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DETERMINING RELIABILITY FUNCTIONS OF STEAM TURBINE IN POWER PLANT 'NIKOLA TESLA, BLOCK A4'

ODREĐIVANJE FUNKCIJA POUZDANOSTI PARNE TURBINE U TERMOELEKTRANI 'NIKOLA TESLA, BLOK A4'

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- Weibull distribution

Ključne reči
- parna turbina
- pouzdanost
- Vejbulova raspodela

Abstract

Determination of reliability indicators of steam turbine system in the thermal power plant 'Nikola Tesla, Block A4' during useful life period is based on a ten-year operational database. By implementation of mathematical theory of reliability to exploitation research data and using simple and complex two-parameter Weibull distribution, the theoretical reliability functions of the considered system are determined. The graphical method is applied to quantitatively determine reliability indicators. Obtained probabilistic laws of failure density and failure rate, according to which the random variable behaves, do not coincide completely with empirical distributions, regardless of whether the theoretical functions are obtained by simple or complex Weibull distribution.

Izvod

Određivanje pokazatelja pouzdanosti parne turbine u termoelektrani 'Nikola Tesla, Blok A4' tokom normalnog radnog veka zasnovano je na desetogodišnjoj pogonskoj dokumentaciji. Na osnovu eksploatacionog istraživanja raspoloživosti i implementacijom primenjene matematičke teorije pouzdanosti, korišćenjem proste i složene dvo-parametarske Vejbulove raspodele, određene su teoretske funkcije pouzdanosti razmatranog sistema. Grafička metoda je korišćena za kvantitativno određivanje pokazatelja pouzdanosti. Dobijeni verovatnosni zakoni promene gustine otkaza i intenziteta otkaza, koji opisuju ponašanje slučajno promenljive veličine, ne podudaraju se u potpunosti sa empirijskim raspodelama, bez obzira da li su teoretske funkcije dobijene na osnovu proste ili složene Vejbulove raspodele.

INTRODUCTION

Reliability is defined as the capability of a technical system to execute its required functions reasonably under given operating conditions for a specific period of time or number of cycles without any failure, /1, 2/. The reliability of the thermal power plant is related to the possibility of giving electricity efficiently and more economically with a reasonable quality assurance of continuity, /3/. A system is usually defined as a group of components assembled in a given functional configuration intending to perform a specific function. From the hierarchical structural point of view, a system is comprised of a number of subsystems, which may be further divided into lower-level subsystems, depending on the purpose of system analysis. Since a thermal power plant is very huge multifaceted and highly integrated system, it can be divided into subsystems or functional areas suitable for analysis /4, 5/. Reliability studies of thermal power systems may be carried out separately or in combination of all functional subsystems, /6/. This work is limited to the estimation of the steam turbine reliability.

The steam turbine is one of the key energy conversion devices of the power plant. For competent thermal power plant, cost-effective production and long run performance, it is essential to maintain a failure free running power plant as much as possible. Outages in the process of the steam turbine system directly cause outages of power plant and disruption in the power system.

Reliability analysis has been gradually recognized as a standard tool for designing, scheduling of operation and maintenance of any technical system. The reliability of the system can be evaluated through the deterministic- and/or probabilistic approach. A fundamental issue in reliability analysis is the uncertainty in the failure occurrences and consequences. The probabilistic properties of a system also should be understood.

Based on the relevant exploitation data of unplanned outages of considered system, it is necessary to create a hypothesis of the class of distribution function to which the random value belongs to (based on analyzing statistical material) and to determine the unknown parameters of the distribution, as well as to assess their accuracy, /7/. One of the basic assumptions in reliability analysis is that failures of repairable systems are independent and random, and the failures are distributed in time according to an appropriate statistical distribution with a time dependent failure rate.

DETERMINING RELIABILITY FUNCTIONS USING SIMPLE WEIBULL DISTRIBUTION

The work investigates the reliability of steam turbine installed in the thermal power plant 'Nikola Tesla, Block A4' (TENT-A4) (installed capacity of 308.5 MW). Reliability estimation is based on a ten year historical failure database which refers to the period from 1996 to 2005. Failure evidence necessary for determining reliability indicators for the considered system is presented in Table 1.

Operating time intervals that include all relevant data required for system analysis are defined for one year periods, or 8760 working hours.

Interpretation of data is one of the key elements of the theory of reliability. Using probability and statistical analysis, the reliability of a power system can be studied in depth /8/. The primary question that requires an answer is: which theoretical distribution model best fits existing data? The physical properties of the stochastic process that is analysed in some cases may suggest possible form of probability distribution. When a law of probabilistic distribution is based on empirical data, the mathematical formulation of the distribution is usually not easily determined, /9/.

Table 1. The exploitation reliability components of the of steam turbine in power plant 'TENT-A4'.

	Observation period		Reliability							
i	Tk_i	T_{i-1}–T_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	Nt_i	f_i	F_i	R_i	λ_i	MR
[-]	[year]	[h]	[-]	[-]	[-]	[h^{-1}]	[-]	[-]	[h^{-1}]	[%]
1	2	3 4	5	6	7	8	9	10	11	12
1	1996	0-8760	1	1	13	0.071	0.071	0.929	0.077	4.86
2	1997	8760-17520	1	2	12	0.071	0.143	0.857	0.083	11.81
3	1998	17520-26280	1	3	11	0.071	0.214	0.786	0.091	18.75
4	1999	26280-35040	1	4	10	0.071	0.286	0.714	0.100	25.69
5	2000	35040-43800	3	7	7	0.214	0.500	0.500	0.429	46.53
6	2001	43800-52560	1	8	6	0.071	0.571	0.429	0.167	53.47
7	2002	52560-61320	0	8	6	0.000	0.571	0.429	0.000	53.47
8	2003	61320-70080	3	11	3	0.214	0.786	0.214	1.000	74.31
9	2004	70080-78840	1	12	2	0.071	0.857	0.143	0.500	81.25
10	2005	78840-87600	2	14	0	0.143	1.000	0.000	$+\infty$	95.14

Having in mind the probabilistic nature of the analysed problem, the Weibull model has been used as the most common solution to engineering problems of this kind, /10-14/. The development of Weibull model for reliability evaluation of steam turbine system of a thermal power plant using the probabilistic approach is discussed and the possibilities and limitations of the suggested model are scrutinized, /15-18/. In a broader scope, this approach can be treated as a part of the risk-based analysis in structural integrity assessment.

The behaviour of thermal power systems in terms of reliability could be best approximated by the Weibull distribution, while using normal, log-normal and exponential distributions, could lead to considerable disagreements, /19/ The Weibull distribution is one of the most widely used in reliability analysis, due to fact that with an appropriate choice of its parameters, all three regions of the bathtub curve can be represented. The Weibull distribution is very flexible and capable of modelling the life of mechanical systems with time dependent failure rate, /11, 20/. Failures of such systems are dominated by aging and mechanical wear out.

In this study the graphical method and probability papers are applied for analysis of the statistical set of data obtained from the exploitation survey of the steam turbine system in TENT-A4. The graphical method is chosen due to its relative simplicity and capability of providing a better understanding about the behaviour of any repairable system, /21/. The two-parameter Weibull distribution is selected in order to simplify graphical analysis. Principles of constructing the probability plotting graph paper and empirical data entry are described by many authors, /19/.

After calculating failure probabilities, the corresponding cumulative percentage of failures (t_i, $F(t_i)_{50\%}$) are plotted in a Weibull probabilistic paper (Fig. 1). Median rank positions are used instead of other ranking methods, because median ranks are at a specific confidence level (50%). By drawing the best fit straight line through the plotted points one can obtain parameter values from Weibull paper as: η = 5.774; β = 1.7421.

Analytical expressions for theoretical reliability functions which represent the distribution laws of the observed random variable, obtained by simple two-parameter Weibull distribution are:

- reliability

$$R_{ts}(t) = \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \quad (1)$$

$$R_{ts}(t) = \exp\left(-5.070\cdot 10^{-9}\cdot t^{1.7421}\right) \quad (2)$$

• failure density

$$f_{ts}(t)=\frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1}\exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \quad (3)$$

$$f_{ts}(t)=8.833\cdot 10^{-5}\cdot t^{0.7421}\cdot\exp\left(-5.070\cdot 10^{-9}\cdot t^{1.7421}\right) \quad (4)$$

• failure rate

$$\lambda_{ts}(t)=\frac{f_t(t)}{R_t(t)}=8.833\cdot 10^{-5}\cdot t^{0.7421} \quad (5)$$

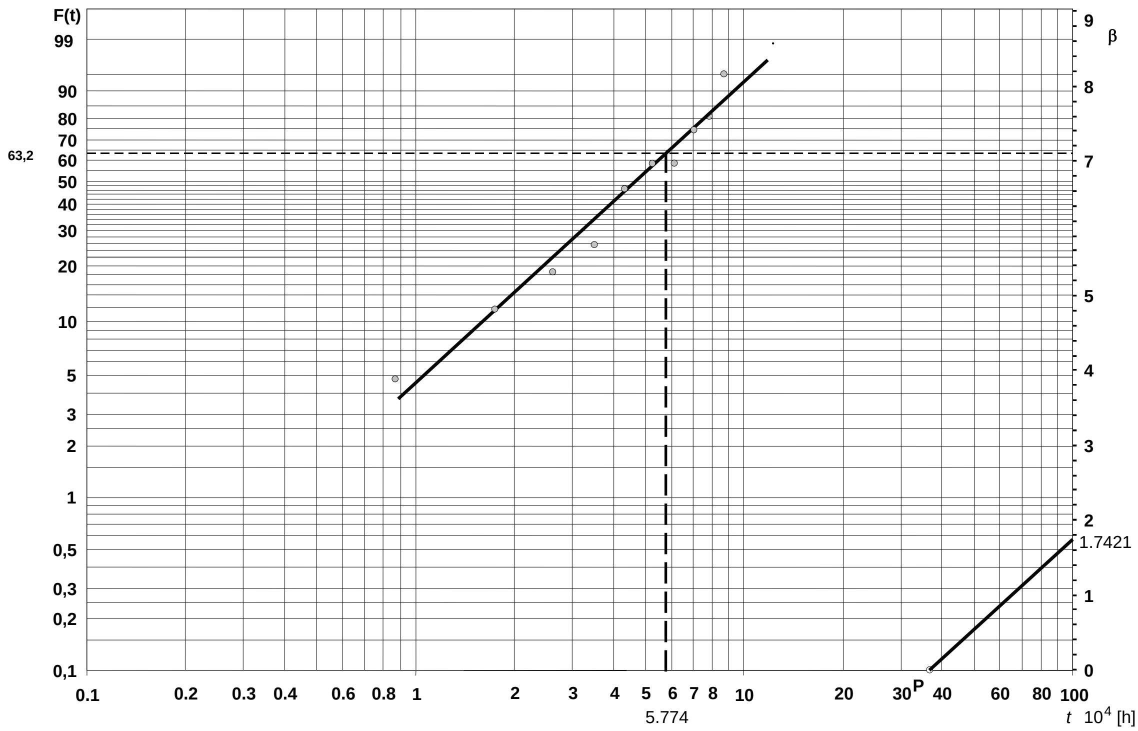

Figure 1. Weibull probability paper for simple distribution.

DETERMINING RELIABILITY FUNCTIONS USING COMPLEX WEIBULL DISTRIBUTION

After calculating failure probabilities (Table 1) and plotting times and their corresponding rank values in a Weibull probabilistic paper, it could be noted that two straight lines better fit those points than one line (Fig. 1).

It is assumed that the data are inhomogeneous, i.e. do not have the same character, and can be approximated with complex distribution. The sample of failure probabilities is divided into two parts, after which the median rank is calculated (Tables 2-3) and plotted for each, as shown in Fig. 2.

By drawing best possible straight lines through plotted points (Fig. 2) we obtain the Weibull distribution parameters for both lines:

$$\eta_{\mathrm{I}}=2.638\ ,\quad \beta_{\mathrm{I}}=1.6579$$
$$\eta_{\mathrm{II}}=7.057\ ,\quad \beta_{\mathrm{II}}=2.6381\ .$$

Table 2. Values of exploitation indicators – line I.

	Tk_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	MR
1	1996	1	1	15.91
2	1997	1	2	38.64
3	1998	1	3	61.36
4	1999	1	4	84.09

Table 3. Values of exploitation indicators – line II.

	Tk_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	MR
1	2000	3	3	25.96
2	2001	1	4	35.58
3	2002	0	4	35.58
4	2003	3	7	64.42
5	2004	1	8	74.04
6	2005	2	10	93.27

The parameters for the best fitted statistical data are estimated by the least-square method. Theoretical reliability functions for each interval are:

$$R_{t\mathrm{I}}(t)=\exp\left(-\left(\frac{t}{\eta_{\mathrm{I}}}\right)^{\beta_{\mathrm{I}}}\right) \quad (6)$$

$$R_{t\mathrm{II}}(t)=\exp\left(-\left(\frac{t}{\eta_{\mathrm{II}}}\right)^{\beta_{\mathrm{II}}}\right) \quad (7)$$

$$R_{t\mathrm{I}}(t)=\exp\left(-4.677\cdot 10^{-8}\cdot t^{1.6579}\right) \quad (8)$$

$$R_{t\mathrm{II}}=\exp\left(-1.618\cdot 10^{-13}\cdot t^{2.6381}\right) \quad (9)$$

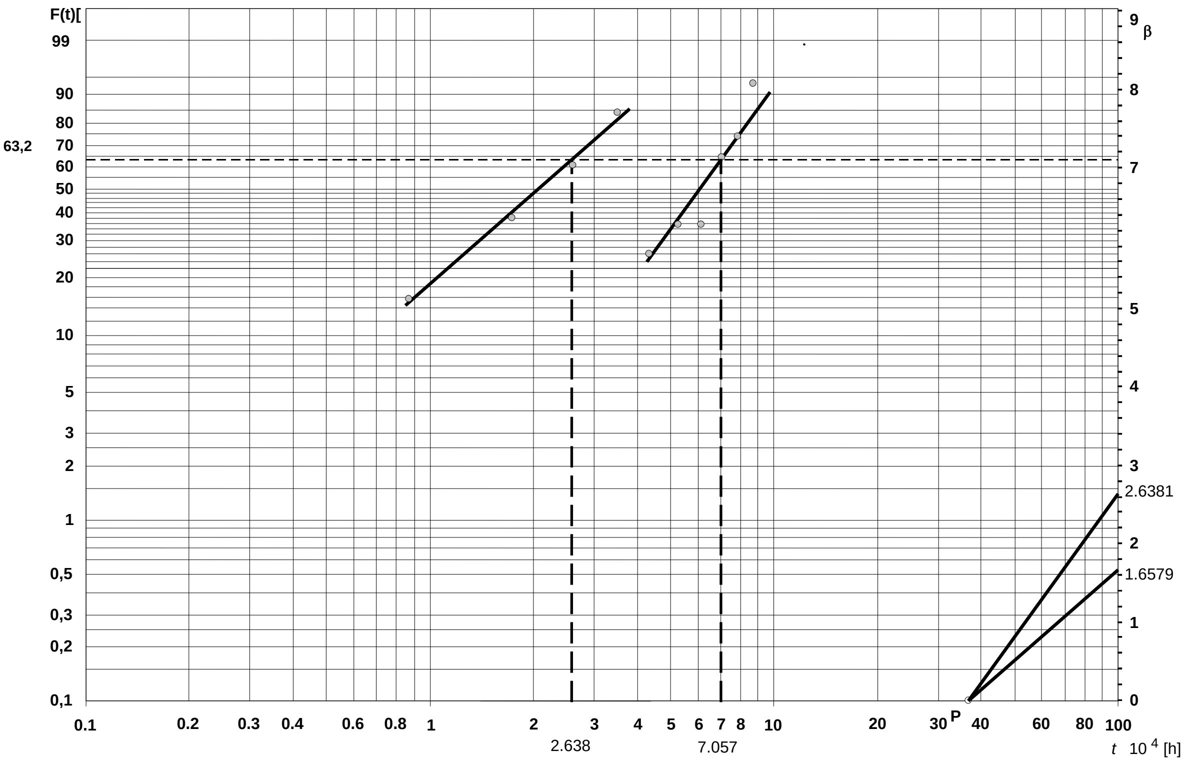

Figure 2. Weibull probability paper for complex distribution.

Analytical expressions for theoretical reliability functions that represent the distribution laws of the observed random variable, obtained by complex two-parameter Weibull distribution are, /20/:

- reliability

$$R_{tc}(t)=\frac{n_I}{n}R_{t\mathrm{I}}(t)+\frac{n_{\mathrm{II}}}{n}R_{t\mathrm{II}}(t) \tag{10}$$

$$R_{tc}(t)=0.4\exp\left(-4.677\cdot 10^{-8}\cdot t^{1.6579}\right)+0.6\exp\left(-1.618\cdot 10^{-13}\cdot t^{2.6381}\right) \tag{11}$$

- failure density

$$f_{tc}(t)=\frac{dF}{dt}=\frac{n_{\mathrm{I}}}{n}\frac{\beta_{\mathrm{I}}}{\eta_{\mathrm{I}}}\left(\frac{t}{\eta_{\mathrm{I}}}\right)^{\beta_{\mathrm{I}}-1}\exp\left(-\left(\frac{t}{\eta_{\mathrm{I}}}\right)^{\beta_{\mathrm{I}}}\right)+\frac{n_{\mathrm{II}}}{n}\frac{\beta_{\mathrm{II}}}{\eta_{\mathrm{II}}}\left(\frac{t}{\eta_{\mathrm{II}}}\right)^{\beta_{\mathrm{II}}-1}\exp\left(-\left(\frac{t}{\eta_{\mathrm{II}}}\right)^{\beta_{\mathrm{II}}}\right) \tag{12}$$

$$f_{tc}(t)=3.102\cdot 10^{-4}\cdot t^{0.6579}\exp\left(-4.677\cdot 10^{-8}\cdot t^{1.6579}\right)+2.56\cdot 10^{-9}\cdot t^{1.6381}\exp\left(-1.618\cdot 10^{-13}\cdot t^{2.6381}\right) \tag{13}$$

- failure rate

$$\lambda_{tc}(t)=\frac{f_{tc}(t)}{R_{tc}(t)}=\frac{3.102\cdot 10^{-4}\cdot t^{0.6579}\exp\left(-4.677\cdot 10^{-8}\cdot t^{1.6579}\right)+2.56\cdot 10^{-9}\cdot t^{1.6381}\exp\left(-1.618\cdot 10^{-13}\cdot t^{2.6381}\right)}{0.4\exp\left(-4.677\cdot 10^{-8}\cdot t^{1.6579}\right)+0.6\exp\left(-1.618\cdot 10^{-13}\cdot t^{2.6381}\right)} \tag{14}$$

Graphical comparisons between the exploitation- and obtained values for theoretical functions of reliability, failure density and failure rate of steam turbine system in TENT-A4 during the considered observation period are shown in Figs. 3-5.

Data required for drawing exploitation reliability indicators are given in Table 1.

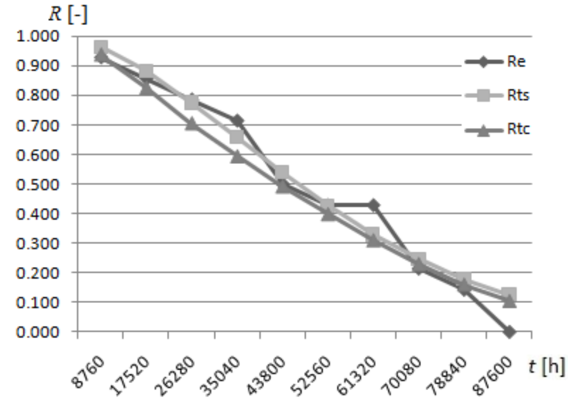

Figure 3. Exploitation and theoretical forms of reliability functions.

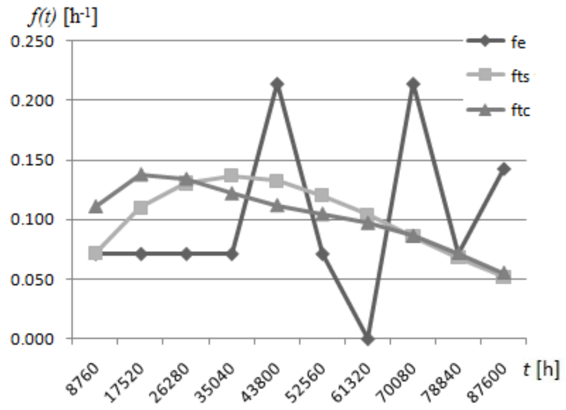

Figure 4. Exploit. and theoretical forms of failure density functions.

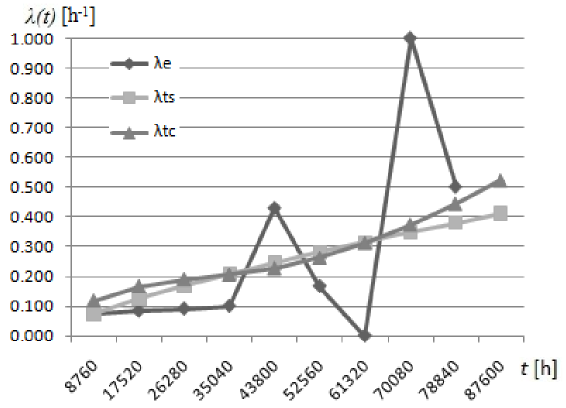

Figure 5. Exploit. and theoretical forms of failure rate functions.

CONCLUSION

Exploitation research of the steam turbine system in TENT-A4 and the application of the reliability theory has enabled the determination of the theoretical distribution law of random variable. The main advantage of utilizing the graphical method and probability papers for finding the class of distribution function is that the complete behavioural tendencies of empirical data could be easily perceived. The considered system does not show typical behaviour in terms of reliability indicators during some intervals of the observation period. Results have shown that the reliability of the steam turbine system could be more precisely represented with a simple, than with a complex Weibull distribution, but the differences are not significant. Obtained theoretical functions of failure density and failure rate poorly coincide with corresponding empirical forms, regardless of whether the theoretical functions are obtained by simple or complex Weibull distribution. Empirical forms of the failure density and failure rate show extremely oscillating behaviour, what is almost impossible to be exactly represented by any distribution function.

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