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MODELLING OF GENERATING EQUIPMENT OPERATION AND RELIABILITY

Operation properties of generating equipment are characterized by the following parameters: mean values of time to failure and to repair and the corresponding failure and repair intensities. Reliability may be expressed by the unit forced outage rate. These parameters are determined using the statistical analysis for the set of generating units located in one power plant. The results of analysis demonstrate the necessity of treating the units individually in spite of their similar technical construction.

Introduction. The problems of guaranteeing the adequate reliability of generating equipment, as well as of forecasting its forced outage rate and random power losses are of great importance from an energy–economics point of view as the generation utilities operate nowadays under the conditions of competition due to wholesale market of electrical energy.

In the statistical analysis, the units of generating equipment may be treated as the set of one-element systems with the distinguished states of availability (service) and failure. It is often assumed that the total renewal of a complex unit is achieved after its modernization or after capital repair and that an after–failure overhaul restores only the effectiveness of equipment with the unchanged function of failure intensity.

The operation of generating equipment is characterized, among others, by such the reliability indexes as the Mean Time to Failure (MTTF) and Mean Time to Repair (MTTR). In the statistical analysis the durations of time to failure and to repair are treated as the positive random variables which are individually tied up with the given equipment.

The first problem considered in a paper is the analysis of probability distributions of operation and failure states of the set of ten similar generation units located in one power plant. As the results of analysis are obtained the different distributions and as a consequence the various values of MTTF, MTTR as well as the failure and repair intensities for generating equipment.

The second problem is concerned with forecasting of forced outage rates and, applying the multiple regression analysis, determination of their functional relation to the various factors describing the operation process of generation equipment. In this case the results also show the differences in reliability characteristics for individual equipment.

Determination of parameters of generation equipment operation. The aim of analyzing the long-term operation of a generating equipment was to establish the probability distributions and the expected values of the following parameters describing a process of unit operation:

- time to failure, time to repair and time of scheduled repair (capital, mean and current repairs).

All these values are treated in probabilistic categories as the random variables [1].

For the group of 200 MW units, the process of their operation has been analyzed with the calculation of the following functions, necessary and sufficient for the general description of the given system: the probability density distribution, probability distribution function, reliability function as well as intensities of in-service state and failure state [2]. It is often observed that the empirical distributions of unit time to failure and repair may be approximated by the exponential distribution, and as a consequence the constant failure and repair intensities may be assumed. The value of mean time to failure (MTTF) is equal in such a case to the reciprocal of failure intensity and, similarly, the mean time to repair (MTTR) is equal to the reciprocal of repair intensity.

The approximations of the most credible probability distributions have been obtained using the computer package Statistics [4].

In the case of nine units of analyzed generating equipment, the distributions of time to failure were found to be approximated by the exponential distributions with the parameter ranging from $2.94 \cdot 10^{-3}$ to $4.19 \cdot 10^{-3}$. It is equivalent to the expected values of Mean Time to Failure differentiating in a range from 238.61 to 340.09 hours. As the distribution of time–in–service for the last unit is concerned, the verification of hypotheses of its approximation by the one–parameter probability distributions have given the negative results. It had to be approximated by the logarithmic–normal distribution with the parameters $\mu = 4.56$ and $\sigma = 2.56$ and the corresponding MTTF= 121.36 hours only. The curve obtained for this unit is shown in Fig. 1.

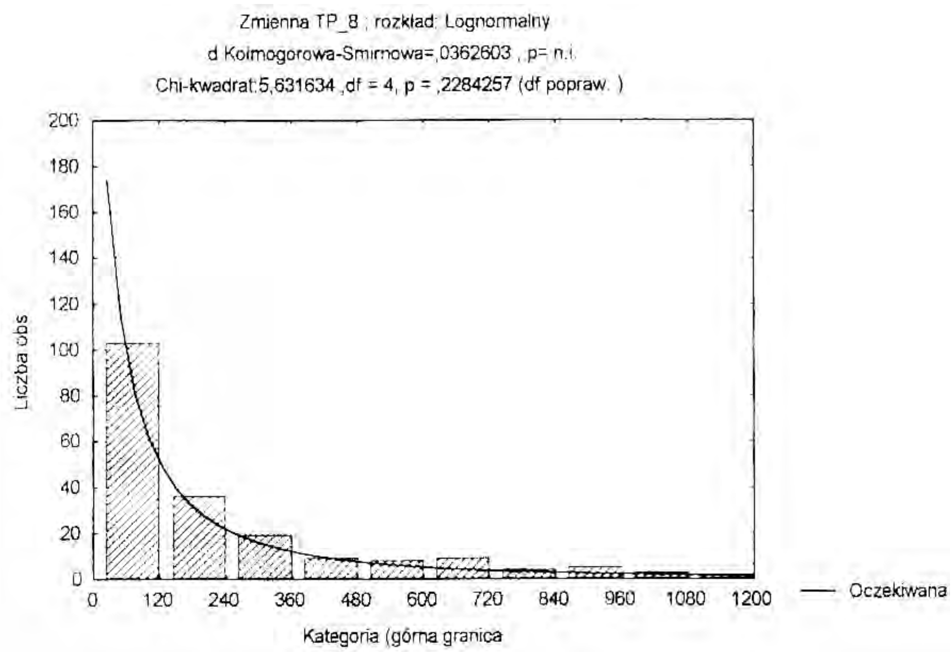


Fig. 1. Probability distribution of time to failure

The expected, for each generating unit, values of MTTF together with confidence intervals are gathered in Table 1.

In the case of time to repair, only for three units of generation equipment it could be approximated by the exponential distribution with the repair intensity $\mu \in < 2.53 \cdot 10^{-2}, 3.95 \cdot 10^{-3} >$, what is equivalent to the MTTR parameter ranging from 34.76 hours up to 252.90 hours. For the other seven generating units, the empirical distributions could not be approximated with adequate likelihood by any of available probability distributions. Insuch a situation, in the span of out–of–service time were distinguished the short disturbances lasting maximum 20 hours, disturbances up to 100 hours and the failures of longer duration. The histograms representing forced outages of generating equipment in these three intervals have been approximated by the different probability distributions. As an example for the generating unit 1 the following distributions have been chosen as the most probable ones for assumed duration range of disturbances and failures: logarithmic – normal, normal and exponential distributions. The acquired curves are shown in Fig. 2.

Table 1

Mean Time To Failure

Unit no.	Lower Boundary	Higher Boundary	Expected value
1	260.43	383.9	322.21
2	194.61	311.86	278.55
3	221.87	375.68	298.77
4	209.06	275.00	242.03
5	230.67	328.20	300.01
6	251.43	378.84	340.09
7	279.50	398.46	338.98
8	194.63	278.24	121.36
9	190.90	262.24	238.61
10	208.77	297.80	273.04

The results of approximation obtained for each unit generating equipment, together with the corresponding probabilities, are demonstrated in Table 2. The disturbances

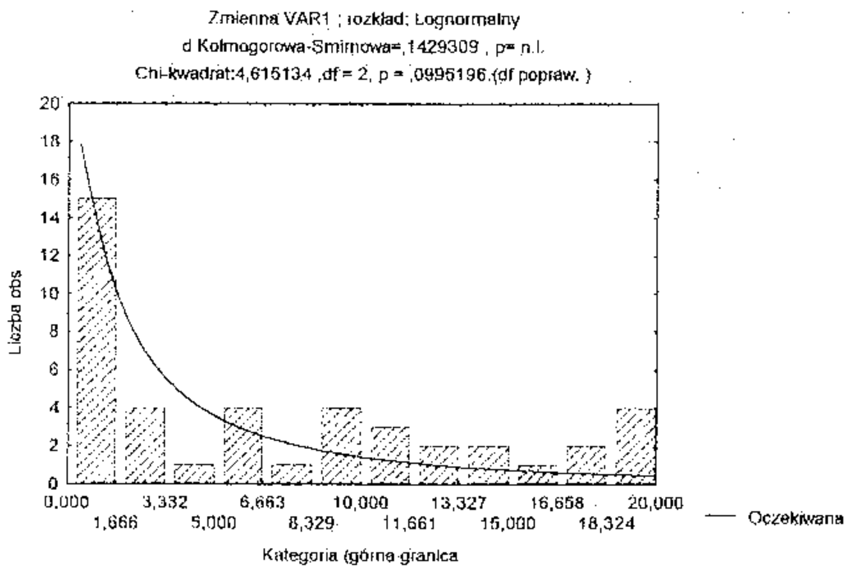
Table 2

Mean Time To Repair

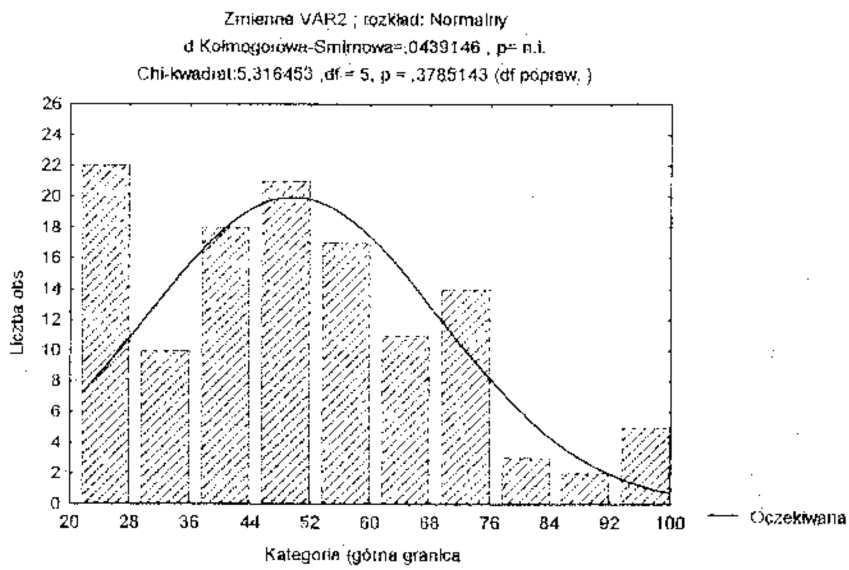
Unit no.	Expected value			Probability		
	$t_a \in <0, 20>$	$t_a \in <20, 100>$	$t_a \in <100, \infty>$	$t_a \in <0, 20>$	$t_a \in <20, 100>$	$t_a \in <100, \infty>$
1	19.78	49.68	466.24	0.23	0.66	0.11
2	39.44					
3	34.76					
4	252.90					
5	6.41	48.41	393.41	0.29	0.59	0.12
6	7.72	51.67	–	0.42	0.49	0.09
7	8.17	52.26	–	0.35	0.54	0.12
8	8.71	46.04	316.65	0.27	0.59	0.14
9	5.93	49.00	342.51	0.33	0.58	0.09
10	15.36	45.93	–	0.39	0.52	0.09

lasting from 20 to 100 hours have the highest probability of occurrence. The failures of longer duration are the least probable: $P \in < 0.09, 0.14 >$.

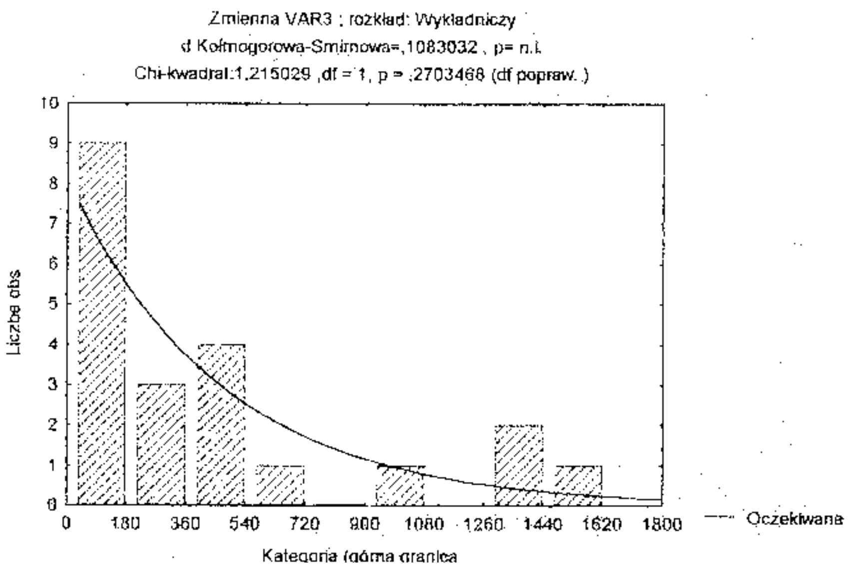
The statistical analysis of hitherto performed overhauls indicated that the real maintenance durations were often different from predicted. It has been demonstrated that, usually the empirical distribution of maintenance durations may be approximated by the normal distribution, while periods between overhauls by the normal or logarithmic – normal distribution.



$t_a \in$ < 0, 20 >
Logarithmic – normal Distribution
$\mu = 1.2046$
$\sigma = 2.3660$



$t_a \in$ < 70, 100 >
Normal distribution
$\mu = 49.6805$
$\sigma = 386.1414$



$t_a > 100$
Exponential Distribution
$\lambda = 0.002145$

Fig. 2. Probability distributions of time to repair

Determination of generating equipment Forced Outage Rates. For the evaluation of uncertainty of the power plant (or the power system as a whole) the following coefficients are being calculated:

- Forced Outage Rate (FOR) with the values of MTTF and MTTR coefficients to be considered for a given year,
- Generalized Forced Outage Rate (GFOR) where the mean time in current repairs is additionally taken into account,
- Cumulative Forced Outage Rate (CFOR) – cumulative value of the FOR coefficients calculated for the span from the first year up to the observed year of unit operation,
- Cumulative Generalized Forced Outage Rate (CGFOR) – cumulative value of the GFOR coefficients.

The problem is formulated as the prediction of the expected value of the FOR factor for each unit of generating equipment, calculated for the next year of unit operation, based on the analysis of the statistical data acquisition in the unit prevailing service. The ten-year operation process of the set of ten fossil fuel generating units of 200 MW nominal capacity located in the same power plant has been, as before, taken into consideration.

As the technique of statistical approximation has been chosen the method of regression analysis. In the case of multiple regression, with the large number of independent variables, determination of regression equation may cause serious numerical problems because of a large dimension of the observation matrix. The regression equation may contain some variables of not vital importance. The problem is to recognize the weight of individual members of the equation and–for the assumed goodness criterion– eventual withdrawal of not essential components.

There are four main procedures of statistical approximation leading to accepted, good solution: the method of all possible regressions, elimination a posteriori, selection a priori and the multiple piecewise regression [3]. The last method was used to determine the expected generating units' forced outage rates. The starting point of the procedure is the calculation of correlation of all independent variables with the dependent variable (calculation of elements of correlation matrix). The regression equation containing only one independent variable is determined using the least square method. It minimizes the influence of random interferences and is the most effective and unbiased estimation of the coefficients. In consecutive numerical iterations are introduced the independent variables of decreasing importance. Evaluation of the approximation is made after each step using the partial Fisher test with calculation of the values of correlation factor R and Fisher number F. The procedure is stopped when the equation contains only significant components.

The FOR coefficient expected in the (m+1)th year of unit operation has been chosen as the dependent variable. The following independent variables, related to each generating unit, have been considered:

- length of the operation time (x_1),
- forced outage rates for the last (m-th) year of unit operation:

FOR (x_2), GFOR (x_3), CFOR (x_4) and CGFOR (x_5),

- identical forced outage rates for the previous (m-1)th year of unit operation ($x_6 – x_9$),
- relative span of time from the last mean overhaul (x_{10}) and from the last capital maintenance or modernization (x_{11}).

As the result of application of the piecewise procedure [4], the following regression equation has been obtained for the one of the unit:

$$y = 1.083\ x_2 + 0.034\ x_{10} - 0.005\ x_{11} - 0.029 \text{ (Fig. 3).}$$

The correlation factor R = 0.999.

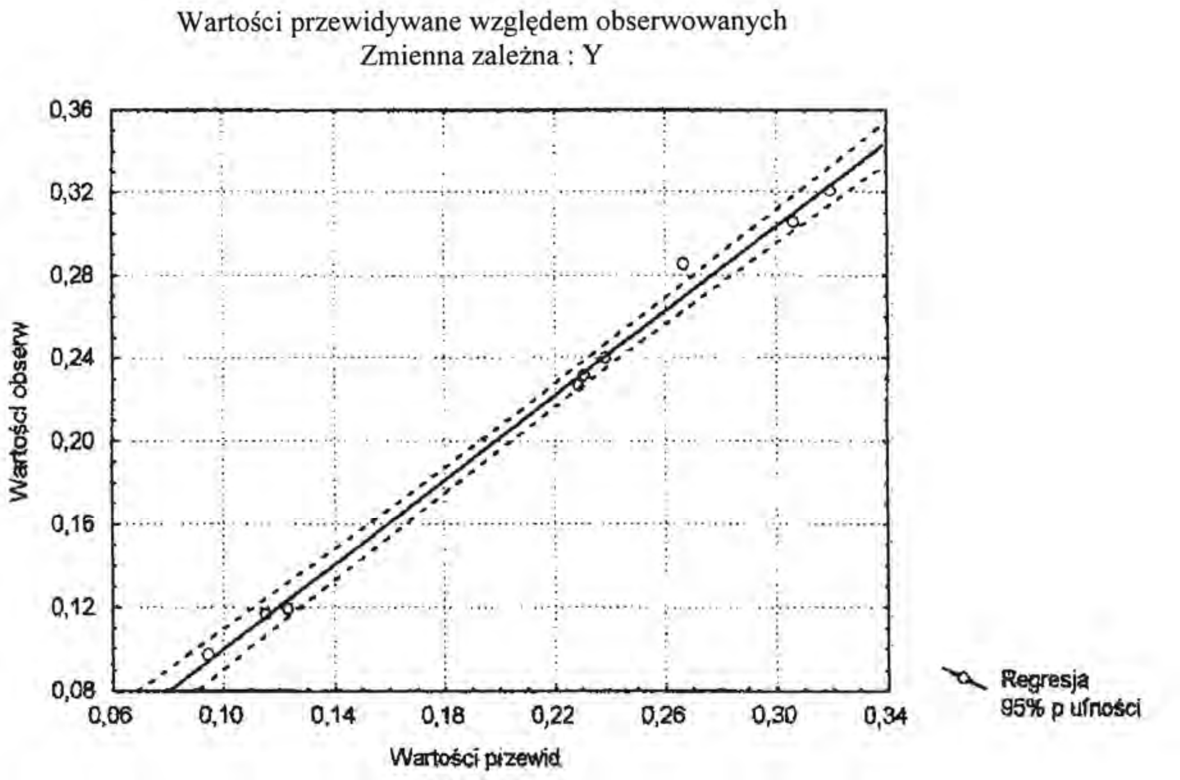


Fig. 3 Curve of regression equation

These results show the impressive matching of the variables and adequacy of the equation. The significant role in the unplanned random failures of the generating units play their forced outage rates (expressing their reliability), in the passing years of service. The conditions of the last year of operation have the decisive influence on the forced outage rates of generating equipment.

The lower significance on a dependent variable has the duration of the unit operation from the last capital overhaul, and the time lapsed from the last mean maintenance, excluding the unit age. These results confirm the assumption that the adequate accuracy may be obtained when analyzing the technical life of generating unit to the span between its introduction to service and its first shutdown for capital maintenance and between such two consecutive repairs. They also demonstrate that, in spite of almost identical construction (some changes are introduced during the unit modernization) and similar operating conditions in the same power plants, the generating units have their individual reliability characteristics.

1. Billinton R., Allan R.N. Reliability evaluation of power systems. Plenum Press. – New York, 1990. 2. Dethoor J.M., Graboillot J.L. La vie des equipments. – Dunod, Paris, 1968. 3. Draper N.R., Smith H. Applied regression analysis. John Wiley. – New York, 1973. 4. Computer package “STATISTICS”. – Statsoft, Cracow, 1999.