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Development of simulation model for performance evaluation of feed water system in a typical thermal power plant

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Abstract: The present paper deals with development of a simulation model for the performance evaluation of feed water system of a thermal power plant using Markov Birth-Death process and probabilistic approach. In present paper, the feed water system consists of four subsystems. After drawing transition diagram for feed water system, differential equations are developed and then solved recursively using probabilistic approach. Then to predict the steady state availability i.e. measure of performance of feed water system, normalizing conditions are used. Thus availability simulation model has been developed. After that, the availability matrix and plots of failure/repair rates of all subsystems are prepared to decide the availability trends. Based upon various availability values in the availability matrix, performance of feed water system has been evaluated. Further the optimum values of failure/repair rates for maximum system availability have also been determined. The finding of this paper might be helpful to the plant management for futuristic maintenance decisions.

Keywords: *Simulation model; Probabilistic approach; Availability model; Availability matrix; Maintenance decisions*

1. Introduction

System availability gives a measure of how well a system performs or meets its design objectives. For increasing the productivity, availability and reliability of equipment / subsystems in operation must be maintained at highest order. To achieve high production goals, the systems should be remain operative (run failure free) for maximum possible duration. A thermal power plant is a complex engineering system comprising of various systems: Coal handling, Steam Generation, Cooling Water, Crushing, Ash handling, Power Generation and Feed Water system. For regular and economical generation of steam, it is necessary to maintain each subsystem of feed water system. So to achieve high production and good quality, there should be highest system availability. Performance analysis consists of three major activities that are components of any problem solving process:

1. Defining the problem,
2. Analyzing data to identify gaps between the desired and actual state, and their causes,
3. Selecting the appropriate solution blend that will address those causes.

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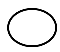
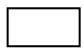
2. Notations


Indicates the system is in full working state.


Indicates the system is in reduced capacity state.


Indicates the system is in failed state.

B,C,F,E	Denotes full working states of Boiler, Condenser, Feed pump and Economizer.
b,c,f,e	Denotes failed states of Boiler, Condenser, Feed pump and Economizer.
F_1	Denotes that the subsystems F is working with standby unit.
E_1	Denotes that the subsystem E is working in reduced capacity state.
$P_0(t)$	Probability of the system working with full capacity at time't'.
$P_3(t)$	Probability of the system in cold standby (working) state.

$P_4(t)$, $P_8(t)$	Probabilities of the system in reduced capacity (working) state.
$P_1(t)$, $P_2(t)$, $P_5(t)$-$P_7(t)$, $P_9(t)$-$P_{15}(t)$	Probabilities of the system in failed state.
ϕ_i ,i=1-4	Mean failure rate of B,C,F,E respectively.
λ_i ,i=1-4	Mean rate of repairs of B,C,F,E respectively.
d/dt	Represents derivative w.r.t. time (t).

3. Literature review

The maintenance of repairable systems has been widely studied by many authors, considering different focus of interest, such as the repair /replacement policy, periodic inspections, degrading, optimization problems, among other topics. Depending on the point of view in the study of the systems, useful quantities in their evolution as performance measures, distribution functions of random times involved in the systems, transient and stationary behavior, simulation models, and many others, have been calculated (Rafael, 2004).

Papers about preventive maintenance policies, and condition based on inspection/replacement policies are frequent in the specialized literature, see Refs (Gertsbakh, 1977; Gertsbakh, 2000). Smith and Dekker (Smith and Dekker, 1997) considered a cold standby system and studied the up and down times, and performed an exponential approximation. When general distributions are involved, the calculations are analytically intractable, and it is necessary to introduce approximation methods for applications. A text of general interest for studying reliability systems and performance measures is that of Hoyland and Rausand (1994). In most of the complex systems encountered in practice, it has been observed that they consist of components and subsystems connected in series, parallel or standby, or a combination of these (Gupta *et al.*, 2007). The rate of failure of each subsystem in a particular system depends upon the operating conditions and repair policies used (Kumar and Pandey, 1993). From economic and operational point of view, it is desirable to ensure an optimum level of system availability. According to Barabady *et al.* (2007), the most important performance measures for repairable system designers and operators are system reliability and availability. Availability and reliability are good evaluations of a system's performance. Their values depend on the system structure as well as the component availability and reliability. These values decrease as the component ages increase; i.e. their serving times are influenced by their interactions Simulation model for feed water system 2 with each other, the applied maintenance policy and their environments (Samrout, 2005).

Performance analysis forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation and evaluation, Joseph, 2006). It is not possible to determine the value of an intervention without having analysis data that would allow one to show improvement over a baseline level of performance (Deming, 1982), thereby highlighting the importance of sound performance analysis practices. An example of a performance analysis effort is described by Clark and Estes (2002), which highlights the importance of conducting quality performance analyses.

Other texts of interest related to the topics studied in the present paper are Avel *et al.* (1999), Belyayev *et al.* (1984), Birolini (1994), Gnedenko *et al.* (1995), Ross (1983), Ushakov (1994, 2000). Barata *et al.* (2000, 2002) solved maintenance problems through Monte-Carlo simulations for deteriorating systems. Lim and Chang (2000) studied a repairable system modeled by a Markov chain with two repair modes.

4. Theory

Feed water unit ensures proper supply of water for sound functioning of thermal Power Plant. The feed water used in the steam boiler is a means of transferring heat energy from the burning fuel to the mechanical energy of the spinning steam turbine. The total feed water consists of re-circulated condensed steam, referred to as condensate, from the steam turbines plus purified makeup water. The feed water cycle begins with condensate water being pumped out of the condenser after traveling through the steam turbines. The water flows through a series of intermediate feed water heaters, heated up at each point with steam extracted from an appropriate duct on the turbines and gaining temperature at each stage (Gupta *et al.*, 2007).

5. Experiment

The transition diagram (Srinath, 1994) as given in Figure 1 of the feed water system shows the various possible states. Based on the transition diagram, a simulation model will be developed.

The failures and repairs for this purpose have been modeled as a birth and death process. The failure and repair rates are statistically independent and these are obtained with the help of history cards and maintenance sheets of various subsystems of the feed water system available with maintenance personnel of the thermal plant. The description of system and assumptions associated with the transition diagram of feed water system are as follows:

5.1. System description

The feed water system consists of four subsystems, which are as follows:

1. Boiler (B): This subsystem is single unit, failure of which leads to system failure,
2. Condenser (C): This subsystem consists of single unit, failure of which leads to system failure,
3. Feed Water Pump (F): This subsystem consists of two pumps, one working at a time and other remains standby. The system failure occurs only when both pumps fail,
4. Economizer (E): This subsystem consists of single unit, failure of which never leads to system failure, rather system work in reduced capacity.

5.2. Assumptions

The assumptions used in developing the probabilistic simulation model are:

1. There is no simultaneous failure. (Khanduja, 2008),
2. A repaired system is as good as new, performance wise, for a specified duration. (Gupta *et al.*, 2008),
3. Service includes repair and / or replacement (Tewari *et al.*, 2003),
4. The system may work at reduced capacity (Kumar *et al.*, 2007),
5. Sufficient repair facilities are provided,
6. Standby systems are of the same nature as that of active systems (Tewari and Kumar, 1992; Tewari and Sharma, 2004),
7. Failure / repair rates are constant over time and statistically independent. (Gupta *et al.*, 2009),
8. System time between failure and repair time follows an exponential distribution.

5.3. Simulation modeling

The simulation model for feed water system of thermal power plant has been developed to predict operational availability of the system. The failure and repair rates of the different subsystems are used as standard input information to the model. The flow of states for the system under consideration has been described in a state transition diagram as shown in Figure 1, which is logical representation of all possible state's probabilities encountered during the failure analysis of a steam thermal power plant.

Formulation is carried out using the joint probability functions based on the transition diagram (Gupta *et al.*, 2009). The system starts from a particular state at time 't' and reaches another state (failed) or remain in the same state (operative) during the time interval Δt. The transition probability depends upon the preceding state of the system. The state of the system defines the condition at any instant of time and the information is useful in analyzing the current state and in the prediction of the failure state of the system. The mathematical Modeling is done using a simple probabilistic consideration and following differential equations are developed using a Markov birth-death process (Kumar *et al.*, 2007).

$$\left(\frac{d}{dt}+\sum_{i=1}^{4}\phi_i\right)P_0(t)=\sum_{i=1}^{4}\lambda_i P_i(t) \tag{1}$$

$$\left(\frac{d}{dt}+\sum_{i=1}^{4}\phi_i+\lambda_3\right)P_3(t)=$$

$$\sum_{i=1}^{4}\lambda_i P_{i+4}(t)+\phi_3 P_0(t) \tag{2}$$

$$\left(\frac{d}{dt}+\sum_{i=1}^{4}\phi_i+\lambda_4\right)P_4(t)=\sum_{i=1}^{2}\lambda_i P_{i+8}(t)$$

$$+\lambda_3 P_8(t)+\lambda_4 P_{11}(t) \tag{3}$$

$$\left(\frac{d}{dt}+\sum_{i=1}^{4}\phi_i+\lambda_3+\lambda_4\right)P_3(t)=\sum_{i=1}^{4}\lambda_i P_{16-i}(t)$$

$$+\phi_4 P_3(t)+\phi_3 P_4(t) \tag{4}$$

$$\left(\frac{d}{dt}+\lambda_m\right)P_i(t)=\phi_m P_j(t) \tag{5}$$

with the initial condition $P_0(0)=1$ and zero otherwise.

Since any thermal plant is a process industry where raw material is processed through various subsystems continuously till the final product is obtained. Thus, putting derivative of all probability equal to zero as attains the long run availability of the system of a thermal plant. Therefore by putting $d/dt = 0$ *at* $t \to \infty$ (Arora and Kumar, 1997) into differential equations, one gets:

$$P_i = (\phi_m / \lambda_m) P_j \tag{6}$$

where in Equation (6), for m = 1, then i = 1 and j=0, i = 5 and j = 3, i = 9 and j = 4, i = 15 and j = 8.

For m = 2, then i = 2 and j = 0, i = 6 and j = 3, i = 10 and j = 4, i = 14 and j = 8. For m = 3, then i = 7 and j = 3, i = 13 and j = 8. For m = 4, then i = 11 and j = 4, i = 12 and j = 8.

Now putting the values of probabilities from Equations (6) in Equations (1) to (4), and solving these equations recursively, we can found the values of all state probabilities in terms of full working state probability i.e. P_0.

$$P_1 = \frac{\phi_1}{\lambda_1} P_0, \quad P_2 = \frac{\phi_2}{\lambda_2} P_0, \quad P_3 = C_6 P_0,$$

$$P_4 = C_7 P_0, \quad P_5 = \frac{\phi_1}{\lambda_1} C_6 P_0, \quad P_6 = \frac{\phi_1}{\lambda_1} C_6 P_0,$$

$$P_7 = \frac{\phi_3}{\lambda_3} C_6 P_0, \quad P_8 = C_5 P_0, \quad P_9 = \frac{\phi_1}{\lambda_1} C_7 P_0,$$

$$P_{10} = \frac{\phi_2}{\lambda_2} C_7 P_0, \quad P_{11} = \frac{\phi_4}{\lambda_4} C_7 P_0, \quad P_{12} = \frac{\phi_4}{\lambda_4} C_5 P_0,$$

$$P_{13} = \frac{\phi_3}{\lambda_3} C_5 P_0, \quad P_{14} = \frac{\phi_2}{\lambda_2} C_5 P_0, \quad P_{15} = \frac{\phi_1}{\lambda_1} C_5 P_0.$$

where

$$C_1 = \phi_3 + \phi_4, \quad C_2 = \phi_4 + \lambda_3, \quad C_3 = \phi_3 + \lambda_4$$

$$C_4 = \lambda_4 + \lambda_3, \quad C_5 = \frac{C_1 C_2 C_3 - \phi_3 \lambda_3 - \phi_4 \lambda_4}{2\lambda_3 \lambda_4}$$

$$C_6 = \frac{\phi_3 + \lambda_4 C_5}{C_2}, \quad C_7 = \frac{C_4 C_5 - C_6 \phi_4}{\phi_3}$$

5.4. Steady state availability using normalizing condition

The probability of full working capacity (without standby systems), namely, P_0 is determined by using normalizing condition: (i.e. sum of the probabilities of all working states, reduced capacity and failed states is equal to 1, Tewari *et al.*, 2003).

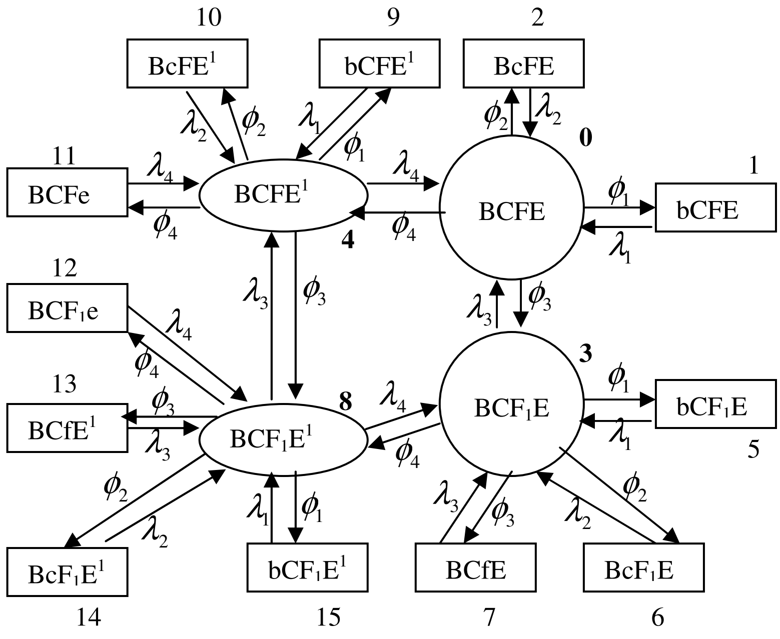


Figure 1: Transition diagram of Feed Water system.

Table1: Availability matrix for various subsystems of Feed Water System.

Subsystem 1: Boiler						
ϕ_1 \ λ_1	0.02	0.04	0.06	0.08	0.1	Constant values
0.0006	0.7425	0.7509	0.7537	0.7551	0.7560	ϕ_2 = 0.0076, λ_2 =0.3
0.0007	0.7398	0.7495	0.7528	0.7544	0.7554	ϕ_3 = 0.06, λ_3 =0.3
0.0008	0.7370	0.7481	0.7518	0.7537	0.7548	ϕ_4 =0.007, λ_4 =0.125
0.0009	0.7343	0.7467	0.7509	0.7530	0.7543	
0.001	0.7316	0.7453	0.7499	0.7523	0.7537	
Subsystem 2: Condenser						
ϕ_2 \ λ_2	0.1	0.2	0.3	0.4	0.5	Constant values
0.0050	0.7541	0.7555	0.7590	0.7631	0.7666	ϕ_1 = 0.0008, λ_1 =0.06
0.0063	0.7483	0.7487	0.7551	0.7609	0.7653	ϕ_3 = 0.06, λ_3 =0.3
0.0076	0.7407	0.7424	0.7518	0.7592	0.7643	ϕ_4 =0.007, λ_4 =0.125
0.0089	0.7305	0.7365	0.7491	0.7578	0.7636	
0.0102	0.7194	0.7309	0.7467	0.7566	0.7630	
Subsystem 3 : Feed Water pump						
ϕ_3 \ λ_3	0.1	0.2	0.3	0.4	0.5	Constant values
0.02	0.7518	0.8129	0.8356	0.8474	0.8546	ϕ_1 = 0.0008, λ_1 =0.06
0.04	0.6535	0.7518	0.7915	0.8129	0.8264	ϕ_2 = 0.0076, λ_2 =0.3
0.06	0.5780	0.6992	0.7518	0.7812	0.7999	ϕ_4 =0.007, λ_4 =0.15
0.08	0.5181	0.6535	0.7159	0.7518	0.7751	
0.1	0.4694	0.6134	0.6833	0.7246	0.7518	
Subsystem 4: Economizer						
ϕ_4 \ λ_4	0.05	0.087	0.125	0.162	0.2	Constant values
0.004	0.7544	0.7713	0.7756	0.7745	0.7689	ϕ_1 = 0.0008, λ_1 =0.06
0.0055	0.7320	0.7552	0.7629	0.7651	0.7644	ϕ_2 = 0.0076, λ_2 =0.3
0.007	0.7112	0.7404	0.7516	0.7570	0.7599	ϕ_3 = 0.06, λ_3 =0.3
0.0085	0.6918	0.7267	0.7414	0.7497	0.7554	
0.01	0.6736	0.7140	0.7321	0.7430	0.7510	

In other words, $\sum_{i=0}^{14} P_i = 1$, therefore

$$P_0 = 1/[(1+\frac{\phi_1}{\lambda_1}+\frac{\phi_2}{\lambda_2})(1+C_5+C\ +C_7)+\frac{\phi_3}{\lambda_3}(C_5+C_6)$$
$$+\frac{\phi_4}{\lambda_4}(C_5+C_7)] \quad (7)$$

Now, the steady state availability of feed water system may be obtained as summation of all working and reduced capacity state probabilities. Hence $A_V = P_0 + P_3 + P_4 + P_8$ or

$$A_V = P_0(1+C_5+C_6+C_7) \quad (8)$$

Therefore, Equation (8) represents the simulation model of the feed water system. It is used for evaluating the performance of this operating system of a thermal plant. This model has been confirmed with the help of availability matrix given in Table 1 and respective graphs (as Figures 2 to 5), showing the effect of failure and repair rate of various subsystems on the performance of the feed water system.

6. Performance evaluation

Performance evaluation forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation, and analysis). From maintenance history sheet of feed water system of thermal power plant and through the discussions with the plant personnel, appropriate failure and repair rates of all four subsystems are taken and availability matrix for different availability values are prepared accordingly by putting these failure and repair rates values in Expression (8) for Av. Table 1 depicts the availability levels for various subsystems of the feed water system. These availability values are then plotted.

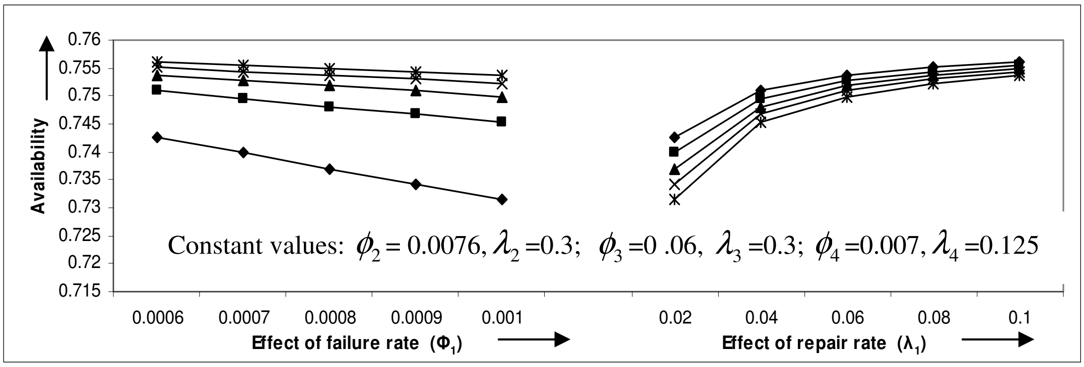


Figure 2: The effect of failure & repair rate of Boiler subsystem on system availability.

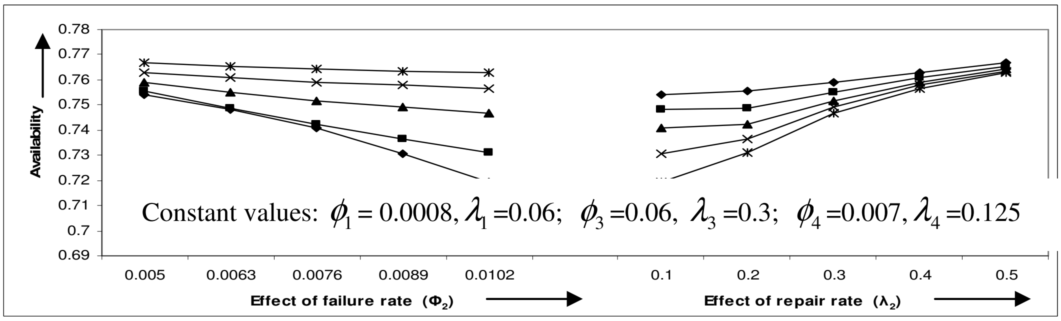


Figure 3: The effect of failure & repair rate of Condenser subsystem on system availability.

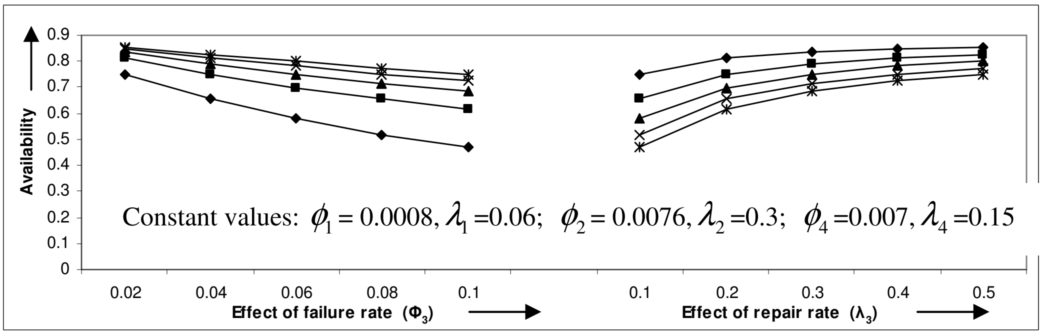


Figure 4: The effect of failure & repair rate of Feed Pump subsystem on system availability.

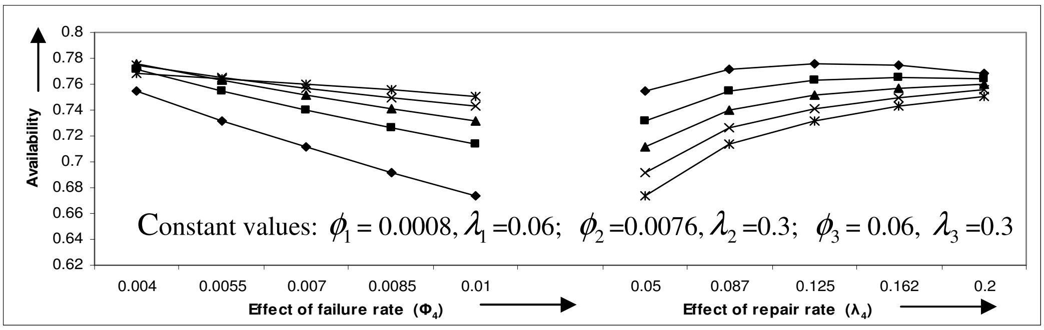


Figure 5: The effect of failure & repair rate of Economizer subsystem on system availability.

Figures 2,3,4 and 5 represent the plots for various subsystems of feed water system, depicting the effect of failure / repair rate of various subsystems on feed water system availability. This model includes all possible states of nature, that is, failure events (ϕ) and the identification of all the courses of action, that is, repair priorities (λ). This model is used to implement the maintenance policies for a feed water system in a thermal plant. The various availability levels may be computed for different combinations of failure and repair rates / priorities. On the basis of analysis, one may select the best possible combination (ϕ, λ) that is, optimal maintenance strategies, to get the maximum availability.

7. Results and discussion

Table 1 and plot in Figure 2 reveal the effect of failure rates (ϕ_1) and repair rates (λ_1) of boiler subsystem on the availability of feed water system. It is observed as failure rate of boiler (ϕ_1) increases from 0.0006 (once in 1667 hrs) to 0.001 (once in 1000 hrs), the system availability decreases by only 1 %. Similarly as repair rate of boiler (λ_1) increases from 0.02 (once in 50 hrs) to 0.1 (once in 10 hrs), the system availability increases by only 1.4%.

Table 1 and plot in Figure 3 highlight the effect of failure rates (ϕ_2) and repair rates (λ_2) of condenser subsystem on the availability of feed water system. It is observed that as failure rate of condenser (ϕ_2) increases from 0.005 (once in 200 hrs) to 0.01 (once in 100 hrs), the system availability decreases by about 4%. Similarly as repair rate of condenser (λ_2) increases from 0.10 (once in 10 hrs) to 0.50 (once in 2 hrs), the system availability increases by about 1.4%.

Table 1 and plot in Figure 4 explain the effect of failure rates (ϕ_3) and repair rates (λ_3) of feed water pump subsystem on the availability of feed water system. It is observed that as failure rate of feed water pump (ϕ_3) increases from 0.02 (once in 50 hrs) to 0.1 (once in 10 hrs), the system availability decreases by about 29%.

Similarly as repair rate of feed water pump (λ_3) increases from 0.10 (once in 10 hrs) to 0.50 (once in 2 hrs), the system availability increases by about 10%.

Table 1 and plot in Figure 5 explain the effect of failure rates (ϕ_4) and repair rates (λ_4) of economizer subsystem on the availability of feed water system .It is observed that as failure rate of economizer (ϕ_4) increases from 0.004 (once in 250 hrs) to 0.01 (once in 100 hrs), the system availability decreases by about 8%. Similarly as repair rate of feed water pump (λ_4) increases from 0.05 (once in 20 hrs) to 0.2 (once in 5 hrs), the system availability increases by about 1.5%.

8. Conclusion

The performance evaluation of the various subsystems of the feed water system of a thermal plant can be effectively done with the help of developed simulation model. It provides the various availability levels (A_v) for different combinations of failure and repair rates for each and every subsystem.

One may select the best possible combination of failure events and maintenance priorities for each subsystem. The optimum values of failure and repair rates for each subsystem are given in following Table 2.

These values help in determining the optimal maintenance strategies, which will ensure the maximum overall availability of feed water system of a thermal plant. The findings of this paper are discussed with the concerned thermal plant management. These results are found to be highly beneficial to the plant management for the evaluation of performance and analysis of availability of feed water system and hence to decide about the maintenance priorities of various subsystems of the system concerned in a thermal plant.

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