Set of indicators for dependability evaluation of gas compression units

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Abstract. *The paper is dedicated to the improvement of the evaluation methods of one of the most important operating characteristics of gas compression units (GCUs), i.e. dependability, under the conditions of decreasing pipeline utilization rate. Currently, the dependability of units is characterized by a set of parameters based on the identification of the time spent by a unit in certain operational state. The paper presents the primary findings regarding the dependability coefficients of GPA-Ts-18 units, 41 of which are operated in multi-yard compressor stations (CSs) of one of Gazprom's subsidiaries. The dependability indicators (technical state coefficient, availability coefficient, operational availability coefficient) identified as part of the research are given as well. GCUs were classified into groups depending on the coefficient values. The feasibility of using integral indicators in the analysis of GCU groups' dependability was examined. It was proposed to use confidence intervals for identification of the integral level of dependability of the operated GCU stock and the ways of maintaining the operability of units under the conditions of decreasing main gas pipeline utilization rate. The Gini index was suggested for the purpose of generalized estimation of GCU groups' dependability. It is shown that the advantage of the Gini coefficient is that is allows taking into account the ranks of the analyzed features in groups. The graphic interpretation of the findings was executed with a Lorenz curve. The paper implements the sigma rule that characterizes the probability of the actual coefficient value being within the confidence interval, i.e. prediction limits (upper and lower), within which the actual values will fall with a given probability. The confidence intervals were identified by the type of coefficients distribution and a standard deviation, . A histogram of an interval range of technical utilization coefficient distribution is given as an example. Testing of the hypothesis of the distribution type at confidence level 0.95 showed that the distribution of coefficients is normal. Using the moment method, the mathematical expectation and mean square deviation for the distribution of the values of each type of dependability indicators were established. Using the sigma rule, all extreme outliers among the GCUs in terms of the level of factor attribute were excluded from the body of input data. All units whose factor attribute value does not fall in the interval were excluded. According to the three sigma rule, 3 and 2 GCUs did not fall in the confidence interval ($\mu \pm 3\sigma$) in terms of the utilization factor and availability factor respectively. The performed analysis of causes of low availability coefficients of the above GCUs showed that the systems had been long in maintenance. The paper sets forth summary data on the maximum allowable value of the Gini index of dependability coefficients (C_{TU}, C_A, C_{OA}) depending on the sample size (the complete sample of 41 units and samples with the interval of 1, 2, 3 sigma). In case of higher values of Gini index it is recommended to adopt measures to individual units in order to improve the dependability of the operated GCU stock.*

Keywords: *gas compression unit, dependability, failure, indicator, operability, three sigma rule.*

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Introduction

One of the most important characteristics of gas compression units (GCUs) is dependability. Dependability of GCU as a whole is defined by the dependability of its elements, support systems and the nature of their interaction [1-3].

The paper sets forth a study of a set of dependability coefficients and the development of indicators to differentiate GCUs by the indicators' value. The developed coefficients may be useful for studying the performance of GCUs operated in multi-yard compressor stations (CSs).

Research scope analysis

The choice of the research object is based on the need to ensure the operability of a gas compression system in emergency mode. It is known that the transfer of mains gas by units of medium and small single capacity improves the flexibility of a system with guaranteed redundancy. At the same time, an emergency shutdown of one of the units causes minimal harm to the process.

The emergency shutdown of a large unit can cause much greater negative effects. There are 5 standard sizes of units of high single capacity (Table 1) operated by Gazprom's subsidiaries.

More than 77% of all 79 units are operated by Gazprom Transgaz Yugorsk.

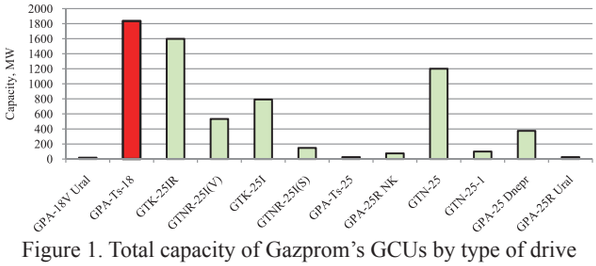


Figure 1. Total capacity of Gazprom's GCUs by type of drive

In accordance with the identified structure of the GCU stock, the GCU-Ts-18, 41 of which are operated in multi-yard (9 compressor yards) CSs, were chosen as the research object. This is a conversion GCU with an aircraft gas turbine. At the time of the research the total operating time of the units was from 20 thousand to 136 thousand hours (113 thousand hours on the average).

Defining GCU dependability coefficients

Currently, the gas turbine (GT) dependability is evaluated using a system of indicators [4, 5] that are based on the identification of the time the unit is in a particular operational state: total operation time T_o during the reporting period T_c; time of the unit on stand-by T_{sb}; time of the unit being under scheduled repair T_{sr}; GCU downtime T_d during the reporting period T_c:

- technical utilization coefficient, C_{TU}
- availability coefficient, C_A
- operational availability coefficient, C_{OA}
- mean time between failures during the reporting period, T_F
- restoration time coefficient, C_R.

Many authors [1, 2] demonstrate that the failure rate that defines the dependability of equipment operation is primarily associated with the GCUs' aging process. Meanwhile, preventive and diagnostic maintenance measures can not only help sustain the GCUs' technical condition, but also correct it. The time mode of the GCU being in each operational state is not directly connected to the total operating time of the unit and is an additional indicator for identifying its dependability. Their mutual independence is confirmed by the value of the cross-correlation coefficient: it lies in the range (-0.094; 0.126) for various coefficients, which confirms the absence of a significant correlation.

Figure 2 shows the distribution of dependability indicators' values for GPA-Ts-18. The analysis is based on the results of 2 years of units' operation.

Figure 3 shows structure diagrams of dependability coefficients' distribution by intervals. Interval estimation of

Table 1. Primary information on gas compression units of high single capacity, Gazprom

No.	Type of GCU	Number of GCUs	Single capacity	Proportion of total capacity in a group of large units
			MW	%
1	GPA-18V Ural	1	18	0.3
	GPA-Ts-18	102	18	27.3
2	GTK-25IR	72	22.2	23.8
	GTNR-25I(V)	24	22.2	7.9
3	GTK-25I	33	24	11.8
4	GTNR-25I(S)	6	24.5	2.2
5	GPA-Ts-25	1	25	0.4
	GPA-25R NK	3	25	1.1
	GTN-25	48	25	17.8
	GTN-25-1	4	25	1.5
	GPA-25 Dnepr	15	25	5.6
	GPA-25R Ural	1	25	0.4
	TOTAL	310		

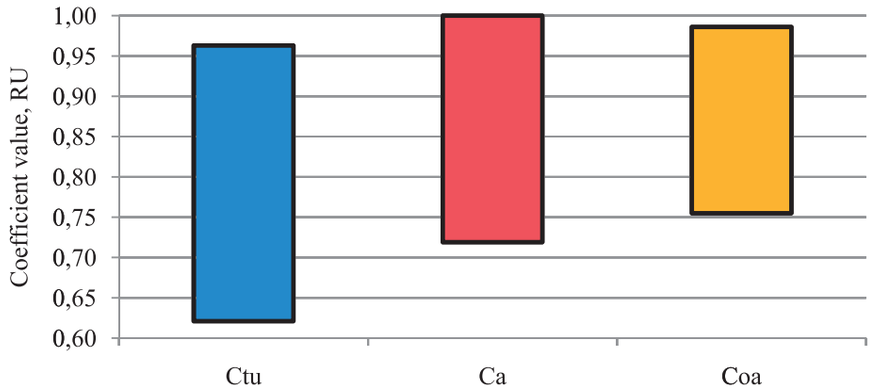


Figure 2. Distribution of dependability indicators values for GCU

dependability coefficients shown in the diagrams was used to develop and justify differentiation indicators.

Results show that the technical utilization coefficient for GPA-Ts-18 units is 0.621÷0.963; availability coefficient is 0.719÷1.0; operational availability coefficient is 0.755÷0.986. Mean time between failures is $T_F = 2900$ hours; mean value of restoration time coefficient is $C_R = 70$ hours.

The value of technical utilization coefficient for converted GCUs should be no less than 0.94, availability coefficient should be no less than 0.98, mean time between failures should be no less than 3500 hours [6].

Thus, most of the GCUs from the examined group have coefficients lower than the values established by GOST [6]: 93% of units in terms of technical utilization coefficient, 10% of units in terms of availability coefficient, 95% of units in terms of operational availability coefficient, 76% of units in terms of mean time between failures.

Definition of GCU integral dependability indicators

The deviation of the coefficients from the standard values is due to a lower main gas pipeline utilization rate that is below the design value and gas being transferred by fewer GCUs. In such complicated conditions, there is a need for additional methods to identify the level of dependability of the GCU operational stock.

In order to make a decision on the general dependability of the enterprise's GCUs for repair planning and operating modes optimization, an integrated assessment of the dependability indicators of the gas compression equipment stock as a whole was performed. The Gini index was used as an integral indicator.

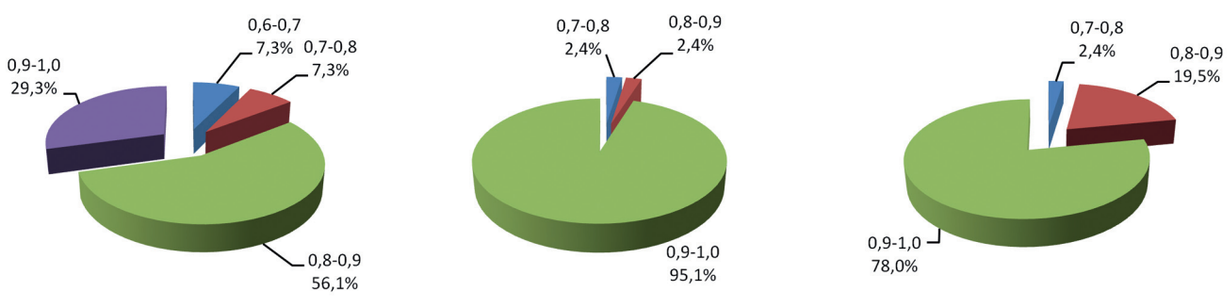
Initially, the Gini coefficient was introduced in the economic science as a measure of the population's income concentration [7] to evaluate the degree of inequality between certain social groups. The indicator was used by the authors of [8, 9] in the oil and gas industry for differentiating equipment according to technical and operating conditions in the extraction, pipeline transportation and processing of hydrocarbons. The Gini coefficient can theoretically range from 0 to 1. The closer the value is to one, the greater the differentiation of equipment by the studied indicator is.

Regarding the assessment of GCUs' dependability level differences, the Gini coefficient will show the differentiation of GCUs by dependability level that is defined by the coefficients of technical utilization, availability and operational availability. The Gini coefficient is calculated using the formula (Figure 4a):

$$K_L = 1 - 2\sum_i X_i \mathrm{cum}\, Y_i + \sum_i X_i Y_i,$$

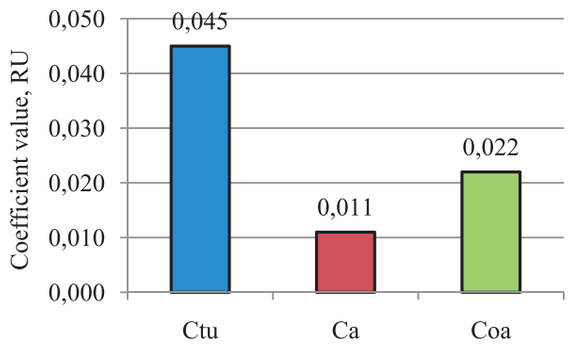
where X_i is the proportion of the GCUs in group i; Y_i is the proportion of the group i in the overall level of coefficients; $cum\, Y_i$ is the cumulative (calculated as progressive total) proportion of the coefficients.

The Gini coefficient is calculated based on the data on GCUs' distribution by the level of dependability indicators. The entire set is divided into N groups with an equal number of GCUs, and the proportion of each group in the total sum of

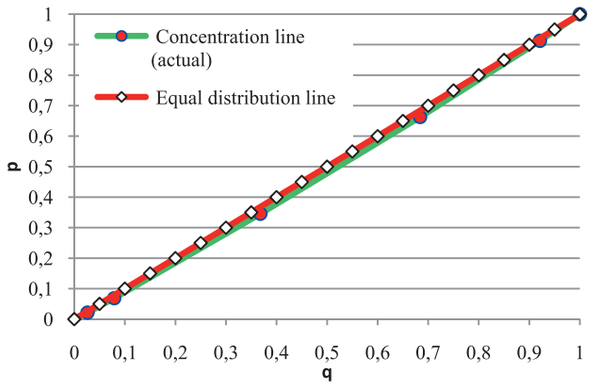


a) technical utilization coefficient b) availability coefficient c) operational availability coefficient

Figure 3. Interval structure of GCU dependability coefficients



a – values of concentration coefficients



b – Lorenz curve of distribution of technical utilization coefficient

Figure 4. Differentiation index for GCU sample (41 units)

the coefficients is identified. A concentration curve (Lorenz curve) was constructed based on the cumulative specific weights (frequencies) by the number of GCUs and specific weights in the total sum of indicators.

The cumulative portion of the groups in the total sum of the indicator (from 0% to 100% or from 0 to 1) is represented by the vertical axis. The cumulative portion of the GCU groups in the total amount (from 0% to 100% or from 0 to 1 as well) is represented by the horizontal axis. If the indicator was distributed equally, each group of GCUs would have exactly the same part of the total sum of the indicator as its percentage. On the graph, this is depicted by the diagonal line called the line of equal distribution.

The actual indicator distribution is the concave concentration line below the diagonal. The further this line is from the diagonal, the more unequal is the distribution of the indicator (the higher the level of concentration). Graphs of technical utilization (Figure 4b), availability and operational availability coefficients' values concentration curves were constructed based on the results of the calculation.

In theory, the characteristic of concentration of coefficients' values may coincide with the line of equal distribution, in which case the differentiation index (Gini) will be equal to zero, and the level of GCUs' dependability in the group will be equal.

As Figure 4a shows, the calculated values of differentiation indexes (Gini) are rather low, which indicates that the difference in the GCUs' level of dependability is insignificant. However, regarding the major part of GCUs, the values of the coefficients are lower than the standard values. At the same time, an uncertainty remains regarding the decision on the choice of strategy of GCU stock operating method in conditions of low main gas pipeline utilization rate.

Statistical analysis of GCU dependability level

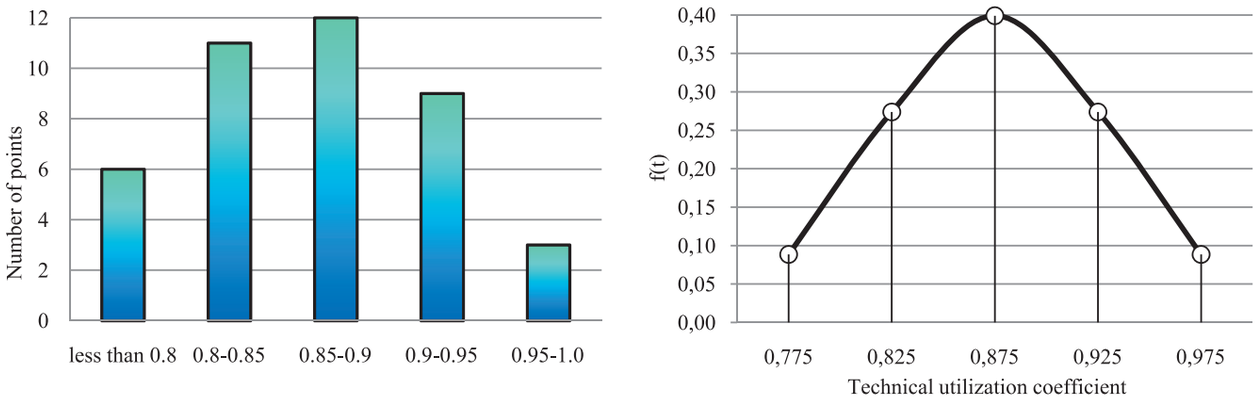
In the dependability theory, the sigma rule characterizes the probability of the next actual value being within the confidence interval. The confidence interval helps identify areas that should be addressed to change the trend and make an informed decision (for example, determine the strategy for GCU repair and maintenance). In regard to dependability coefficients, the confidence interval is the prediction limits (upper and lower), within which with a given probability the actual values will lie.

When the confidence interval is:

- 3 sigma, than there is a 0.3% probability that the value of the parameter lies outside the confidence interval;
- 2 sigma, than there is a 4.5% probability that the value of the parameter lies outside the confidence interval;

Table 2. Evaluation of the body of data of coefficients CTU, CA, COA according to the sigma rule

Designation of coefficient	Intervals for body of coefficient data	Intervals of factor indicator values	Number of units in an interval	Specific weight of units in an interval in the total number, %
1	*2*	*3*	*4*	*5*
C_{TU}	$\bar{y}-\sigma \le y_i \le \bar{y}+\sigma$	$0.817 \le y_i \le 0.933$	30	73.2
	$\bar{y}-2\sigma \le y_i \le \bar{y}+2\sigma$	$0.760 \le y_i \le 0.990$	37	90.2
	$\bar{y}-3\sigma \le y_i \le \bar{y}+3\sigma$	$0.702 \le y_i \le 1.048$	38	92.7
C_A	$\bar{y}-\sigma \le y_i \le \bar{y}+\sigma$	$0.977 \le y_i \le 0.993$	12	29.3
	$\bar{y}-2\sigma \le y_i \le 2\bar{y}+2\sigma$	$0.970 \le y_i \le 1.0$	39	95.1
	$\bar{y}-3\sigma \le y_i \le \bar{y}+3\sigma$	$0.962 \le y_i \le 1.008$	39	95.1
C_{OA}	$\bar{y}-\sigma \le y_i \le \bar{y}+\sigma$	$0.889 \le y_i \le 0.962$	28	68.3
	$\bar{y}-2\sigma \le y_i \le 2\bar{y}+\sigma$	$0.852 \le y_i \le 0.998$	39	95.1
	$\bar{y}-3\sigma \le y_i \le \bar{y}+3\sigma$	$0.716 \le y_i \le 1.035$	41	100



a) histogram of distribution b) normal density

Figure 5. Distribution of technical utilization coefficient

- 1 sigma, than there is a 31.7% probability that the value of the parameter lies outside the confidence interval.

The confidence interval is constructed using the distribution of technical utilization coefficient and a standard deviation, σ. Figure 5a shows a histogram of an interval range of technical utilization coefficient distribution.

Tests of the hypothesis of the distribution type at confidence level 0.95 showed that the distribution of coefficients is normal (Figure 5). Using the moment method, the mathematical expectation and mean square deviation for the intervals of coefficients' values were calculated (Figure 5b).

Using the sigma rule, all extreme outliers among the GCUs in terms of the factor attribute level were excluded from the input data (Table 2).

Table 3 shows calculated values of the differentiation index (Gini) for samples with intervals 1σ, 2σ, 3σ.

In accordance with the Chebyshev's theorem, the "three sigma" rule is widely used in engineering to ensure the dependability of equipment stock operation with a sufficient degree of probability. Not all values fall in the interval (μ±3σ). Three GCUs can be excluded having the lowest technical utilization coefficient values of 0.621 (GPA no. 3 KTs-10), 0.663 (GPA no. 1 KTs-2) and 0.681 (GPA no. 4 KTs-7).

Table 3. Calculated values of the differentiation index (Gini) for samples with intervals 1σ, 2σ, 3σ

Interval of values	Gini index		
	for C_{TU}	for C_A	for C_{OA}
1 sigma	0.016	0	0.006
2 sigma	0.029	0	0.016
3 sigma	0.032	0	0.019

According to the three sigma rule, values of availability coefficient 0.816 (GPA no. 1 KTs-2) and 0.719 (GPA no. 4 KTs-7) did not fall in the confidence interval.

The performed analysis of causes of low values of availability coefficient of the above GCUs showed that the units had been long in maintenance due to failure and delay in the delivery of spare parts.

Figure 6 shows summary data on the Gini differentiation index of dependability coefficients (C_{TU}, C_A, C_{OA}) depending on the sample size (the complete sample of 41 units and samples with the interval of 1σ, 2σ and 3σ).

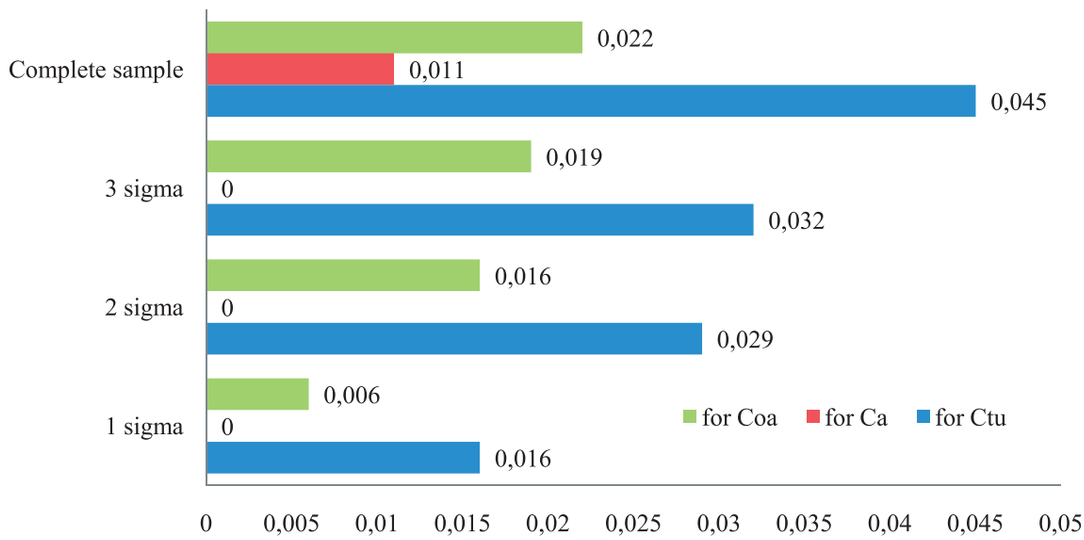


Figure 6. Histogram of Gini differentiation index distribution

To sum up, according to the "three sigma" rule, the value of the Gini index for converted GPA-Ts-18 units should be no greater than 0.032 for the technical utilization coefficient, no greater than 0 for the availability coefficient and no greater than 0.019 for the operational availability coefficient.

The advantage of the Gini coefficient over the arithmetic mean value of the coefficients for the analyzed groups is that the indicators are calculated more accurately. The Gini index allows taking into account the ranks of the analyzed attributes in groups (eliminating the influence of isolated GCUs) and identifying the degree of differentiation of GCU groups in terms of dependability.

Conclusion

1. The values of dependability coefficients were determined (a sample of 41 GCU-Ts-18 units was analyzed): the technical utilization coefficient is 0.621÷0.963; the availability coefficient is 0.719÷1.0; the operational availability coefficient is 0.755÷0.986. Meanwhile, most of the GCUs from the examined group have coefficients lower than the values established by GOST, the reason being the decrease in main gas pipeline utilization rate.

2. Indicators of differentiation of GCU groups by dependability level (Gini) for technical utilization coefficient, availability coefficient and operational availability coefficient were suggested. The advantage of Gini coefficient is that is allows taking into account the ranks of the analyzed attributes in groups making the calculations of differentiation level more accurate.

3. According to the "three sigma" rule, the value of Gini index for GPA-Ts-18 units with the total operating time being up to 136 thousand hours should be no greater than 0.032 for the technical utilization coefficient, no greater than 0 for the availability coefficient and no greater than 0.019 for the operational availability coefficient. In case of higher values of Gini index it is recommended to adopt measures to individual units in order to improve the dependability of the operated GCU stock.

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