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DETERMINING THE RELIABILITY FUNCTIONS OF THE BOILER TUBING SYSTEM IN POWER PLANT 'NIKOLA TESLA, BLOCK A4'

ODREĐIVANJE FUNKCIJA POUZDANOSTI CEVNOG SISTEMA KOTLA U TERMOELEKTRANI 'NIKOLA TESLA, BLOK A4'

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Keywords
- boiler tubing system
- reliability
- Weibull distribution

Abstract

The objective of this paper is a representation of the probabilistic reliability assessment of boiler tubing system in the fossil fuel power plant. Exploitation research of the reliability indicators of a boiler tubing system in the fossil fuel power plant 'Nikola Tesla, Block A4' during useful life period is based on an eleven-year failure database. By applying the reliability theory, based on statistics and theory of possibility, and using simple and complex two-parameter Weibull distribution, the theoretical reliability functions of the specified system are determined. Obtained probabilistic laws of failure occurrence by different Weibull distribution models are compared in order to evaluate how close listed mathematical distributions describe behaviour of such a system in terms of reliability. Shown results make possible to acquire a better knowledge of current state of the system, as well as a more accurate estimation of its behaviour during future exploitation.

Ključne reči
- cevni sistem kotla
- pouzdanost
- Vejbulova raspodela

Izvod

Cilj ovog rada je predstavljanje verovatnosne tehnike za procenu pouzdanosti cevnog sistema kotla u termoelektrani. Eksploataciono istraživanje pokazatelja pouzdanosti u termoelektrani 'Nikola Tesla, Blok A4' tokom normalnog radnog veka zasnovano je na jedanaestogodišnjoj pogonskoj dokumentaciji o zastojima. Primenom teorije pouzdanosti, zasnovanoj na statistici i teoriji verovatnoće, korišćenjem proste i složene dvo-parametarske Vejbulove raspodele, određene su teoretske funkcije pouzdanosti navedenog sistema. Verovatnosni zakoni pojave zastoja dobijeni različitim modelima Vejbulove raspodele su upoređeni kako bi se procenila preciznost kojom navedene matematičke raspodele opisuju pouzdanost navedenog sistema. Prikazani rezultati pružaju mogućnost boljeg uvida u trenutno stanje sistema, kao i precizniju procenu njegovog ponašanja tokom buduće eksploatacije.

INTRODUCTION

Reliability has become one of the highest priorities of power systems, and it ranks along with cost and efficiency as a measure of successful operation. The general objective of maintenance is to make use of the relevant information regarding failures and repairs. Therefore it is imperative to investigate the reliability characteristics of the system, for taking necessary measures regarding maximization of the power supply.

The boiler tubing system is one of the most important systems of the thermal power plant from the standpoint of reliability, since it is the most susceptible to failures. Boiler tubes have limited life and could fail due to various failure mechanisms, /1/. Outages in the process of the boiler tubing system directly cause outages of power plant and disruption in the power system.

Reliability evaluation of a boiler tubing system demands starting considerations:
- definition of system boundaries to limit the extent of the analysis;
- selection of the analysis method, in order to be able to study the phenomena correctly.

Control limits are adopted in order to determine the transmission limits of the thermal power subsystems within the thermal scheme, /2/.

Based on the relevant exploitation data of unplanned outages of the considered system, the following three tasks related to determining the characteristics of random variables are solved, /3/:
- creating a hypothesis of the class of distribution function to which the random value belongs, on the basis of analysing the statistical material,
- validation of the hypothesis,
- determining the unknown parameters of the distribution and evaluation of their accuracy.

Having in mind the probabilistic nature of the problem analysed, the Weibull model has been used, as the most common solution to engineering problems of this kind /4-8/. The paper discusses the development of Weibull model for reliability evaluation of boiler tubing system of a thermal power plant using the probabilistic approach and scrutinizes the possibilities and limitations of the suggested model, /9-12/. In a broader scope, this approach can be treated as a part of the risk-based analysis in structural integrity assessment.

DETERMINING RELIABILITY FUNCTIONS USING SIMPLE WEIBULL DISTRIBUTION

This paper presents an exploitation research on the reliability of the boiler tubing system in the power plant Nikola Tesla, Block A4 (TENT-A4) (installed capacity of 308.5 MW) which was conducted in the period from 1996 to 2006. Failure evidence necessary for determining reliability indicators for the considered system are 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 analyses, the reliability of a power system can be studied in depth, /13/. 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 form of the distribution is usually not easy to determine, /14/.

Table 1. The exploitation reliability components of the boiler tubing system in the 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	12	12	107	0.101	0.101	0.899	0.112	9.80
2	1997	8760-17520	8	20	99	0.067	0.168	0.832	0.081	16.50
3	1998	17520-26280	10	30	89	0.084	0.252	0.748	0.112	24.87
4	1999	26280-35040	6	36	83	0.050	0.303	0.697	0.072	29.90
5	2000	35040-43800	10	46	73	0.084	0.387	0.613	0.137	38.27
6	2001	43800-52560	19	65	54	0.160	0.546	0.454	0.352	54.19
7	2002	52560-61320	13	78	41	0.109	0.655	0.345	0.317	65.08
8	2003	61320-70080	8	86	33	0.067	0.723	0.277	0.242	71.78
9	2004	70080-78840	10	96	23	0.084	0.807	0.193	0.435	80.15
10	2005	78840-87600	10	106	13	0.084	0.891	0.109	0.769	88.53
11	2006	87600-96360	13	119	0	0.109	1.000	0.000	+∞	99.41

The behaviour of thermal power systems in terms of reliability could be best approximated by the Weibull distribution, while using normal, lognormal and exponential distributions could lead to considerable disagreements, /15/. 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 life of mechanical systems with time dependent failure rate, /5, 16/. Failures of such systems are dominated by aging and mechanical wear.

In this study, the graphical method and probability papers are applied for analysis of the statistical set of data obtained by the exploitation survey of the boiler tubing 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, /17/. The two-parameter Weibull distribution is selected in order to simplify graphical analysis. Principles of constructing probability plotting graph paper and empirical data entry are described by many authors, /15, 18/.

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 fitted straight line through the plotted points one can obtain parameter values from the Weibull paper as: $\eta = 5.374$; $\beta = 1.5617$. Analytical expressions for theoretical reliability functions which represent distribution laws of the observed random variable, obtained by simple two-parameter Weibull distribution are, /19/:

– reliability (Eqs.(1) and (2)):

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

$$R_{ts}(t) = \exp\left(-4\cdot 10^{-8}\cdot t^{1.5617}\right) \tag{2}$$

failure density (Eqs.(3) and (4)):

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

$$f_{ts}(t) = 6.402\cdot 10^{-4} t^{0.5617}\exp\left(-4\cdot 10^{-8} t^{1.5617}\right) \tag{4}$$

failure rate (Eq.(5)):

$$\lambda_{ts}(t) = \frac{f_t(t)}{R_t(t)} = 6.402\cdot 10^{-4} t^{0.5617} \tag{5}$$

DETERMINING RELIABILITY FUNCTIONS USING COMPLEX WEIBULL DISTRIBUTION

After calculating of 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. they do not have the same character, and can be approximated with complex distribution. The sample of failure probabilities is divided into two parts, /20/, after which the median rank is calculated (Tables 2 and 3) and plotted for each (as shown in Fig. 2).

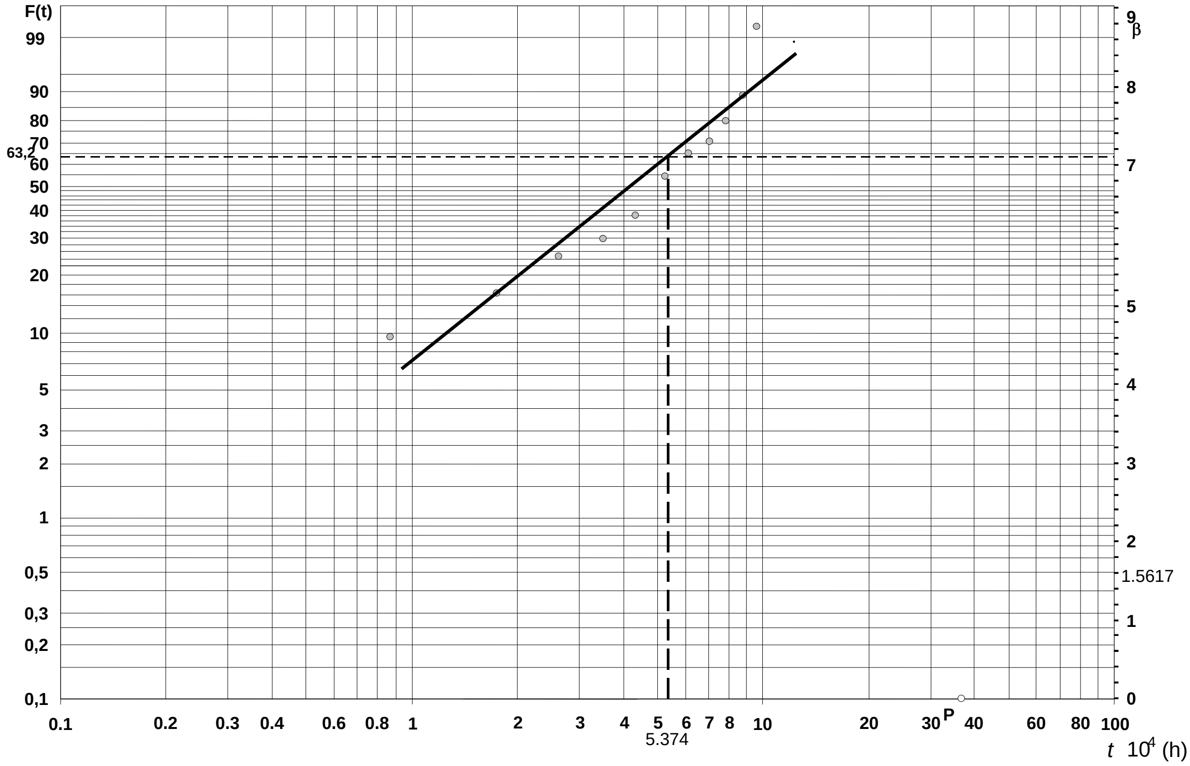

Figure 1. Weibull probability paper for simple distribution.

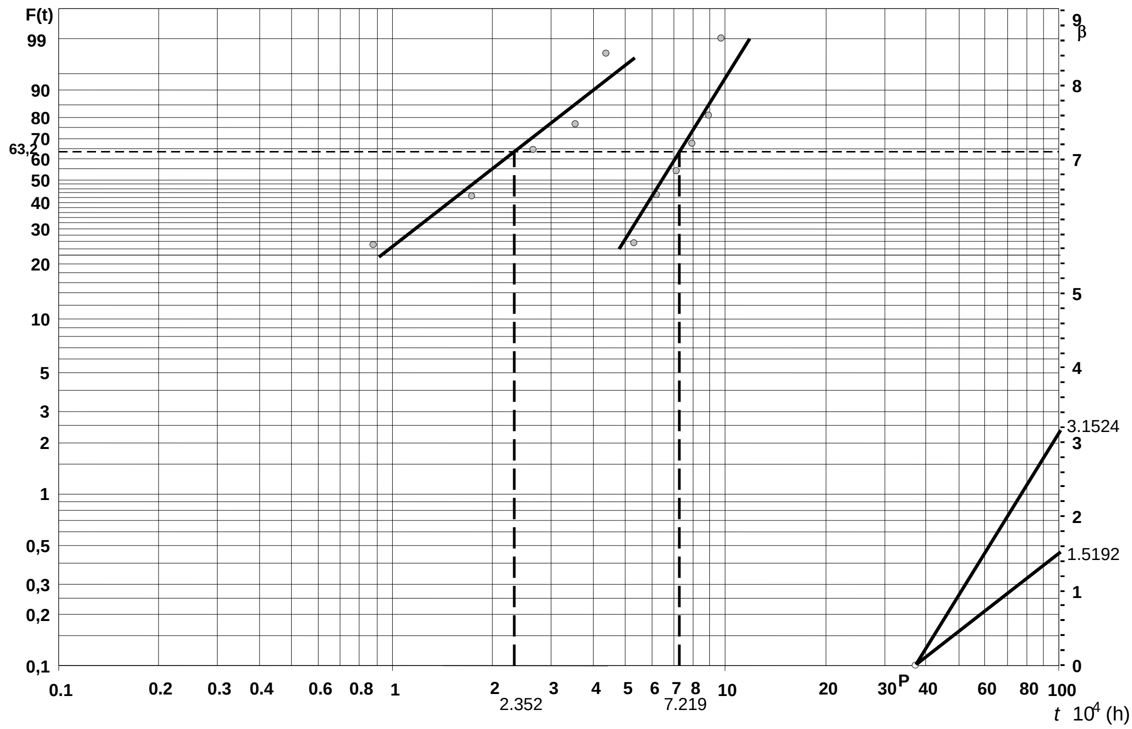

Figure 2. Weibull probability paper complex distribution.

Table 2. Values of exploitation indicators – line I.

	Tk_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	MR
1	1996	12	12	25.22
2	1997	8	20	42.46
3	1998	10	30	64.01
4	1999	6	36	76.94
5	2000	10	46	98.49

Table 3. Values of exploitation indicators – line II.

	Tk_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	MR
1	2001	19	19	25.48
2	2002	13	32	43.19
3	2003	8	40	54.09
4	2004	10	50	67.71
5	2005	10	60	81.34
6	2006	13	73	99.05

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

$$\eta_I = 2.352,\ \beta_I = 1.5192$$
$$\eta_{II} = 7.219,\ \beta_{II} = 3.1524$$

The parameters for the best fitted statistical data are estimated by the least-square method. Theoretical reliability functions for each interval are (Eqs.(6)-(9)):

$$R_{tI}(t) = \exp\left(-\frac{t}{\eta_I}\right)^{\beta_I} \tag{6}$$

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

$$R_{tI}(t) = \exp\left(-2.28\cdot 10^{-7} t^{1.5192}\right) \tag{8}$$

$$R_{tII} = \exp\left(-4.832\cdot 10^{-16} t^{3.1524}\right) \tag{9}$$

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

- reliability (Eqs.(10) and (11)):

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

$$R_{tc}(t) = 0.4545\exp\left(-2.28\cdot 10^{-7} t^{1.5192}\right) + 0.5455\exp\left(-4.832\cdot 10^{-16} t^{3.1524}\right) \tag{11}$$

- failure density (Eqs.(12) and (13)):

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

$$f_{tc}(t) = 1.5778\cdot 10^{-3} t^{0.5192}\exp\left(-2.28\cdot 10^{-7} t^{1.5192}\right) + 8.3095\cdot 10^{-12} t^{2.1524}\exp\left(-4.832\cdot 10^{-16} t^{3.1524}\right) \tag{13}$$

- failure rate (Eq.(14)):

$$\lambda_{tc}(t) = \frac{f_{tc}(t)}{R_{tc}(t)} = \frac{1.5778\cdot 10^{-3} t^{0.5192}\exp\left(-2.28\cdot 10^{-7} t^{1.5192}\right) + 8.3095\cdot 10^{-12} t^{2.1524}\exp\left(-4.832\cdot 10^{-16} t^{3.1524}\right)}{0.4545\exp\left(-2.28\cdot 10^{-7} t^{1.5192}\right) + 0.5455\exp\left(-4.832\cdot 10^{-16} t^{3.1524}\right)} \tag{14}$$

Graphical comparisons between exploitation and obtained values for theoretical functions of reliability, failure density and failure rate of boiler tubing system in TENT-A4 during the considered observation period are shown in Figs. 3, 4 and 5, respectively.

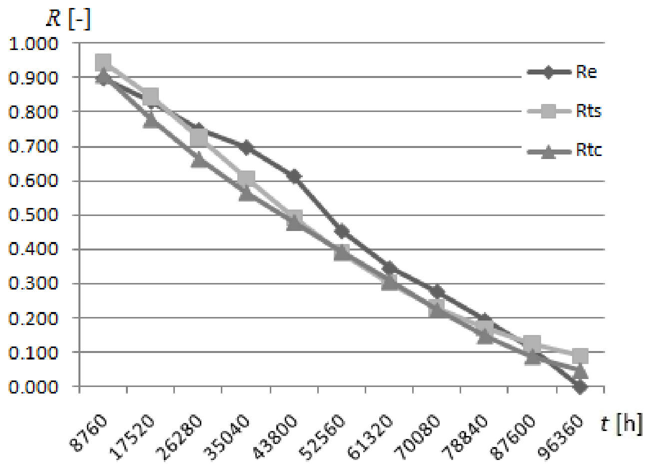

Figure 3. Exploitation and theoretical forms of the reliability functions.

The data required for drawing exploitation reliability indicators were given in tab. 1.

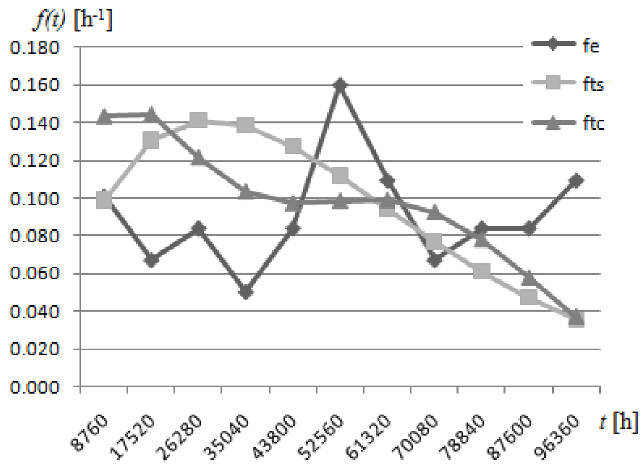

Figure 4. Exploitation and theoretical forms of the failure density functions.

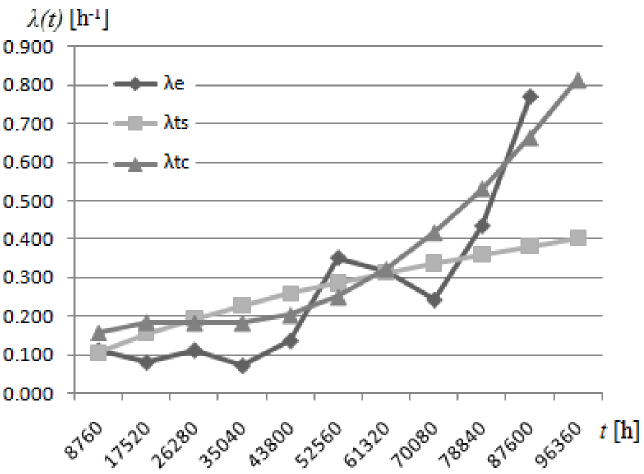

Figure 5. Exploitation and theoretical forms of the failure rate functions.

CONCLUSION

Application of the reliability theory enabled determination of the theoretical distribution laws of random variable according to the exploitation research of the boiler tubing systems in TENT-A4. The initial hypothesis that the distribution of the observed random variable approaches the Weibull distribution has been confirmed. Results of this study have shown that reliability of boiler tubing system could be more precisely represented with simple, than with complex Weibull distribution, but the differences are not significant. Empirical forms of the failure density and failure rate show zigzag-type behaviour, what is almost impossible to be exactly represented by any distribution function. The comparison of empirical and the theoretical failure density functions displays that functions obtained by both simple and complex Weibull distribution practically failed to reproduce empirical data. Finally, better matching between empirical and theoretical failure rate function obtained by complex Weibull distribution is demonstrated. It has led us to the conclusion that for describing the theoretical distribution law of the failure rate during the useful life period of the boiler tubing system, it is more precise to use rather complex than the simple distribution.

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