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Boundary values of fiducial intervals of technical and economic indicators of TPP power units

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ABSTRACT

Reducing the risk of erroneous decisions when comparing and ranking the efficiency of the main equipment and devices of thermal power plants (TPP) of EPS can be achieved by developing an automated system for controlling the accuracy of initial data. This difficulty is caused by the multivariate nature of technical and economic indicators (TEI), the source of which is the data of statistical reporting in the form of ZTEKh (energo). Previous studies made it possible to develop a method and an algorithm for calculating the fiducial intervals of a cluster of TEI implementations, the classification of which according to possible types of attributes is impractical. The paper addresses two issues: how these intervals change over time, and how the nature of the distribution of homogeneous TEI implementations within the fiducial interval changes. Reducing the risk of an erroneous decision when comparing and ranking TPP power units is a prerequisite for successful benchmarking of powerful power units, reducing operating costs. The need to solve the problem of improving the maintenance and repair of equipment, the service life of which exceeds the calculated one, should be considered urgent, as well as the preparation of appropriate methodological recommendations.

Basic concepts and definitions.

Fiducial distribution and intervals. Fiducial distributions were proposed by Fisher in 1935 and determine to what extent we can trust ("fiducial" means "based on trust") any given value of an unknown indicator (parameter) of this distribution. According to Fischer, "one should only trust decisions based on empirical evidence." Taking into account different opinions on the issue of reliability of fiducial distributions, Academician A.N. Kolmogorov noted in 1942 in [1] that with a small sample size, the best interval estimates are given by fiducial distributions.

Multivariate data. It is necessary to distinguish between samples of random variables from the general population, the distribution of which is known, and samples from a finite population of multivariate random variables, the distribution law of which depends on the significance of the randomly changing set of interrelated features and their varieties.

Confidence and fiducial intervals. Confidence intervals of indicators are determined

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analytically using known formulas for some initial assumptions. These include, first of all, knowledge of the distribution law of the general population of random variables, a sufficient number of implementations in the sample, and the random nature of the sample. In real conditions, the distribution of random variables is unknown, the number of implementations of homogeneous samples, as a rule, is calculated in units, these samples (clusters) are not random, since they are formed as a result of the classification of a finite set of multivariate data according to specified types of features. Simulation modeling allows obtaining a statistical distribution function of indicators for a sample from the general population. In this case, the boundary values of the confidence and fiducial intervals coincide. But the fiducial approach allows obtaining the boundary values of the interval for multivariate data, regardless of the type of distribution law of random variables and the sample size. Therefore, the method of confidence intervals should be considered as a special case of the fiducial approach.

Classification of multivariate data. The multivariate nature of the input data determines an unreasonably wide range of their possible values for the entire data set. The greatest impact on the width of the fiducial TEI is exerted by erroneous implementations and implementations of the trigger mode. For instance, when a power unit is launched at the end of a month after repairs, a number of average monthly TEI values will exceed the nominal value by several times. These include the specific consumption of equivalent fuel, the specific consumption of electrical and thermal energy in the auxiliary power system (AP), etc. Overcoming these difficulties is achieved by eliminating from the set of data scarce data with significant varieties of features and the transition to homogeneous data (clusters). In homogeneous data, the classification of the population according to any criterion and their varieties is inappropriate.

1. Problem statement

Ensuring the error-free and homogeneous implementations of the monthly average TEI values made it possible to reduce the risk of erroneous decisions when comparing and ranking EPS facilities. The method and algorithm for solving this problem is presented in [2]. The most time-consuming component of this method is the determination of the boundary values of the fiducial interval (BVFI) by the statistical distribution function (s.d.f.) of possible TEI implementations within one calendar year. The sources of these implementations are the forms of statistical reporting 3TEKh (energo) [3]. The spread of deviations in the implementation of the monthly average TEI values in a number of cases is so significant that even with an automated calculation performed on a computer by an operator, their analysis requires the involvement of a specialist. For this reason, monthly adjustments to BVFI are unacceptable and necessitate a revision of the method for their refinement. Let us denote the lower and upper BVFI for an arbitrary TEI, respectively, as $\underline{\Pi}^{\phi}$ and $\overline{\Pi}^{\phi}$.

This paper will address two issues. The first of them will clarify the nature of the change of $\underline{\Pi}^{\phi}$ and $\overline{\Pi}^{\phi}$ over a number of years of observation, and the second will clarify how significantly the patterns of s.d.f. of possible implementations change TEI $F^{T}(\Pi)$ in the interval $[\underline{\Pi}^{\phi};\overline{\Pi}^{\phi}]$.

2. Analysis of BVFI change by year

Table 1 shows BVFIs for a number of TEI boiler units (BU) of 300 MW power units of a steam turbine power plant (STPP) running on gas-oil fuel for 2011, 2013 and 2018.

Table 1

Boundary values of the fiducial interval changing over time

N	TEI		$\underline{\Pi}^{ф}$			$\overline{\Pi}^{ф}$		
	type	unit of m.	2011	2013	2018	2011	2013	2018
1	$T_п$	^0C	223	229.6	228.5	252.9	245.8	244.4
2	$T_в$	^0C	258	264.2	269.4	298.0	295.0	293.6
3	$T_{уг}$	^0C	99.6	98.4	103.8	117.1	119.4	125.7
4	$K_в$	p.u.	1.053	1.062	1.069	1.210	1.231	1.227
5	ΔS	%	35.6	35.8	36.2	46.1	45.5	45.3
6	$\eta_б$	%	89.3	90.2	90.80	92.63	92.4	92.31
7	$Э_Э$	%	1.88	1.90	1.92	2.92	2.91	2.88
8	$Э_Т$	%	0.98	1.11	1.12	1.93	1.86	1.84
9	$\eta_н$	%	83.5	83.6	84.21	87.23	86.6	86.48
10	$b_Т$	g/kWh	321.2	318.7	319.8	344.2	344.9	345.8

In Table 1, the following designations are adopted: $T_п$ – temperature of feed water; $T_в$ – air temperature after the RVP; $T_{уг}$ – temperature of exhaust gases; $K_в$ – coefficient of excess air; ΔS – air infiltration on the loop; $\eta_б$ – plant efficiency gross; $Э_Э$ – consumption of electricity in the auxiliary system of the BU; $Э_Т$ – consumption of heat energy in the auxiliary system of the BU ; $\eta_н$ – plant efficiency net; $b_т$ – specific consumption of equivalent fuel; Π_i – symbol of the i-th TEI, where $i=1,n_п$; $n_п$ – the number of considered TEI; $\underline{\Pi}^{ф}$ and $\overline{\Pi}^{ф}$ – respectively, the lower and upper boundary values of the fiducial interval of the i-th TEI.

As follows from this table, there is no significant change in the values of $\underline{\Pi}^{ф}$ and $\overline{\Pi}^{ф}$ from year to year. The observed discrepancy indicates a small increase in $\underline{\Pi}^{ф}$ and a small decrease (with the exception of $T_{УГ}$, $K_В$ and $b_Т$) in $\overline{\Pi}^{ф}$ over time, which, in fact, reflects the ageing process. The insignificant changes in $\underline{\Pi}^{ф}$ and $\overline{\Pi}^{ф}$ allow us to conclude that it is advisable to switch from monthly correction of the fiducial interval to annual. This change of the intervals $[\underline{\Pi}^{ф};\overline{\Pi}^{ф}]$ is explained by the possibility of operational management of TEI values. With an increase in the service life, these possibilities are limited due to an increase in the amount of residual wear and due to insufficient qualifications of personnel.

The increase in residual wear and the invariability of the strategy for diagnostics of the technical condition and repair, in turn, lead to an increase in the rate of wear, to the emergence of a danger of damage, to accidents.

Insufficient qualifications of personnel is caused by a sharp difference between the system of maintenance and repair of equipment with a short service life and equipment whose service life is close or even exceeds the standard, the lack of instructions and guidelines regulating the maintenance of ageing equipment.

In this regard, one cannot fail to note three possible directions for overcoming these difficulties. The first direction is the most radical, consisting in dismantling the equipment, the service life of which exceeds the calculated one, and replacing it with new, more modern one. Unfortunately, this direction is not always feasible. For instance, the cost of replacing power units of a FTPP with a capacity of 2400 MW running on gas-oil fuel with power units of a gas turbine power plant (GTPP) on the world energy market costs about 1.2 billion dollars [4]. And, as a rule, no country, including the economically developed ones, can or wants to afford it, because this equipment has a "mass of opportunities" to extend its service life.

The second direction is modernization, which will make it possible for equipment to work efficiently (economically, reliably and safely) for another 10-15 years. The cost of such modernization for the same FTPP is approximately 30% of the cost of the GTPP, i.e. about 0.36 billion dollars, which is also problematic for a government to allocate immediately.

The third direction is the ability to ensure the operability of equipment, which cannot be replaced with new one or completely modernized in the coming years but is extremely necessary to ensure energy security. Ability means not the load of the equipment exceeding the maximum permissible value, timely diagnostics of its technical condition, and in some cases continuous diagnostics, the minimum possible duration of operation with the permissible load, timely restoration of defects in auxiliary devices (partial modernization).

Over time, which largely depends on our skill (qualifications), changes in TEI can manifest themselves in changes in the nature of the distribution of s.d.f. $F^{*}(\Pi)$ caused by an increase in the significance of the deviation of TEI implementations and their normative value. And this is one of the most serious signs that residual wear has reached the maximum permissible value.

3. Comparison of s.d.f. of populations of possible implementations of the same type TEI

Methods for comparing s.d.f. of samples are well known, and the specifics of their practical application are described in sufficient detail in many publications [5, 6, 7, etc.]. In conditions when the number of TEI implementations in these samples is in the tens, the automated assessment of the nature of their discrepancy by traditional methods encounters certain difficulties. Moreover, it is assumed that these statistics are samples from the general population, the distribution of which is known. The character of the distribution of the TEI set is given only by the s.d.f. This discrepancy can be overcome by the recommended method and algorithm [8, 9]. Suppose that we know two unmistakable and homogeneous populations of possible implementations of monthly mean values of the i-th TEI over the year.

The first population $S(\Pi_i, t_1) \cong \{\Pi_{i,1,1}, \Pi_{i,1,2}, \Pi_{i,1,3}, ...\Pi_{i,1,n_{i1}}\}$ was observed in year t_1, and the second one $S(\Pi_i, t_2) \cong \{\Pi_{i,2,1}, \Pi_{i,2,2}, \Pi_{i,2,3}, ...\Pi_{i,2,n_{i2}}\}$ was observed in year t_2, where $n_{i,1}$ and $n_{i,2}$ are the number of implementations of the first and the second populations, respectively. Let us agree that $n_{i,1} \le n_{i,2}$. It is required to check the assumption (H_0) about the random nature of the discrepancy of their s.d.f. $F^{*}(\Pi_i, t_1)$ and $F^{*}(\Pi_i, t_2)$. An outline block diagram of the algorithm for assessing the nature of the discrepancy of s.d.f. $F^{*}(\Pi_i, t_1)$ and $F^{*}(\Pi_i, t_2)$ is given in Fig. 1.

Let us consider some features of each block of this algorithm.

Block 1. Entering the populations $S(\Pi_i, t_1)$ and $S(\Pi_i, t_2)$;

Block 2. Creating a single population of monthly mean values of the i-th TEI observed in years t_1 and t_2, denoted by $\{S(\Pi_i, t_\Sigma)\}$;

Block 3. Placing implementations of the i-th TEI of populations $S(\Pi_i, t_1)$ and $\{S(\Pi_i, t_\Sigma)\}$ in ascending order;

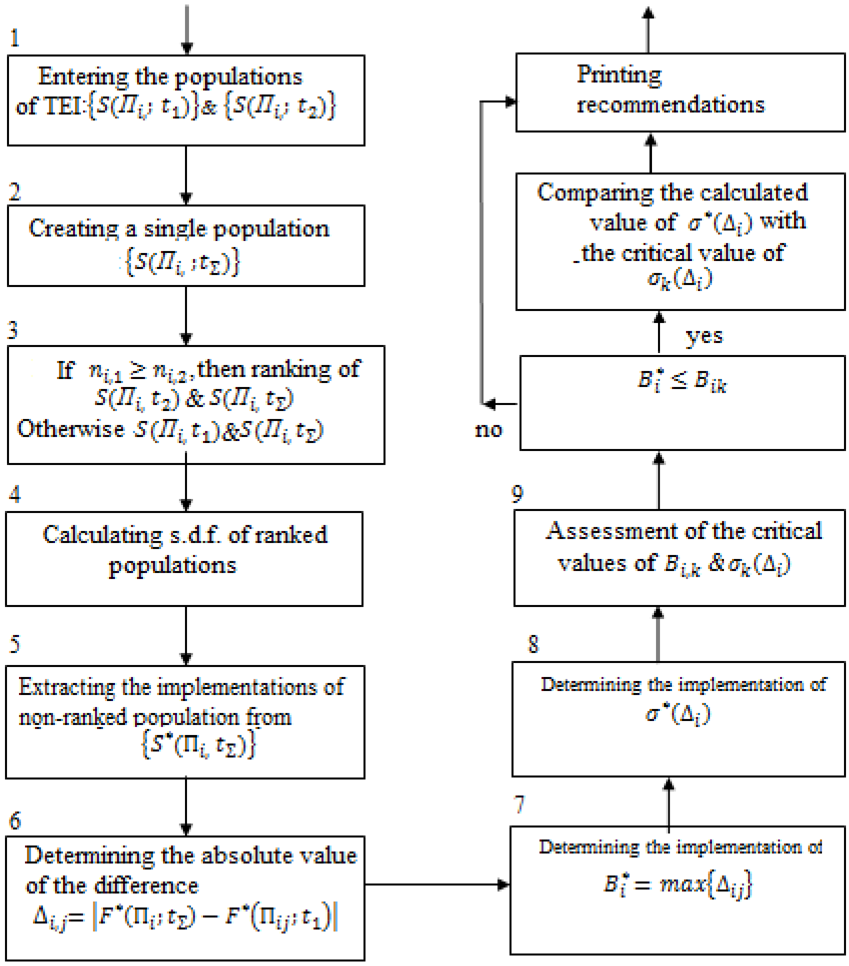

Fig. 1. Outline block diagram of the algorithm algorithm for controlling the significance of the discrepancy of the s.d.f. $F^*(\Pi_i;t_1)$ and $F^*(\Pi_i;t_\Sigma)$

Block 4. Calculating s.d.f. of ranked (r) populations $S^*_P(\Pi_i, t_1)$ and $\{S^*_P(\Pi_i, t_\Sigma)\}$ from the formulas $F^*(\Pi_{i,j}, t_1) = j/n_{i,1}$ and $F^*(\Pi_{i,j}, t_\Sigma) = j/(n_{i,1} + n_{i,2})$;

Block 5. Extracting from the population $S_P(\Pi_i, t_\Sigma)$ the implementations of the population $S(\Pi_i, t_2)$ and the corresponding values of s.d.f. $F^*(\Pi_i, t_\Sigma)$;

Block 6. Determining the absolute value of the discrepancies Δ_i of s.d.f. $F^*(\Pi_i, t_\Sigma)$ and $F^*(\Pi_i, t_1)$ for each implementation of the population $S(\Pi_i, t_1)$;

Block 7. Determining the maximum value from $n_{i,1}$ implementations of the value Δ_i is determined, which is denoted as B_i and is the statistics of the criterion for checking the assumption (H_0). In [10] it was noted that the criterion based on B_i is still insufficient to ensure the reliability of the decision. At least one more criterion is needed, which would reflect other statistical properties of the set of implementations Δ_i. As a second statistic, the value of the standard deviation of the implementations Δ_i is applied, which we denote as $\sigma^*(\Delta_i)$;

Blocks 8 and 9. Determining the arithmetic mean of the implementations Δ_i from the formula $M^*(\Delta_i) = n_{i,1}^{-1} \sum_{j=1}^{n_{i,1}} \Delta_{i,j}$ and further – the mean square deviation $\sigma^*(\Delta_i)$ from the formula

$$\sigma^*(\Delta_i) = \sqrt{\left\{ \sum_{j=1}^{n_{i,1}} \left[\Delta_{i,j} - M^*(\Delta_i) \right]^2 \Big/ (n_{i,j} - 1) \right\}}$$

Block 10. The criterion for assessing the significance of the discrepancy of the s.df. $F^*(\Pi_i,t_1)$ and $F^*(\Pi_i,t_2)$ based on the statistics B_i and $\sigma^*(\Delta_i)$, respectively, have the form (1) and (2):

$$\left.\begin{array}{l} \text{O=if } B_i \le B_{i,\kappa}, \text{then } H \Rightarrow H_0. \\ \text{otherwise } H \Rightarrow H_1, \end{array}\right\} \quad (1)$$

where: H_1 – the assumption of a nonrandom discrepancy of s.d.f. $F^*(\Pi_i,t_1)$ and $F^*(\Pi_i,t_\Sigma)$; $B_{i,\kappa}$ – critical value of the statistic B_i; index $\Rightarrow$ meaning “correspondence”. It is assumed that if the discrepancy of s.d.f. $F^*(\Pi_i;t_1)$ and $F^*(\Pi_i;t_\Sigma)$ with a level of significance α can be taken as random, then the discrepancy of $F^*(\Pi_i;t_1)$ and $F^*(\Pi_i;t_2)$ is also random.

The second criterion based on statistics $\sigma^*(\Delta_i)$ has a similar form:

$$\left.\begin{array}{l} \text{if } \sigma^*(\Delta_i) \le \sigma_k(\Delta_i), \text{ then } H \Rightarrow H_0, \\ \text{otherwise } H \Rightarrow H_1 \end{array}\right\} \quad (2)$$

where $\sigma_k(\Delta_i)$ is the critical value of the statistic $\sigma^*(\Delta_i)$

4. Express method for calculating the critical values of B_i and $\sigma^*(\Delta_i)$

The critical values of the statistics B_i and $\sigma^*(\Delta_i)$ can be experimentally obtained by multiple simulation modeling of possible TEI implementations of a sample size $n_{i,1}$ by s.d.f. $F^*(\Pi_i,t_\Sigma)$, assessment of the implementations of the corresponding statistics, ranking them and finding the implementations for the given level of significance α. Such calculations were carried out for a number of n_i and α [8,9]. These experimental data made it possible to establish an analytical relationship between the critical value of statistics and the volume n_i for a number of α. It has been established that:

– relationship between the critical values of the statistics B_i and $\sigma^*(\Delta_i)$ with a reliability of at least 0.995 is characterized by a power function, namely $B_{i,k} = A \cdot n_i^{-b}$. The values of the coefficients A and в for α=0.05 and α=0.10 are given in Table 2.

Table 2

Coefficients of the regression equation

Statistics	Regression coefficient	Level of significance	
		0.05	0.10
$B_{i,k}$	A	1.79	0.459
	b	0.942	0.453
$\sigma_k(\Delta_i)$	A	0.428	0.540
	b	0.385	0.551

– the reliability of the above approach is confirmed by the established relationship between the statistic B_v and Kolmogorov statistic D_n [5], namely:

$$2\left[1 - F^*(B_i)\right] = \left[1 - F(D_n)\right]. \quad (3)$$

Equation (3) also answers the question why the algorithm for calculating B_i cannot be used to compare with the critical value D_n.

5. Calculation example

For illustrative purposes, Table 3 shows an example of comparing two populations of monthly mean values of the relative value of specific electricity consumption in the auxiliary power system of boiler units of 300 MW power units of FTPP running on gas-oil fuel ($Э_э$) for two adjacent months. The choice of populations is explained only by the desire to reduce the cumbersomeness of calculations. So, if the number of monthly mean values of $Э_э$ implementations over a month is equal to the number of operating power units, then the actual number of $Э_э$ realizations over a year will be approximately 12 times greater. The comparison results are shown in the appendix of Table 3 and indicate the homogeneity of the samples.

Table 3

Control of the reliability of the assumption about the random discrepancy of the s.d.f. $F^*(Э_{э,2;}t_1)$ and $F^*(Э_{э,2;}t_2)$

N	$Э_{э.1}(t_1)$	$Э_{э.2}(t_2)$	$Э_{э.2}(t_2)$	$F^*(Э_{э.2;}t_2)$	$F^*(Э_{э.2;}t_2)$	$F^*(Э_{э.2;}t_2)$	$\Delta(Э_э)$	Appendix
1	2.36	2.25	-2.18	0.083	0.2	0.166	0.034	$B(Э_э)$=0.150
2	2.30	2.33	2.25	0.166	0.4	0.250	0.150	$M^*[\Delta(Э_э)]$=0.067
3	2.37	2.38	2.27	0.250	0.6	0.583	0.017	$\sigma^*[\Delta(Э_э)]$= 0.039
4	2.28	2.34	-2.28	0.333	0.8	0.667	0.133	at α=0.05
5	2.18	2.27	-2.30	0.417	1	1	0.000	$B(Э_э)_к$=0.504
6	2.32		-2.32	0.500				$\sigma[\Delta(Э_э)]$= 0.182
7	2.35		-2.33	0.583				
8			-0.34	0.667				
9			-2.35	0.750				
10			-2.36	0.833				
11			-2.37	0.917				
12			2.38	1.0				

6. Conclusion

– monthly adjustment of the boundary values of the fiducial interval of homogeneous TEI implementations is not advisable. Their annual updating is quite sufficient;
– the stability of the boundary values of the fiducial interval of TEI is conditioned by the possibility of their operational adjustment. However, such adjustment, as a rule, is associated with both overloading of individual corners and with an increase in the specific consumption of the equivalent fuel;
– with unchanged fiducial boundaries, the ageing process manifests itself as a change in the patterns of TEI distributions within the fiducial interval. The distribution becomes asymmetric;
– criteria for controlling changes in TEI distribution are proposed. It is recommended to calculate the critical values of these criteria by the express method, which significantly reduces the time of their calculation by simulation modeling.

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