# Stochastic Analysis and Performance Evaluation of a Complex Thermal Power Plant

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**Abstract:**
This paper present the stochastic analysis and performance evaluation of the thermal power plant which serve as an improvement of Vora 2011, by the use of performance evaluation using probabilistic approach. The research study consists mainly three sub-systems namely boiler, super heater and re-heater connected in series configuration with two type of preventive maintenance ie offline and online. The analysis shows that as failure rate increases, the availability decreases and as repair rate increases, the availability of the system increases and vice-versa. Performance matrices shows that Super heater subsystem is the most critical subsystem among the three subsystems in the power generation plant as far as maintenance is concern, as its availability percentage is the least among the three subsystem and boiler subsystem is having the higher percentage of availability with about 99% level. The results of the analysis are found beneficial to the plant management for the availability analysis of the system.

**Key words:** *Reliability, Availability, Maintainability*.

## Introduction

The thermal power plant is a complex engineering system comprising of various units i.e. coal handling, Steam Generation, Cooling Water, Crushing, Ash handling, Power Generation and Feed water system, etc. these elements are connected in complex configuration. One of the most important and critical unit of thermal power plant is the steam and power generation (TG) unit. The optimization of each unit in relation to one another is required to make the power plant more profitable and viable for operation. The effectiveness of a power plant is given by the following equation and mainly affected by reliability, availability and maintainability of the plant and capability to perform as needed/required.

$$\text{Effectiveness of a power plant} = \mathrm{Re}\,liability \times Availability \times Ma\,\mathrm{int}\,ainability$$

Reliability is essential for proper utilization and maintenance of any system and equipments. Therefore it had gained much importance among manufacturers. Reliability deals with the development of new techniques for increasing the system effectiveness by reducing the frequency of failures and minimizing the high maintenance costs.

The available literature reflects that several approaches have been used to analyzed the steady state behavior of various systems Dhillon *et al* . (1981) have frequently used the Markovian approach for the availability analysis, using exponential distribution for failure and repair times. Kumar *et al.* (1988,1989 and 1993) dealt with reliability, availability and operational behavior analysis for different systems in the paper plant. Srinath (1994) has explained a

Markov model to determine the availability expression for a simple system consisting of only one component Gupta *et al.*(2005) have evaluated the reliability parameters of butter manufacturing system in a diary plant considering exponentially distributed failure rates of various components. The reliability of the system is determined by forming the differential equations with the help of transition diagram using Markovian approach and the solving these differential equations with the help of fourth order Runge-Kutta method. They applied the recursive method for calculating long run availability and MTBF using numerical technique.

Sunand *et al*. (1999) deal with maintenance management for ammonia synthesis system in fertilizer plant. Shooman (1996) suggested different methods for the reliability computations of system with dependant failures. Sunand *et al.* (2007) discussed simulated availability of $CO_2$ cooling system in a fertilizer plant. Rajiv *et al.* (2008) have developed decision support system for stock preparation system of paper plant. They also dealt with availability of bleaching system of paper plant. Gupta *et al.* (2008) developed the performance models and decision support system for a feed water unit of thermal power plant with the help of mathematical formulation based on Markov Birth-Death process using probabilistic approach. In this the decision matrices are developed which provide the various performance levels for different combinations of failure and repair rates for all sub systems. The model developed helps in to decide about correct and orderly execution of proper maintenance in order to enhance the performance of the feed water unit of the thermal power plant. Kalyanmoy Deb (1995) has explained the optimization techniques and how they can be used in the engineering problems.

Goldberg (2001) made a systematic study on G.A. mechanism, and identified three basic operations: reproduction, crossover and mutation. So that the G.A. has higher opportunity for obtaining near optimal solutions. Tewari et al. (2003, 2005) dealt with development of decision support system of refining system of sugar plant. They determined the availability for the refining system with elements exhibiting independent failures and repairs or the operation with standby elements for sugar industry. They also dealt with mathematical modeling and behavioral analysis for a refining system of a sugar industry using Genetic Algorithm.

Castro and Cavalca (2003) presented an availability optimization problem of an engineering system assembled in series configuration which has the redundancy of units and terms of maintenance as optimization parameters. Genetic Algorithm was used to reach the objective of availability, considering installation and maintenance costs. Chales and Kondo (2003) tackled a multi objective combinatorial optimization problem. They used Genetic Algorithm to optimize the availability and cost of a series and parallel repairable system. Ying-Shen Juang et al. (2008) proposed a genetic algorithm based optimization model to optimize the availability for a series parallel system. The objective is to determine the most economical policy of component's mean time between failure (MTBF) and mean time to repair (MTTR). Wang et al. (2009) performed the reliability optimization of a series-parallel system with fuzzy approach. The highly reliable system been recognized with increasing automation and use of highly complex systems. According to Lieberman (1973), the probabilistic analysis of the system under given operative conditions is helpful in the design modification, for minimum failure of the system and thus to optimize the system working. Goel and Shrivastava (1991) has ignored the dependent structure for failure and repair times for repairable systems and the above-mentioned authors considered a correlation structure for the problem and obtained some reliability measures. Other papers in this area are Goel et al. (1994) and Goel et al. (1995). In this paper, three-unit systems with a repair facility as considered. Since for a large-scale and complex network generally requires exponential time for the exact calculation of the reliability, a variety of alternative methods to estimate the network reliability using Markov death-birth process have been proposed.

Based on different assumptions, availability measures for a two-unit system with repair facility were obtained by several researchers. Rajamanickam et al. (1997) have assumed that the failure times and repair times for the components are independently distributed. Corder (1976) states that the raw material is processed through various equipment to get the final product in a process plant. The poor design, poor maintenance, lack of communication and coordination, defective planning, lack of skills and scarcity of inventories are main causes of failure. Thus highly skilled maintenance personnel are required to run a process plant. A thermal power plant is a complex engineering system comprising of various systems: Coal handling, Steam generators, Flue gas and air, Cooling water, Ash handling, Power Generation, Feed water and Condensate system connected either in series or in parallel or in combination of both (Arora and Kumar (1993) and Arora et al. (1995)). It is required to run the various subsystems of plant failure free for, a long period for maximum availability power generation. These subsystems are subjected to random failure and after repairs/replacement can be taken back into use. The operating conditions and repair policies used are the key factors for sub-systems and their components. The performance analysis can be used as tool to ensure the maximize level of system availability.

Several mathematical models are developed by Dhillon (1983) and Balaguruswamy (1984) to predict the availability. Most of these models, Krishnamurthi et al. (1996) and Sahner (1996) are based on the Markovian approach with the failure and the repair rates are constant assumption. Now a days, reliability analysis techniques have been accepted as standard tools for the planning and operation of complex thermal power plants. Due to increasing complexity and its components behaviors, it is becoming more and more difficult to model and analyze using existing conventional tools. Markov Chains (MCs) have proven as effective tool for modeling complex dynamic component behavior.

From the literature review, it has been observed that most of the researchers have confined their work to the development and analysis of theoretical models only. Such works are of little practical significance. Only a few researchers have developed real models for actual plant conditions and those too have not given any useful suggestions regarding performance enhancement of industrial systems. Now in order to fulfill this deficiency, efforts have been made in the present research to develop performance model based on real situation for the screening unit. The performance in terms availability has been evaluated on the basis of Markov birth-death process. After that, the busy period and profit analysis were also added to serve as a shortcoming or lapses on the former research conducted by the optimal availability level is attained by selecting the different combination of failure and repair rates of the subsystems of thermal plant in order to enhance the overall performance of the plant. So, the findings of the research will be highly beneficial to the plant management in futuristic maintenance planning and control.

### 1.1. Symbols and Nomenclature

The symbols and notations associated with the transition diagram are as follows;

◯ : indicate the system is in full working state

▭ : indicate the system is in failed state.

A,B,C: Represent full working states of subsystems.

$F_1$ : Denote that the subsystem F is working on standby unit.

a,b,c : Represent failed states of subsystems.

$P_o(t)$ : Probability of the system working with full capacity at time 't'

$P_1(t)$ : Probability of the system in online preventive maintenance.

$P_2(t)$ : Probability of the system in offline preventive maintenance.

$P_3(t)$ to $P_5(t)$ : Probability of the system in failed state.

$\lambda_i,\ i = 1, 2, 3$ Mean failure rate of A,B,C,D elements respectively.

$\mu_i, i = 1, 2, 3$ Mean repair rate of A,B,C,D elements respectively.

$\alpha_1$ = Failure rate of offline preventive maintenance.

$\alpha_2$ = Failure rate of online preventive maintenance.

$\beta_1$ = Repair rate of online preventive maintenance.

$\beta_1$ = Repair rate of offline preventive maintenance.

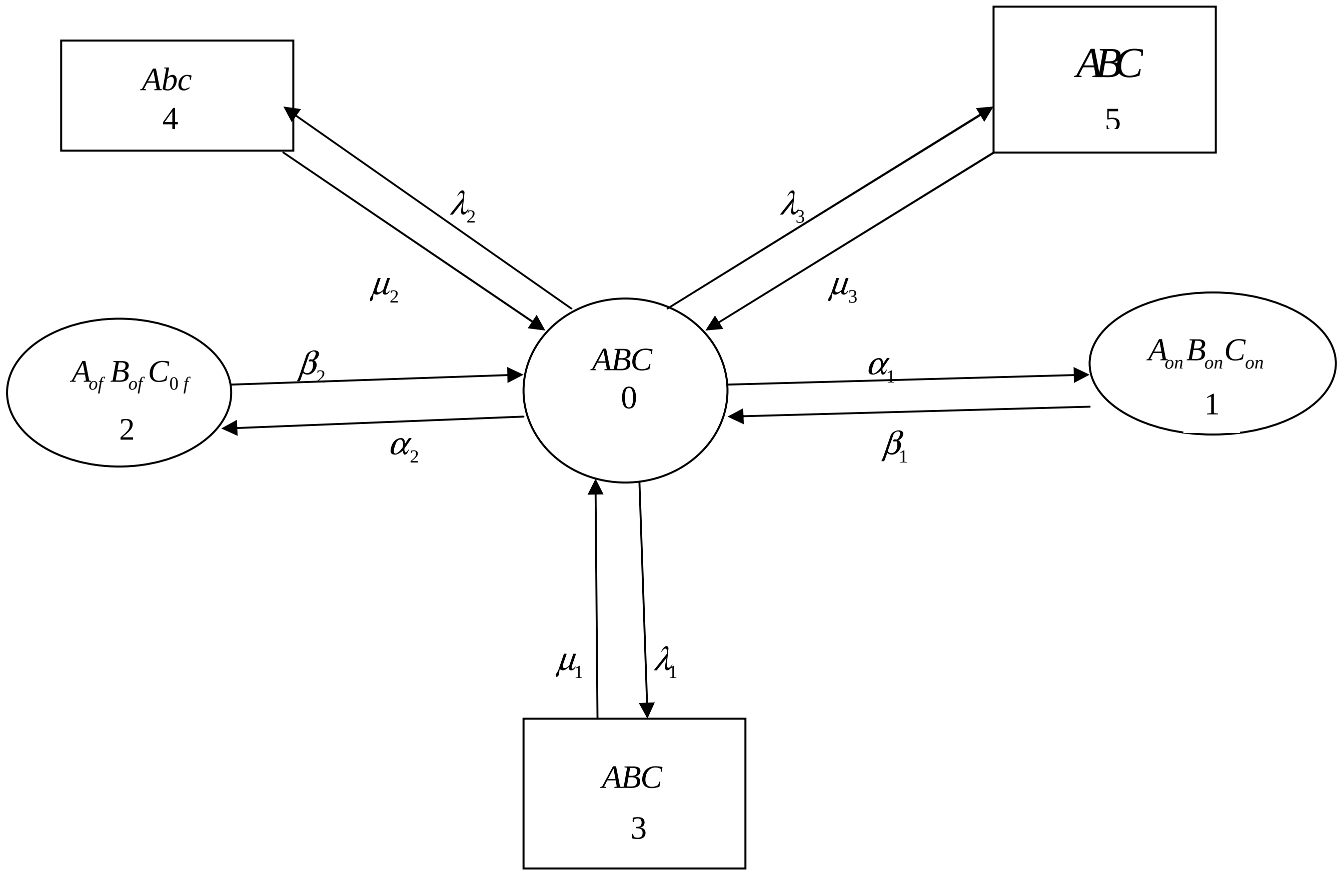



Fig 1. Transition Diagram of the system.

## 1.2. System Simulation Modeling

The prediction/calculation of reliability of a system with each element exhibiting failures and involving repair/standby operations is complicated. In such cases, the use of Markov model technique which has much appeal and work well when failure rates and repair rates are constant.

The simulation model for steam generation system has been developed for marking the stochastic analysis and performance evaluation using Markov concept. Formulation is carried out using the joint probability functions based on the transition diagram. These probabilities are mutually exclusive and provide scope to implement Markovian approach, the failure and repair rates of the different subsystems are used as standard input information to the model. The present performance evaluation is concerned with a discrete-state continuous-time model, is called a Markov process. Let the probability of n occurrences in time t be denoted by $p_n$(t), i.e

$$\text{Probability } (x = n, t) = p_n(t) \qquad (n = 0,1,2 \ldots) \tag{1}$$

According to Markov if $p_0$ (t) represent the probability of zero occurrences in the time t. The probability of zero occurrences in time $(t+\Delta t)$ is given by Equation (Eq.). 1, i.e. $p_0(t+\Delta t)$ = (1-$\lambda.\Delta t$) $p_0\ t$

Similarly $p_1(t+\Delta t) = (\varphi.\Delta t)\ p_0\ t$ (2)

The Eq. (2) shows the probability of one occurrence in time $(t+\Delta t)$ and is composed of two parts, mainly (a) probability of zero occurrences in time t multiplied by the probability of of one occurrence in the interval $\Delta t$ and (b) the probability of one occurrence in time t multiplied by the probability of no occurrences in the time interval $\Delta t$, as stated by Srinath (2005). Then simplifying and putting $\Delta t \to 0$, one gets,

$$(\frac{d}{dt}+\phi)P_0(t) = \lambda.P_0(t) \tag{3}$$

Using the concept used in Eq. (3) and various probability considerations, the following differential equations associated with the transition diagram of steam and turbo-generator system are formed, as described by Kumar *et al.* (2007).

$$p_i(t)+\Sigma(\varphi_i p_0)(t) = \Sigma\lambda_j.p_k(t) \tag{4}$$

For m=1 i=2 and j=0 respectively;

m=2 i=3 and j=0 respectively;

m=2 i=3 and j=0 respectively;

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

Since the thermal plant is a process industry where raw material is processed through various subsystems continuosly till the final product is obtained. Then, according to Arora *et al.(1997*), to get the long run availability of the system i.e. steady state, put derivative of all probability equal to zero, in to differential Eq.(5-7)

i.e. $p_0$

$$p_1 = (\varphi_1/\lambda_1)p_0 \qquad p_2 = (\varphi_2/\lambda_2)p_0 \qquad p_3 = (\varphi_3/\lambda_3)p_0 \tag{5}$$

## 2. Steady State Availability

The steady state availability of Steam and power generation system may be obtained as summation of all working state's probabilities and failed states equals to 1:

i.e. $\sum_{i=1}^{i=3} p_i = 1$ Therefore putting the values of $p_0 - p_3$ and solving, one gets

$$p_0 + p_1 + p_2 + p_3 = 1 \tag{5}$$

$$A_v = p_0 = \frac{1}{1+(\frac{\varphi_1}{\lambda_1})+(\frac{\varphi_2}{\lambda_2})+(\frac{\varphi_3}{\lambda_3})} \tag{6}$$

Equation 6 represents the steady state availability simulation model of steam and power generation system.

## 3. Result and Discussion

The performance analyzed using the developed model. On the basis of availability values as given in tables 1-3, the following observations were made , which reveals the effect of failure and repair rates of various subsystems on the availability of steam and power generation system.

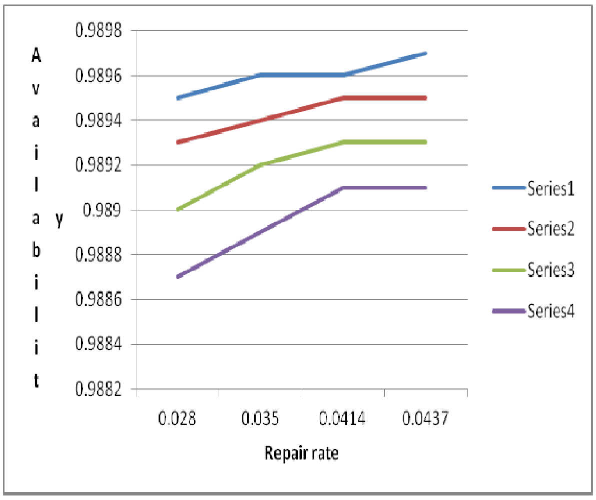
### 3.1 Subsystem A: boiler

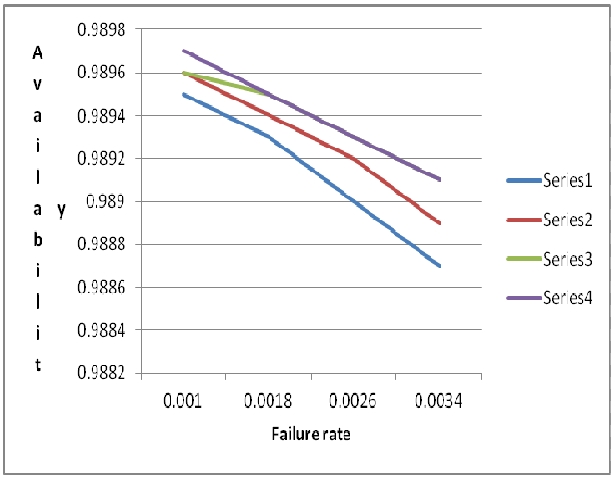
Table 1. and fig 2-3 reveal the effect of failure and repair rates of boiler subsystem on the availability of steam generation on TG generation system of the power plant. Boiler tube puncture, leakage and flame failure are the most common reasons of failure that courses sudden stoppage of the complete power generation (TG) unit of the power plant. It is observed that for some known values of failure/ repair rates of super heater and re-heater as failure rate of boiler increases from 0.001(once in 1000hrs) to 0.0034(34 in 10000hrs), the unit availability decreases by only x/ . Similarly as repair rate of boiler increases from 0.028 (28 in 1000 hrs ) to 0.0437 (437 in 10000 hrs), the unit availability increases by

Table 1. availability matrix of boiler subsystem of steam and power generation unit

| $\lambda$ / $\mu$ | 0.028 | 0.035 | 0..0414 | 0.0437 | Constant values |
|---|---|---|---|---|---|
| 0.0010 | 0.9895 | 0.9896 | 0.9896 | 0.9897 | |
| 0.0018 | 0.9893 | 0.9894 | 0.9895 | 0.9895 | |
| 0.0026 | 0.9890 | 0.9892 | 0.9893 | 0.9893 | |
| 0.0034 | 0.9887 | 0.9889 | 0.9891 | 0.9891 | |




### 3.2 Subsystem B: Super heater

Table 2. and fig 4-5 reveal the effect of failure and repair rates of super heater subsystem on the availability of steam generation on TG generation system of the power plant. Super heater tube puncture, leakage and flame failure are the most common reasons of failure that courses sudden stoppage of the complete power generation (TG) unit of the power plant. It is observed that for some known values of failure/ repair rates of boiler and re-heater as failure rate of boiler increases from 0.0001(1 failure in 1000hrs) to 0.000228(228 in 1000000hrs), the unit availability decreases by only x/ . Similarly as repair rate of super- heater increases from 0.014 (14 in 1000 hrs ) to 0.023 (23 in 1000 hrs), the unit availability increases by

Table 2. availability matrix of super heater subsystem of steam and power generation unit

| $\lambda$ / $\mu$ | 0.014 | 0.017 | 0..020 | 0.023 | Constant values |
|---|---|---|---|---|---|
| 0.00010 | 0.9772 | 0.9773 | 0.9773 | 0.9774 | |
| 0.00015 | 0.9771 | 0.9772 | 0.9772 | 0.9773 | |
| 0.00020 | 0.9769 | 0.9770 | 0.9771 | 0.9772 | |
| 0.000228 | 0.9768 | 0.9770 | 0.9771 | 0.9771 | |

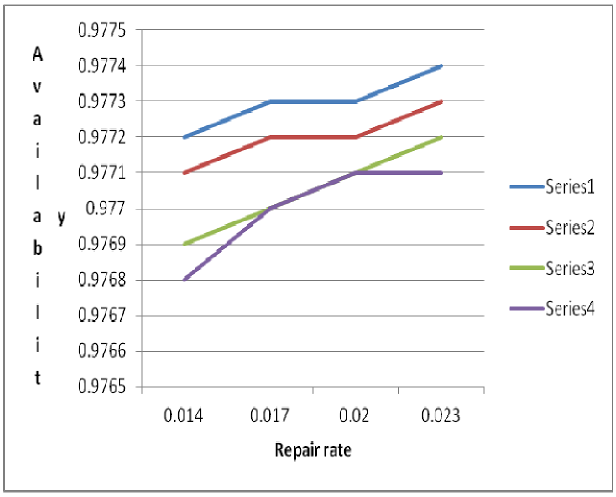



Fig4. Effect of failure rate on availability

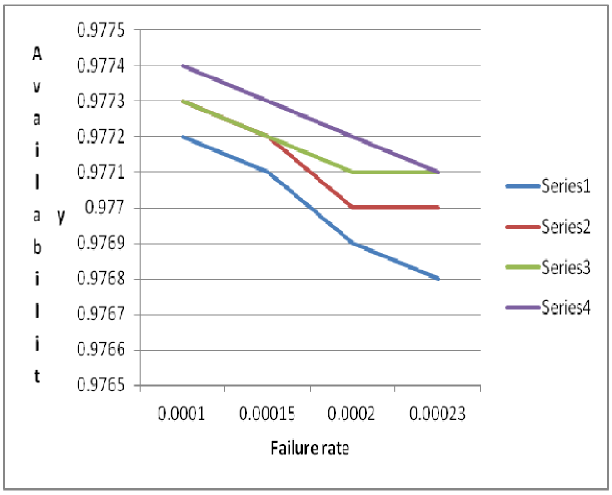



Fig5. Effect of repair rate on availability

### 3.3 Subsystem C: Re-heater

Table 3. and fig 6-7 reveal the effect of failure and repair rates of boiler subsystem on the availability of steam generation on TG generation system of the power plant. Re- heater tube puncture, leakage and flame failure are the most common reasons of failure that courses sudden stoppage of the complete power generation (TG) unit of the power plant. It is observed that for some known values of failure/ repair rates of boiler and super heater as failure rate of boiler increases from 0.0020(20 failures in 1000hrs) to 0.0068(68 in 10000hrs), the unit availability decreases by only x/ . Similarly as repair rate of turbine increases from 0.014 (14 in 1000 hrs ) to 0.050 (5 in 100 hrs), the unit availability increases by

Table 3. availability matrix of re-heater subsystem of steam and power generation unit

| $\lambda$ \ $\mu$ | 0.014 | 0.023 | 0.036 | 0.050 | Constant values |
|---|---|---|---|---|---|
| 0.0020 | 0.9713 | 0.9738 | 0.9752 | 0.9759 | |
| 0.0035 | 0.9665 | 0.9708 | 0.9733 | 0.9746 | |
| 0.0050 | 0.9617 | 0.9679 | 0.9744 | 0.9732 | |
| 0.0068 | 0.9561 | 0.9644 | 0.9692 | 0.9716 | |

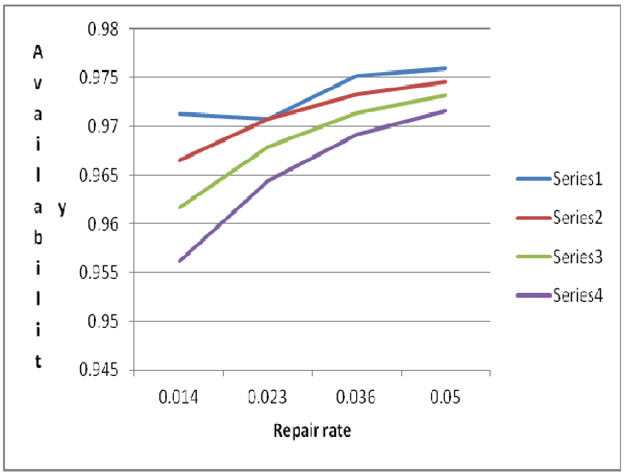



Fig6. Effect of failure rate on availability

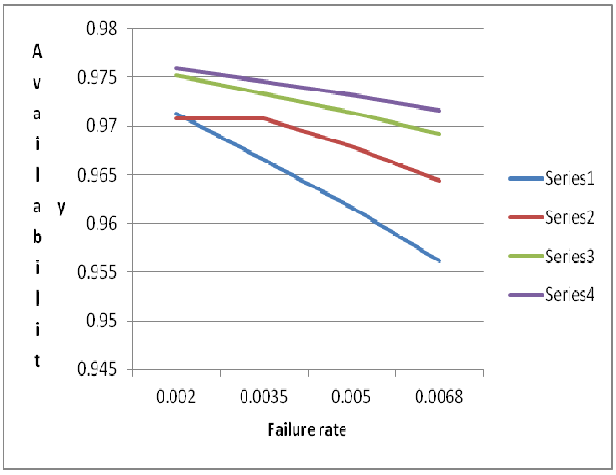



Fig7. Effect of repair rate on availability

Table 4 shows the optimum values of failure/ repair rates of boiler, super heater and re-heater subsystem of steam and power generation unit. The values of maximum availability and related failure / repair rates of subsystems are given in table 4.

Table 4 optimum values of failure/repair rates of subsystem of steam and power generation

| S/N | Subsystem | Failure rate ($\lambda$) | Repair rate ($\mu$) | Max. Availability level |
|---|---|---|---|---|
| 1 | Boiler | 0.0437 | 0.0010 | 99% |
| 2 | Super heater | 0.0232 | 0.00010 | 97% |
| 3 | Re heater | 0.050 | 0.0020 | 98% |

## 4. Conclusion

The system availability has been excellent, mainly due to the low failure rates and supported by the extra ordinary state of the art repair facilities and well trained highly experienced skilled manpower/maintenance personnel. It can be concluded from Table 1-3 that as failure rate increases, the availability decreases and as repair rate increases, the availability of the system increases and vice-versa the expression 6 depict the availability simulation model, which further helps in analysis evaluating the performance various subsystems of steam generation of thermal power plant. Performance matrices as given in table 1-4 and figure 2-7 clearly shows that Super heater subsystem is the most critical subsystem among the three subsystems in the power generation plant as far as maintenance is concern and required immediate attention, as its availability percentage is the least among the three subsystem. Further, Boiler subsystem is having the higher percentage of availability with about 99% level. These results are definitely beneficial to the plant management for the availability analysis of the system under study.

Moreover large number of failures takes due to improper design and overstress of components. This can be avoided by improving the existing components design and selecting high strength high temperature resistance materials for higher performance. It can be said that these will reduces failure rates for various sub-systems performance and increases on the availability of steam generation system of the power plant to accomplish the goal of sufficient high performance. The unit performance can be also being improved using redundancy technique.

**REFERENCES**

[1] Castro H.F., Cavalca K. (2003), Availability optimization with Generic Algorithm; International Journal of Quality and Reliability Management 20(7); 847-863.

[2] Chales C., Kondo A. (2003), Availability allocation to repairable systems with Genetic Algorithms: a multi-objective formulation; Reliability Engineering and System Safety 82(3); 319-330.

[3] Dillon B.S., Singh C. (1981), Engineering Reliability –New Techniques and applications; John Willey and sons; New York.

[4] Goldberg D.E. (2001) Genetic Algorithm in Search; Optimization and Machine Learning, Pearson Edition; Asia .

[5] Gupta p.Lal A., Sharma R., Singh J.( 2005), Numerical analysis of reliability and availability of the series processes in butter oil processing plant; International Journal of Quality and Reliability Management 22(3); 303-316.

[6] GuptaS., Kumar A., Sharmar R., Tewari P.C. (2008), A performance modeling and decision support system for a feed water unit thermal power plant; South African Journal of industrial Engineering 19(2); 125-134.

[7] Juang Ying-Shen,Lin Shui-Shun,Kao Hsing-Pei (2008), A knowledge management system for series-parallel availability optimization and design; Journal of Expert System with Application 34; 181-193.

[8] Kalyanmoy Deb (1995) Optimization for Engineering Design : Algorithms and examples; Prentice Hall of India, New Delhi; India.

[9] Kumar D., Singh I.P.,Singh J.(1988), Reliability analysis of the feeding system in the paper industry; *Microelectronics Reliability* 28(2); 213-215.

[10] Kumar D., Singh J., Pandey P.C. (1989) Availability analysis of the washing system in the paper industry; *Microelectronics Reliability* 29; 775-778.

[11] Kumar D., Singh J., Pandey P.C. (1993), Operational behavior and profit function for a bleaching and screening system in the paper industry; *Microelectronics Reliability* 33;1101-1105.

[12] Shooman M.L. (1996), Reliability computation for systems with dependents failures*; IEEE Annual Symposium on Reliability; 44-56.*

[13] Srinath L.S. (1994), Reliability Engineering; 3rd edition, East-West Press pvt. Ltd.; India.

[14] Sunand Kumar, Dinesh Kumar, Mehta N.P. (1999), Maintenance management for ammonia synthesis system in a urea fertilizer plant; International Journal of Management and System (IJOMAS) 15(3);211-214.

[15] Sunand Kumar,Tewari P.C., Sharma Rajiv (2007), Simulated availability of $CO_2$ cooling system in a fertilizer plant; Indusrial Engineering Journal (Indian Institution of Industrial Engineering, Mumbai ) 36(10);19-23.

[16] Tewari P.C., Kumar D., Mehta N.P. (2003), Decision support system of refining system of sugar plant; Journal of Institute of Engineers (India) 84; 41-44.

[17] Tewari P.C., Joshi D., Sreenivasa Rao M. (2005), Mathematical modeling and behavior analysis of a refining system using Genetic Algorithm; Proceedings of Natural Conference on Competitive Manufacturing Technology & Management for Global Marketing, Chennai;133-134.