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Determining the Reliability Function of the Thermal Power System in the Power Plant "Nikola Tesla, Block B2"

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Abstract: In the modern world, where a uninterrupted energy supply is required for proper functioning, thermal energy systems are key components of the infrastructure. Considering the complexity of these systems, it is essential to develop procedures that enable specific determination of the reliability function of thermal energy systems. Analysis of the reliability of the thermal energy system is crucial for maintaining the stability and efficiency of the system. In this paper, by applying the mathematical theory of reliability to the exploitation research data and using simple and complex two-parameter Weibull distribution, the theoretical reliability functions of the thermal power plant Nikola Tesla, Block B2 were determined. A significant advantage of such a study is the possibility of an early and thorough understanding of the logic and mechanisms of risky behavior in the system, as well as a more precise assessment of its functioning throughout the future exploitation.

Keywords: Thermal power system, Reliability, Weibull distribution.

1. Introduction

A reliable and uninterrupted supply of energy from thermal energy systems is crucial for social stability and economic development. In the last few years, with the ageing of infrastructure and increasingly severe climatic stresses, the reliability of energy systems has become a topic of wider importance around the world [1]. The thermal power system comprises a complex infrastructure and requires attentive planning and monitoring to ensure continuous energy delivery. In the event of a malfunction and stoppage during the operation of the thermal power system, the outcome is reflected in a direct outage of the power plant and disturbances in the power system. Resolving those delays requires quick and efficient detection of causes, as well as the application of appropriate measures to eliminate them. Therefore, reliability analysis becomes crucial in the identification of potential issues and risks that may lead to interruptions in electricity supply.

Term reliability means the probability of working without outages for a certain period of time and under certain environmental conditions, *i.e.* the probability that the production process of technical systems takes place without interruption and downtime by providing the required deadlines, production volumes, product range, and quality (criterion function) with planned normative materials, labour and costs for a specified time period and predetermined working conditions [2].

Ensuring the stable operation of the thermal energy system is a challenging task due to the complexity and numerous components that comprise the system. It is needed to conduct thorough and long-term research in order to understand the characteristics of these components. Accordingly, in this paper, the reliability of the thermal energy system in the thermal power plant Nikola Tesla, Block B2 (TENT-B2) for the period 2012-2023 was examined. Simple and complex two-parameter Weibull distributions were used for modelling the reliability of the thermal power system during the normal life period.

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

2. Determining reliability functions using simple Weibull distribution

Reliability theory is grounded in probability theory and mathematical statistics and represents a process in which elements can be found in the working condition or at a standstill. If the system performs its intended function, reliability is defined positively. An initial assumption in reliability analysis is that failures of repairable systems are independent and occur randomly. That means that a failure in one component of the system will not directly cause a breakdown in another part. During the regular operation of the system, random failures occur sporadically, the frequency of which can be determined. Similarly, it is important to take into account that as the system ages, the failure rate increases, and this phenomenon continues throughout the system's lifetime. In other words, the reliability reduction is typical for systems that age, so with the passage of time, they fail more frequently.

The thermal energy system consists of a large number of components, which are often exposed to various influences that can affect their functionality and reliability. That is why it is necessary to continuously monitor the system's performance and identify potential failures in order to determine the regularity of the behaviour of these components. For the analysis and improvement of reliability, it is essential to consider the historical data of exploitation research. In order to determine the real indicators and characteristics of reliability, it was necessary to have all relevant data about the exploitation of the mentioned system. The key source of information relies on the annual downtime reports, which are in the legal possession of TENT-B2.

Exploitation data related to the normal life period of the system are crucial for reliability analysis. The system failure rate is considered relatively constant during that period. The interpretation of this data is very important for understanding system performance and forecasting inevitable failures. In the process of analysis, the selection of the right theoretical model of probability distribution is of significant importance. However, determining the mathematical form of distribution is often not straightforward, especially when relying on empirical data.

The characteristics and behaviour of all technical systems are by nature highly stochastic quantities and processes, which is one of the essential features of the concept of reliability. It means that all information related to the reliability of thermal power systems are random variables, subjected to specific laws of probability. Therefore, collected data can be processed only with the help of statistical mathematics [3]. To define the reliability of the aforementioned system, it is required to analyze the number of unplanned outages, which are shown in Tab. 1. Operating time intervals that include all data required for system analysis are defined on an annual basis, or 8760 working hours. These intervals are defined for the period from 2012 to 2023.

Table 1. Data on operational reliability of the system

Observation period			Reliability						
i	Tk_i	T_{i-1} T_i	Nn_i	$\sum_{i=1} Nn_i$	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
1	2012	0-8760	15	15	114	0.12	0.12	0.88	0.1316
2	2013	8760-17520	7	22	107	0.05	0.17	0.83	0.0650
3	2014	17520-26280	8	30	99	0.06	0.23	0.77	0.0810
4	2015	26280-35040	9	39	90	0.07	0.30	0.70	0.1000
5	2016	35040-43800	10	49	80	0.08	0.38	0.62	0.1250
6	2017	43800-52560	13	62	67	0.10	0.48	0.52	0.1940
7	2018	52560-61320	14	76	53	0.11	0.59	0.41	0.2640
8	2019	61320-70080	7	83	46	0.05	0.64	0.36	0.1520
9	2020	70080-78840	5	88	41	0.04	0.68	0.32	0.1220
10	2021	78840-87600	9	97	32	0.07	0.75	0.25	0.2810
11	2022	87600-96360	15	112	15	0.12	0.87	0.13	1.000
12	2023	96360-105120	17	129	0	0.13	1.00	0	+∞

Determining the distribution based on empirical data is not a simple task. Due to the complexity of this process, it is primarily recommended to enter the data into the probability paper for Weibull two-parameter distributions. The use of graphical methods and probability papers in order to find a class of distribution functions and their parameters, despite their relative simplicity, has a number of benefits that can meet requirements beyond the scope of engineering practice [4]. The graphical method of the Weibull distribution enables a visual presentation of data and helps to understand the behaviour of the system during exploitation.

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 [5]. The Weibull distribution, as well as its modified forms, can describe diverse forms for failure rate functions and is widely used in lifetime modeling within the scope of reliability engineering [6]. The reason for the very frequent practical application of the Weibull distribution stems from the fact that many forms of failure can be very well approximated by it. Also, the Weibull distribution can include decreasing, constant and increasing functions of failure intensity [7].

In this paper, by applying the graphical method and probability, an analysis of the collected data obtained during the exploitation of the thermal power system in TENT B-2 was carried out. Principles of constructing the probability plotting graph paper and empirical data entry have been described by many authors [8-9].

Based on operational reliability indicators of the thermal power plant system, the data shown in Table 1. can be entered as points in the Weibull probability paper in order to obtain the parameters η and β, as shown in (Fig. 1).

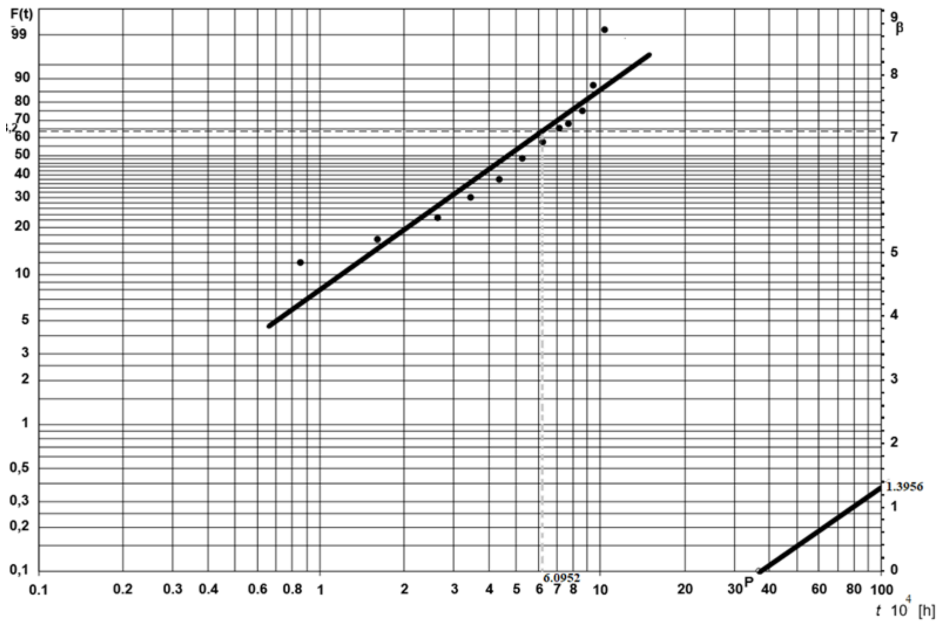

Figure 1. Weibull probability paper for simple Weibull distribution

The Weibull distribution parameters were obtained by drawing the best fitted straight lines through the plotted points,:

$\eta = 6.0952, \beta = 1.3956$

The listed functions are analytical expressions that represent distribution laws of the observed random variable [10]:

Reliability
$$R_{ts}(t) = \exp\left(\frac{-t^{1.3956}}{12.4601}\right) \tag{9}$$

Failure density
$$f_{ts}(t) = 0.112 \cdot t^{0.3956} \cdot \exp\left(\frac{-t^{1.3956}}{12.4601}\right) \tag{10}$$

Failure rate
$$\lambda_{ts}(t)\frac{f_t(t)}{R_t(t)} = 0.112 \cdot t^{0.3956} \tag{11}$$

3. Determining reliability functions using complex Weibull distribution

Based on the results of plotting the probability of failures and time plots and their respective cumulative failure percentages $\left(t_i, F(t_i)_{50\%}\right)$ on the Weibull probability paper, it has been identified that two lines fit the indicated points better than one line.

For the case of the complex two-parameter Weibull distribution, the failure probability samples for the observed time interval were divided into two parts [11]. Following the separation of samples, the cumulative percentage of failures was calculated for each of the parts, and a chart was drawn based on applicable data. In this particular case, the first time interval includes 7 (Table 2), while the second includes 5 years (Table 3).

Table 2. Values of exploitation indicators - line I

i	Tk_i	Nn_i	$\sum_{i=1} Nn_i$	f_i	F_i
[-]	$[year]$	[-]	[-]	$[h^{-1}]$	[-]
1	2012	15	15	0.31	0.31
2	2013	7	22	0.14	0.45
3	2014	8	30	0.16	0.61
4	2015	9	39	0.18	0.79
5	2016	10	49	0.2	0.99

Table 3. Values of exploitation indicators - line II

i	Tk_i	Nn_i	$\sum_{i=1} Nn_i$	f_i	F_i
[-]	$[year]$	[-]	[-]	$[h^{-1}]$	[-]
1	2017	13	13	0.16	0.16
2	2018	14	27	0.17	0.33
3	2019	7	34	0.09	0.42
4	2020	5	39	0.06	0.48
5	2021	9	48	0.11	0,59
6	2022	15	63	0.19	0.78
7	2023	17	80	0.21	0.99

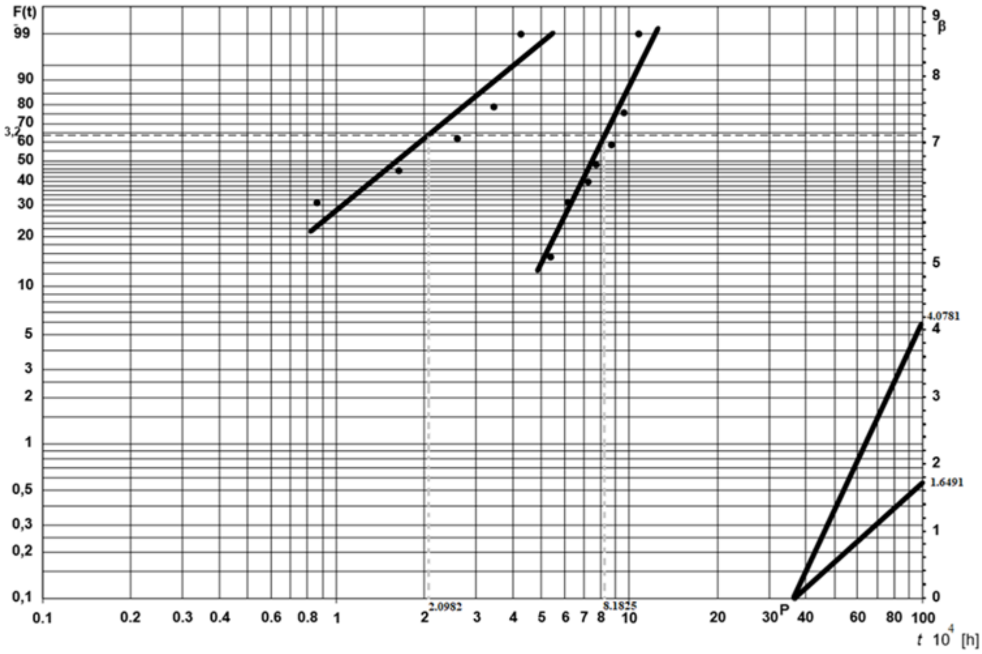

Figure 2. Weibull probability paper for complex Weibull distribution

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

$$\eta_I = 2.0982, \beta_I = 1.6491$$

$$\eta_{II} = 8.1825, \beta_{II} = 4.0781$$

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

$$R_{tI} = \exp\left(-7.462 \cdot 10^{-8} \cdot t^{1.6491}\right) \tag{12}$$

$$R_{tI} = \exp\left(-9.220 \cdot 10^{-21} \cdot t^{4.0781}\right) \tag{13}$$

Analytical expressions for theoretical reliability functions which represent the distribution laws of the observed random variable for the complex two-parameter Weibull distribution are [12]:

Reliability

$$R_{tc}(t) = 0.38 \cdot \exp\left(-7.462 \cdot 10^{-8} \cdot t^{1.6491}\right) + 0.62 \cdot \exp\left(-9.220 \cdot 10^{-21} \cdot t^{4.0781}\right) \tag{14}$$

Failure density

$$f_{tc}(t) = 4.674 \cdot 10^{-4} \cdot t^{0.6491} \cdot \exp\left(-7.462 \cdot 10^{-8} \cdot t^{1.6491}\right) + 2.332 \cdot 10^{-16} \cdot t^{3.0781} \cdot \exp\left(-9.220 \cdot 10^{-21} \cdot t^{4.0781}\right) \tag{15}$$

Failure rate

$$\lambda_{tc}(t) = \frac{4.674 \cdot 10^{-4} \cdot t^{0.6491} \cdot \exp\left(-7.462 \cdot 10^{-8} \cdot t^{1.6491}\right) + 0.62 \cdot \exp\left(-9.220 \cdot 10^{-21} \cdot t^{4.0781}\right)}{0.38 \cdot \exp\left(-7.462 \cdot 10^{-8} \cdot t^{1.6491}\right) + 0.62 \cdot \exp\left(-9.220 \cdot 10^{-21} \cdot t^{4.0781}\right)} \tag{16}$$

Graphical comparisons between operational and obtained values for theoretical functions of reliability, failure density and failure rate of the thermal power system in TENT-B2 during the observation period were shown in figs 3-5.

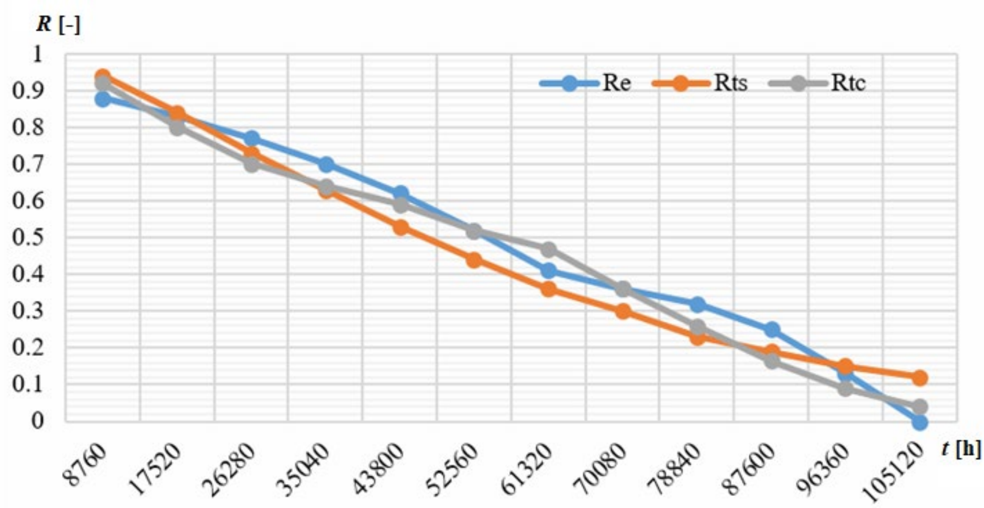

Figure 3. Exploitation and theoretical forms of the reliability functions

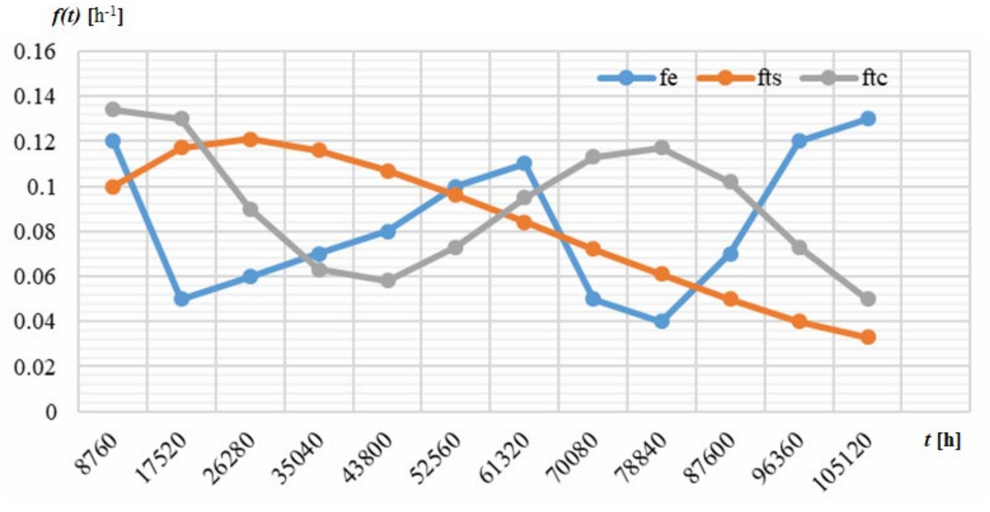

Figure 4. Exploitation and theoretical forms of the failure density functions

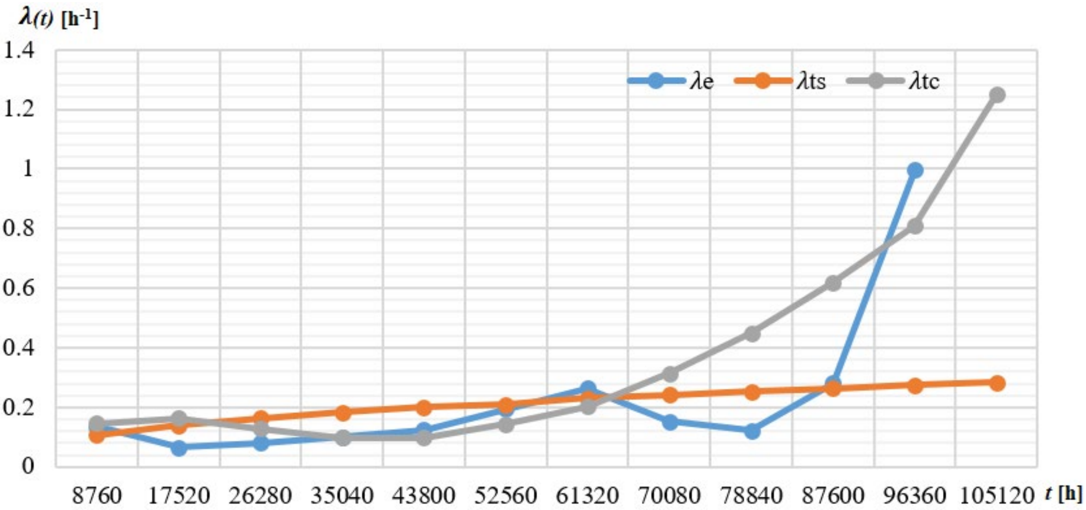

Figure 5. Exploitation and theoretical forms of the failure rate functions

4. Conclusion

The operational research of the thermal power system in the TENT-B2 and application of reliability theory resulted in presentation of theoretical laws of random variable distribution. The assessment of reliability, failure density and failure rates were implemented by the graphic method and probability paper, which enabled the analysis and interpretation of data in a visually clear manner. An initial hypothesis suggesting that the distribution of this random variable approaches the Weibull distribution is confirmed. The findings disclosed that the functions obtained by the simple and complex Weibull distributions failed to accurately reproduce the empirical data. Finally, a relatively good data match between empirical and theoretical failure rate functions was obtained by complex Weibull distribution. It is more accurate to use the complex rather than the simple Weibull distribution to estimate the distribution law of the failure rate during the useful life of this particular thermal power system.

Nomenclature

Latin symbols

F_i	Unrealiability $\left(=\sum_{i=1}^{n} f_i\right)$, $[-]$
f_i	Failure density $\left(=N_{n_i}/\sum_{i=1}^{n} N_{n_i}\right)$, $\left[h^{-1}\right]$
$F(t_i)_{50\%}$	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, $[-]$
$\sum_{i=1}^{n} N_{n_i}$	Cumulative sum of failures $\left(j=\sum_{i=i}^{n} N_{n_1}\right)$, $[-]$
N_t	Reverse cumulative sum of failures, $[-]$
R_i	Reliability, $[-]$
t	Time, $[h]$
T_k	Calendar time, $[year]$

Greek symbols

β	Shape parameter, $[-]$
η	Scale parameter, $[-]$
λ	Failure rate $(=N_{n_i}/N_{t_i})$, $\left[h^{-1}\right]$

Subscripts

e	Exploitation
i	Number of operating intervals of the system
t	Theoretical

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References

[1] Bao, M., Ding, Y., Yin, X., Shao, C., Definitions and Reliability Evaluation of Multi-state Systems Considering State Transition Process and its Application for Gas Systems, Reliability Engineering and System Safety, 207 (2021), pp. 107387
[2] SRPS A. A2.005
[3] Kalaba, D., Thermal Power System Reliability, (in Serbian), University of Priština, Faculty of Tehnical Sciences, Kosovska Mitrovica, 2011
[4] Barlow, R., Engineering Reliability, SIAM, Philadelphia, 1998
[5] Kalaba, D., Radaković, Z., Đorđević, M., Kirin, S., Determining the Theoretical Reliability Function of Thermal Power System Using Simple and Complex Weibull Distribution, Thermal Science, 18 (2014), pp. S229-S238
[6] Jia, X., Reliability Analysis for Weibull Distribution With Homogeneous Heavily Censored Data Based on Bayesian and Least-Squares Methods, Applied Mathematical Modelling, 83 (2020), pp. 169-188
[7] Ahmada, A., Ghazal, M., Exponentiated Additive Weibull Distribution, Reliability Engineering and System Safety, 193 (2020), pp. 106663
[8] McCool, J., Using the Weibull Distribution: Reliability, Modeling, and Inference, John Wiley & Sons Inc., New Jersey, 2012
[9] Milčić, D., Reliability of Mechanical Systems (in Serbian), Faculty of Mechanical Engineering, University of Nis, Nis, 2005
[10] Murthy, P., Min, X., Renyan, J., Weibull Models, John Wiley & Sons Inc., New York, 2004
[11] Milčić, D., Mijajlovi, M., Reliability of Mechanical Systems – Collection of Solved Tasks (in Serbian), Faculty of Mechanical Engineering, University of Nis, Nis, 2008
[12] Nelson, W., Weibull Prediction of a Future Number of Failures, Quality and Reliability Engineering, 16 (2000) pp. 23-26