PERFORMANCE MODELING OF FURNACE DRAFT AIR CYCLE IN A THERMAL POWER PLANT

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Abstract:

This paper discusses the performance analysis of the furnace draft air cycle in a thermal power plant. The furnace draft air cycle in a thermal power plant has three main subsystems. These subsystems are arranged in series and parallel configurations. For the analysis of availability, formulation of the problem is carried out using Markov Birth-Death process based upon probabilistic approach. Failure and repair rates for all the subsystems have been taken from maintenance history sheets of plant. A transition diagram representing interrelationship among the full working, reduced capacity and failed states has been developed. The effect of failure and repair rates of each subsystem on the system availability has been determined. The results are supplied to the management, which will help to improve the overall performance of the thermal power plant concerned.

***Key words**: Performance Modeling; Probabilistic approach; Availability matrix; Markov approach; Transition diagram .*

1. Introduction

In furnace draft air cycle, the hot air from Primary air fan goes to primary air distribution headers where the air is used as medium to transport coal from primary air feeders to coal bunkers in the furnace. Flue gases from furnace are passed to chimney through Induced Draft fans (I.D.) fans. 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. Singh [1] formulated mathematical models for a standby redundant complex system under preemptive repeat repair policy; standby redundant complex system having two classes with many components under preemptive resume repair policy. Singh et al. [2] analyzed the cost of one server two – unit [one priority and the other ordinary] cold standby systems with two modes – normal and total failure. Failure and delivery time distribution were assumed to be exponential whereas repair and replacement time distributions were arbitrary. The system has been analyzed to determine the reliability measures [MTSF, steady state availability, busy period analysis of repairman, etc] by using regenerative point technique. Kumar et al. [3] developed a mathematical model for calculating the reliability and availability of crystallizer system in sugar plants. The crystallizer system consists of basic repairable sub-systems in series. Each sub-system was considered as being: Good, Reduced, or Failed. They assumed that some subsystems can fail together due to common cause. Steady-state availability and various state probabilities were derived using Laplace transformation technique. Zhao [4] developed a generalized availability model for repairable components and series systems including perfect and imperfect repair. The general distribution was assumed for a repaired component. Dekker [5] had given an overview on the role of operations research models for maintenance model in which both costs and benefits of maintenance were qualified and in which an optimum balance between both was obtained. Jenson [6] emphasized on near future with respect to reliability activities at the components as well as at the system level. Zhang [7] studied the stochastic behavior of an [N+1]-unit standby system under preemptive priority repair rule and obtained the expressions for transient and steady states of the system using supplementary variables and Laplace transforms. Nag C.N. [8] evaluated various reliability parameters such as reliability, failure density, failure rate & mean time to failure of a Hydraulic Unit. Author also demonstrated the fault tree diagram for determining the probable cause for any fault, which occurred during its course of operation. Nakamura et al. [9] described a maintenance scheduling for Pump systems in thermal power stations in order to reduce the maintenance cost during the whole period of operation, while keeping the current reliability level of the pump system. The dimensional reduction method was used to solve the problem in which a few available data were used together with other factors relating to the failure of pumps. Grall et al. [10] presented a predictive maintenance structure for a gradually deteriorating single-unit system [continuous time/continuous state]. The proposed model was used for optimal inspection & replacement decision in order to balance the cost engaged by failure & unavailability of the system. Verma et al. [11] worked for the measurement of effectiveness of the 2-component non-identical system. Markovian approach was used in order to derive the reliability characteristics such as reliability function & mean time between failures. From J.A Van [12] economical point of view, high reliability is desirable to reduce the maintenance costs of systems. J. Barabady et al. [13] Since failure cannot be prevented entirely, it is important to minimize both its probability of occurrence and the impact of failures when they do occur. To maintain the designed reliability, availability and maintainability characteristics and to achieve expected performance, an effective maintenance program is a must and the effective maintenance is characterized by low maintenance cost.

1.1 Organization of the paper

The paper is organized systematically as below:

The section 2 describes the furnace draft air cycle of thermal plant, system description, assumptions and notations for drawing the transition diagram. Section 3 discusses mathematical modeling, its analysis with Markov approach. Section 4 describes the performance analysis of the system. Section 5 and 6 consists of results and conclusion of developed decision support system.

2. System Description

Furnace Draft Air Cycle Subsystems

Furnace draft air cycle consists of various subsystems connected in series and parallel combination for air supply to furnace. The schematic diagram of system is shown below (Figure 1). The optimization of each sub-system in relation to one another is required to make the power plant more profitable and viable for operation.

2.1. Unit Description

Furnace draft air cycle consists of following subsystems:

(i) Primary air fan (A): Consist of two units, failure of one make system at reduced capacity and failure of both results into system failure.

(ii) Furnace (B): Having single unit, failure of which results in to system failure.

(iii) Induced draft fan (C): Consist of three units, failure of one reduces the capacity of system and failure of two fans results into system at reduced capacity.

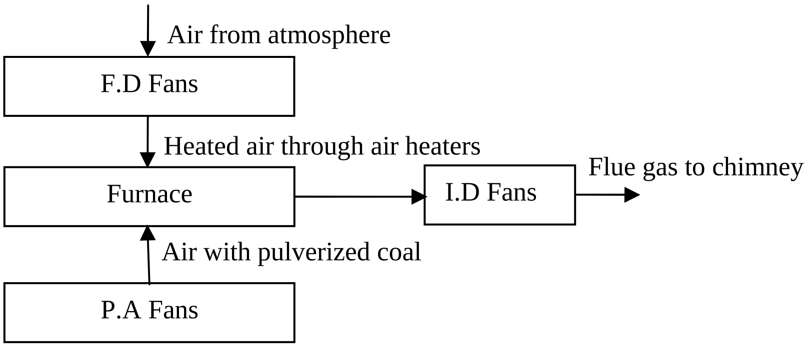

Figure 1 Furnace draft air cycle

2.2 Assumptions for Model Development and System State Transition Diagram

For the development of the probabilistic model, the following assumptions are used:

1. Failure and repair rates for each subsystem are constant and statistically independent.
2. Not more than one failure occurs at a time.

3. A repaired unit is as good as new, performance wise.
4. The standby units are of the same nature and capacity as the active units.

The transition diagram of furnace draft air cycle is shown below in figure 2.

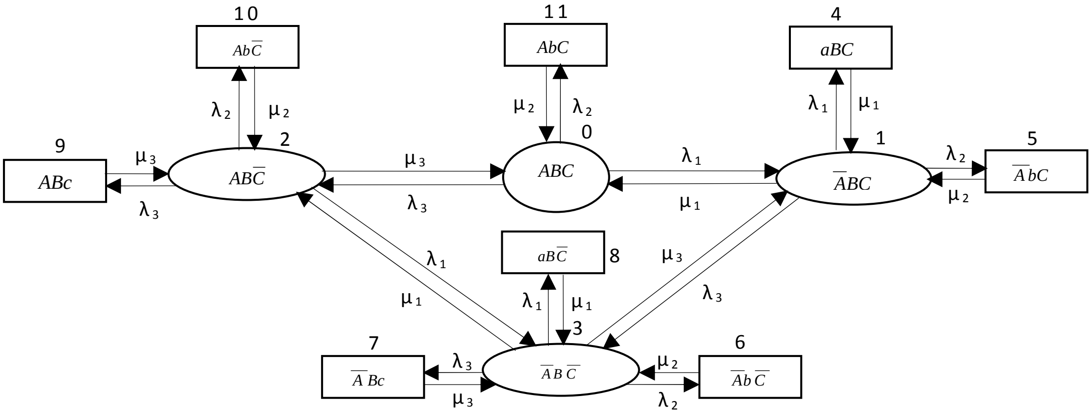

Figure 2 Transition diagram of furnace draft air cycle

2.2. Symbols and Nomenclature

The symbols and notations associated with the transition diagram (Figure 2) are as follows;

○ : Indicates the system is in full working state.
▭ : Indicates the system is in failed state.
⬭ : Indicates the system is in reduced state.
Av : Steady state availability of the system.
A, B, C : Subsystems in good operating state.
a,b,c : Indicates the failed state of A,B,C
$\bar{A}$, $\bar{C}$: Indicates the reduced state of A,C
λ_i : Mean constant failure rates from states $A, B, C, \bar{A}, \bar{C}$ to the states $\bar{A}, b, \bar{C}, a, c$
μ_i : Mean constant repair rates from states $\bar{A}, b, \bar{C}, a, c$ to the States $A, B, C, \bar{A}, \bar{C}$
$P_i(t)$: Probability that at time '*t*' all units are good and the system is in ith state.
' : Derivatives w.r.t. '*t*'

3. Mathematical modeling

Probability consideration gives following differential equations (Eq. 1 – Eq. 12) associated with the Transition Diagram (Figure 2).

$$P_0'(t) + (\lambda_1 + \lambda_2 + \lambda_3)P_0(t) = \mu_1 P_1(t) + \mu_3 P_2(t) + \mu_2 P_{11}(t) \tag{1}$$

$$P_1'(t) + (\lambda_1 + \lambda_2 + \lambda_3 + \mu_1)P_1(t) = \lambda_1 P_0(t) + \mu_1 P_4(t) + \mu_2 P_5(t) + \mu_3 P_3(t) \tag{2}$$

$$P_2'(t) + (\lambda_1 + \lambda_2 + \lambda_3 + \mu_3)P_2(t) = \lambda_3 P_0(t) + \mu_3 P_9(t) + \mu_2 P_{10}(t) + \mu_1 P_3(t) \tag{3}$$

$$P_3'(t) + (\lambda_1 + \lambda_2 + \lambda_3 + \mu_3 + \mu_1)P_3(t) = \lambda_1 P_2(t) + \lambda_3 P_1(t) + \mu_2 P_6(t) + \mu_3 P_7(t) + \mu_1 P_8(t) \tag{4}$$

$$P_4'(t) + \mu_1 P_4(t) = \lambda_1 P_1(t) \tag{5}$$

$$P_5'(t) + \mu_2 P_5(t) = \lambda_2 P_1(t) \tag{6}$$

$$P_6'(t) + \mu_2 P_6(t) = \lambda_2 P_3(t) \tag{7}$$

$$P_7'(t) + \mu_3 P_7(t) = \lambda_3 P_3(t) \tag{8}$$

$$P_8'(t) + \mu_1 P_8(t) = \lambda_1 P_3(t) \tag{9}$$

$$P_9'(t) + \mu_3 P_9(t) = \lambda_3 P_2(t) \tag{10}$$

$$P_{10}'(t) + \mu_2 P_{10}(t) = \lambda_2 P_2(t) \tag{11}$$

$$P_{11}'(t) + \mu_2 P_{11}(t) = \lambda_2 P_0(t) \tag{12}$$

Initial conditions at time $t = 0$ are

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

Steady State Availability

The steady state availability of the system can be analyzed by setting t→ ∞ and d/dt→ 0
The limiting probabilities from equations (1) – (12) are:

$$(\lambda_1 + \lambda_2 + \lambda_3)P_0 = \mu_1 P_1 + \mu_3 P_2 + \mu_2 P_{11} \quad (13)$$

$$(\lambda_1 + \lambda_2 + \lambda_3 + \mu_1)P_1 = \lambda_1 P_0 + \mu_1 P_4 + \mu_2 P_5 + \mu_3 P_3 \quad (14)$$

$$(\lambda_1 + \lambda_2 + \lambda_3 + \mu_3)P_2 = \lambda_3 P_0 + \mu_3 P_9 + \mu_2 P_{10} + \mu_1 P_3 \quad (15)$$

$$(\lambda_1 + \lambda_2 + \lambda_3 + \mu_3 + \mu_1)P_3 = \lambda_1 P_2 + \lambda_3 P_1 + \mu_2 P_6 + \mu_3 P_7 + \mu_1 P_8 \quad (16)$$

$$\mu_1 P_4 = \lambda_1 P_1 \quad (17)$$

$$\mu_2 P_5 = \lambda_2 P_1 \quad (18)$$

$$\mu_2 P_6 = \lambda_2 P_3 \quad (19)$$

$$\mu_3 P_7 = \lambda_3 P_3 \quad (20)$$

$$\mu_1 P_8 = \lambda_1 P_3 \quad (21)$$

$$\mu_3 P_9 = \lambda_3 P_2 \quad (22)$$

$$\mu_2 P_{10} = \lambda_2 P_2 \quad (23)$$

$$\mu_2 P_{11} = \lambda_2 P_0 \quad (24)$$

Solving the above equations, we get:
Let us assume,

$P_1 = L_1 P_0$, $P_2 = L_2 P_0$, $P_3 = L_3 P_0$, $P_4 = K_1 L_1 P_0$, $P_5 = K_2 L_1 P_0$, $P_6 = K_2 L_3 P_0$, $P_7 = K_3 L_3 P_0$, $P_8 = K_1 L_3 P_0$, $P_9 = K_3 L_2 P_0$, $P_{10} = K_2 L_2 P_0$, $P_{11} = K_2 P_0$ Where,

$$K_1 = \frac{\lambda_1}{\mu_1},\ K_2 = \frac{\lambda_2}{\mu_2},\ K_3 = \frac{\lambda_3}{\mu_3},\ K_4 = \frac{\lambda_4}{\mu_4},\ L_1 = \frac{(T_2 T_3 - \lambda_1 \mu_1)\lambda_1 + \lambda_3(\lambda_1 \mu_3)}{T_1 T_2 T_3 - T_1 \lambda_1 \mu_1 - T_2 \mu_3 \lambda_3},$$

$$L_2 = \frac{(T_1 T_3 - \lambda_3 \mu_3)\lambda_3 + \lambda_1 \lambda_3 \mu_1}{T_1 T_2 T_3 - T_1 \lambda_1 \mu_1 - T_2 \mu_3 \lambda_3},\ L_3 = \frac{\lambda_3 \lambda_1 T_1 - T_2 \lambda_1 \lambda_3}{T_1 T_2 T_3 - T_1 \lambda_1 \mu_1 - T_2 \mu_3 \lambda_3}$$

Now using normalizing conditions i.e. sum of all the probabilities is equal to one, we get: $\sum_{i=0}^{11} P_i = 1$

$$P_0 = \left[1 + L_1 + L_2 + L_3 + K_1 L_1 + +K_2 L_1 + K_2 L_3 + K_3 L_3 + K_1 L_3 + K_3 L_2 + K_2 L_2 + K_2\right]^{-1}$$

$$[A_V] = P_0 + P_1 + P_2 + P_3 = [1 + L_1 + L_2 + L_3]P_0$$

4. Performance Analysis

The failure and repair rates of various subsystems of furnace draft air cycle have been taken from the maintenance history sheet of thermal power plant. The decision support system deals with the quantitative analysis of all the factors viz. courses of action and states of nature, which influence the maintenance decisions associated with the Steam generation system. The decision matrices are developed to determine the various availability levels for different combinations of failures and repair rates. Table 1, 2, 3 represent the decision matrices for various subsystems of furnace draft air cycle. Accordingly, maintenance decisions can be made for various subsystems keeping in view the repair criticality and we may select the best possible combinations of failure and repair rates.

5. Results and Discussion

Tables 1 to 3 and figure 3 to 5 reveal the effect of failure and repair rates of Primary air fans, Furnace & Induced draft fans on the steady state availability of the furnace draft air cycle. Table 1& figure 3 reveals the effect of failure and repair rates of Primary air fan on the availability of the system. It is observed that for some known values of failure / repair rates of Furnace & Induced draft fan (λ_2=0.0006, λ_3= 0.0001, μ_2=0.02, μ_3=0.02), as the failure rates of Primary air fan increases from 0.001 to 0.005, the availability decreases by about 13.16%. Similarly as repairs rates of Primary air fan increases from 0.01 to 0.05, the availability increases by about 0.008%.

Table 1: Effect of Failure and Repair Rates of Primary air fan on Availability

λ_1 μ_1	0.001	0.002	0.003	0.004	0.005	Constant values
0.01	0.9623	0.9404	0.9097	0.8738	0.8356	λ_2=0.0006, μ_2=0.02, λ_3=0.0001, μ_3=0.02
0.02	0.9686	0.9623	0.9527	0.9404	0.9259	
0.03	0.9698	0.9669	0.9623	0.9562	0.9489	
0.04	0.9702	0.9686	0.9659	0.9623	0.9579	
0.05	0.9704	0.9694	0.9676	0.9652	0.9623	

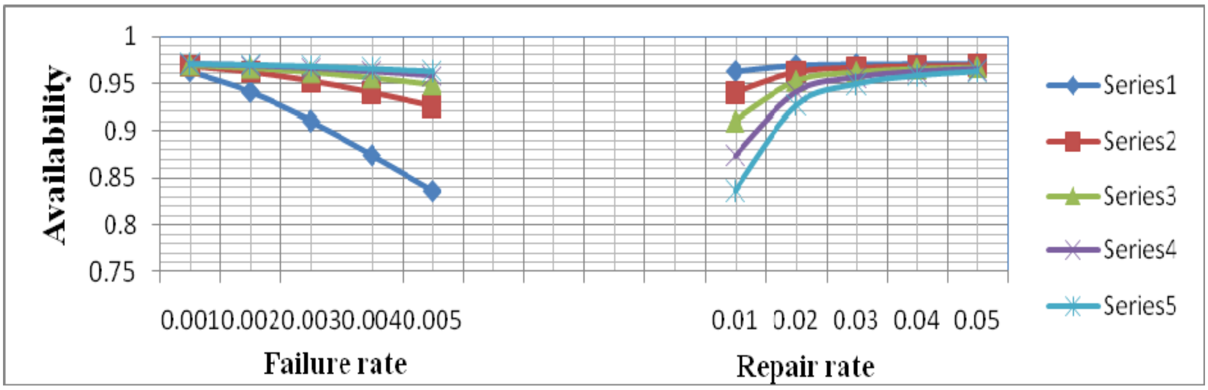

Figure 3: Effect of Failure and Repair Rates of Primary air fan on Availability

Table 2 & figure 4 reveals the effect of failure and repair rates of Furnace subsystem on the availability of the system. It is observed that for some known values of failure / repair rates of Primary air fans & Induced draft fans (λ_1=0.001, λ_3= 0.0001, μ_1=0.01, μ_3=0.2), as the failure rates of Furnace increases from 0.0006 to 0.001, the availability decreases by about 1.89%. Similarly as repairs rates of Furnace increases from 0.02 to 0.10, the availability increases by about 1.96%.

Table 2: Effect of Failure and Repair Rates of Furnace on Availability

λ_2 μ_2	0.0006	0.0007	0.0008	0.0009	0.001	Constant values
0.02	0.9623	0.9577	0.9531	0.9486	0.9441	λ_1=0.001, μ_1=0.01, λ_3=0.0001, μ_3=0.02
0.04	0.9717	0.9685	0.9654	0.9623	0.9592	
0.06	0.9764	0.9740	0.9717	0.9693	0.9670	
0.08	0.9793	0.9774	0.9754	0.9736	0.9717	
0.10	0.9812	0.9796	0.9780	0.9764	0.9748	

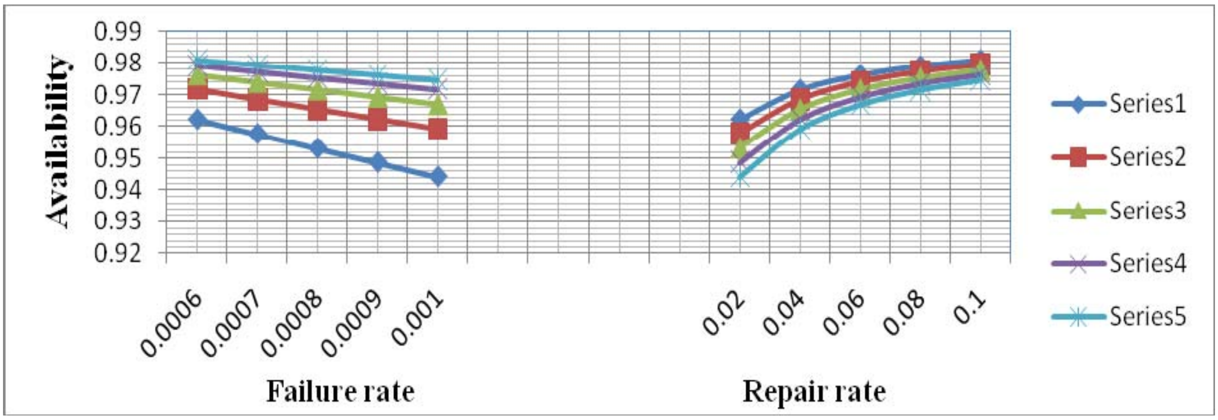

Fig 4: Effect of Failure and Repair Rates of Furnace on Availability

Table 3 & figure 5 reveals the effect of failure and repair rates of Induced draft fans subsystem on the availability of the system. It is observed that for some known values of failure / repair rates of Primary air fan & Furnace (λ_1=0.001, λ_2= 0.0006, μ_1=0.01, μ_2=0.02), as the failure rates of Induced draft fans increases from 0.0001 to 0.0005, the availability decreases by about 0.0005%. Similarly as repairs rates of Induced draft fans increases from 0.02 to 0.06, the availability increases by about 0.00002%.

Table 3: Effect of Failure and Repair Rates of Induced draft fan on Availability

λ_3 μ_3	0.0001	0.0002	0.0003	0.0004	0.0005	Constant values
0.02	0.962356	0.962288	0.962174	0.962016	0.961815	λ_2=0.0006, μ_2=0.02, λ_1=0.001, μ_1=0.01
0.03	0.962369	0.962338	0.962288	0.962217	0.962126	
0.04	0.962373	0.962356	0.962327	0.962288	0.962236	
0.05	0.962376	0.962364	0.962346	0.962320	0.962288	
0.06	0.962377	0.962369	0.962356	0.962338	0.962315	

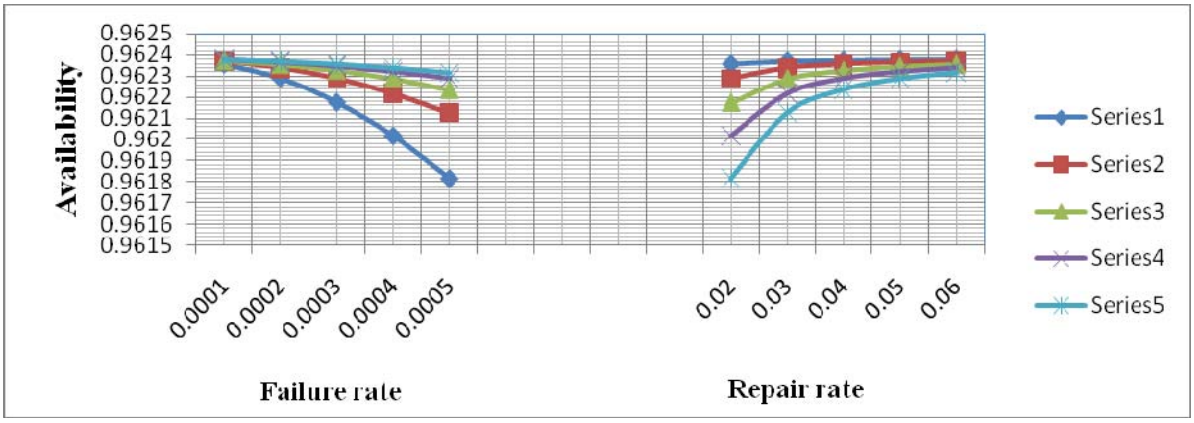

Figure 5: Effect of Failure and Repair Rates of Induced draft fan on Availability

6. Conclusion

The decision support system for furnace draft air cycle has been developed with the help of mathematical modeling using probabilistic approach. The decision matrices are also developed. These matrices facilitate the maintenance decisions to be made at critical points where repair priority should be given to some particular subsystem of furnace draft air cycle. Decision matrices for the availability analysis have been also represented from table 1 to 3.These tables may easily identify the failure and repair rates of the various subsystems at which maximum availability achieved. Decision matrix as given in table 1 clearly indicates that the Primary air fan is most critical subsystem as far as maintenance aspect is concerned. So, it should be given top priority as the effect of its failure and repair rates on the unit availability is much higher than that of furnace & Induced draft fan. Therefore, on the basis of repair rates, the maintenance priority should be given as per following order:

1. Primary air fans
2. Furnace
3. Induced draft fans

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