Performance Evaluation and Availability Analysis of Steam Generating System in a Thermal Power Plant

P.C. Tewari, Sanjay Kajal, and Rajiv Khanduja

Abstract— **The paper deals with the development of availability model and performance analysis for Steam Generating system of a Thermal Power Plant. The system comprises of three subsystems viz. High Pressure Heaters, Economizer and Boiler Drum, which are connected in series. The availability model of Steam Generating system has been developed on the basis of probabilistic approach using Markov Birth – Death Process. The Chapman–Kolmogorov equations developed are further solved recursively in order to develop the Steady State Availability i.e. performance index. The system performance has been analyzed in terms of availability levels for different combinations of failures and repair rates. The data for various subsystems has been taken from the maintenance history sheets of the plant concerned**.

.

***Index Terms*—Availability, Markov Birth-Death Process, Performance Evaluation, Chapman–Kolmogorov Equations.**

I. Introduction

System availability which is defined as the combination of reliability and maintainability is a measure of the performance of the system under the specified conditions. In most of the complex plants, it has been observed that these consist of systems and subsystems connected in series, parallel or a combination of these. A Thermal Power Plant is a complex engineering system which provides electric power for domestic, commercial, industrial and agricultural use. Availability and Reliability problems may cause shut down of the plant or reduce the generation of power resulting in load shedding and many other problems including lose of productive activities. For improving the productivity, availability and reliability of systems/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. But practically these systems are subjected to random failures due to poor design, wrong manufacturing techniques, lack of operative skills, poor maintenance, overload, delay in starting maintenance and human error etc. These causes lead to non-availability of an industrial system resulting into improper utilization of resources (man, machine, material, money and time). So, to achieve high production and good quality, there should be highest system availability (long run system availability).

Several researches gave various theories in the field of availability and reliability for complex process and manufacturing industries.. Singh and Mahajan [1] examined the reliability and long run availability of a Utensil manufacturing plant using Laplace transforms. Gupta, Lal, Sharma and Singh [2] studied the behavior of Cement manufacturing plant using Runge-Kutta Method. Kiureghian and Ditlevson [3] analyzed the availability, reliability, and downtime of system with repairable components. Asha and Nair [4] examined the relationship between mean time to failure in an age replacement model with hazard rate and mean residual life functions. Garg et al. [5] developed a reliability model of a block- board manufacturing system in the plywood industry using time dependent and steady state availability under idealized and faulty Preventive Maintenance (PM). Mange and Singh [6] discussed the availability of a complex system consisting of two independent repairable subsystems using “pre-emptive repeat repair discipline” where A is a priority and B is non-priority. Selvik and Aven [7] extend the reliability centered maintenance (RCM) method in offshore oil and gas industry when uncertainties and risk factors are there.

II. System Description

A. The Steam Generating system consists of following three sub-systems:

High Pressure Heaters (A): Two heaters working in parallel. The system works with one unit in reduced capacity.

Economizer (B): Consist of one unit subjected to minor and major failure. In Economizer, heat carried in flue gases are used to increase the boiler feed water temperature from 231°c to 280°c. Partial failure of Economizer can set the system to reduced working condition, while major failure can cause complete failure of system.

.**Boiler Drum (C)**: One unit subjected to major failure only.

The following notations and assumptions are addressed for the purpose of mathematical analysis of the system.

B. Assumptions:

i) All the sub-systems are initially operating and in good condition.

Manuscript submitted April 10, 2011 .
The industrial survey was done at Thermal Power Plant, Bhatinda (Punjab), India

Dr. P.C. Tewari (Associate Professor) is with the Mechanical Engineering Department, National Institute of Technology, Kurukshetra, India.
Phone:+91-9896434963; (e-mail: pctewari1@rediffmail.com).
Sanjay Kajal (Assistant Professor) is with the Mechanical Engineering Department ,U.I.E.T., Kurukshetra University, Kurukshetra, India.
Phone:+91-9416177583; (e-mail:sanjay_kajal@rediffmail.com).
Rajiv Khanduja (Associate Professor) is with the Mechanical Engineering Department, Yamuna Institute of Engineering and Technology, Yamuna Nagar, India.
Phone:+91-9896237144; (e-mail:rajiv_khanduja@rediffmail.com).
.

ii) Failure and repair rates are constant.
iii) Each unit works as good as new after repair.
iv) Failure and repair rates are statistically independent.
v) Economizer on failure from the reduced state $\overline{B}$ is repaired back to the good state '*B*' only.

C. Notations:

$A,\ B,\ C$	: Subsystems are in operating state.
$\overline{A}, \overline{B}$	: Indicates that *A* & *B* are working in reduced capacity.
a, b, c	: Indicates the failed state of *A,B,C* .
λ_i	: Mean constant failure rates from states $\overline{A}, \overline{B}, A, B, C, B$ to the states $a, b, \overline{A}, \overline{B}, c, b$.
μ_i	: Mean constant repair rates from states $a, b, \overline{A}, \overline{B}, c, b$ to the States $\overline{A}, \overline{B}, A, B, C, B$.
$P_i(t)$	: Probability that at time '*t*' all units are good and the system is in *i*th state.
(')	: Derivatives w.r.t. '*t*'.

III. PERFORMANCE EVALUATION

The performance evaluation of the Steam Generating system has been carried out with the help of simple probabilistic approach based upon Markov birth-death process. The Chapman–Kolmogorov differential equations are developed based on the transition diagram as shown in Figure 1, which are as follows:

$$P_0'(t) + \sum_{i=3}^{6} \lambda_i P_0(t) = \sum_{i=3}^{4} \mu_i P_{i-2}(t) + \mu_5 P_4(t) + \mu_6 P_8(t) \quad (1)$$

$$P_1'(t) + \left(\lambda_1 + \sum_{i=4}^{6} \lambda_i + \mu_3\right) P_1(t) = \lambda_3 P_0(t) + \mu_4 P_3(t) + \mu_5 P_5(t) + \mu_1 P_6(t) + \mu_6 P_7(t) \quad (2)$$

$$P_2'(t) + \left(\sum_{i=2}^{3} \lambda_i + \lambda_5 + \mu_4\right) P_2(t) = \mu_3 P_3(t) + \mu_5 P_9(t) + \lambda_4 P_0(t) \quad (3)$$

$$P_3'(t) + \left(\sum_{i=1}^{2} \lambda_i + \lambda_5 + \sum_{\mu=3}^{4} \mu_i\right) P_3(t) = \mu_1 P_{11}(t) + \mu_5 P_{10}(t) + \lambda_3 P_2(t) + \lambda_4 P_1(t) \quad (4)$$

$$P_i'(t) + \mu_5 P_i(t) = \lambda_5 P_j(t) \quad (5)$$

For $i = 4, j = 0$ and $i = 5, j = 1$

$$P_6'(t) + \mu_1 P_6(t) = \lambda_1 P_1(t) \quad (6)$$

$$P_i'(t) + \mu_6 P_i(t) = \lambda_6 P_j(t) + \lambda_2 P_k(t) \quad (7)$$

For $i = 7, j = 1, k = 3$ and $i = 8,\ j = 0, k = 2$

$$P_i'(t) + \mu_5 P_i(t) = \lambda_5 P_j(t) \quad (8)$$

For $i = 9, j = 2$ and $i = 10, j = 3$

$$P_{11}'(t) + \mu_1 P_{11}(t) = \lambda_1 P_3(t) \quad (9)$$

Initial conditions at time $t = 0$ are

$P_i(t) = 1$ for $i = 0$

$= 0$ for $i \neq 0$

In the process industry, we require long run availability of the system, which is obtained by putting $d/dt \to 0$ and taking probabilities independent of t.

For steady state availability, transition rates are taken to be constant.

A. Steady State Availability using Normalizing conditions

The limiting probabilities from equations (1) – (9) are:

$$\sum_{i=3}^{6} \lambda_i P_0 = \sum_{i=3}^{4} \mu_i P_{i-2} + \mu_5 P_4 + \mu_6 P_8$$

$$\left(\lambda_1 + \sum_{i=4}^{6} \lambda_i + \mu_3\right) P_1 = \lambda_3 P_0 + \mu_4 P_3 + \mu_5 P_5 + \mu_1 P_6 + \mu_6 P_7$$

$$\left(\sum_{i=2}^{3} \lambda_i + \lambda_5 + \mu_4\right) P_2 = \mu_3 P_3 + \mu_5 P_9 + \lambda_4 P_0$$

$$\left(\sum_{i=1}^{2} \lambda_i + \lambda_5 + \sum_{\mu=3}^{4} \mu_i\right) P_3 = \mu_1 P_{11} + \mu_5 P_{10} + \lambda_3 P_2 + \lambda_4 P_1$$

$\mu_5 P_i = \lambda_5 P_j$ For $i = 4, j = 0$ and $i = 5, j = 1$

$\mu_1 P_6 = \lambda_1 P_1$

$\mu_6 P_i = \lambda_6 P_j + \lambda_2 P_k$ For $i = 7, j = 1, k = 3$ and $i = 8,\ j = 0, k = 2$

$\mu_5 P_i = \lambda_5 P_j$ For $i = 9, j = 2$ and $i = 10, j = 3$

$\mu_1 P_{11} = \lambda_1 P_3$

On solving these equations recursively, we can found the values of all state probabilities in terms of full working state probability i.e. P_0

$$P_1 = N_1 P_0 \qquad P_2 = N_2 P_0 \qquad P_3 = N_3 P_0$$

$$P_4 = \frac{\lambda_5}{\mu_5} P_0 \qquad P_5 = \frac{\lambda_5 N_1}{\mu_5} P_0 \qquad P_6 = \frac{\lambda_1 N_1}{\mu_1} P_0$$

$$P_7 = \left(\frac{\lambda_6}{\mu_6} N_1 + \frac{\lambda_3}{\mu_6} N_3\right) P_0 \qquad P_8 = \left(\frac{\lambda_2}{\mu_6} N_2 + \frac{\lambda_6}{\mu_6}\right) P_0$$

$$P_9 = \frac{\lambda_5 N_2}{\mu_5} P_0 \qquad P_{10} = \frac{\lambda_5 N_3}{\mu_5} P_0 \qquad P_{11} = \frac{\lambda_1 N_3}{\mu_1} P_0$$

Where

$$N_1 = \frac{\lambda_3}{Y_1}\left[1 + \frac{\lambda_4(\lambda_2 + \lambda_4)}{Y_2 Y_3}\right] \qquad N_2 = \frac{N_1 \lambda_4 \mu_3}{Y_2 Y_3} + \frac{\lambda_4}{Y_2}$$

$$N_3 = \frac{N_2 \lambda_3}{N_3} + \frac{N_1 \lambda_4}{N_3}$$

$$Y_1 = \left[(\lambda_4 + \mu_3) - (\lambda_2 + \mu_4)\left(\frac{\lambda_4}{Y_3} + \frac{\lambda_3 \lambda_4 \mu_4}{Y_2 Y_3 Y_3}\right)\right]$$

$$Y_2 = \left[(\lambda_2 + \lambda_3 + \mu_4) - \frac{\lambda_3 \mu_3}{Y_3}\right] \qquad Y_3 = (\lambda_2 + \mu_3 + \mu_4)$$

The probability of full working capacity (without standby systems) i.e. P_0 is determined by using normalizing conditions i.e. sum of all the probabilities of all working

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

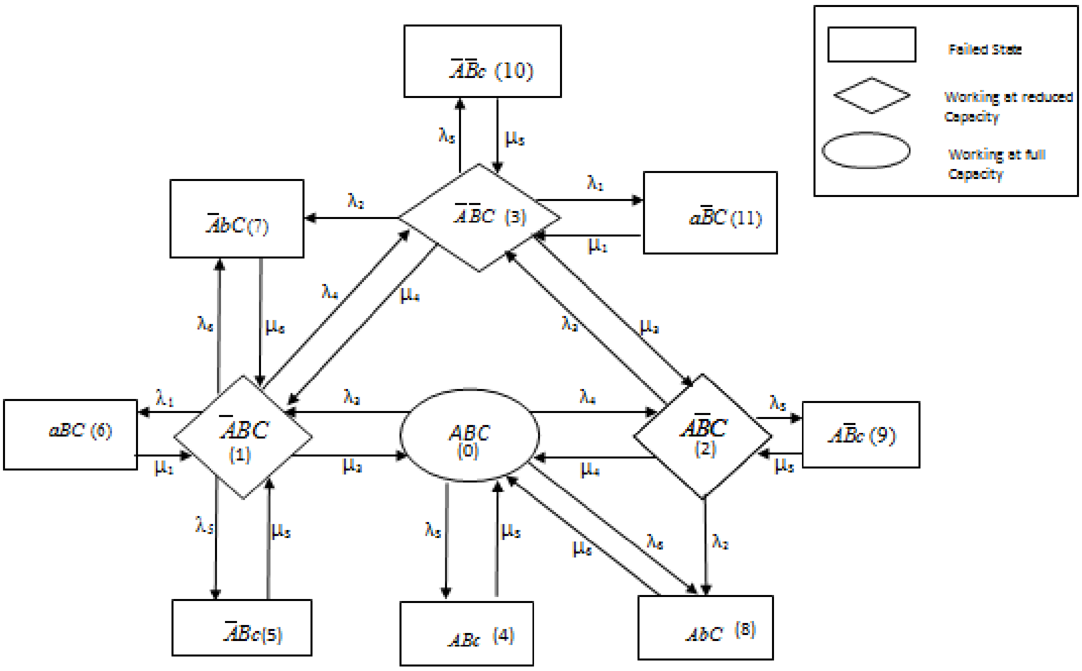

Figure 1: Transition Diagram of Steam Generating System

states, reduced capacity and failed states, is equal to one, we get, $\sum_{i=0}^{11} P_i = 1$

$$P_0 = \left[1 + \frac{\lambda_5}{\mu_5} + \frac{\lambda_6}{\mu_6} + \left(1+\frac{\lambda_1}{\mu_1}+\frac{\lambda_5}{\mu_5}+\frac{\lambda_6}{\mu_6}\right)N_1 + \left(1+\frac{\lambda_5}{\mu_5}+\frac{\lambda_2}{\mu_6}\right)N_2 + \left(1+\frac{\lambda_1}{\mu_1}+\frac{\lambda_5}{\mu_5}+\frac{\lambda_3}{\mu_6}\right)N_3 \right]^{-1}$$

Now, the steady state availability of Steam Generating system (*Av.*) may be obtained as summation of all working and reduced capacity state probabilities, i.e.

$$A_{v.} = P_0 + P_1 + P_2 + P_3 = [1 + N_1 + N_2 + N_3]P_0$$

Availability index which is derived from the above equation can be used for maintenance planning and maintenance scheduling of Steam Generating system of a thermal power plant.

IV. AVAILABILITY ANALYSIS

The failure and repair rates of various subsystems of Steam Generating system are taken from the maintenance history sheets of a thermal power plant. The availability matrices are developed to analyze the various performance levels for different combinations of failures and repair rates. Table 1, 2, 3 represent the availability matrices for various subsystems of Steam Generating system. Accordingly, maintenance decisions can be made for various subsystems keeping in view the repair criticality and we may select the best possible combinations (λ, μ).

V. RESULTS AND DISCUSSION

Table 1 to 3 show the effect of failure and repair rates of High Pressure Heater, Boiler Drum & Economizer on the steady state availability of the Steam Generating system. Table 1 reveals the effect of failure and repair rates of High Pressure Heater subsystem on the availability of the Steam Generating system. It is observed that for some known values of failure / repair rates of Economizer & Boiler Drum (λ_2=0.002, λ_3= 0.0015, λ_4=0.002, λ_5=0.003, λ_6=0.002, μ_2=0.10, μ_3=0.05, μ_4=0.10, μ_5=0.10, μ_6=0.10), as the failure rates of High Pressure Heater increases from 0.0015 (once in 667 hrs) to 0.0075 (once in 133 hrs), the availability decreases by 0.31%. Similarly as repairs rates of High Pressure Heater increases from 0.05 (once in 20 hrs) to 0.25 (once in 4 hrs), the availability increases by 0.06%.

Table 2 depicts the effect of failure and repair rates of Economizer subsystem on the availability of the Steam Generating system. It is observed that for some known values of failure / repair rates of High Pressure Heater & Boiler Drum (λ_1=0.0015, λ_2= 0.002, λ3=0.0015, λ_4=0.002, λ_5=0.003, μ_1=0.05, μ_2=0.10, μ_3=0.05, μ_4=0.10, μ_5=0.10), as the failure rates of Economizer increases from 0.002 (once in 500 hrs) to 0.010 (once in 100 hrs), the availability decreases by 6.61%. Similarly as repairs rates of Economizer increases from 0.10 (once in 10 hrs) to 0.50 (once in 2 hrs), the availability increases by 1.47%.

The effect of failure and repair rates of Boiler Drum subsystem on the availability of the Steam Generating system is shown in Table 3. It is observed that for some known values of failure / repair rates of High Pressure Heater & Economizer (λ_1=0.0015, λ_2= 0.002, λ_3=0.0015, λ_4=0.002, λ_6=0.002, μ_1=0.05, μ_2=0.10, μ_3=0.05, μ_4=0.10, μ_6=0.10), as the failure rates of Boiler Drum increases from 0.003 (once in 334 hrs) to 0.015 (once in 67 hrs), the availability decreases by 9.75%. Similarly as repairs rates of Boiler Drum increases from 0.10 (once in 10 hrs) to 0.50 (once in 2 hrs), the availability increases by 2.22%.

ISBN: 978-988-19252-2-0
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)

Table 1: Availability Matrix for High Pressure Heater of Steam Generating System

λ_1 \ μ_1	0.05	0.10	0.15	0.20	0.25	Constant values
0.0015	0.9516	0.9520	0.9521	0.9522	0.9522	λ_2=0.002,λ_3= 0.0015,
0.0030	0.9508	0.9516	0.9518	0.9520	0.9521	λ_4=0.002, λ_5=0.003,
0.0045	0.9500	0.9512	0.9515	0.9518	0.9519	λ_6=0.002,μ_2=0.10,
0.0060	0.9493	0.9508	0.9513	0.9516	0.9517	μ_3=0.05,μ_4=0.10,
0.0075	0.9485	0.9504	0.9511	0.9514	0.9516	μ_5=0.10, μ_6=0.10

Table 2: Availability Matrix for Economizer of Steam Generating System

λ_6 \ μ_6	0.10	0.20	0.30	0.40	0.50	Constant values
0.002	0.9516	0.9607	0.9638	0.9658	0.9663	λ_1=0.0015,λ_2= 0.002,
0.004	0.9342	0.9518	0.9578	0.9608	0.9626	λ_3=0.0015, λ_4=0.002,
0.006	0.9011	0.9429	0.9518	0.9563	0.9590	λ_5=0.003,μ_1=0.05,
0.008	0.8902	0.9343	0.9459	0.9518	0.9554	μ_2=0.10,μ_3=0.05,
0.010	0.8855	0.9258	0.9382	0.9474	0.9518	μ_4=0.10, μ_5=0.10

Table 3: Availability Matrix for Boiler Drum of Steam Generating System

λ_5 \ μ_5	0.10	0.20	0.30	0.40	0.50	Constant values
0.003	0.9516	0.9654	0.9685	0.9724	0.9738	λ_1=0.0015, λ_2= 0.002,
0.006	0.9252	0.9516	0.9607	0.9654	0.9682	λ_3=0.0015, λ_4=0.002,
0.009	0.9002	0.9382	0.9516	0.9584	0.9626	λ_6=0.002, μ_1=0.05,
0.012	0.8765	0.9252	0.9426	0.9516	0.9571	μ_2=0.10, μ_3=0.05,
0.015	0.8541	0.9125	0.9338	0.9448	0.9516	μ_4=0.10, μ_6=0.10

VI. CONCLUSION

The developed availability model is used for performance analysis of various subsystems of Steam Generating system. The availability levels which depict the system performance for different combinations of failure and repair rates are shown by various availability matrices. The best combination of failure events and repair course of action can be chosen from these matrices which could further be utilized for maintenance planning and scheduling.

On the basis of repair rates, the maintenance priorities should be given as per following order:

1. Boiler Drum
2. Economizer
3. High Pressure Heater

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 performance evaluation and availability analysis of Steam Generating system.

ACKNOWLEDGEMENT

Author is thankful Sh. Sahib Singh, Superintendent Engineer, Thermal Power Plant, Bhatinda for providing every possible help for the work.

REFERENCES

[1] Singh J., and Mahajan P., "Reliability of Utensils Manufacturing Plant – A Case Study", Opsearch, Vol. 36, No.3, pp. 260-269, 1999 .
[2] Gupta P., Lal A.K., Sharma R.K. and Singh J., "Behavioral Study of the Cement manufacturing Plant – A Numerical Approach" , Journal of Mathematics and Systems Sciences, Vol. 1, No. 1, pp.50-694, 2005.
[3] Kiureghian A.D. and Ditlevson O.D., "Availability, Reliability & downtime of system with repairable components", Reliability Engineering and System Safety, Volume 92, Issue 2, pp. 66-72, 2007.
[4] Asha G., Nair N., "Reliability properties of mean time to failure in age replacement models", International Journal of Reliability, Quality and Safety Engineering (IJRQSE), Volume: 17, Issue: 1 pp. 15-26, 2010 .
[5] Garg Savita et al., "Availability and maintenance scheduling of a repairable block-board manufacturing system", International Journal of Reliability and Safety 2010 - Vol. 4, No.1, pp. 104 - 118, 2010.
[6] Ram Mangey, Singh S.B., "Availability, MTTF and cost analysis of complex system under preemptive-repeat repair discipline using Gumbel-Hougaard family copula", International Journal of Quality & Reliability Management, Vol. 27 Issue 5, pp.576 – 595, 2010.
[7] Selvik J.T. and Aven , " A framework for reliability and risk centered maintenance" Reliability Engineering and System Safety, Volume 96, Issue 2, pp. 324-331, 2011.