the compatibility indicator for this design can be improved by bringing the schedule of change in the speed of the scenes closer to the base. This problem is solved by modeling the geometric parameters of the rocker gear.

Using the above methodology for evaluating compatibility at the stage of designing an ED allows to choose the best technical solution that meets the functional purpose – control of the PSV, increase the technical efficiency of the final product (the system ED-PSV) and minimize electric motor power.

Next, an algorithm for implementing the methodology for evaluating the compatibility of ED with heterogeneous elements within a complex technical system, taking into account real operating conditions, is considered.

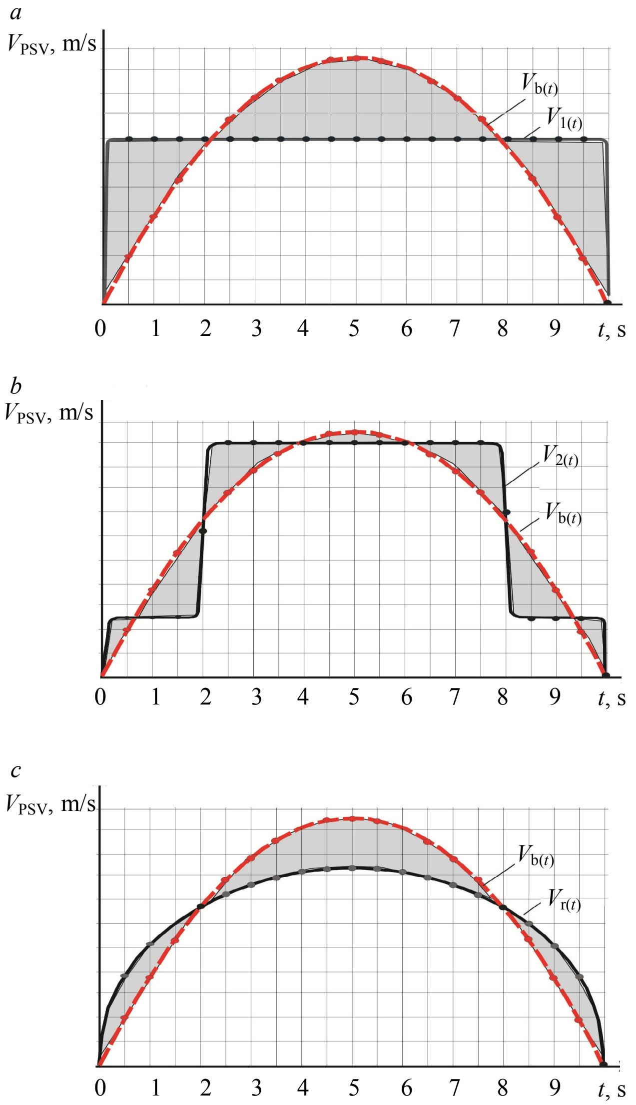

Fig.6. Graphical interpretation of the implementation results of the methodology for evaluating the compatibility of ED with PSV using single-speed (*a*), two-speed (*b*) and rocker drives (*c*)

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Prerequisites for the development of a method for evaluating the compatibility of ED with heterogeneous elements within a complex technical system. The above method allows to assess the technical system consisting of two interacting elements – ED and PSV. In this case, the condition is accepted that there are no additional factors affecting the variability of the output characteristics. Obviously, in this case we are creating ideal operating conditions that may not correspond to reality.

When commissioning the "ED-PSV" systems, it must be taken into account that the drive electric motor is controlled by a stationary control system (CS). Thus, in real conditions, the consumer operates a technical system (TS) consisting of three ED-PSV-CS elements, each element affects the variability of the output characteristics, and the level of technical compatibility of the elements determines the technical efficiency of the final system and, accordingly, its value to the consumer [5].

Under these conditions, an assessment based on one technical characteristic does not provide a complete picture of the level of compatibility of elements within the framework of the TS [7]. The most informative method is the assessment of compatibility by a complex indicator [11], for example, by an indicator that determines the functional efficiency of TS.

A method for evaluating the compatibility of ED with dissimilar elements within the framework of a complex technical system. To assess the level of technical compatibility of elements within the TS, the following formula is used

$$Э_f = \frac{A_{ef}}{A_{real}}, \quad (11)$$

where A_{ef} – effective work necessary to implement the objective function of the system; A_{real} – real work produced by the system as a result of the interaction of elements combined in it.

The value of effective work is a known quantity – the initial characteristic for designing a TS. Finding the value of real work requires a structural and functional description of the TS, taking into account the technical characteristics that are integrated into the system of elements and their mutual influence on the functioning of the system.

An example implementation of the method for "ED-PSV-CS" TS. Here are the results of evaluating the technical efficiency of the system, including the typical design of a single-speed electric drive with an asynchronous electric motor. The effective work of the TS "ED-PSV-CS" is taken equal to the work necessary to complete the normalized duty cycle, i.e. movement of the working body of the valve from the "open" position to the "closed" position, provided that the required tightness is ensured.

The value of effective work for the "ED-PSV-CS" TS system can be calculated by the formula

$$A_{\text{ya}} = \int_0^{\varphi_l} M_l d\varphi_l, \quad (12)$$

where M_l – necessary torque to ensure leakproof shut-off of the pipeline during the open-closed duty cycle; φ_l – angle of rotation of the movable element of the threaded pair of reinforcement required to ensure tightness.

For further calculations, it is necessary to make explanations based on the results of theoretical and experimental studies executed by the authors [1, 2, 5, 8, 15].

The output characteristics of the ED-PSV-CS TS are influenced by the parameters of its subsystems: PSV – reinforcement stiffness, ED - output shaft speed, CS – subsystem response time delay [4]. Depending on the combination of these parameters, the normalized value of the torque to ensure a leakproof shut-off of the pipeline during the open-closed duty cycle can have a different value [12].

Some "ED-PSV-CS" TS will be insensitive to the increment $\Delta\varphi_{\text{off}}$ (increment of the angle of rotation of the movable element of the threaded reinforcement pair during the delay of operation of the CS). These are systems with low rigidity PSV, or low frequency of rotation of the electric drive.

For other systems, even a small value of $\Delta\varphi_{off}$ will be sufficient for a multiple increase in the resulting torque of the electric drive relative to the calculated value of M_l. These systems include TS, combining high-speed electric drives and PSVs with high stiffness. Most of these systems are currently operated at critical facilities, including nuclear power plants.

According to the authors, such a sensitivity to increment $\Delta\varphi_{off}$ is a sign of non-compliance with the requirements for compatibility of elements in the design.

Given the above explanations, the value of the real work for the "ED-PSV-CS" TS can be found by the formula.

$$A_r = A_\Sigma = A_{ef} + A_{off} + A_E, \tag{13}$$

where A_{off} – work performed by the system during the delay of the CS when the motor is turned off; A_E – work performed by the system under the action of inertia forces of moving elements after the motor is turned off.

The last term in formula (13) is explained by the fact that after the electric motor is switched off, the moving parts of the system (rotor, worm, power screw, nut, etc.) continue to move under the action of inertia forces, which also leads to an increase in the rotation angle of the movable element of a threaded pair of reinforcement, but by $\Delta\varphi_E$.

The resulting work ratio A_{ef} and A_r allows to visually evaluate the graphs in Fig.7.

From the graphs shown in Fig.7 it can be seen that the work carried out by the "ED-PSV-CS" TS differs significantly from the effective work necessary to perform the target function.

Analytical calculations carried out for typical systems with hardness PSV – 10 N·m/deg., ED rotation speed – 32 rpm and a minimum control time delay of CS – 20 ms showed that no more than 45 % of energy accumulated in systems is spent on useful work [8]. The level of technical compatibility of elements within the framework of the "ED-PSV-CS" TS, calculated according to formula (11), for the systems under analysis did not reach 0.65 with a base value of 1.

It has been experimentally proved that in systems with low values of the level of compatibility of elements, actual power characteristics exceed the required values from 1.6 to 3.8 times [4, 13]. As a result, the locking forces of the PSV increase significantly, which leads to additional stresses in its elements, breakdown of the PSV parts, and power screw bending.

The results of the study allow to make the following proposal aimed at increasing the level of technical compatibility of TS components. To exclude the influence of the delay time of the control system when the motor is turned off, it is necessary to give a command to turn off proactively, i.e. earlier. As a result, the magnitude of the work A_{off} will actually be zero (Fig.7). Then the real work will differ from efficient work by a very small amount A_E (see formula (13) and Fig.7), and the level of technical compatibility of elements within the framework of the TS calculated according to formula (11) will increase and will approach a base value of one. In this situation, there will be no emergent property and a significant increase in the locking force PSV, which will eliminate the breakdown of parts in the TS.

Assessing the compatibility level during the design of the "ED-PSV-CS" TS allows to rationally select the elements of the system,

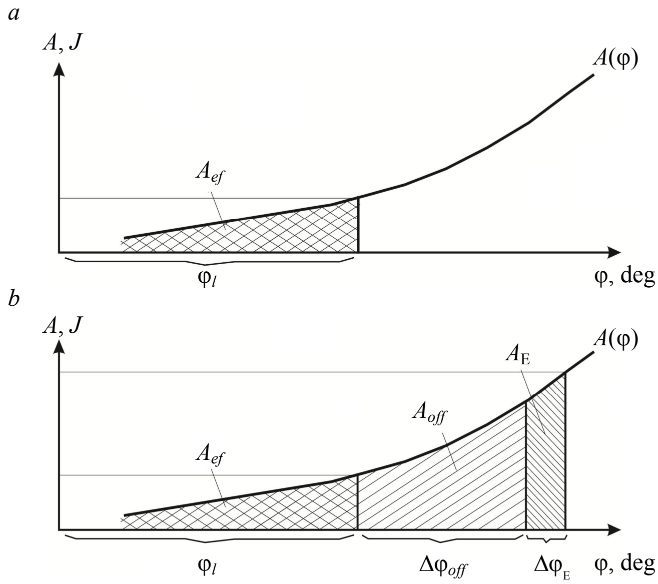

Fig.7. Functional efficiency of systems without ensuring a balance of energies: *a* – graph of effective work necessary to implement the target function of the system; *b* – graph of actual work performed by the system as a result of the interaction of elements combined in it ($A_r = A_{ef} + A_{off} + A_E$)

providing a balance of energies and rigidity and improving the quality of the systems while reducing their energy consumption.

Conclusion. One of the main conditions for ensuring the quality of complex technical objects at all stages of the life cycle is compliance with the principle of compatibility [3, 7]. The principle is to ensure the complementarity of heterogeneous structural elements within the system. The implementation of the principle involves the establishment of criteria for the compatibility of elements and the development of methods for their assessment. The methods presented in the paper explain various approaches to assessing the compatibility of elements in TS, including ED. The difference in approaches lies in the indicators underlying the assessment of a single indicator in the first method and a complex indicator in the second method. The similarity of approaches is the aim pursued by the authors – to increase the functional efficiency of the TS with minimal weight and size and power characteristics, which allows optimizing the ratio of price and quality, increasing the competitiveness of the final product.

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