DETERMINING THE RELIABILITY FUNCTION OF THE THERMAL POWER SYSTEM IN POWER PLANT "NIKOLA TESLA, BLOCK B1"

by

Dragan V. KALABA [a], ***Milan Lj. DJORDJEVIĆ*** [a*], ***and Snežana D. KIRIN*** [b]

[a] Faculty of Tehnical Sciences, University of Priština, Kosovska Mitrovica, Serbia
[b] Innovation Center of the Faculty of Mechanical Engineering, Belgrade, Serbia

Original scientific paper
DOI: 10.2298/TSCI140610144K

Representation of probabilistic technique for evaluation of thermal power system reliability is the main subject of this paper. The system of thermal power plant under study consists of three subsystems and the reliability assessment is based on a sixteen-year failure database. By applying the mathematical theory of reliability to exploitation research data and using complex two-parameter Weibull distribution, the theoretical reliability functions of specified system have been determined. Obtained probabilistic laws of failure occurrence have confirmed a hypothesis that the distribution of the observed random variable fully describes 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 behavior during future exploitation. Final benefit is opportunity for potential improvement of complex system maintenance policies aimed at the reduction of unexpected failure occurrences.

Key words: *thermal power system, reliability, Weibull distribution*

Introduction

One of the most important requirements of any thermal power plant is to guarantee its higher reliability for maximization of power supply. Reliability has come to be one of the highest priorities of power systems, and it ranks along with cost and efficiency as a measure of successful operation. The large component count, unique component types, high internal stress levels, complex design, manual assembly and abundant opportunities for design errors led to potential high overall failure rates and decrease in reliability.

The higher availability of a complex thermal power plant is depending upon higher reliability and maintainability of its subsystems and components, which will not perform satisfactorily unless they are maintained properly. 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 power supply.

Most reliability analyses are conducted with the purpose of aiding decision makers in making thoroughly considered decisions. These decisions may be related to the system design layout, the maintenance and overhaul schedule, the risk acceptability, or any other decision that demands an assessment of reliability characteristics of a system.

---

* Corresponding author; e-mail: milan.djordjevic@yahoo.com

The essential problem related to the maintenance of complex systems and structures is related to the challenges of predicting the failure behavior of their components with due account of the associated uncertainties. The principal element which has supported the rise of reliability engineering as a scientific discipline is the theory of probability and statistics.

Reliability engineering is nowadays a well established, multidisciplinary scientific discipline which aims at providing a group of formal methods to investigate the uncertain boundaries between system operation and failure, by addressing the following questions [1,2]:

- why systems fail (using the concepts of reliability physics to discover causes and mechanisms of failure and to identify consequences),
- how to develop reliable systems,
- how to measure and test reliability in design, operation, and management, and
- how to maintain systems reliable, by maintenance, fault diagnosis, and prognosis.

To assess the reliability of a thermal power system, aspects of multiple disciplines have to be considered:

- definition of system boundaries to limit the extent of the analysis, and
- selection of the analysis method, in order to be able to study the phenomena correctly.

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 structure 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.

In this study the thermal power system is represented as a set of three subsystems: fossil fuel boiler, steam turbines, and three-phase alternator. System boundaries are adopted in order to determine the transmission limits of the thermal power subsystems within the thermal scheme [3]. The control limit that encloses the thermal power system does not encompass: systems for storage and delivery of fuel, systems for collecting and treatment of cooling water, the block transformer and the ash dump.

A variety of methods for expressing the reliability of a system could be employed. 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.

Data collection and classification

Exploitation research on the reliability of thermal power system of coal-fired power plant "Nikola Tesla, Block B1" (TENT-B1), in the period 1995-2012, should define the function, or the probabilistic law, according to which occurs the complete unplanned standstill. Although this thermal power plant has two units with installed capacity of 620 MW both, the reliability characteristics of their thermal power systems may not be the same. Data collections have been carried out over a long period of time for true failure and repair characterization (fig. 1). Maintenance data is collected from the plant's maintenance logbook records over a period of 16 years, which are sorted and classified for analysis.

In technical terms, reliability is measured by the probability that a system or a component will work without failure during a specified time interval under given operating conditions.

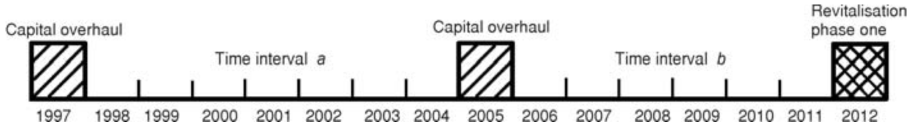

Figure 1. Observation time representation

Reliability is defined positively, in terms of a system performing its intended function, and no distinction is made between failures. Nevertheless, for system reliability analysis, there must be a great deal of concern not only with the probability of failure but also with the potential consequences of failures that present severe safety and economic loss or inconvenience.

Failures could be considered as inevitable in complex systems, although careful design, manufacturing, and maintenance policy can control their occurrence and consequences. The design and operation of complex systems is always a trade-off between achieving the required performance and acceptable reliability. It is neither economically nor technologically feasible to produce complex equipment that can sustain trouble-free operation for an indefinite period of time.

Standards differentiate between two main categories of failure classification – by cause or effect. A random failure is a physical failure occurring at random time, which is due to natural degradation mechanism in the equipment. A systematic failure is related in a deterministic way to a certain cause, when errors are made during the specification, design, operation or maintenance phase of the system. In this study all the failures are taken into account and classification by cause or effect was not performed.

The quantitative analysis of equipment failures by reliability engineering methods is based under a commonly adopted assumption that systems can be in two states: functioning or faulty. Although overall performance of many systems (such as the power generation, manufacturing, production, and other systems), can settle on different levels of the nominal capacity, depending on the operative conditions of their constitutive elements, the reliability of the thermal power systems could be evaluated by binary quantification techniques [4-6].

Determining the reliability functions of the thermal power system in TENT-B1

In reliability analysis it is assumed that the failures of repairable systems are independent and random. This means that a failure in one component, even though it may cause the system to malfunction, will not cause other components to fail, and that the failures are distributed in time according to an appropriate statistical distribution with a time dependent failure rate. For reliability decay, failures occur more often than just before the last failure over time. Reliability decay is typical for systems that are aging and failing more often over time.

A fundamental element of the reliability analysis of any complex system is the appropriate characterization, representation, propagation, and interpretation of uncertainty [7]. Uncertainty is an unavoidable component affecting the behavior of systems and more so with respect to their limits of operation. With respect to uncertainty, the final objective of reliability analysis and risk assessment is to produce insights in the analysis outcomes which can be meaningfully used by the decision makers. With respect to the treatment of uncertainty, in the reliability analysis and risk assessment practice both types of uncertainties are represented by means of probability distributions [8].

The properties and behaviour of all technical systems are by nature highly stochastic quantities and processes, what is one of the most important features of the reliability concept. It means that all information related to the reliability of thermal power system in TENT-B1 are random variables, subjected to specific laws of probability. Therefore, collected data could be processed only with the help of statistical mathematics. Failure evidence necessary for determining reliability and unreliability indicators for previously mentioned system are presented in tab. 1.

Table 1. The exploitation reliability components of the thermal power system in TENT-B1

	Observation period			Reliability						
	Tk_{i}	$T_{i\text{-}1}$	T_{i}	Nn_{i}	$\sum_{i=1}^{n} Nn_i$	Nt_{i}	f_{i}	F_{i}	R_{i}	λ_{i}
	[year]	[h]		[–]	[–]	[–]	[h^{-1}]	[–]	[–]	[h^{-1}]
1	2	3	4	5	6	7	8	9	10	11
1	1997	General overhaul								
2	1998	0-8760		11	11	73	0.131	0.131	0.869	0.151
3	1999	8760-17520		11	22	62	0.131	0.262	0.738	0.177
4	2000	17520-26280		20	42	42	0.238	0.500	0.5	0.476
5	2001	26280-35040		8	50	34	0.095	0.595	0.405	0.235
6	2002	35040-43800		8	58	26	0.095	0.690	0.31	0.308
7	2003	43800-52560		13	71	13	0.155	0.845	0.155	1
8	2004	52560-61320		13	84	0	0.155	1	0	+∞
9	2005	General overhaul								
10	2006	0-8760		12	12	54	0.182	0.182	0.818	0.222
11	2007	8760-17520		10	22	44	0.152	0.333	0.667	0.227
12	2008	17520-26280		8	30	36	0.121	0.455	0.545	0.222
13	2009	26280-35040		12	42	24	0.182	0.636	0.364	0.5
14	2010	35040-43800		19	61	5	0.288	0.924	0.076	3.8
15	2011	43800-52560		5	66	0	0.076	1	0	+∞
16	2012	Revitalisation								

Operating time intervals that include all data required for system analysis are defined for one year periods, or 8760 working hours, for the period from 1997 until 2012.

Interrpretation of data is one of the key elements of the theory of reliability. Using probability and statistics analyses, the reliability of a power system can be studied in depth [9]. The primary question that requires an answer is which theoretical distribution model best fits existing data. The physical properties of the stohastic process that is analized in some cases may suggest possible form of probability distribution. In practice, when a law of probabilistic distribution is based on empirical data, the mathematical form of the distribution is usually not easy to determine [10].

Since reliability analysis aims at determining the adequate reliability function of the system, exploitation research of the reliability of thermal power systems in power plant should define the function, or the probabilistic law, according to which occurs the complete unplanned standstill.

In order to determine the characteristics of random variable based on relevant exploitation data of presented system, a hypothesis of the class of distribution function to which belongs the random value should be created. Determining the unknown parameters of the distribution and evaluation of their accuracy are achievable on the basis of analysing the statistical material.

Different probabilistic techniques could be applied for analysis of the statistical set of data obtained by the exploitation survey of the thermal system in TENT-B1. The use of grafical method and probability papers in order to find a class of distribution function and their parameters, despite their relative simplicity, have a number of benefits that can meet the requirements beyond the scope of engineering practice [11]. Moreover, the proposed graphical method oftenly provides a better understanding about the behavior of any repairable system [12].

Previous studies indicate that the behavior of the thermal power systems in therms of reliability could be best approximated by two-parameter and three-parameter Weibull distribution, while using normal, lognormal and exponential distributions could lead to considerable disagreements [3].

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 modeling life of mechanical systems with time dependent failure rate [13, 14]. Failures of such systems is dominated by aging and mechanical or electrical wear out.

In this study the two-parameter Weibull distribution is chosen in order to simplify graphical analysis. Principles of constructing probability plotting graph paper and empirical data entry are described by many authors [3, 15], so for the purpose of brevity it will not be here described.

After calculating of failure probabilities and plotting times and their corresponding cumulative percentage of failures (t_i, $F(t_\mathrm{i})_{50\%}$) in a Weibull probabilistic paper, it was obvious that two straigt lines better fit those points than one line for both the observed time intervals (between the overhouls and revitalisation period). We assumed that the data are inhomogeneous, *i. e.* they do not have the same character, and that they can be approximated with complex distribution.

This is consistent with previous findings that for describing the theoretical distribution law of random variable during useful life period of the thermal power system, it is more precise to use complex than simple Weibull distribution [3], what has been evidenced by better matching of the system's empirical data and complex theoretical reliability functions.

The samples of failure probabilities for both time intervals was divided into two parts [16], after which the cumulative percentage of failures is calculated and plloted for each (as shown in figs. 2 and 3).

Drawing the best fitted straight lines through the plotted points we obtained the Weibull distribution parameters [17]:

– time interval *a* (1998-2004):

$$\eta_{\mathrm{I}a} = 1.826; \beta_{\mathrm{I}a} = 2{,}4163, \quad \eta_{\mathrm{II}a} = 5.217; \beta_{\mathrm{II}a} = 9.0291$$

– time interval *b* (2006-2011):

$$\eta_{\mathrm{I}b} = 1.331; \beta_{\mathrm{I}b} = 2.2086, \quad \eta_{\mathrm{II}b} = 3.943; \beta_{\mathrm{II}b} = 6.5962$$

The parameters for the best fitted statistical data are estimated by least-square method. Theoretical reliability functions for each sample are, eqs. (1) and (2):

– time interval *a*:

$$R_{\mathrm{tI}a}(t) = \exp(-0.2334t^{2.4163}), \quad R_{\mathrm{tII}a}(t) = \exp(-3.3292\cdot 10^{-7}t^{9.0291}) \tag{1}$$

– time interval *b*:

$$R_{\mathrm{tI}b}(t) = \exp(-0.5318t^{2.2086}), \quad R_{\mathrm{tII}b}(t) = \exp(-1.1744\cdot 10^{-4}t^{6.5962}) \tag{2}$$

Analytical expressions for theoretical reliability functions which represent the distribution laws of the observed random variable for the complex Weibull distribution, eqs. (4) and (5) of the whole set are calculated according to eq. (3):

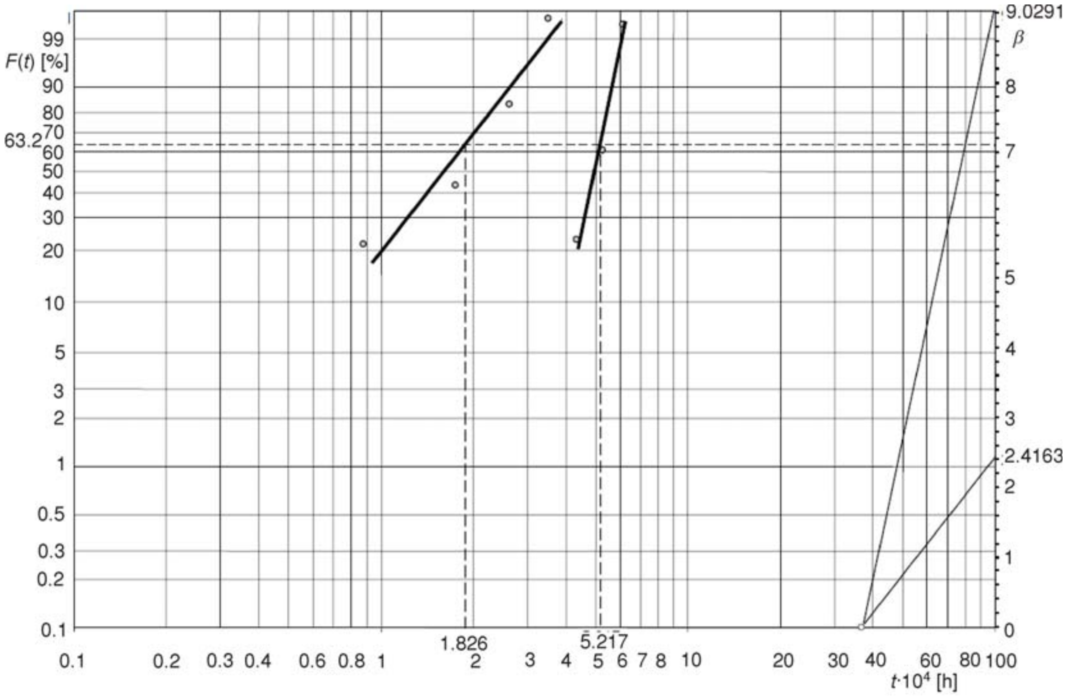

Figure 2. Weibull probability paper for complex distribution for time interval *a*

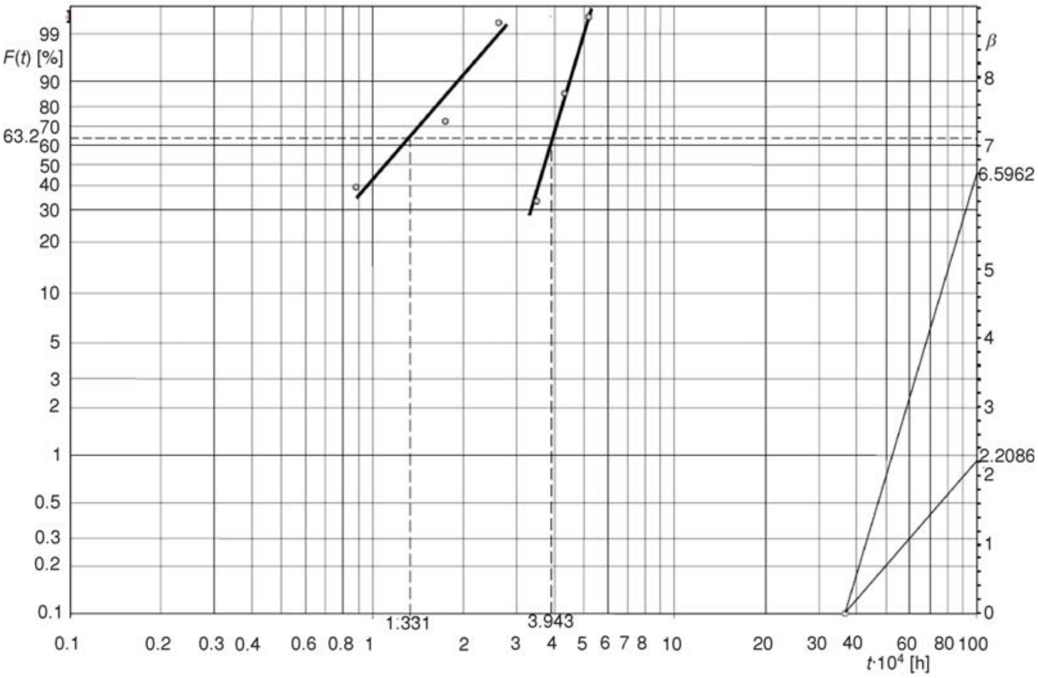

Figure 3. Weibull probability paper for complex distribution for time interval *b*

$$R_{\mathrm{t}}(t) = \frac{n_{\mathrm{I}}}{n} R_{\mathrm{tI}}(t) + \frac{n_{\mathrm{II}}}{n} R_{\mathrm{tII}}(t) \tag{3}$$

$$R_{\mathrm{t}a}(t) = 0.5952\exp(-0.2334t^{2.4163}) + 0.4048\exp(-3.3292\cdot 10^{-7}\,t^{9.0291}) \tag{4}$$

$$R_{\mathrm{t}b}(t) = 0.4545\exp(-0.5318t^{2.2086}) + 0.5455\exp(-1.174\cdot 10^{-4}\,t^{6.5962}) \tag{5}$$

Probability theory imposes restrictive conditions on the specification of the likelihood of events as a result of the requirement that the probabilities of the occurrence and nonoccurrence of an event must sum to one. As a result, the theoretical unreliability functions for complex Weibull distribution could be calculated as in eq. (6):

$$F_{\mathrm{t}}(t) = 1 - R_{\mathrm{t}}(t) \tag{6}$$

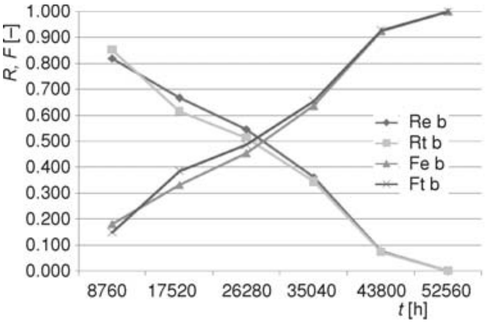

Figure 4. Exploitation and theoretical forms of reliability and unreliability functions for time period *a*

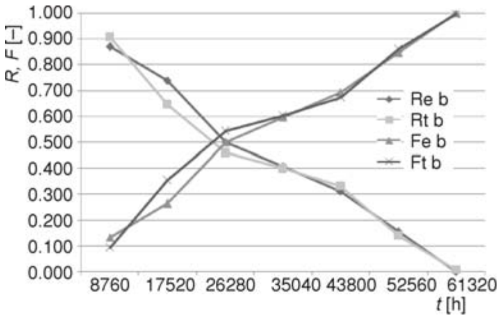

Figure 5. Exploitation and theoretical forms of reliability and unreliability functions for time

Graphical comparisons between exploitation and obtained values for theoretical functions of reliability and unreliability of thermal power system in TENT-B1 during both observation periods are shown in figs. 4 and 5, while fig. 6. shows comparison of theoretical functions of reliability for different periods. The data required for drawing functions of exploitation reliability and unreliability are given in tab. 1.

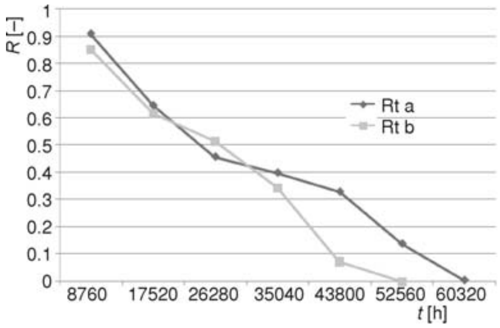

Figure 6. Theoretical forms of reliability functions for time periods *a* and *b*

Conclusions

Exploitation research of the thermal power system in TENT-B1 enable us to determine the theoretical distribution law of random variable by application of the reliability theory. The main adventage of utilization of graphical method and probability papers for finding the class of distribution functions is that the complete behavioral tendencies of empirical data could be easily perceived. The complex Weibull distribution is very suitable for the reliability quantification of thermal power systems during operation periods between successive capital overhauls, what has been evidenced by close matching of the system's empirical data and obtained complex theoretical reliability functions. Values of Weibull distribution shape parameter β indicate that failures of the thermal power system in TENT-B1 are mainly a consequences of material fatigue, mechanical or electrical wear out and aging. The benefit of the study lies in the potential early and continued understanding of the logics and mechanisms underpinning the system uncertain failure behaviour, which complement other methods and information in order to achieve maximum availability through optimized maintenance and prompt recovery.

Nomenclature

F_i – unrealiability $(= \sum_{i=1}^{n} f_i)$, [–]
f_i – failure density (= Nni/$\sum_{i=1}^{n} Nn_\mathrm{i}$), [–]
$F(t_\mathrm{i})_{50\%}$ – cumulative percentage of failures or median rang, (= $(j - 0{,}3)/(n + 0.4)$), [%]
n – total number of failures in the reported period, [–]
N_n – total number of failures, [–]
$\sum_{i=1}^{n} Nn_i$ – cumulative sum of failures, ($j = \sum_{i=1}^{n} Nn_i$), [–]
N_t – reverse cumulative sum of failures, [–]
R_i – reliability, [–]
T_k – calendar time, [year]

Greek symbols

β – shape parameter, [–]
η – scale parameter, [–]
λ – failure rate (= $Nn_\mathrm{i}/Nt_\mathrm{i}$), [–]

Subscripts

a – time interval 1998-2004
b – time interval 2006-2011
i – number of operating intervals of the system
e – exploitation
t – theoretical

References

[1] Cai, K. Y., *Introduction to Fuzzy Reliability*, Kluwer, Boston, Mass., USA, 1996
[2] Aven, T., Jensen, U., *Stochastic Models in Reliability*, Springer, New York, USA, 1999
[3] Kalaba, V. D., *et al.*, Determining the Theoretical Reliability Function of Thermal Power System Using Simple and Complex Weibull Distribution, *Thermal Science,* DOI:10.2298/TSCI120611168K
[4] Levitin, G., Lisnianski, A., *Multi-State System Reliability Analysis and Optimization, Handbook of Reliability Engineering*, Springer, London, Berlin, New York, 2003
[5] Barlow, R., *et al.*, *Reliability and Decision Making*, Chapman and Hall, New York, USA, 1993
[6] Rigdon, S. E., Basu, A. P., *Statistical Methods for the Reliability of Repairable Systems*, John Wiley and Sons, Inc., New York, USA, 2000
[7] Helton, J. C., Burmaster, D. E., Guest Editorial: Treatment of Aleatory and Epistemic Uncertainty in Performance Assessments for Complex Systems, *Reliability Engineering and System Safety, 54* (2006), 2-3, pp. 91-94
[8] Aven, T., *Foundations of Risk Analysis*, John Wiley and Sons, New York, USA, 2003
[9] Zio, E., *An Introduction to the Basics of Reliability and Risk Analysis*, World Scientific Publishing Co. Ltd., Singapore, 2007
[10] Rausand, M., Arnjlot, H., *System Reliability Theory; Models, Statistical Methods and Application*s 2nd ed., John Wiley and Sons, New York, USA, 2004
[11] Barlow, R., *Engineering Reliability*, SIAM, Philadelphia, Penn., USA, 1998
[12] Kalaba, D., *et al.*, Determining the Availability Function of the Thermal Power System in Power Plant "Nikola Tesla, Block A4", *Proceedings*, 5th International Conference on Power Plants, Zlatibor, Serbia, 2012, pp. 469-484
[13] Nordman, J. D., *et al.*, Weibull Prediction Intervals for a Future Number of Failures, *Technometrics , 44* (2002), 1, pp. 15-23
[14] Nelson, W., Weibull Prediction of a Future Number of Failures, *Quality and Reliability Engineering International, 16* (2000), 1, pp. 23-26
[15] Milčić, D., Reliability of Mechanical Systems (in Serbian), Faculty of Mechanical Engineering, University of Nis, Nis, Serbia, 2005
[16] Milčić, D., Mijajlović, M., Reliability of Mechanical Systems – Collection of Solved Tasks (in Serbian), Faculty of Mechanical Engineering, University of Nis, Nis, Serbia, 2008
[17] Ebeling, C., An Introduction to Reliability and Maintainability Engineering, Waveland Press., Inc., Long Grove, Ill., USA, 2009

Paper submitted: June 10, 2014
Paper revised: October 23, 2014
Paper accepted: December 18, 2014