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Steady State Behaviour of a Cold Standby System Consisting of Turbine, Boiler and Fans

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Abstract: Electricity plays a vital role in any industrial engineering system. The power plant system in any industry serves as a backbone to it. The paper deals with the steady state behaviour of a cold standby system operating in a power plant system. The system comprises of a turbine, a high pressure boiler, a cold standby unit: three low pressure boilers and three fans: PA fan, FD fan and ID fan. A cold standby unit which comprises of three low pressure boilers acts as a redundant system for main high pressure boiler. The analysis has been done based on the real data. There is only one technician available to do the desired job of repair or replacement as per requirement of the failure. Various parameters for effectiveness of the system have been computed using Semi Markov process and regenerative point technique. Graphical study along with interpretation has also been done to study the behaviour of the reliability and cost benefit analysis of the present study.

Keywords: Standby systems; Semi Markov process; Regenerative point technique.

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I. INTRODUCTION

In Industrial engineering systems, electric supply plays a major role in keep the systems running. More and more industries are installing their own power plants within the firm as it is more economical and it makes the manufacturing process more efficient. Our study deals with the study of power plant installed at Bunge Pvt. Ltd., Rajpura (Punjab), India. The study is based on the real data provided by the system. The literature of reliability holds numerous studies regarding standby systems, identical units, dissimilar units, etc. under different circumstances. Researchers [1-7] have contributed much by studying reliability and various parameters of the industrial systems. Singh and Saini [5] discussed the computational analysis of parameters affecting economy of one gas and one steam turbine system with scheduled inspection. In it, they have developed a model considering variation in demand and power production capacity for a system comprising one gas and one stream turbine. But there is still lack of studies related reliability analysis of power plant engineering systems. Our aim is to fill this gap.

The study involves the reliability and profit evaluation of a power plant system. The units of a power plant system taken into consideration in the present paper are: Turbine, Main Boiler (high pressure boiler), three low pressure boilers acting as redundant system for main boiler, three fans: PA (Primary Air) fan, FD (Force Draught fan) and ID (Induced Draft) fan. Whenever failure occurs in high pressure boiler, all three low pressure boilers start operating altogether as the capacity of all low pressure boilers to bring out work is equivalent to the work of main high pressure boiler. The whole system comes at halt under the following circumstances:

i. Both turbine and boiler cannot fail simultaneously.
ii. Any other fan cannot fail while occurrence of failure of one fan.
iii. Any two cold standby low pressure boilers cannot fail simultaneously.

If the failure occurs in any component of the turbine, the repairman repairs/replaces that component as per operation required for that component. There is a single technician available to do the desired job for complete system. Repair/Replacement is done on FCFS (First-cum-First-serve) basis.

Earlier, the industry involved three low pressure boilers which were kept as one primary unit into the system. But with the advancement and time, one high pressure boiler was installed which acts as primary unit now and the older three low pressure boilers were made a cold standby unit. Our study is based on the present system. Various measures of system effectiveness such as MTSF (Mean time to system failure), Availability, Busy period of repairman, Profit etc have been computed using Semi Markov process and Regenerative point technique. Graphical interpretation has also been done with the interpretation for the analysis of the present model developed for the system.

II. MODEL DESCRIPTION

A state transition diagram in fig. 1 shows various transitions of the system. The epochs of entry into states 0,1,2,3,4,5,8,9,10 and 11 are regenerative points and thus these are regenerative states. The states 6,7 and 8 are failed states.

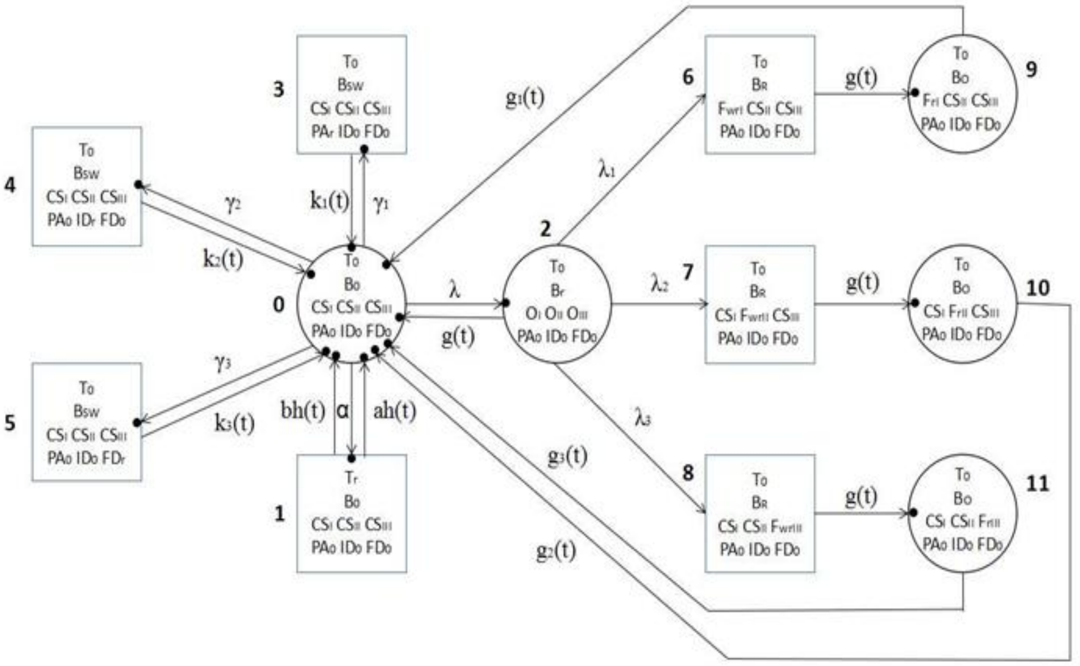

Fig. 1

III. NOTATIONS

α	Constant failure rate of turbine
λ	Constant failure rate of boiler
$\lambda_1/\ \lambda_2/\ \lambda_3$	Constant failure rate of cold standby low pressure boiler (Unit 1/2/3)
$\gamma_1/\ \gamma_2/\ \gamma_3$	Constant failure rate of PA/ID/FD fan
a/ b	probability that a fault is minor/major
$g(t)/\ G(t)$	pdf/ cdf of repair time for main boiler
$g_1(t)/\ G_1(t)$	pdf/ cdf of repair time for low pressure boiler (Unit 1)
$g_2(t)/\ G_2(t)$	pdf/ cdf of repair time for low pressure boiler (Unit 2)
$g_3(t)/\ G_3(t)$	pdf/ cdf of repair time for low pressure boiler (Unit 3)
$h(t)/\ H(t)$ state	pdf/ cdf of repair time for repair/replacement of the component of turbine at failed
$k_1(t)/\ K_1(t)$	pdf/ cdf of repair time for PA fan
$k_2(t)/\ K_2(t)$	pdf/ cdf of repair time for ID fan
$k_3(t)/\ K_3(t)$	pdf/ cdf of repair time for FD fan
$T_0/\ B_0/\ PA_0/\ ID_0/\ FD_0$	Turbine/ Boiler/ PA/ ID/ FD fan is in operative state
$CS_I/\ CS_{II}/\ CS_{III}$	Low pressure boiler 1/2/3 is in cold standby state
$T_r/\ B_r/\ PA_r/\ ID_r/\ FD_r$	Turbine/ Boiler/ PA/ ID/ FD fan is under repair
B_{SW}	Boiler is switched off
B_R	Boiler is under repair from the previous state
$F_{rI}/F_{rII}/F_{rIII}$	Cold standby low pressure boiler 1/2/3 is under repair
$F_{wrI}/F_{wrII}/F_{wrIII}$	Cold standby low pressure boiler 1/2/3 is waiting for repair

IV. TRANSITION PROBABILITIES

The non-zero elements p_{ij}, are obtained as under :

$$p_{01} = \frac{\alpha}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad p_{02} = \frac{\lambda}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3}$$

$$p_{03} = \frac{\gamma_1}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad p_{04} = \frac{\gamma_2}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3}$$

$$p_{05} = \frac{\gamma_3}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad p_{10} = h^*(0)$$

$$p_{20} = g^*(\lambda_1+\lambda_2+\lambda_3) \qquad p_{26} = \frac{\lambda_1[1-g^*(\lambda_1+\lambda_2+\lambda_3)]}{\lambda_1+\lambda_2+\lambda_3} = p_{29}^{(6)}$$

$$p_{27} = \frac{\lambda_2[1-g^*(\lambda_1+\lambda_2+\lambda_3)]}{\lambda_1+\lambda_2+\lambda_3} = p_{2,10}^{(7)} \qquad p_{28} = \frac{\lambda_3[1-g^*(\lambda_1+\lambda_2+\lambda_3)]}{\lambda_1+\lambda_2+\lambda_3} = p_{2,11}^{(8)}$$

$$p_{30} = k_1^*(0) \qquad p_{40} = k_2^*(0)$$

$$p_{50} = k_3^*(0) \qquad p_{69} = g^*(0) = p_{7,10} = p_{8,11}$$

$$p_{90} = g_1^*(0) \qquad p_{10,0} = g_2^*(0) \qquad p_{11,0} = g_3^*(0)$$

By these transition probabilities, it can be verified that

$$p_{01}+p_{02}+p_{03}+p_{04}+p_{05}=1$$

$$p_{20}+p_{26}+p_{27}+p_{28}=1 \qquad p_{20}+p_{29}^{(6)}+p_{2,10}^{(7)}+p_{2,11}^{(8)}=1$$

$$p_{10}=p_{30}=p_{40}=p_{50}=p_{69}=p_{7,10}=p_{8,11}=p_{90}=p_{10,0}=p_{11,0}=1$$

The unconditional mean time taken by the system to transit for any regenerative state j, when it is counted from epoch of entrance into that state i, is mathematically stated as –

$$m_{ij} = \int_0^\infty t\,dQ_{ij}(t) = -q_{ij}^{*'}(0), \text{Thus}-$$

$$m_{01}+m_{02}+m_{03}+m_{04}+m_{05}=\mu_0$$

$$m_{10}=t_1$$

$$m_{20}+m_{26}+m_{27}+m_{28}=\mu_2 \qquad m_{20}+m_{29}^{(6)}+m_{2,10}^{(7)}+m_{2,11}^{(8)}=s$$

$$m_{30}=f_1 \qquad m_{40}=f_2$$

$$m_{50}=f_3 \qquad m_{69}=s=m_{7,10}=m_{8,11}$$

$$m_{90}=s_1 \qquad m_{10,0}=s_2$$

$$m_{11,0}=s_3$$

where,

$$t_1=\int_0^\infty \overline{H}(t)dt \qquad s=\int_0^\infty \overline{G}(t)dt$$

$$f_1=\int_0^\infty \overline{k}_1(t)dt \qquad f_2=\int_0^\infty \overline{k}_2(t)dt$$

$$f_3=\int_0^\infty \overline{k}_3(t)dt \qquad s_1=\int_0^\infty \overline{G}_1(t)dt$$

$$s_2=\int_0^\infty \overline{G}_2(t)dt \qquad s_3=\int_0^\infty \overline{G}_3(t)dt$$

The mean sojourn time in the regenerative state i (μ_i) is defined as the time of stay in that state before transition to any other state, then we have -

$$\mu_0 = \frac{1}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad \mu_1 = h^*(0)$$

$$\mu_2 = \frac{1-g^*(\lambda_1+\lambda_2+\lambda_3)}{\lambda_1+\lambda_2+\lambda_3} \qquad \mu_3 = k_1^*(0)$$

$$\mu_4 = k_2^*(0) \qquad \mu_5 = k_3^*(0)$$

$$\mu_6 = g^*(0) = \mu_7 = \mu_8 \qquad \mu_9 = g_1^*(0)$$

$$\mu_{10} = g_2^*(0) \qquad \mu_{11} = g_3^*(0)$$

V. MEAN TIME TO SYSTEM FAILURE

The mean time to system failure when the system starts from the state 0, is

$$T_0 = \frac{N}{D}$$

Where

$$N = \mu_0 + \mu_2 p_{02}$$

$$D = 1 - p_{02}p_{20}$$

VI. EXPECTED UP-TIME OF THE SYSTEM

The steady state availability of the system is given by:

$$A_0 = \frac{N_1}{D_1}$$

Where

$$N_1 = M_0 + p_{02}[M_2 + M_9 p_{29}^{(6)} + M_{10} p_{2,10}^{(7)} + M_{11} p_{2,11}^{(8)}]$$

$$D_1 = \mu_0 + p_{02}[s + s_1 p_{29}^{(6)} + s_2 p_{2,10}^{(7)} + s_3 p_{2,11}^{(8)}] + t_1 p_{01} + f_1 p_{03} + f_2 p_{04} + f_3 p_{05}$$

VII. Busy period of Repairman (for Repair only)

The steady state busy period of a repairman while repairing the system is given by:

$$B_R = \frac{N_2}{D_1}$$

Where

$$N_2 = W_1 p_{01} + p_{02}[W_2 + W_9 p_{29}^{(6)} + W_{10} p_{2,10}^{(7)} + W_{11} p_{2,11}^{(8)}] + W_3 p_{03} + W_4 p_{04} + W_5 p_{05}$$

And D_1 is already specified.

VIII. BUSY PERIOD OF REPAIRMAN (FOR REPLACEMENT ONLY)

The steady state busy period of a repairman doing replacement of units the system is given by:

$$B_{RP} = \frac{N_3}{D_1}$$

Where

$$N_3 = W_1 p_{01}$$

And D_1 is already specified.

IX. EXPECTED NO. OF VISITS OF REPAIRMAN

The steady state expected no. of visits of the repairman is given by:

$$V_R = \frac{N_4}{D_1}$$

Where

$$N_4 = p_{01} + p_{02} + p_{03} + p_{04} + p_{05} = 1$$

And D_1 is already specified.

X. PROFIT ANALYSIS

The expected profit incurred of the system is:

$$P = C_0 A_0 - C_1 B_R - C_2 B_{RP} - C_3 V_R$$

C_0 = Revenue per unit up time of the system
C_1 = Cost per unit up time for which the repairman is busy in repair
C_2 = Cost per unit up time for which the repairman is busy in replacement
C_3 = Cost per visit of the repairman

XI. GRAPHICAL INTERPRETATION

For graphical analysis following particular cases are considered:

$$g(t)=\beta e^{-\beta t} \qquad g_1(t)=\beta_1 e^{-\beta_1 t}$$

$$g_2(t)=\beta_2 e^{-\beta_2 t} \qquad g_3(t)=\beta_3 e^{-\beta_3 t}$$

$$h(t)=r e^{-rt} \qquad k_1(t)=p e^{-pt}$$

$$k_2(t)=ie^{-it} \qquad k_3(t)=fe^{-ft}$$

$$p_{01} = \frac{\alpha}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad p_{02} = \frac{\lambda}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3}$$

$$p_{03} = \frac{\gamma_1}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad p_{04} = \frac{\gamma_2}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3}$$

$$p_{05} = \frac{\gamma_3}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad p_{10} = 1$$

$$p_{20} = \frac{\beta}{\lambda_1+\lambda_2+\lambda_3+\beta} \qquad p_{26} = \frac{\lambda_1}{\lambda_1+\lambda_2+\lambda_3+\beta} = p_{29}^{(6)}$$

$$p_{27} = \frac{\lambda_2}{\lambda_1+\lambda_2+\lambda_3+\beta} = p_{2,10}^{(7)} \qquad p_{28} = \frac{\lambda_3}{\lambda_1+\lambda_2+\lambda_3+\beta} = p_{2,11}^{(8)}$$

$$p_{30} = 1 = p_{40} = p_{50} = p_{69} = p_{7,10} = p_{8,11} = p_{90} = p_{10,0} = p_{11,0}$$

$$\mu_0 = \frac{1}{\alpha+\lambda+\gamma_1+\gamma_2+\gamma_3} \qquad \mu_1 = \frac{1}{r}$$

$$\mu_2 = \frac{1}{\lambda_1+\lambda_2+\lambda_3+\beta} \qquad \mu_3 = \frac{1}{p}$$

$$\mu_4 = \frac{1}{i} \qquad \mu_5 = \frac{1}{f}$$

$$\mu_6 = \frac{1}{\beta} = \mu_7 = \mu_8 \qquad \mu_9 = \frac{1}{\beta_1}$$

$$\mu_{10} = \frac{1}{\beta_2} \qquad \mu_{11} = \frac{1}{\beta_3}$$

Various Graphs have been plotted to study the model and are given as under with their analysis:

The graphical behaviour of MTSF w.r.t. failure rate of turbine (α) for different values of rate of failure of PA fan (γ_1) is shown by Fig. 2. It is analyzed that MTSF decreases with the increase in the values of the failure rate of turbine (α). MTSF also decreases as failure rate of PA fan (λ_1) increases.

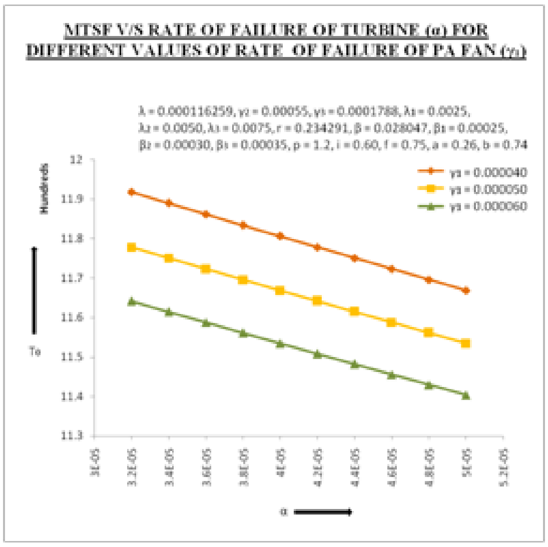

Fig. 2

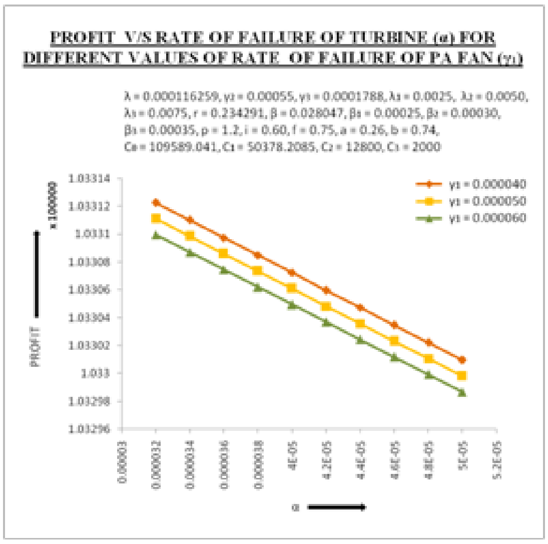

Fig. 3

Fig. 3 interprets the behaviour of profit w.r.t. to failure rate of turbine (α) for different values of failure rate of PA fan (λ_1). As the values of failure rate of turbine (α) increases, the profit decreases. Also, the profit decreases as failure rate of PA fan (λ_1) increases.

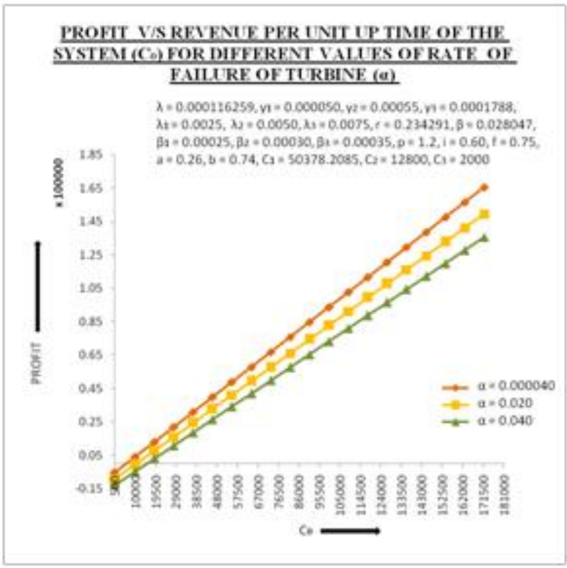

Fig. 4

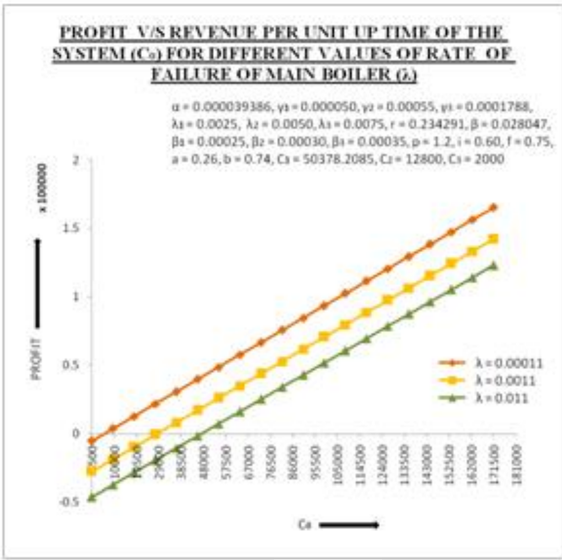

Fig. 5

The behaviour of the profit w.r.t. revenue per unit uptime of the system (C_0) for different values of rate of failure of turbine (α) is shown by Fig. 4. It can be interpreted that the profit increases with increase in the values of C_0. Following conclusions can be drawn from the graph:

1. For α = 0.000040, profit is > or = or < according as C_0 > or = or < 6029, i.e. the revenue per unit uptime of the system in such a way so as to give C_0 not less than 6029 to get positive profit.
2. For α = 0.020, profit is > or = or < according as C_0 > or = or < 10824, i.e. the revenue per unit uptime of the system in such a way so as to give C_0 not less than 10824 to get positive profit.
3. For α = 0.040, profit is > or = or < according as C_0 > or = or < 15616, i.e., i.e. the revenue per unit uptime of the system in such a way so as to give C_0 not less than 15616 to get positive profit.

Fig. 5 depicts the behaviour of the profit w.r.t. revenue per unit uptime of the system (C_0) for different values of rate of failure of main boiler (λ). It can be interpreted that the profit increases with increase in the values of C_0. Following conclusions can be drawn from the graph:

1. For $\lambda = 0.00011$, profit is > or = or < according as C_0 > or = or < 5744, i.e. the revenue per unit uptime of the system in such a way so as to give C_0 not less than 5744 to get positive profit.
2. For $\lambda = 0.0011$, profit is > or = or < according as C_0 > or = or < 28383, i.e. the revenue per unit uptime of the system in such a way so as to give C_0 not less than 28383 to get positive profit.
3. For $\lambda = 0.011$, profit is > or = or < according as C_0 > or = or < 47217, i.e., i.e. the revenue per unit uptime of the system in such a way so as to give C_0 not less than 47217 to get positive profit.

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