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MAINTENANCE PERFORMANCE EVALUATION OF POWER GENERATION SYSTEM OF A THERMAL POWER PLANT*

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Abstract– The present research deals with the opportunities for the availability predictive modeling of a thermal plant using the Markov process and probabilistic approach. These opportunities will be identified by evaluation of a power generation system of a thermal power plant. This feasibility study covers two areas: development of a predictive model and evaluation of performance with the help of the developed model. The present system under study consists of four subsystems with three feasible states: full working, reduced capacity working and failed. Failure and repair rates of all subsystems are assumed to be constant. After drawing a transition diagram, differential equations are generated and then a probabilistic predictive model using Markov approach has been developed, considering some assumptions. The availability matrix for each subsystem is also developed, which provides various availability levels for different combinations of failure and repair rates of all subsystems. On the basis of this study, the performance of a power generation system is evaluated. The developed model helps in the comparative evaluation of alternative maintenance strategies.

Keywords– Probabilistic approach, predictive model, transition diagram, markov approach and availability matrix

1. INTRODUCTION

Today's engineering systems are becoming more complicated. Besides well-known series and parallel systems, more and more models are being used, such as standby redundant systems, k-out-of-n systems, consecutive k-out-of-n systems, deterioration systems, and repair systems [1]. The reliability prediction of engineering systems is becoming increasingly important because of factors such as cost, risk of hazard, competition, public demand, and usage of new technology. High reliability level is desirable to reduce the overall costs of production and risk of hazards of larger, more complex and sophisticated systems such as thermal power plant. Gupta *et al.* [2] states that it is necessary to maintain the thermal power plant to provide reliable and uninterrupted electrical supply for a long time. In order to obtain regular and economical generation of electrical power, a plant should be maintained at a sufficiently high availability level corresponding to the minimum overall cost.

Reliability engineering has attracted many researchers since the 1960's due to the critical importance of reliability in a variety of systems. As explained by Tzafestas in 1980 [3], one of the undeniable steps in the design of multi-component systems is the problem of using the available resources in the most effective way so as to maximize the overall system reliability, or so as to minimize the consumption of resources while achieving specific reliability goals. Several methods exist that can be used to improve the system reliability. The most known are: reduction of the system complexity, allocation of the components'

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reliability and allocation of redundancy alone or combined with reliability allocation, or the practice of planned maintenance and repair schedule.

The diversity of system structures, resource constraints, and options for reliability improvement has led to construction and analysis of several optimization models [4]. According to Stanley and Malhoit [5], there are two general types of methods for analyzing the system's reliability, each with its own merits and shortcomings. Traditional Markov and Markov cut set approaches are able to produce exact answers when the system components have exponential failure and repair times. Unfortunately, as the system complexity increases with a large number of components and interrelationships between components, the amount of effort required for determining the cut sets or the transition model for the system can be prohibitive. More recently, with the introduction of computer simulation, Monte Carlo methods are gaining popularity for reliability analysis of complex systems.

Monte Carlo methods for the evaluation of the reliability of a parallel supplied, non redundant, uninterruptible power supply was applied by Singh and Mitra [6], in which exact solutions were derived through Markov methods. Modarres and Azaron [7] have successfully obtained the reliability function of time-dependent systems by applying the shortest path analysis in stochastic networks by using continuous time Markov processes. According to Nakagawa [8], the most important problem in reliability theory is to estimate statistically at what time an operating unit will fail in the near future. Using such a reliability point of view, failure distributions and their parameters have been estimated, some reliability quantities have been well defined and maintenance policies to prevent failures have been practically considered and analytically discussed [9-12].

Groote [13] concludes that maintenance plays a key role in an organization's long-term profitability and has increasingly become part of a total performance approach, together with other topics such as productivity, quality, safety, and environment. This has been reflected in the desire of organizations to improve maintenance performance. 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, and optimization problems, among other topics [14]. Maintenance performance is generally hard to measure, as one should not only consider quantifiable parameters but also the quality of the performed maintenance and its organization [15-17]. Lim and Chang [18] studied a repairable system modeled by a Markov chain with two repair modes. A text of general interest for studying reliability systems and performance measures is that of Høyland and Rausand [19]. Other texts of interest related to the topics studied in the present paper are Gnedenko *et al.* [20], Avel *et al.* [21], Birolini [22], Belyayev *et al.* [23], Ushakov [24], Ross [25], Ushakov [26], Balaguruswamy [27] and Dhillon [28].

Performance evaluation forms the foundation for all other performance improvement activities (e.g. solution design and development, implementation, and evaluation)[29]. The performance of the twin-entry radial flow turbine under steady state and partial admission conditions is modeled using one-dimensional performance prediction by Ghassemi et al. [30]. Performance modeling is an activity in which the performance of a system is characterized by a set of performance parameters whose quantitative values are used for evaluating the system's availability. Performance modeling has a very important role in the power generation system of a thermal power plant. An example of a performance evaluation effort is described by Clark and Estes [31], by presenting a case study illustrating that data-driven analysis leads to better solutions for performance improvement. The study describes a computer hardware manufacturing company that was experiencing a decrease in productivity and an increase in assembly mistakes/damaged goods.

In this research, a maintenance performance evaluation approach is proposed. The approach is focused towards the development of a predictive model, which ultimately helps in several maintenance decisions. The actual failure and repair data on the identified power generation system has been used in the analysis. The proposed model provides an integrated modeling and analysis framework for performance evaluation of the power generation system of a thermal power plant.

a) Organization of paper

The next section of this paper describes the processing and description of the power generation system used for developing the transition diagram. The assumptions used for development of the model are also listed in this section. This is followed by a section which deals with the development of a predictive model. Section 4 describes the performance evaluation made in this study. Results and conclusions are presented in the final section of the research paper.

2. POWER GENERATION SYSTEM

The need for having an efficient and reliable power generation system is well recognized in view of the large capacity power stations being installed in India. Operating power plants efficiency is very important in the economics of power generation. Gupta *et al.* [32] describes the thermal power plant as a complex engineering system comprised of various systems: coal handling, steam generation, cooling water, steam and water, crushing, condensate, ash handling, power generation and feed water system. Amongst the several utilities, the power generation system constitutes the most essential part of a thermal power plant. Power generation system, with whatever may be the operational intentions, i.e. continuous or intermittent, is expected to furnish excellent performance. The high performance of such a power generation system can be achieved with a highly reliable power plant and perfect maintenance [32]. According to Arora and Kumar [33], the hot gases evolved (by coal burning) circulate in the boiler drum, conduct heat to the circulating water and finally leave through the boiler chimney. The circulating water is converted into dry and saturated steam at a pressure of 147 kg/cm^2 and temperature of 340^o C, and then superheated to 540°C. After that, it is sent to the turbo-generator system, converting from pressure to kinetic + mechanical + electrical energy. The steam in doing so loses its thermal energy and is converted into water after passing through a condenser (maintained at a negative pressure). The cooling system for the generator rotor cooling, seal oil system for preventing coolant leakage, turbine governing system for regulating steam supply and turbine lubrication system for removing heat from the bearings are provided.

a) Assumptions

The analysis presented herein is based on the following assumptions:

1. A repaired unit is as good as new, performance wise, for a specified duration [34].
2. Failure/repair rates are constant over time and statistically independent.
3. Sufficient repair facilities are provided and standby units are of the same nature as that of active units.
4. Service includes repair and/or replacement [35].
5. System time between failure and repair time follows an exponential distribution.
6. There are no simultaneous failures among subsystems and subsystems may work at reduced capacity.

b) System description

The performance of the system depends on the configuration and performance of its subsystems. A typical system consists of subsystems connected to each other either in series or in parallel. The power generation systems comprise the following four subsystems:

1. The assembly of generator cooling and seal oil unit constituting one subsystem, denoted by A, the failure of which reduces the capacity of the plant and loss in production.

2. Turbine lubrication unit constituting another subsystem, denoted by B, failure of which reduces the capacity of the plant and loss in production.
3. Condensate evacuation & regenerative unit constituting one subsystem and is denoted by C. Its failure reduces the capacity of the plant and loss in production.

Turbine governing unit is another subsystem, denoted by D, arranged in series with other subsystems. Failure of this subsystem causes the complete failure of the system.

3. PREDICTIVE MODELING

Modeling starts with the preparation of a transition diagram, which is helpful in analyzing reliability, and the availability of a repairable system. The flow of states for the present system under consideration has been described in a transition diagram [36], which is a logical representation of all possible state probabilities (Fig. 1) encountered during the availability analysis of a power generation system. The failure and repair rates of the different subsystems are used as standard input information to the model. Formulation is carried out using the joint probability functions based on the transition diagram.

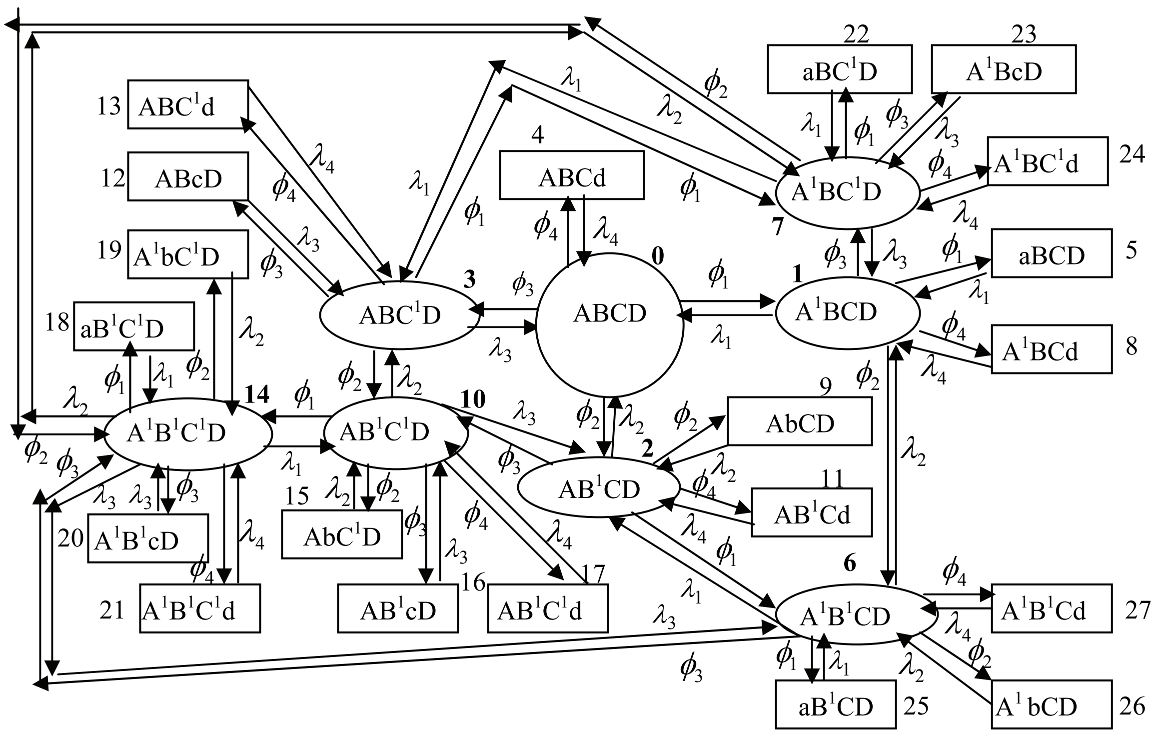

Fig. 1. Transition diagram of power generation system

a) Modeling approach

According to Markov, if $P_0(t)$ represent the probability of zero occurrences in time t, then the probability of zero occurrences in time (t + Δt) is given by Eq. (1); i.e.

$$P_0(t+\Delta t) = (1-\lambda t)P_0(t) \tag{1}$$

Similarly,

$$P_1(t+\Delta t) = (\phi.\Delta t).P_0(t) + (1-\lambda.\Delta t)P_1(t) \tag{2}$$

Equation (2) shows the probability of one occurrence in time (t + Δt) and is composed of two parts, namely, (a) probability of zero occurrences in time t multiplied by the probability of one occurrence in the interval Δt and (b) the probability of one occurrence in time t multiplied by the probability of no occurrences in the interval Δt, as stated by Srinath [36]. Then simplifying and putting $\Delta t \rightarrow 0$, one gets

$$(P'(t)+\phi)P_1(t) = \lambda.P_0(t) \tag{3}$$

The system starts from a particular state at time 't' and reaches another state (failed) or remains in the same state (operative) during the time interval Δt. Modeling is done using a simple probabilistic consideration and differential equations are developed using a Markov birth-death process [37]. Using the concept used in eq. 3 and various probability considerations, the following differential equations associated with the transition diagram of the power generation system are formed.

$$P'_i(t) + \sum(\phi_i P_i)(t) = \sum \lambda_j P_j(t) \text{ Where, for } i = 1to4; j = 1to4 \text{ respectively} \tag{4}$$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_1 P_{i-1}(t) \tag{5}$$

For $i = 1, r = 1to4, m = 1$

$j = 1, k = 5; j = 2, k = 6; j = 3, k = 7; j = 4, k = 8$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_2 P_{i-2}(t) \tag{6}$$

Where for $i = 2, r = 1to4, m = 2$

$j = 1, k = 6; j = 2, k = 9; j = 3, k = 10; j = 4, k = 11$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_3 P_{i-3}(t) \tag{7}$$

Where for $i = 3, r = 1to4, m = 3$

$j = 1, k = 7; j = 2, k = 10; j = 3, k = 12; j = 4, k = 13$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_1 P_{i-4}(t) + \phi_2 P_{i-5}(t) \tag{8}$$

Where for $i = 6, r = 1to4; m = 1,2$

$j = 1, k = 25; j = 2, k = 26; j = 3, k = 14; j = 4, k = 27$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_2 P_{i-7}(t) + \phi_3 P_{i-8}(t) \tag{9}$$

Where for $i = 10, r = 1to4; m = 2,3$

$j = 1, k = 14; j = 2, k = 15; j = 3, k = 16; j = 4, k = 17$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_1 P_{i-4}(t) + \phi_3 P_{i-6}(t) \tag{10}$$

Where for $i = 7, r = 1to4; m = 1,3$

$j = 1, k = 22; j = 2, k = 14; j = 3, k = 23; j = 4, k = 24$

$$P'_i(t) + \sum(\phi_r + \lambda_m)P_i(t) = \sum \lambda_j P_k(t) + \phi_1 P_{i-4}(t) + \phi_2 P_{i-7}(t) + \phi_3 P_{i-8}(t) \tag{11}$$

Where for $i = 14, r = 1to4; m = 1,2,3$

$j = 1, k = 18; j = 2, k = 19; j = 3, k = 20; j = 4, k = 21$

$$P'_i(t) + \lambda_4 P_i(t) = \phi_4 P_k(t) \qquad 12)$$

Where for $i = 4, 8, 11, 13, 17, 21, 24, 27; \text{k} = 0,1,2,3,10,14,7,6$ respectively.

$$P'_i(t) + \lambda_3 P_i(t) = \phi_3 P_k(t) \tag{13}$$

Where for $i = 12,16,20,23; \text{k} = 3,10,14,7$ respectively.

$$P'_i(t) + \lambda_2 P_i(t) = \phi_2 P_k(t) \tag{14}$$

Where for $i = 9,15,19,26$; $\mathrm{k} = 2,10,14,6$ respectively.

$$P'_i(t) + \lambda_1 P_i(t) = \phi_1 P_k(t) \tag{15}$$

Where for $i = 5,18,22,25$; $\mathrm{k} = 1,14,7,6$ respectively.

With the initial condition P_0 (0) =1, 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 the derivative of all probabilities equal to zero, so as to attain the long run availability of the system of a thermal plant and solving these equations recursively, the following are the values of all state probabilities in terms of full working state probability i.e. P_0.

$$P_1 = C_{37} P_0$$
$$P_2 = C_{39} P_0$$
$$P_3 = C_{38} P_0$$
$$P_4 = \frac{\phi_4}{\lambda_4} P_0$$
$$P_5 = \frac{\phi_1}{\lambda_1} P_1$$
$$P_6 = C_{40} P_0$$
$$P_7 = C_{42} P_0$$
$$P_8 = \frac{\phi_4}{\lambda_4} P_1$$
$$P_9 = \frac{\phi_2}{\lambda_2} . P_2$$
$$P_{10} = C_{43} P_0$$
$$P_{11} = \frac{\phi_4}{\lambda_4} P_2$$
$$P_{12} = \frac{\phi_3}{\lambda_3} P_3$$
$$P_{13} = \frac{\phi_4}{\lambda_4} P_3$$
$$P_{14} = C_{41} P_0$$
$$P_{15} = \frac{\phi_2}{\lambda_2} P_{10}$$
$$P_{16} = \frac{\phi_3}{\lambda_3} P_{10}$$
$$P_{17} = \frac{\phi_4}{\lambda_4} P_{10}$$
$$P_{18} = \frac{\phi_1}{\lambda_1} P_{14}$$
$$P_{19} = \frac{\phi_2}{\lambda_2} P_{14}$$
$$P_{20} = \frac{\phi_3}{\lambda_3} P_{14}$$
$$P_{21} = \frac{\phi_4}{\lambda_4} P_{14}$$
$$P_{22} = \frac{\phi_1}{\lambda_1} P_7$$
$$P_{23} = \frac{\phi_3}{\lambda_3} P_7$$
$$P_{24} = \frac{\phi_4}{\lambda_4} P_7$$
$$P_{25} = \frac{\phi_1}{\lambda_1} P_6$$
$$P_{26} = \frac{\phi_2}{\lambda_2} P_6$$
$$P_{27} = \frac{\phi_4}{\lambda_4} P_6$$

where C_{37} to C_{43} are constants and their values are as follows:

$$C_{37} = \frac{C_1 - C_{33}\lambda_2 - C_{36}\lambda_3}{\lambda_1 - C_{34}\lambda_2 + C_{35}\lambda_3},\ C_{38} = C_{36} + C_{37}C_{35},\ C_{39} = C_{33} - C_{37}C_{34},\ C_{40} = C_{24}C_{37} + C_{25}C_{39} - C_{26},$$

$$C_{41} = C_{27}C_{37} + C_{28}C_{39} - C_{29}, \quad C_{42} = \frac{C_{41}\lambda_2 + C_{38}\phi_1 + C_{37}\phi_3}{C_6}$$

$$C_{43} = \frac{C_{41}\lambda_1 + C_{38}\phi_2 + C_{39}\phi_3}{C_7}$$

where C_1 to C_{36} are further constants and the following are their values:

$C_1 = (\phi_1 + \phi_2 + \phi_3)$, $C_2 = (\phi_2 + \phi_3 + \lambda_1)$, $C_3 = (\phi_1 + \phi_3 + \lambda_2)$, $C_4 = (\phi_1 + \phi_2 + \lambda_3)$,

$C_5 = (\phi_3 + \lambda_1 + \lambda_2)$, $C_6 = (\phi_2 + \lambda_1 + \lambda_3)$, $C_7 = (\phi_1 + \lambda_2 + \lambda_3)$, $C_8 = (\lambda_1 + \lambda_2 + \lambda_3)$,

$C_9 = (1 - \frac{\phi_1\lambda_1}{C_7C_8} - \frac{\phi_2\lambda_2}{C_6C_8} - \frac{\phi_3\lambda_3}{C_5C_8})$, $C_{10} = (1 - \frac{\phi_1\lambda_1}{C_1C_2} - \frac{\phi_2\lambda_2}{C_1C_3} - \frac{\phi_3\lambda_3}{C_1C_4})$, $C_{11} = \frac{\phi_1\phi_2}{C_9}\left(\frac{1}{C_7C_8} + \frac{1}{C_6C_8}\right)$,

$C_{12} = \frac{\phi_1\phi_3}{C_9}\left(\frac{1}{C_7C_8} + \frac{1}{C_5C_8}\right)$, $C_{13} = \frac{\phi_2\phi_3}{C_9}\left(\frac{1}{C_6C_8} + \frac{1}{C_5C_8}\right)$, $C_{14} = \lambda_1\lambda_2\left(\frac{1}{C_1C_2} + \frac{1}{C_1C_3}\right)$,

$C_{15} = \lambda_1\lambda_3\left(\frac{1}{C_1C_2} + \frac{1}{C_1C_4}\right)$, $C_{16} = \lambda_2\lambda_3\left(\frac{1}{C_1C_3} + \frac{1}{C_1C_4}\right)$, $C_{17} = \frac{C_{10}}{C_{14}}$, $C_{18} = \frac{C_{15}}{C_{14}}$, $C_{19} = \frac{C_{16}}{C_{14}}$,

$C_{20} = \left(\frac{C_1C_4}{\lambda_3} + \frac{\phi_1\lambda_1}{\lambda_3} + \frac{\phi_2\lambda_2}{\lambda_3} - \phi_3\right)$, $C_{21} = \frac{\lambda_1}{\lambda_3}(C_2 + C_4)$, $C_{22} = \frac{\lambda_2}{\lambda_3}(C_3 + C_4)$, $C_{23} = \frac{2\lambda_1\lambda_2}{\lambda_3}$,

$C_{24} = \frac{C_{21}}{C_{23}}$, $C_{25} = \frac{C_{22}}{C_{23}}$, $C_{26} = \frac{C_{20}}{C_{23}}$, $C_{27} = \frac{C_{24}C_5 - \phi_2}{\lambda_3}$, $C_{28} = \frac{C_{25}C_5 - \phi_1}{\lambda_3}$, $C_{29} = \frac{C_{26}C_5}{\lambda_3}$,

$C_{30} = \frac{C_{27} - C_{13}}{C_{11}}$, $C_{31} = \frac{C_{28} - C_{12}}{C_{11}}$, $C_{32} = \frac{C_{29}}{C_{11}}$, $C_{33} = \frac{C_1 + C_{32}\lambda_3}{\lambda_2 + C_{31}\lambda_3}$, $C_{34} = \frac{\lambda_1 + C_{30}\lambda_3}{\lambda_2 + C_{31}\lambda_3}$,

$C_{35} = \frac{C_{34}\lambda_2 - \lambda_1}{\lambda_3}$, $C_{36} = \frac{C_{1-}C_{33}\lambda_2}{\lambda_3}$

b) Steady state availability

The probability of full working capacity (without standby units), 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) [33].

i.e $\sum_{i=0}^{27} P_i = 1$, therefore

$$P_0 = \frac{1}{\left[\begin{array}{l}(1+\frac{\phi_4}{\lambda_4})*(1+C_{37}+C_{38}+C_{39}+C_{40}+C_{41}+C_{42}+C_{43}) + \frac{\phi_1}{\lambda_1}(C_{37}+C_{40}+C_{41}+C_{42}) + \frac{\phi_2}{\lambda_2}(C_{39}+C_{40}+C_{41}+C_{43}) \\ +\frac{\phi_3}{\lambda_3}(C_{38}+C_{40}+C_{41}+C_{42}+C_{43})\end{array}\right]}$$

Now, the steady state availability of the power generation system may be obtained as the summation of all full working and reduced capacity working state probabilities.

Hence $A_V = P_0 + P_1 + P_2 + P_3 + P_6 + P_7 + P_{10} + P_{14}$

$$\text{Or } Av. = P_0(1 + C_{37} + C_{38} + C_{39} + C_{40} + C_{41} + C_{42} + C_{43}) \tag{16}$$

Therefore, Eq. (16) represents the predictive model of the power generation system.

4. PERFORMANCE EVALUATION

The performance of the system is mainly affected by the failure and repair rates of its subsystem. This model forms the foundation for design and development, implementation and analysis, which are all performance improvement activities. These unit parameters ensure the high availability or performance of the power generation system. From the maintenance history sheet of the power generation system and through discussions with the plant personnel, appropriate failure and repair rates of all subsystems are taken and availability matrices are prepared accordingly by putting these failure and repair rate values in Eq. (16), the availability simulation model (A_v.). This model includes all possible states of nature, that is, failure events (ϕ_i) and the identification of all the courses of action, i.e, repair priorities (λ_i). Tables 1-4 represent the availability matrices for various subsystems of the power generation system and availability values in these matrices are plotted and shown in Figs. 2-5. These matrices simply reveal the various availability levels for different combinations of failure and repair rates. On the basis of the analysis made, the best possible combinations (ϕ, λ) may be selected. These availability values in the availability matrices further help in obtaining the optimum values of failure and repair rates of various subsystems of the power generation system.

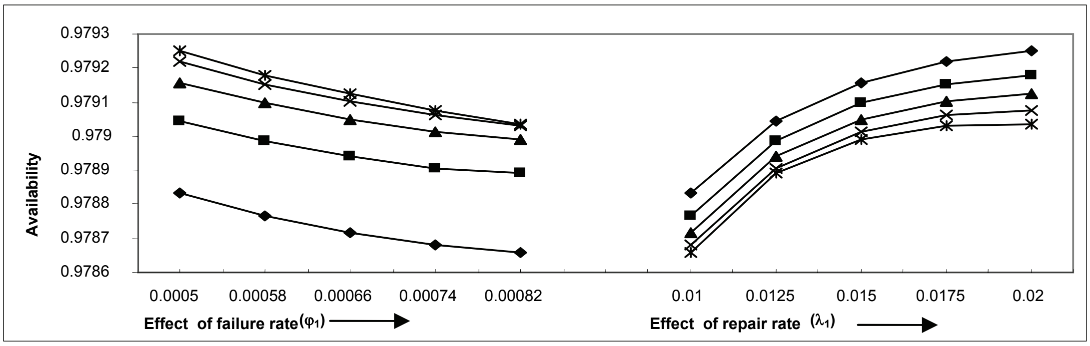

Fig. 2. Effect of failure and repair rates of subsystem A on system availability

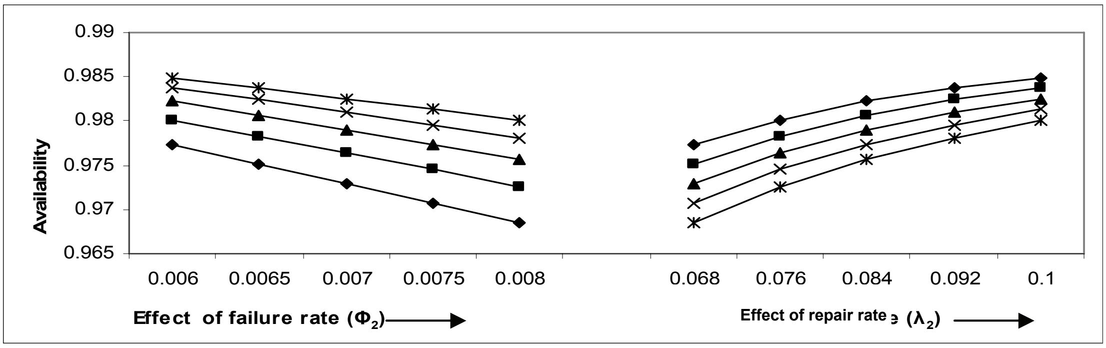

Fig. 3. Effect of failure and repair rates of subsystem B on system availability

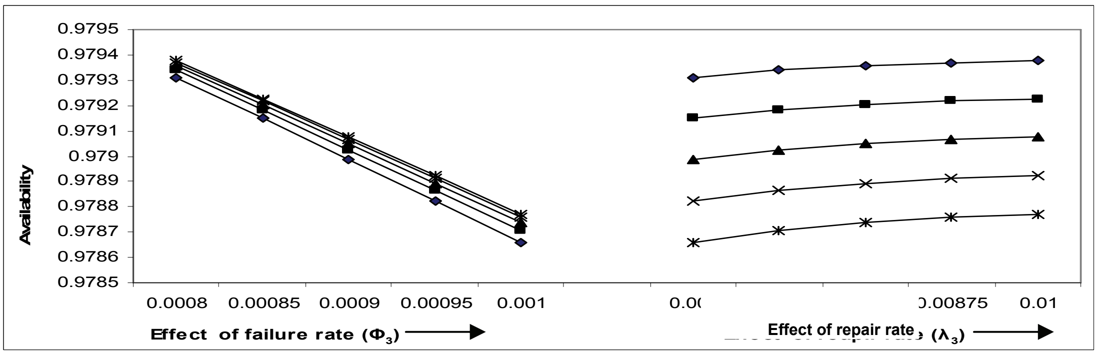

Fig. 4. Effect of failure and repair rates of subsystem C on system availability

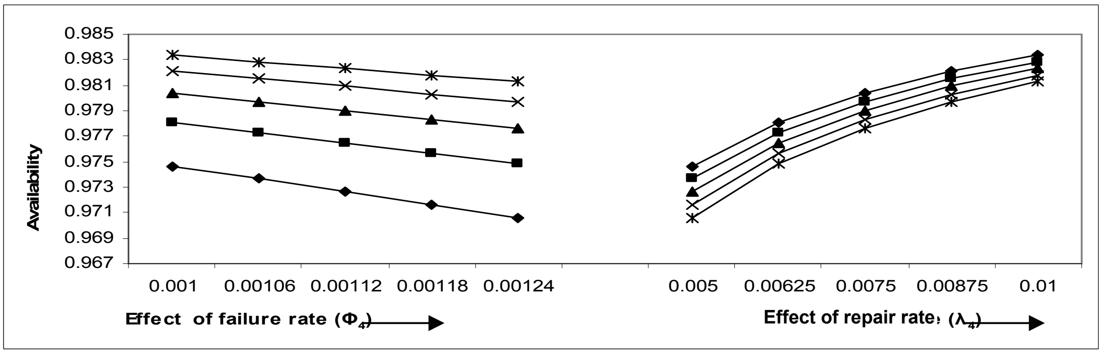

Fig. 5. Effect of failure and repair rates of subsystem D on system availability

5. RESULTS AND DISCUSSION

The performance of the power generation system is analyzed with the developed predictive model. On the basis of availability values, as given in Tables 1-4 and plots in Figs. 2-5, the following observations are made, which reveal the effect of failure and repair rates of various subsystems on the availability of the power generation system.

Table 1. Availability matrix of subsystem A of power generation system

→ Availability (Av) → A_0

ϕ_1 \ λ_1	0.0100	0.0125	0.0150	0.0175	0.0200	Constant values
0.00050	0.978834	0.979044	0.979155	0.979217	0.979250	$\phi_2 = 0.007, \lambda_2 = 0.084$
0.00058	0.978767	0.978985	0.979096	0.979154	0.979181	$\phi_3 = 0.0009, \lambda_3 = 0.0075$
0.00066	0.978715	0.978939	0.979049	0.979102	0.979123	$\phi_4 = 0.00112, \lambda_4 = 0.0075$
0.00074	0.978679	0.978907	0.979014	0.979061	0.979075	
0.00082	0.978658	0.978890	0.978992	0.979032	0.979037	

Table 2. Availability matrix of subsystem B of power generation system

→ Availability (Av) → A_0

ϕ_2 \ λ_2	0.068	0.076	0.084	0.092	0.100	Constant values
0.0060	0.977326	0.980125	0.982199	0.983747	0.984898	$\phi_1 = 0.00066, \lambda_1 = 0.015$
0.0065	0.975189	0.978315	0.980648	0.982408	0.983738	$\phi_3 = 0.0009, \lambda_3 = 0.0075$
0.0070	0.972996	0.976453	0.979049	0.981023	0.982533	$\phi_4 = 0.00112, \lambda_4 = 0.0075$
0.0075	0.970749	0.974543	0.977405	0.979597	0.981287	
0.0080	0.968450	0.972586	0.975719	0.978130	0.980003	

Table 3. Availability matrix of subsystem C of power generation system

→ Availability (Av) → A_0

ϕ_3 \ λ_3	0.00500	0.00625	0.00750	0.00875	0.01000	Constant values
0.00080	0.979310	0.979339	0.979356	0.979368	0.979376	$\phi_1 = 0.00066, \lambda_1 = 0.015$
0.00085	0.979150	0.979183	0.979203	0.979217	0.979226	$\phi_2 = 0.007, \lambda_2 = 0.084$
0.00090	0.978988	0.979025	0.979049	0.979065	0.979076	$\phi_4 = 0.00112, \lambda_4 = 0.0075$
0.00095	0.978825	0.978867	0.978894	0.978911	0.978924	
0.00100	0.978661	0.978707	0.978737	0.978758	0.978772	

Table 4. Availability matrix of subsystem D power generation system

→ Availability (Av) → A_0

ϕ_4 \ λ_4	0.00500	0.00625	0.00750	0.00875	0.01000	Constant values
0.00100	0.974671	0.978124	0.980440	0.982100	0.983350	$\phi_1 = 0.00066, \lambda_1 = 0.015$
0.00106	0.973640	0.977293	0.979744	0.981502	0.982825	$\phi_2 = 0.007, \lambda_2 = 0.084$
0.00112	0.972611	0.976463	0.979049	0.980904	0.982300	$\phi_3 = 0.0009, \lambda_3 = 0.0075$
0.00118	0.971584	0.975635	0.978355	0.980307	0.981776	
0.00124	0.970559	0.974809	0.977662	0.97971	0.981253	

(i) Subsystem A: Generator cooling and seal oil unit

The effect of failure and repair rates of subsystem A on the availability of a power generation system is shown in Table 1 and Fig. 2. It is observed that for some known constant values of failure/repair rates of the other three subsystems (as given in Table 1), as the failure rate of subsystem A increases from 0.00050 (five failures in 10000 hrs) to 0.00082 (82 failures in 100000 hrs), the system availability decreases. Similarly, as the repair rate of subsystem A increases from 0.01 (once in 100 hrs) to 0.02 (once in 50 hrs), the system availability increases.

(ii) Subsystem B: Turbine lubrication unit

The effect of failure and repair rates of the subsystem B turbine lubrication subsystem on the availability of a power generation system is depicted by Table 2 and Fig. 3. It is observed that for some known constant values of the failure/repair rates of the other three subsystems (as given in Table 2), as the failure rate of subsystem B increases from 0.006 (06 failures in 1000 hrs) to 0.008 (08 failures in 1000 hrs), the system availability decreases. Similarly, as the repair rate of subsystem B increases from 0.068 (68 times in 1000 hrs) to 0.1 (once in 10 hrs), the system availability increases slightly, but shows an increasing trend.

(iii) Subsystem C: Condensate evacuation and regenerative unit

The effect of failure and repair rates of subsystem C on the availability of a power generation system is depicted by Table 3 and Fig. 4. It is observed that for some known constant values of the failure/repair rates of the other three subsystems (as given in Table 3), as the failure rate of subsystem C increases from 0.0008 (08 failures in 10000 hrs) to 0.001 (once in 1000 hrs), the system availability shows a decreasing trend. Similarly, as the repair rate of subsystem C increases from 0.005 (once in 200 hrs) to 0.01 (once in 100 hrs), the system availability shows an increasing trend.

(iv) Subsystem D: Turbine governing unit

The effect of the failure and repair rates of subsystem D on the availability of a power generation system is shown by Table 4 and Fig. 5. It is observed that for some known constant values of failure/repair rates of the other three subsystems (as given in Table 4), as the failure rate of subsystem D increases from 0.00100 (100 failures in 100000 hrs) to 0.00124 (124 failures in 100000 hrs), the system availability decreases. Similarly, as the repair rate of subsystem D increases from 0.005 (once in 200 hrs) to 0.01 (once in 100 hrs), the system availability shows an increasing trend.

The maximum availability level for each subsystem is given in Table 5, which further helps in identifying the optimum values of failure and repair rates for the maximum availability of each subsystem.

Table 5. Optimum values of failure and repair rates of various subsystems of the power generation system

S. No.	Failure rates (ϕ_i)	Repair rates (λ_i)	Maximum availability level
1.	ϕ_1 = 0.0005	λ_1= 0. 02	97.92%
2.	ϕ_2 = 0.006	λ_2 = 0.1	98.48%
3.	ϕ_3 = 0.0008	λ_3 = 0.01	97.93 %
4	ϕ_4 = 0.001	λ_4 = 0.01	98.33 %

6. CONCLUSION

The model analyzed and presented here provides a useful tool in making maintenance decisions. It can thus be concluded that this model provides the various availability levels for different combinations of failure and repair rates for every subsystem of a power generation system. It is also concluded and evident from Tables 1-5 and Figs. 2-5, that as the failure rate increases, the availability goes on decreasing and as the repair rate increases, the availability goes on increasing. One may select the best possible combination of failure events and repair priorities for each subsystem. The system availability has been excellent, mainly because of the low failure rate, supported by the state of the art repair facilities. The developed model helps in determining the optimal maintenance strategies, which will ensure the maximum overall availability of the power generation system. The developed matrices depict the optimum values of failure and repair rates for the maximum availability level for each subsystem. Such results are found to be highly beneficial to the plant management for the availability analysis of a power generation system of a thermal plant.

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SYMBOLS AND NOTATIONS

The symbols and notations used in the present paper are as follows:

○ indicate the subsystems in full capacity working state

◯ indicate the subsystems in reduced capacity working state

▭ indicate the subsystems in failed state

A,B,C,D denotes the full capacity working states of subsystems A,B,C and D respectively

A^1, B^1, C^1 denotes that the subsystem A, B and C are working with reduced capacity

a,b,c,d denotes the failed states of subsystems A,B,C and D respectively

P_0 (t) indicate the probability that at time 't' the subsystems are working in full capacity

$P_i(t)$ i=1-3, 6,7,10 and 14 indicate the probabilities that at time 't', the subsystems are working in reduced capacity

$P_i(t)$ i=4,5,8,9, 11-13, 15-27 indicate the probabilities that at time 't' the subsystems are in failed states

ϕ_i and λ_i , i=1-4 indicate the mean failure rates and repair rates of subsystems A,B,C and D respectively

$P'(t)$ represents the derivative w.r.t. time (t)

Av. steady state availability of the system

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