PERFORMANCE AND BEHAVIOR ANALYSIS OF WATER CIRCULATION SYSTEM OF A THERMAL POWER PLANT

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Abstract

This paper analyses the performance and behavior of water circulation system (WCS) of a thermal power plant in fuzzy environment. For this purpose, fuzzy λ–τ technique coupled with petrinet modelling has been used. To address the vagueness in data, trapezoidal fuzzy numbers have been employed in fuzzy λ–τ technique. Various reliability indicators of WCS viz. failure rate, repair time, expected number of failures, mean time between failures, reliability and availability have been computed at ±15%, ±25% and ±40% spreads using fuzzy λ–τ technique. Further, fuzzy values of reliability indicators have been defuzzified employing COA method and the failure dynamics of WCS have been studied on account of decreasing / increasing trends of reliability indicators. The outcomes of this study are of great importance for plant personnel / management to enhance the availability of WCS.

Keywords: thermal power plant, water circulation system, fuzzy λ–τ technique, trapezoidal fuzzy number

1. Introduction

Thermal power plant is a prominent source of electricity generation. It is a complex arrangement of various systems / subsystems / components. The highest availability of a thermal power plant depends upon reliability and maintainability of each of its systems / subsystems. Unfortunately, system failure cannot be avoided entirely, but it can be reduced to minimum possible level by proper planning and following a suitable maintenance strategy [1]. Therefore, the failure prediction of each system in a thermal power plant is necessary for its successful and perpetual operation. Further, Water is an essential fluid used in a thermal power plant for ash removal, condenser cooling and steam generation etc. WCS of a thermal power plant regulates the flow of water and plays a vital role in its proper functioning. Therefore, it should remain operative with full capacity for longer duration.

Several techniques namely Markov technique, fault tree analysis and petrinet among others, are available in the literature for assessment of the performance / behavior of a system [2, 3]. The performance of many real-world industrial systems such as urea plants, sugar mills, paper mills and thermal power plants have been improved by using the probabilistic Markov technique, which considers a constant repair time and failure rate. Gupta et al. [4] calculated reliability indicators for plastic-pipe production plants, while, Garg et al. [5] analysed performance of a cattle feed plant employing Markov technique. Sikos and Klemes [6] optimised the availability, reliability and maintainability of a heat exchanger in a thermal power plant employing Markov technique. Modgil et al. [7] employed Markov technique to discuss the performance of a shoe upper manufacturing unit. Sharma and Vishwakarma [8] analysed performance of feeding system in a sugar industry employing Markov technique. Malik and Tewari [9] modeled the performance of water flow system in a thermal power plant using Markov technique.

To handle the uncertainty / imprecision of data due to system complexity as well as ambiguity in human verdicts, several academicians have employed fuzzy methodology (FM) for reliability analysis of systems in different sectors like healthcare, tunnel boring machines, power distribution systems and process industries. In fuzzy methodology, fuzzy numbers can be represented by triangular, trapezoidal, normal, gamma, gaussian types of membership functions. In literature, most of the studies using fuzzy methodology have been conducted using triangular membership functions due to their simplicity.

Fuzzy λ–τ technique using petrinet was proposed by Knezevic and Odoom [10] to analyse the behavior of a general production plant. Verma et al. [11] employed vague λ–τ technique with triangular fuzzy numbers and petrinet model to assess the reliability of combustion system of a gas turbine plant. The reliability of coal handling unit of a thermal power plant has been investigated by Kumar and Panchal [12] using fuzzy λ–τ technique with triangular fuzzy numbers. Srivastava et al. [13] analysed the reliability of a CNG dispensing unit using fuzzy λ–τ technique with triangular fuzzy numbers. Gopal and Panchal [14] evaluated the risk and reliability of milk process industry implementing fuzzy λ–τ technique with triangular fuzzy numbers. The performance of juice clarification unit has been analysed by Kushwaha et al. [15] employing triangular fuzzy numbers in intuitionistic fuzzy λ–τ technique.

In this paper, the performance of WCS in a thermal power plant has been analysed employing trapezoidal fuzzy numbers in fuzzy λ–τ technique coupled with petrinet modelling. The interval expressions for OR / AND transitions of petrinet model of WCS have been evaluated using trapezoidal fuzzy numbers. Here, trapezoidal fuzzy numbers have been chosen in the light of a comparison study presented by Princy and Dhenakaran [16]. They compared trapezoidal and triangular fuzzy membership functions and revealed the fact that "although trapezoidal membership functions make the procedure more complex but their performance is still better than the triangular membership functions". To counter the vagueness of input data, some reliability indicators of WCS have been evaluated at ±15%, ± 25% and ± 40% spreads. Then the obtained fuzzy values of reliability indicators have been defuzzified using COA method for quantitative analysis of performance of WCS.

2. Proposed Methodology

Fuzzy λ–τ technique [10] is a quantitative technique for analysing the performance of repairable systems in an ambiguous environment. In order to study the behavior of complex repairable systems, failure and repair rates are assumed to be constant in this technique. Moreover, this technique uses fuzzified values of repair time and failure rate data of each of its components / subsystems. This technique is more powerful than Markov technique since it takes care of ambiguity in repair time and failure rate data. Numerous researchers have implemented it in various areas like sugar mills, thermal power plants and chemical sector, among others. The various steps of methodology used in this paper are given below:

Step 1: Collect the information regarding various components and subsystems of WCS to construct its fault tree model and then its analogous petrinet model.

Step 2: Collect the data for failure rate and repair time of various components and subsystems of WCS.

Step 3: Fuzzify failure and repair data of each components and subsystems of WCS using trapezoidal membership function.

Step 4: Compute various reliability indicators of WCS at different spreads.

Step 5: Defuzzify the fuzzy values of reliability indicators employing COA method.

Step 6: Analyse the behavior of WCS.

3. Preliminaries

This section discusses some fuzzy set theory concepts to be used in this paper [17-19].

3.1. Fuzzy set

A fuzzy set $\widetilde{A}$ is defined as

$$\widetilde{A} = \left\{ \left(x, \mu_{\widetilde{A}}(x) \right) : x \in X \right\}, \tag{1}$$

where, $\mu_{\widetilde{A}} : X \rightarrow [0,1]$ is the membership function.

3.2. Fuzzy number

A normal convex fuzzy set $\widetilde{A}$ on real line R is called fuzzy number if its support is bounded.

3.3. Trapezoidal fuzzy number

A trapezoidal fuzzy number $\widetilde{A} = (l_1, l_2, u_1, u_2)$ has its membership function $\mu_{\widetilde{A}}(x)$ given by

$$\mu_{\widetilde{A}}(x) = \begin{cases} \dfrac{x-l_1}{l_2-l_1}, & l_1 \le x \le l_2 \\ 1, & l_2 \le x \le u_1 \\ \dfrac{u_2-x}{u_2-u_1}, & u_1 \le x \le u_2 \\ 0, & otherwise \end{cases} . \tag{2}$$

3.4. α–cut of a trapezoidal fuzzy number

The α-cut of the trapezoidal fuzzy number $\widetilde{A}$ is given by

$$[l^{\alpha}, u^{\alpha}] = [l_1 + (l_2 - l_1)\alpha, u_2 - (u_2 - u_1)\alpha], \qquad \text{where, } \alpha \in [0,1]$$

and is shown in the figure 1.

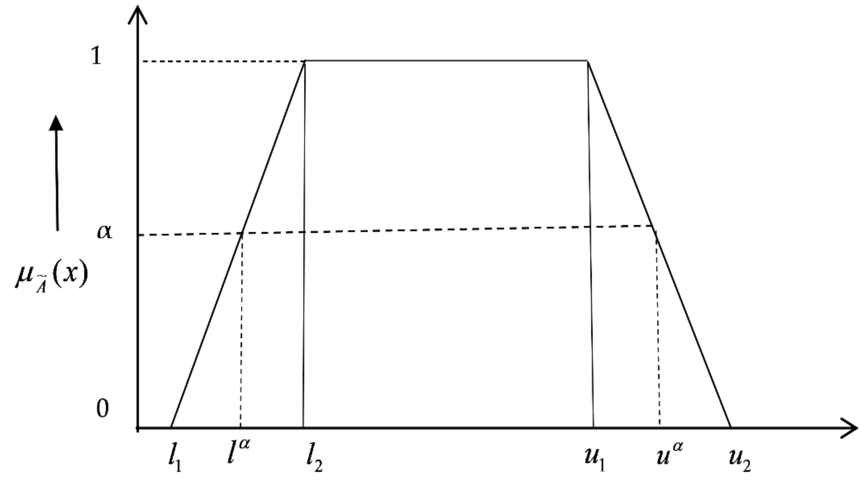

Figure 1: *Trapezoidal fuzzy number with α-cut*

4. An application

Water circulation system has a significant role for proper functioning of a thermal power plant and therefore should remain operative for longer duration. The hot water collected from the condenser enters into the condensate extraction pump and then passes to low pressure (LP) heater where its temperature is further increased to improve the system efficiency. The hot water further passes through the deaerator where the dissolved gases are removed from the hot water. The ash content free water then enters into the high pressure (HP) heater with the help of the boiler feed pump and further enters into the economiser. In economiser, the hot flue gases exiting the boiler are used to heat the feed water. This heated water enters the boiler drum, where super-heated steam is generated by super heaters of boiler. This steam is expanded in turbine to produce mechanical energy by the turbine shaft. Then the exhaust steam is condensed in condenser. Figure 2 depicts schematic flow diagram of WCS. It is made up of five subsystems as described below:

i. **Subsystem 1 (SS_1):** It consists a condensate extraction pump (CEP) which is used to extract the condensate. The system will stop working if CEP fails.

ii. **Subsystem 2 (SS_2):** It is made up of three LP heaters which are linked in a parallel arrangement and are used to raise the condensate's temperature. If one of them fails, the system will run at a lower efficiency.

iii. **Subsystem 3 (SS_3):** It consists a deaerator to extract dissolved gases from hot water obtained from LP heater. The efficiency of the system reduces if deaerator fails.

iv. **Subsystem 4 (SS_4):** Three boiler feed pumps (BFP) are connected in a parallel configuration in this subsystem. They are responsible for supplying hot water to the HP heater. The system efficiency is reduced if any of these pumps fails.

v. **Subsystem 5 (SS_5):** It is made up of two HP heaters that are connected in a parallel manner. They are used to further heat the water received from the boiler feed pump. The efficiency of the system reduces if anyone HP heater fails.

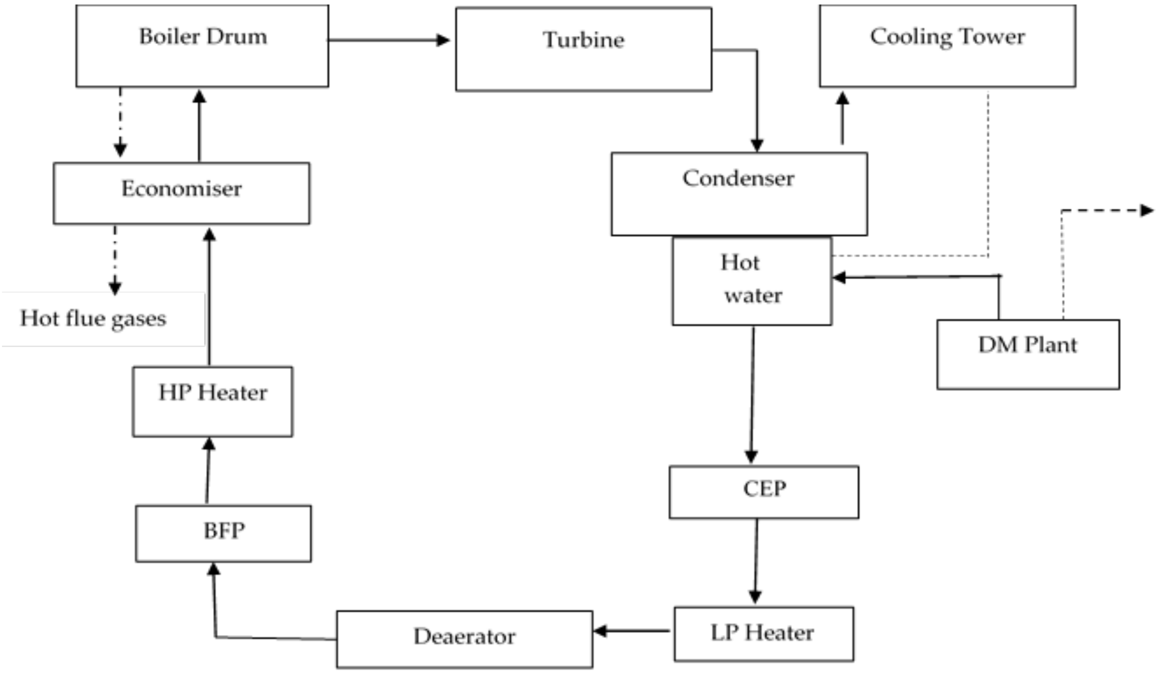

Figure 2: *Flow diagram of water circulation system*

5. Reliability Analysis of WCS

The reliability of WCS has been calculated using following steps:

Step 1. Fault tree and petrinet models construction: First a fault tree model of the complicated parallel and series arrangement of the WCS has been prepared (figure 3) and then its equivalent petrinet model has been developed (figure 4). The AND gate represents the parallel arrangement of components, while, the OR gate represents the series arrangement of components in these models.

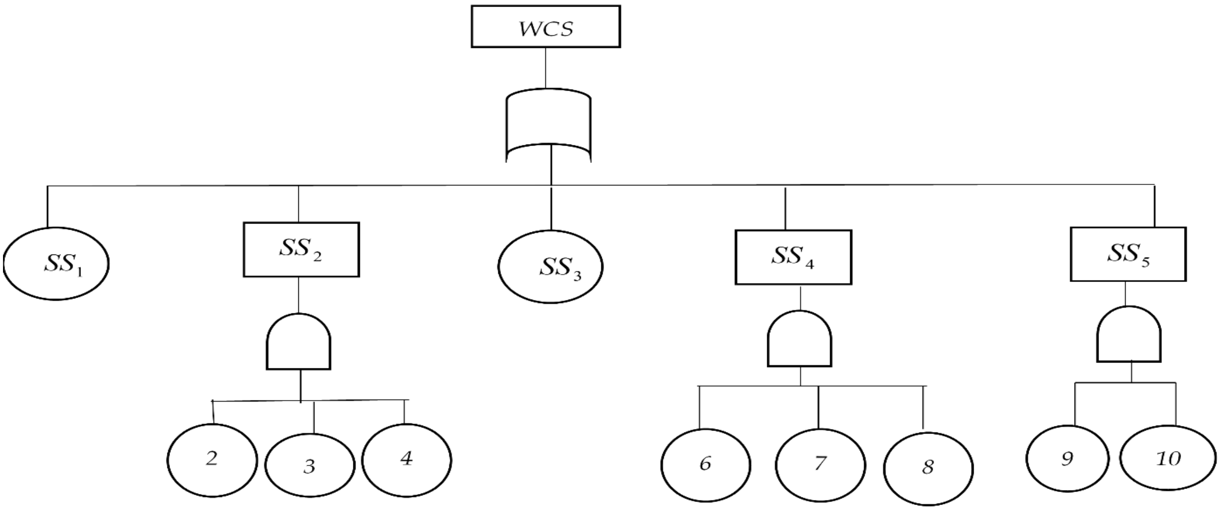

Figure 3: *Fault tree model of WCS*

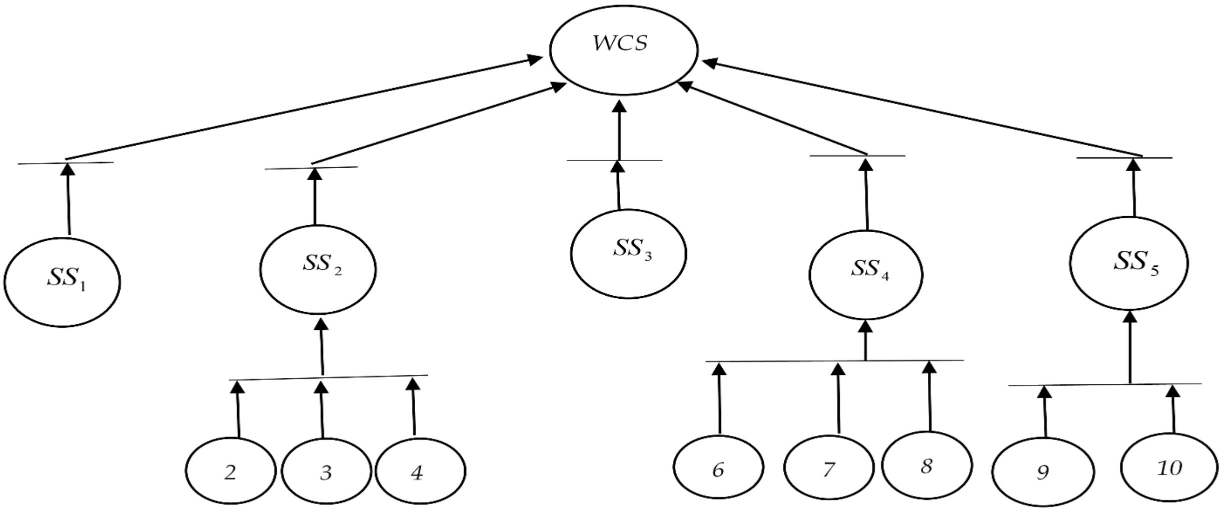

Figure 4: *Petrinet model of WCS*

Step 2. Data extraction: The failure and repair data of all ten components of WCS acquired from service logbook and validated by a maintenance specialist are given in Table 1 [20].

Table 1: *Failure and repair data of different components of WCS*

Components	Failure rate λ_k (failures / h)	Repair time τ_k (h)
Condensate extraction pump (SS_1) ($k = 1$)	5.78×10^{-5}	11
Low pressure heater (SS_2) ($k = 2, 3, 4$)	3.85×10^{-5}	16
Deaerator (SS_3) ($k = 5$)	1.15×10^{-4}	9
Boiler feed pump (SS_4) ($k = 6, 7, 8$)	1.15×10^{-4}	11
High pressure heater (SS_5) ($k = 9, 10$)	3.85×10^{-5}	11

Step 3. Fuzzification of crisp data: The acquired crisp data for repair time and failure rate has been fuzzified into trapezoidal fuzzy numbers using trapezoidal membership functions to reduce ambiguity in the collected data. The values of $\lambda_{k2}, \lambda_{k3}, \tau_{k2}$ and τ_{k3} have been fixed at ±10% of acquired crisp data whereas the values of $\lambda_{k1}, \lambda_{k4}, \tau_{k1}$ and τ_{k4} have been changed at ±15%, ± 25% and ± 40% spreads for each component of the system. Figure 5 depicts trapezoidal fuzzy numbers for failure rate (λ_k) and repair time (τ_k) for k^{th} component.

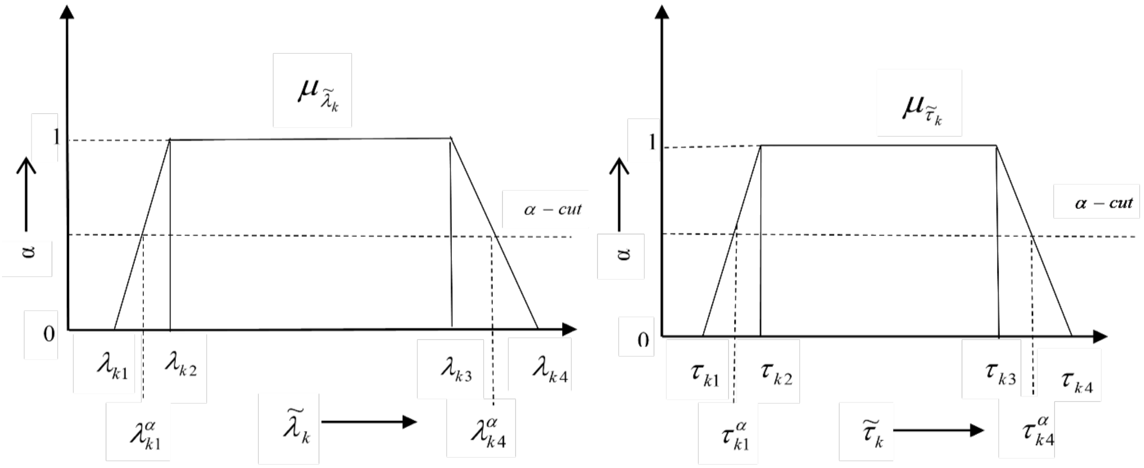

Figure 5: *Trapezoidal fuzzy numbers for failure rate* (λ_k) *and repair time* (τ_k) *for* k^{th} *component*

Step 4. Computation of fuzzy reliability indicators: After fuzzifying the failure rate and repair time of all the components of WCS shown in petrinet model (figure 4) as trapezoidal fuzzy numbers, the fuzzy failure rate and repair time of the top most position of petrinet model of WCS are evaluated using interval expressions for OR / AND transitions presented in equations (3-6). These interval expressions are obtained utilising the extension principle and α-cut along with interval arithmetic operations on the basic λ-τ expressions for OR / AND gates given in Table 2.

Table 2: *Basic expressions for λ-τ technique*

Gate	λ_{OR}	τ_{OR}	λ_{AND}	τ_{AND}
Expressions (n-inputs)	$\sum_{k=1}^{n}\lambda_k$	$\dfrac{\sum_{k=1}^{n}\lambda_k\tau_k}{\sum_{k=1}^{n}\lambda_k}$	$\prod_{l=1}^{n}\lambda_l\left[\sum_{l=1}^{n}\prod_{\substack{l=1\\k\neq l}}^{n}\tau_l\right]$	$\dfrac{\prod_{k=1}^{n}\tau_k}{\sum_{l=1}^{n}\left[\prod_{\substack{k=1\\k\neq l}}^{n}\tau_k\right]}$

Interval expressions for OR transition

$$\tau^{\alpha}=\left[\frac{\sum_{k=1}^{n}\left[\{\lambda_{k1}+(\lambda_{k2}-\lambda_{k1})\alpha\}.\{\tau_{k1}+(\tau_{k2}-\tau_{k1})\alpha\}\right]}{\sum_{k=1}^{n}\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\}},\ \frac{\sum_{k=1}^{n}\left[\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\}.\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}\right]}{\sum_{k=1}^{n}\{\lambda_{k1}+(\lambda_{k2}-\lambda_{k1})\alpha\}}\right], \tag{3}$$

$$\lambda^{\alpha}=\left[\sum_{k=1}^{n}\{\lambda_{k1}+(\lambda_{k2}-\lambda_{k1})\alpha\},\ \sum_{k=1}^{n}\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\}\right]. \tag{4}$$

Interval expressions for AND transition

$$\tau^{\alpha}=\left[\frac{\prod_{k=1}^{n}\{\tau_{k1}+(\tau_{k2}-\tau_{k1})\alpha\}}{\sum_{l=1}^{n}\left[\prod_{\substack{k=1\\k\neq l}}^{n}\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}\right]},\ \frac{\prod_{k=1}^{n}\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}}{\sum_{l=1}^{n}\left[\prod_{\substack{k=1\\k\neq l}}^{n}.\{\tau_{k1}+(\tau_{k2}-\tau_{k1})\alpha\}\right]}\right], \tag{5}$$

$$\begin{aligned}\lambda^{\alpha}=\Big[&\Pi_{k=1}^{n}\{\lambda_{k1}+(\lambda_{k2}-\lambda_{k1})\alpha\}.\sum_{l=1}^{n}\left[\Pi_{k=1,k\neq l}^{n}\{\tau_{k1}+(\tau_{k2}-\tau_{k1})\alpha\}\right],\\ &\Pi_{k=1}^{n}\{\lambda_{k4}-(\lambda_{k4}-\lambda_{k3})\alpha\}.\sum_{l=1}^{n}\left[\Pi_{k=1,k\neq l}^{n}\{\tau_{k4}-(\tau_{k4}-\tau_{k3})\alpha\}\right]\Big].\end{aligned} \tag{6}$$

To analyse the performance of WCS quantitatively the reliability indicators viz., failure rate, repair time, expected number of failures, mean time to failure, mean time to repair, mean time between failures, reliability and availability are calculated using expressions given in Table 3 at ±15%, ±25% and ± 40% spreads for $\alpha = 0.0\ (0.1)\ 1.0$.

Table 3: *Expressions for reliability indicators*

Reliability indicator	**Expression**
Expected number of failures	$ENOF = \frac{\lambda \gamma t}{\gamma + \lambda} + \frac{\lambda^2}{(\gamma + \lambda)^2}\left[1 - e^{-(\gamma + \lambda)t}\right]$
Mean time to failure	$MTTF = \frac{1}{\lambda}$
Mean time to repair	$MTTR = \frac{1}{\gamma} = \tau$
Mean time between failures	$MTBF = MTTF + MTTR$
Reliability	$R = e^{-\lambda t}$
Availability	$A = \frac{\gamma}{\gamma + \lambda} + \frac{\lambda}{\gamma + \lambda} e^{-(\gamma + \lambda)t}$

The left and right spread fuzzy values of the reliability indicators of WCS at 15% spread are presented in Table 4 and Table 5, respectively. The fuzzy reliability indicators at ±15%, ± 25% and ± 40% spreads for $\alpha = 0.0\ (0.1)\ 1.0$ are depicted in figure 6.

Table 4: *The left spread fuzzy values of WCS at 15% spread*

α	Failure Rate $\times 10^{-4}$ (/h)	Repair Time (h)	ENOF $\times 10^{-2}$	MTBF $\times 10^{3}$ (h)	Reliability	Availability
1.0	1.555441	7.118736	2.610373	5.266834	0.968564	0.997535
0.9	1.546797	7.007978	2.595923	5.242912	0.968423	0.997487
0.8	1.538153	6.898654	2.581470	5.219206	0.968282	0.997438
0.7	1.529509	6.790745	2.567017	5.195713	0.968142	0.997389
0.6	1.520865	6.684231	2.552621	5.172431	0.968001	0.997339
0.5	1.512222	6.579095	2.538106	5.149355	0.967861	0.997288
0.4	1.503578	6.475318	2.523648	5.126484	0.967720	0.997236
0.3	1.494934	6.372881	2.509189	5.103816	0.967579	0.997183
0.2	1.486290	6.271767	2.494729	5.081346	0.967439	0.997129
0.1	1.477647	6.171960	2.480267	5.059073	0.967298	0.997074
0	1.469003	6.073441	2.465804	5.036994	0.967158	0.997019

Table 5: *The right spread fuzzy values of WCS at 15% spread*

α	Failure Rate $\times 10^{-4}$ (/h)	Repair Time (h)	ENOF $\times 10^{-2}$	MTBF $\times 10^{3}$ (h)	Reliability	Availability
1.0	1.901244	12.999494	3.186822	6.442043	0.974207	0.998894
0.9	1.909890	13.191290	3.201183	6.478163	0.974349	0.998917
0.8	1.918536	13.385785	3.215540	6.514689	0.974490	0.998940
0.7	1.927182	13.583026	3.229894	6.551628	0.974632	0.998962
0.6	1.935829	13.783060	3.244246	6.588987	0.974773	0.998984
0.5	1.944475	13.985935	3.258594	6.626774	0.974915	0.999006
0.4	1.953122	14.191699	3.272938	6.664995	0.975056	0.999027
0.3	1.961768	14.400403	3.287279	6.703659	0.975198	0.999048
0.2	1.970415	14.612099	3.301617	6.742773	0.975339	0.999069
0.1	1.979061	14.826838	3.315951	6.782345	0.975481	0.999089
0	1.987708	15.044674	3.330282	6.822383	0.975623	0.999109

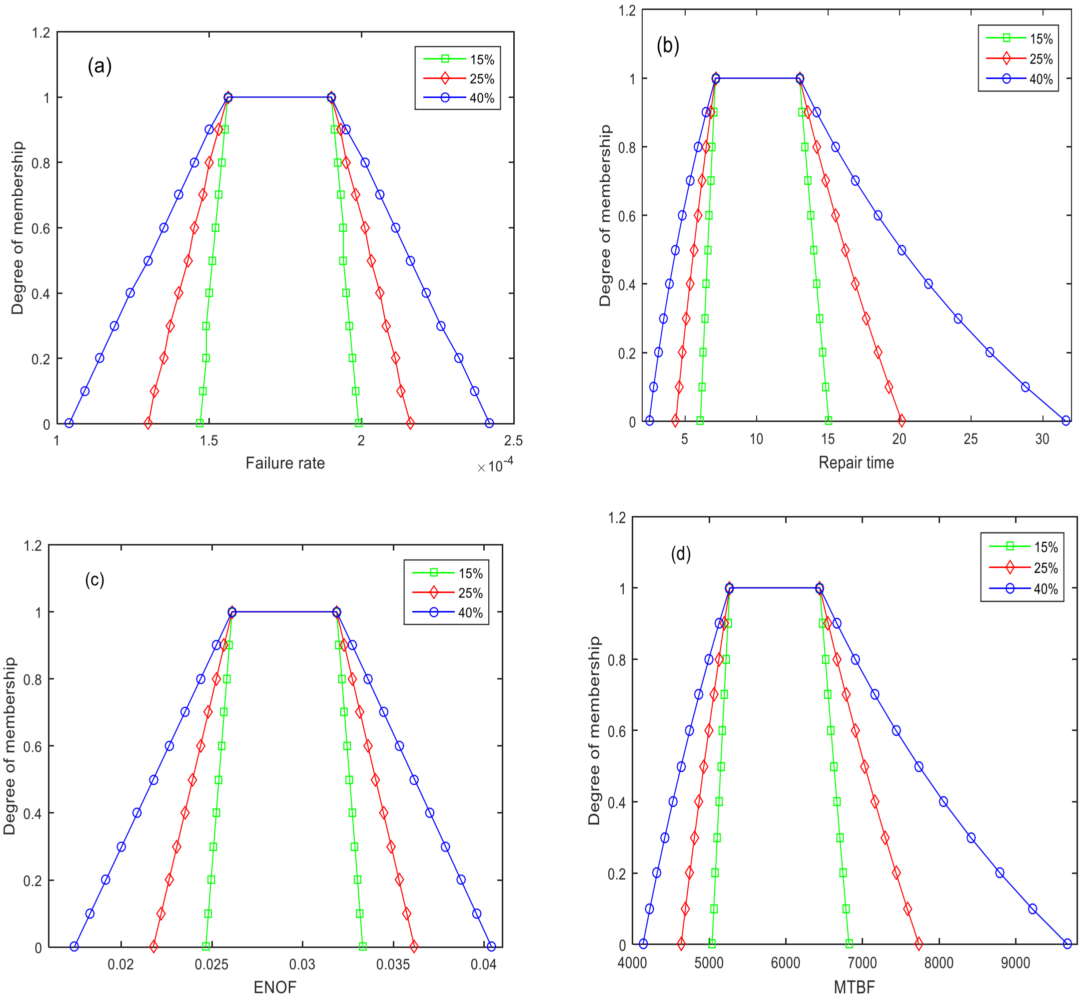

Figure 6: *Graph representation of fuzzy reliability indicators*

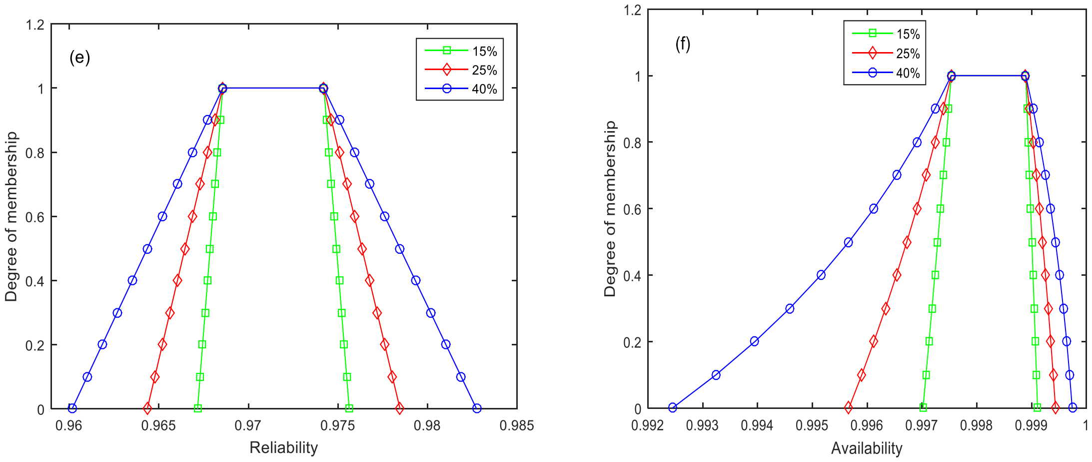

Figure 6: *Graph representation of fuzzy reliability indicators (continued)*

Step 5. Defuzzification of fuzzy reliability indicators: The fuzzy results of reliability indicators are defuzzified by employing COA method for defuzzification. The reliability indicators have been defuzzified for ±15%, ±25% and ±40% spreads using equation (7) and are presented in Table 6 together with their crisp values.

$$\bar{x} = \frac{\int_{x_1}^{x_2} x.\mu_{\tilde{A}}(x)dx}{\int_{x_1}^{x_2} \mu_{\tilde{A}}(x)dx} \qquad (7)$$

Table 6: *Values of reliability indicators of WCS*

Reliability Indicator	**Crisp Value**	**Defuzzified Values**		
		Spreads		
		± 15 %	± 25 %	± 40 %
Failure rate $\times 10^{-4}$ (/h)	1.728332	1.730000	1.730000	1.731031
Repair time (h)	9.668175	10.327083	11.320939	14.323654
ENOF $\times 10^{-2}$	2.898757	2.898380	2.897209	2.894103
MTBF $\times 10^{3}$ (h)	5.795593	5.894658	6.043965	6.493699
Reliability	0.971382	0.971388	0.971397	0.971421
Availability	0.998332	0.998134	0.997831	0.996912

6. Results and Discussion

It is observed from the behavioral graphs given in figure 6 that the membership curves of many reliability indicators are deformed trapezoids, whose non-parallel sides are parabolic. Further, it is demonstrated that the defuzzified values vary with changes in spread. For instance, for the spread expansion from ±15% to ±25%, the failure rate does not change, the reliability increases marginally, the repair time and MTBF increase by 9.62% and 2.53%, respectively, the ENOF and availability decrease by 0.04% and 0.03%, respectively. Further, for spread expansion from ±25% to ±40%, failure rate, repair time, MTBF and reliability increase by 0.06%, 26.52%, 7.44% and 0.002%, respectively, while, ENOF and availability decrease by 0.10% and 0.09%, respectively. The effect of spread change is most significant on repair time in comparison to other reliability indicators, resulting in system availability loss. These findings will assist plant managers in planning and adapting best maintenance policy to improve performance of WCS and minimise operational and maintenance expenses.

7. Conclusion

In this study, the performance of WCS of a thermal power plant has been analysed using fuzzy λ–τ technique. Trapezoidal fuzzy numbers have been employed to remove ambiguity in acquired data. To eliminate unexpected failure of the plant, the trend of different reliability indicators viz. repair time, failure rate, reliability, availability, ENOF and MTBF with respect to spread changes has been analysed. The maintenance personnels of the considered system should focus at system's availability because it diminishes by increasing spread, which is unfavorable. The reason behind this is that repair time varies more rapidly in comparison to other reliability indicators. A structured framework has been established in this research to assist maintenance engineers for improving availability of the considered plant.

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