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DETERMINING THE RELIABILITY FUNCTION OF THE THERMAL POWER SYSTEM IN POWER PLANT 'NIKOLA TESLA, BLOCK B1' USING THE WEIBULL DISTRIBUTION

ODREĐIVANJE FUNKCIJE POUZDANOSTI TERMOENERGETSKOG SISTEMA „NIKOLA TESLA, BLOK B1" KORIŠĆENJEM VEJBULOVE RASPODELE

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- termoenergetski sistem
- pouzdanost
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Abstract

The assessment of thermal power system reliability represents a key step towards maintaining the stability and efficiency of the system. Through the application of mathematical models, risk analysis, and maintenance strategies, it is possible to optimise system performance and reduce the risk of failures. This paper presents an assessment of the reliability of the thermal energy system in fossil fuel power plant 'Nikola Tesla, Block B1', based on a twelve-year failure database. By implementing the theory of reliability, based on statistics and theory of possibility, and using the simple and complex two-parameter Weibull distribution, the theoretical functions of the failure rate are determined. A significant advantage of such a study is the opportunity of an early and in-depth understanding of the logic and mechanisms of system risk behaviour, and a more precise assessment of its functioning throughout future exploitation.

Izvod

Procena pouzdanosti termoenergetskog sistema predstavlja ključni korak ka održavanju stabilnosti i efikasnosti sistema. Primenom matematičkih modela, analiza rizika i strategija održavanja, moguće je optimizovati performanse sistema i smanjiti rizik od kvarova. U ovom radu prikazana je procena pouzdanosti termoenergetskog sistema termoelektrane na fosilna goriva „Nikola Tesla, Blok B1", koja se bazira na dvanaestogodišnjoj bazi podataka o zastojima. Primenom teorije pouzdanosti, koja se temelji na statistici i teoriji verovatnoće, kao i korišćenjem proste i složene dvoparametarske Vejbulove raspodele, određene su teorijske funkcije intenziteta otkaza. Značajna prednost ovakve studije je mogućnost blagovremenog i dubljeg razumevanja logike i mehanizama rizika unutar sistema, kao i preciznija procena njegovog funkcionisanja tokom buduće eksploatacije.

INTRODUCTION

The thermal energy system is the main component of the thermal power plant since it includes a complex infrastructure that enables conversion of heat into electricity. Outages in the process of thermal energy system operation directly cause power plant outages and disruptions within the power system. Dealing with failures during operation of a thermal energy system requires a quick and efficient determination of cause and application of adequate measures to settle the issue. In addition, teams of assigned engineers improve the system operation on a daily basis in order to reduce the number of interruptions to a minimum. Therefore, during the exploitation of the thermal energy system, it is required that all elements of the system are available and reliable, as in such a way maximal effectiveness is achieved and constant production of electricity is ensured. Reliability of a thermal energy system is a key aspect of maintaining stability and efficiency of the system, /1-2/. More generally, reliability is often used in different engineering applications as shown in /3-7/.

In this paper, reliability is defined as a probability at a certain degree of confidence, that the system will successfully, without failure, perform the function for which it is intended, within the specified performance limits, during the specified duration of tasks, when used in compliance with the prescribed manner and for the intended purpose, under specified load levels, taking into account previous system usage time /8-9/. In order to ensure safe operation of thermal energy systems, the reliability assessment of the system should be carried out for both long and short terms of a time scale, /10/.

In this paper, the reliability of the thermal energy system in the power plant 'Nikola Tesla, Block B1' (TENT-B1) is examined in the period from 2012 to 2023. Simple and complex two-parameter Weibull distributions were used for modelling the reliability of the thermal energy system during the exploitation time.

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 thermal power subsystems within the thermal scheme, /11/.

DETERMINING RELIABILITY FUNCTIONS USING SIMPLE WEIBULL DISTRIBUTION

The reliability theory is grounded on mathematical principles, especially on the theory of probability and statistics /12/, and it represents processes in which elements can be found in an operational state or in a state of failure. If the system performs its intended function, reliability is defined positively. One of the basic assumptions in reliability analysis is that malfunctions of repairable systems are independent and random, meaning that a failure of one component, though it may cause a system failure, will not lead to failure in other components. Random failures occur during the regular operation of a system for which the frequency can be determined. The aging of the system leads to an increased failure rate and this trend continues throughout the system's lifetime.

As the thermal energy system consists of numerous components, ensuring the reliability of the system's operation is a very complex task. In order to determine the legitimacy of these components' behaviours, comprehensive and long-term research is needed. Since this reliability survey is based on exploitation research, it is essential to obtain all relevant data regarding the exploitation history of these objects to determine real indicators and characteristics. The main sources of information are the annual reports of downtimes, which are in the legal possession of TENT.

The properties and behaviour of all technical systems are by nature highly stochastic quantities and processes, which is one of the most important features of the reliability concept. 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 /11/.

Failure evidence necessary for determining reliability indicators for the considered system is presented in Table 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.

The presented operating data related to the regular period of the system's lifetime are essential for reliability analysis. The system failure rate is considered relatively constant during that period. Interpretation of this data is key to understanding system performance and forecasting future critical failures. After analysing this data, one of the key questions is which theoretical distribution model best fits the existing records? Selecting the right model can be of great importance for predicting future behaviour and managing system failures. Physical properties of the stochastic process analysed in some cases may suggest a 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, /13/.

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, /14/. The Weibull distribution, as well as its modified forms, can describe diverse forms for failure rate functions, and is widely used in lifetime modelling within the scope of reliability engineering, /8/. The reason for 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 model the life of systems with time dependent failure rate, /8-16/.

Here, an analysis of collected data obtained during the exploitation of the thermal energy system in TENT B-1 is carried out by applying the graphical method and probability. 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, /17/. The graphical method of the Weibull distribution enables a visual presentation of data and helps to understand the behaviour of the system in exploitation. Principles of constructing the probability plotting graph paper and empirical data entry are described by authors /18-19/.

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 and obtain the parameters η (scale parameter) and β (shape parameter), as shown in Fig. 1. Drawing the best fitted straight lines through plotted points, the Weibull distribution parameters are thus obtained: $\eta = 5.2213$, $\beta = 1.2321$.

Listed functions are analytical expressions that represent distribution laws of the observed random variable /20/:

- Reliability

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

$$R_{ts}(t) = \exp\left(\frac{-t^{1.2321}}{7.6625}\right). \tag{2}$$

- Failure density

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

$$f_{ts}(t) = 0.1608 t^{0.2321} \exp\left(\frac{-t^{1.2321}}{7.6625}\right). \tag{4}$$

- Failure rate

$$\lambda_{ts}(t) \frac{f_t(t)}{R_t(t)} = 0.1608 t^{0.2321}. \tag{5}$$

DETERMINING RELIABILITY FUNCTIONS USING COMPLEX WEIBULL DISTRIBUTION

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

Table 1. Values of operational reliability indicators and reliability components of the system.

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_t
[-]	[year]	[h]	[-]	[-]	[-]	[h^{-1}]	[-]	[-]	[h^{-1}]
1	2	3-4	5	6	7	8	9	10	11
1	2012	0-8760	25	25	149	0.14	0.14	0.86	0.1680
2	2013	8760-17520	15	40	134	0.09	0.23	0.77	0.1120
3	2014	17520-26280	17	57	117	0.10	0.33	0.67	0.1450
4	2015	26280-35040	12	69	105	0.07	0.40	0.60	0.1140
5	2016	35040-43800	18	87	87	0.10	0.50	0.50	0.2070
6	2017	43800-52560	11	98	76	0.06	0.56	0.44	0.1450
7	2018	52560-6132	15	113	61	0.09	0.65	0.35	0.2460
8	2019	61320-70080	8	121	53	0.05	0.70	0.30	0.1510
9	2020	70080-78840	8	129	45	0.05	0.75	0.25	0.1800
10	2021	78840-87600	12	141	33	0.07	0.82	0.18	0.3600
11	2022	87600-96360	15	156	18	0.09	0.91	0.09	0.8333
12	2023	96360-105120	18	174	0	0.10	1.00	0	+∞

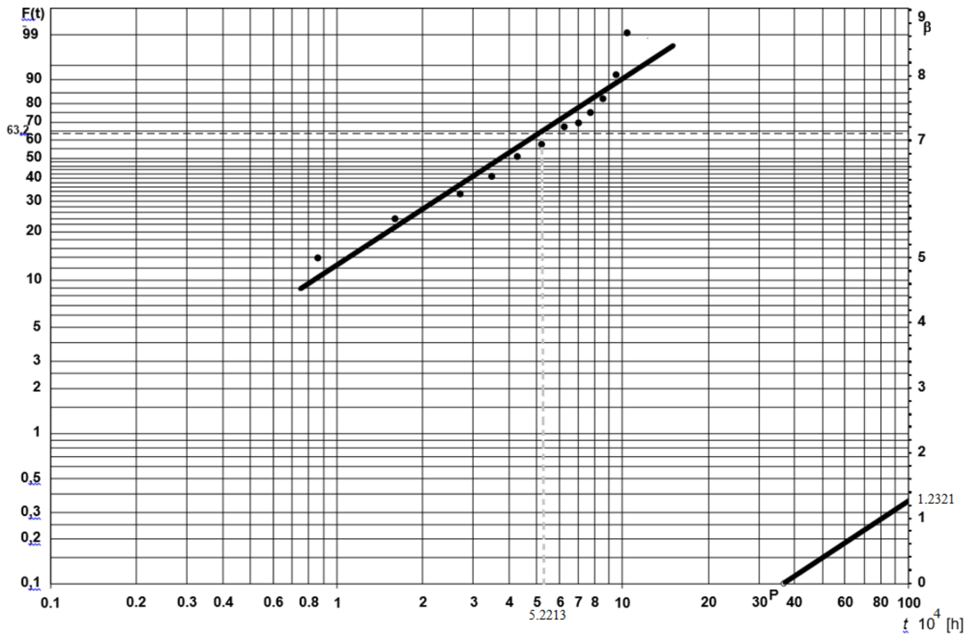

Figure 1. Weibull probability paper for simple distribution.

Table 2. Values of exploitation indicators - line I.

	Tk_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	f_i	F_i
1	2012	25	25	0.22	0.22
2	2013	15	40	0.13	0.35
3	2014	17	57	0.15	0.5
4	2015	12	69	0.11	0.61
5	2016	18	87	0.15	0.76
6	2017	11	98	0.1	0.86
7	2018	15	113	0.13	0.99

Table 3. Values of exploitation indicators - line II.

	Tk_i	Nn_i	$\sum_{i=1}^{n} Nn_i$	f_i	F_i
1	2019	8	8	0.13	0.13
2	2020	8	16	0.13	0.26
3	2021	12	28	0.2	0.46
4	2022	15	43	0.25	0.71
5	2023	18	61	0.29	1

By drawing the best possible straight lines through the plotted points (Fig. 2), the Weibull distribution parameters are obtained for both lines: η_{I} = 2.8523, β_{I} = 1.4875, η_{II} = 8.825, β_{II} = 8.1973.

Parameters for the best fitted statistical data are estimated by the least-square method, providing theoretical reliability functions for each interval:

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

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

$$R_{t\,\mathrm{I}}=\exp\left(-2.728\cdot 10^{-7}\,t^{1.4875}\right), \quad (8)$$

$$R_{t\,\mathrm{II}}=\exp\left(-2.874\cdot 10^{-41}\,t^{8.1973}\right). \quad (9)$$

Analytical expressions for theoretical reliability functions that represent the distribution laws of the observed random variable for the complex two-parameter Weibull distribution are as follows, /21/:

- Reliability

$$R_{tc}(t)=\frac{n_1}{n}R_{t\mathrm{I}}(t)+\frac{n_2}{n}R_{t\mathrm{II}}(t)\,, \tag{10}$$

$$R_{tc}(t)=0.6495\exp\left(-2.728\cdot10^{-7}t^{1.4875}\right)+0.3505\exp\left(-2.874\cdot10^{-41}t^{8.1973}\right). \tag{11}$$

- Failure density

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

$$f_{tc}(t)=2.636\cdot10^{-3}t^{0.4875}\exp\left(-2.728\cdot10^{-7}t^{1.4875}\right)+8.257\cdot10^{-37}t^{7.1973}\exp\left(-2.874\cdot10^{-41}t^{8.1973}\right). \tag{13}$$

- Failure rate

$$\lambda_{tc}=\frac{f_{tc}(t)}{R_{tc}(t)}=\frac{2.636\cdot10^{-3}t^{0.4875}\exp\left(-2.728\cdot10^{-7}t^{1.4875}\right)+8.257\cdot10^{-37}t^{7.1973}\exp\left(-2.874\cdot10^{-41}t^{8.1973}\right)}{0.6495\exp\left(-2.728\cdot10^{-7}t^{1.4875}\right)+0.3503\exp\left(-2.874\cdot10^{-41}t^{8.1973}\right)}\,. \tag{14}$$

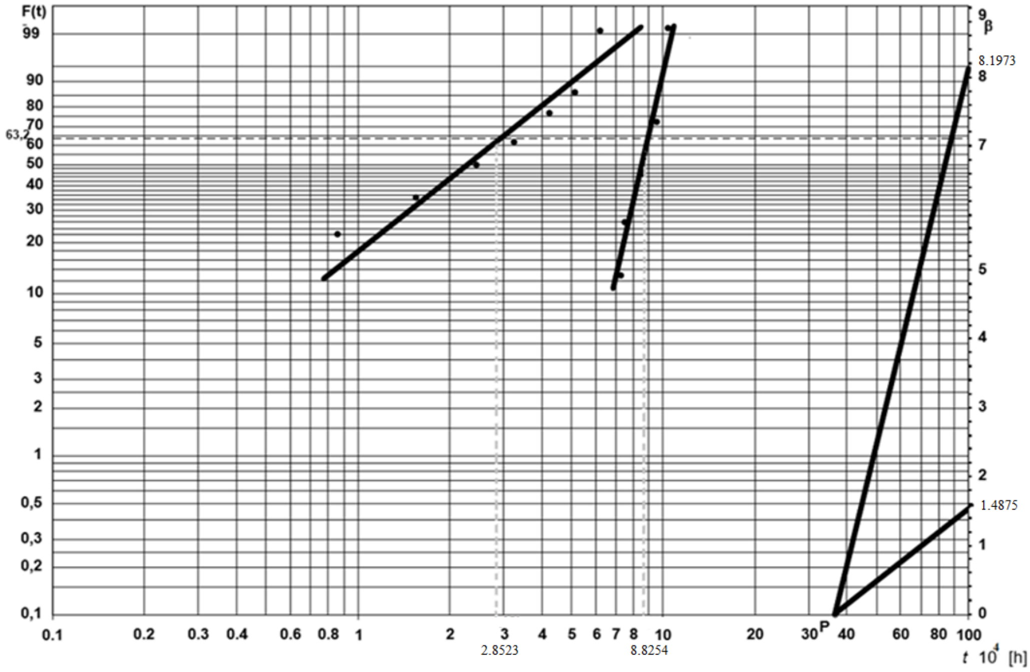

Figure 2. Weibull probability paper for complex distribution.

Graphical comparisons between operational and obtained values for theoretical reliability functions, failure density and failure rate of the thermal energy system TENT-B1 during the observation period are shown in Figs. 3-5.

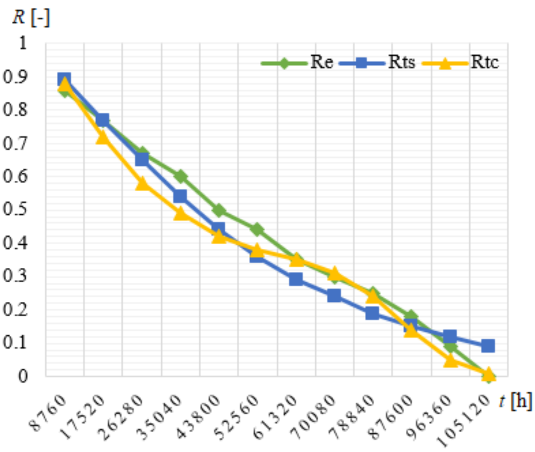

Figure 3. Exploitation and theoretical forms of reliability functions.

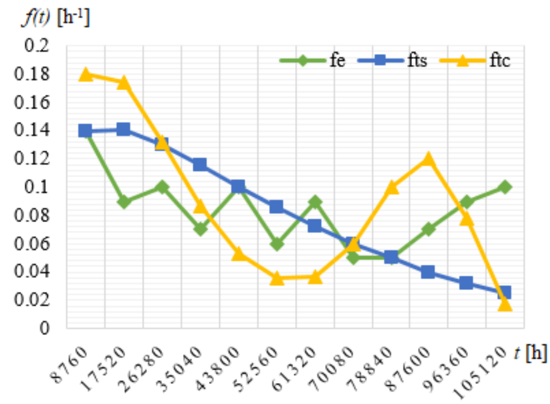

Figure 4. Exploitation and theoretical forms of failure density functions.

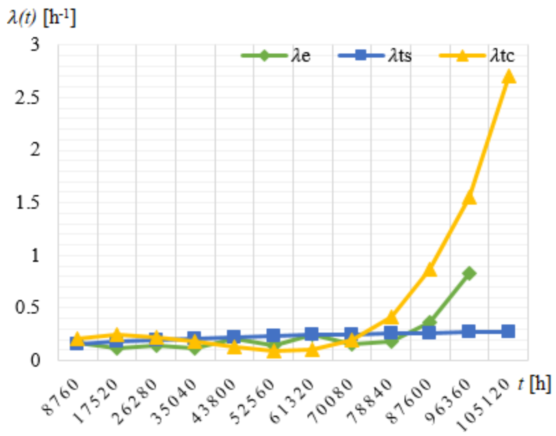

Figure 5. Exploitation and theoretical forms of failure rate functions.

CONCLUSIONS

Based on the exploitation research of the thermal energy system in TENT-B1 and the application of reliability theory, an insight into the laws of theoretical distribution of random variables are obtained. The confirmation of initial hypothesis that the distribution of this random variable approximates the Weibull distribution indicates relevance and applicability of this approach. For the sake of achieving a key goal of this research, the theoretical functions of the failure rate of thermal energy system are determined that required precise modelling of failure density and reliability functions.

By comparing the empirical and theoretical functions of the failure density, we come to the conclusion that the functions obtained by simple and complex Weibull distribution failed to accurately reproduce the empirical data. In the case of this particular thermal power system, it is more accurate to use a simple rather than a complex Weibull distribution to estimate the distribution law of the failure rate during the normal operation period.

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