# Reliability and Cost-Benefit Analysis of a Power Plant Comprising two Gas and one Steam Turbines with Scheduled Inspection

**Dalip Singh, Gulshan Taneja**

***Abstract*: A reliability model for a power generating system comprising two gas turbines and one steam turbine is developed wherein scheduled inspection is done at regular interval of time for maintenance. Initially, all the three units i.e. two gas turbines as well as one the steam turbine are operating and working of the system is called the working at full capacity. On failure of one of the gas turbines with steam turbine working, the system works at reduced capacity. If both the gas turbines get failed, the system goes to down state, whereas on failure of steam turbine, the system may be kept in the up state with one of the gas turbines working or put to down state according as the buyer of the power so generated is ready to pay higher amount or not and this is working in single cycle. Three types of scheduled inspection, that is, minor, path and major are done in this order at regular intervals of time for maintenance. System is analyzed by making use of semi - Markov processes and regenerative point technique. Various measures of system effectiveness such as mean time to system failure, availability at full capacity, availability at reduced capacity, availability in single cycle, expected down time, expected time for minor, path and major inspection, busy period for repair and expected number of visits have been obtained. Cost- benefit analysis has been carried out. Graphical study has been made and interesting conclusions are drawn.***

***Key Words:* Power Plant comprising Two Gas Turbines and One Steam Turbine, Scheduled Inspection, Reliability, Cost-Benefit**

## I. INTRODUCTION

In today scenario, the technology is aiming at making our lives smooth and simple with the development of new and complex systems catering to the needs of the society. The impact of failure or mismanagement of power generating and power distribution systems and other such systems is simply frightening. As a consequence, the importance of reliability at all stages of manufacturing a system comes into picture. Reliability is defined as the probability the system is performing its purpose adequately for intended period, under the given operating conditions. A lot of work has been done in the field of reliability by large number of researcher including Taneja, Singh and Minocha [1], Rizwan, Khurana and Taneja [2], Padamvathi, Rizwan, Pal and Taneja [3], Singh, Rishi, Taneja and Manocha [4] . Contribution has also been made for the analysis of reliability models for systems with two dissimilar units which include Baohe [5], Tuteja, Vashisthat and Taneja [6], Parashar and Taneja [7], Goyal, Singh and Taneja [8]. In most of the studies on two dissimilar units, one unit was taken as operative and other as standby.

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However, there may be situations where both the dissimilar units may be operative. Singh and Taneja [9] examined a system with two dissimilar units system wherein both the units may be operative. They developed a reliability model for a power generating system comprising one gas and one steam turbine. However, it may also be observed in Gas turbine power plants that systems may comprise two gas turbines and one steam turbine. Need of taking this additional gas turbine arises because of the fact that on the failure of the gas turbine the system goes to down state as the steam turbine cannot work without the gas turbine.

Keeping this aspect in view, we, in the present paper, study the reliability and cost-benefit analysis of a gas turbine power plant comprising two gas turbines and one steam turbine considering variation in demand and power production capacity. Taking additional unit, undoubtedly, enhances the reliability of the system but may or may not increase the cost depending on the production and demand. Initially, all the three units i.e. two gas turbines as well as one steam turbine are operative and working of the system is called the working at full capacity. On failure of one of the gas turbines with steam turbine working, the system works at reduced capacity. If both the gas turbines get failed, the system goes to down state; whereas on failure of the steam turbine, the system may be kept in the up state with one of the gas turbines working or put to down state according as the buyer of the power so generated is ready to pay higher amount or not and this is working in single cycle. Three types of scheduled inspection for maintenance, that is, minor, path and major are done in this order at regular intervals of times for maintenance. System is analysed by making use of semi-Markov processes and regenerative point technique. Various measures of system effectiveness such as mean time to system failure, availability at full capacity (i.e. when two gas turbines and one steam turbine is working), availability at reduced capacity (i.e. when one gas turbine and one steam turbine is working), availability in single cycle (i.e. when the only gas turbine is working), expected down time, expected times for minor, path and major inspection, busy period for repair and expected number of visits have been obtained. Cost-benefit analysis has been carried out. Graphical study has been made for a particular case.

## II. MODEL DESCRIPTION AND ASSUMPTIONS



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(1) Failure time, requirement of inspection time and time of doing inspection/maintenance are assumed to follow exponential distributions whereas the repair times have arbitrary distributions.

(2) After every repair, unit becomes as good as new.

(3) All the random variables are independent.

(4) System fails completely on failure of all the three units.

(5) When both the gas turbines and one steam turbine are operative then working of the gas turbine plant is called working at full capacity.

(6) When one gas turbine and one steam turbine are operative then working of the gas turbine plant is called working at reduced capacity.

(7) When only the gas turbine is operative then working of the gas turbine plant is called working in single cycle.

(8) System is put to downstate during inspections and also when the steam turbine is failed and there is no buyer of power generated in single cycle.

## III. NOTATIONS

$O_{gt}$ : Gas turbine operative

$O_{gt_1}$ : Gas turbine operative after 1st inspection /scheduled inspection.

$O_{gt_2}$ : Gas turbine operative after 2nd inspection/scheduled inspection.

$O_{st}$ : Steam turbine operative

$O_{st_1}$ : Steam turbine operative 1st inspection /scheduled inspection.

$O_{st_2}$ : Steam turbine operative 2nd inspection/scheduled inspection

$U_{rgt}$ : Gas turbine under repair

$U_{rst}$ : Steam turbine under repair

$U_{Rgt}$ : Repair of gas turbine continuing from previous state.

$U_{Rst}$ : Repair of steam turbine continuing from previous state.

$d_{gt}$ : Gas turbine put to down mode

$d_{st}$ : Steam turbine put to down mode

$W_{rgt}$ : Gas turbine waiting for repair

$W_{rst}$ : Steam turbine waiting for repair

$Insp_1$ : First type of inspection (Minor inspection).

$Insp_2$ : Second type of inspection (Path inspection).

$Insp_3$ : Third type of inspection (Major inspection).

$\lambda$ : Failure rate of gas turbine.

$\alpha$ : Failure rate of steam turbine.

p : Probability that there is dire demand of electricity and the customer is ready to pay higher amounts.

q : 1-p i.e the probability that the customer is not ready to pay the amount higher than the normal rates.

$g_1(t)$, $G_1(t)$ : pdf and cdf of repair time of gas turbine

$g_2(t)$, $G_2(t)$ : pdf and cdf of repair time of steam turbine

$\beta_1$ : Rate of requirement of scheduled inspection/maintenance.

$\gamma_1, \gamma_2, \gamma_3$ : Rate of doing minor, path, major inspection or maintenance.

## IV. TRANSITION PROBABILITIES AND MEAN SOJOURN TIMES

The possible transitions are shown as in **Table 1**.The epochs of entry into states 0, 1, 2, 3, 10, 11, 12, 13, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 36, 37 and 38 regeneration points and thus 0, 1, 2, 3, 10, 11, 12, 13, 14, 15, 16, 23, 24, 25, 26, 27, 28, 29, 36, 37 and 38 regenerative states. States 1, 14, 27 are up states with reduced capacity. States 3, 10, 16, 23, 29, 36 are single cycle up states, when only gas turbine is operative and states 5, 7, 18, 20, 31 and 33 are single cycle failed states due to repair in gas/steam turbine. States 12, 25, 38 are down states due to inspections and 2, 4, 6, 11, 15, 17, 19, 24, 28, 30, 32, 37 are also down states as only the steam turbine/gas turbine is operable. States 8, 9, 21, 22, 34, 35 are failed states. The various states of the state transition diagram with their numbers and symbols are as under:

**Table I: Possible States with Status**

| State No. | Status | State No. | Status | State No. | Status |
|---|---|---|---|---|---|
| 0 | $O_{gt}, O_{gt}, O_{st}$ | 13 | $O_{gt_1}, O_{gt_1}, O_{st_1}$ | 26 | $O_{gt_2}, O_{gt_2}, O_{st_2}$ |
| 1 | $O_{gt}, U_{rgt}, O_{st}$ | 14 | $O_{gt_1}, U_{rgt_1}, O_{st_1}$ | 27 | $O_{gt_2}, U_{rgt_2}, O_{st_2}$ |
| 2 | $d_{gt}, d_{gt}, U_{rst}$ | 15 | $d_{gt_1}, d_{gt_1}, U$ | 28 | $d_{gt_2}, d_{gt_2}, U_{rst_2}$ |
| 3 | $O_{gt}, d_{gt}, U_{rst}$ | 16 | $O_{gt_1}, d_{gt_1}, U$ | 29 | $O_{gt_2}, d_{gt_2}, U_{rst_2}$ |
| 4 | $W_{rgt}, U_{Rgt}, d_{st}$ | 17 | $W_{rgt_1}, U_{Rgt_1}, d_{st}$ | 30 | $W_{rgt_2}, U_{Rgt_2}, d_{st_2}$ |
| 5 | $O_{gt}, U_{Rgt}, W_{rst}$ | 18 | $O_{gt_1}, U_{Rgt_1}, W$ | 31 | $O_{gt_2}, U_{Rgt_2}, W_{rst_2}$ |
| 6 | $d_{gt}, U_{Rgt}, W_{rst}$ | 19 | $d_{gt_1}, U_{Rgt_1}, W_{rs}$ | 32 | $d_{gt_2}, U_{Rgt_2}, W_{rst_2}$ |
| 7 | $O_{gt}, W_{rgt}, U_{Rst}$ | 20 | $O_{gt_1}, W_{rgt_1}, U$ | 33 | $O_{gt_2}, W_{rgt_2}, U_{Rst_2}$ |
| 8 | $W_{rgt}$, $U_{Rgt}, W_{rst}$ | 21 | $W_{rgt_1}, U_{Rgt_1}, W$ | 34 | $W_{rgt_2}, U_{Rgt_2}, W_{rs}$ |
| 9 | $W_{rgt}, W_{rgt}, U_{Rst}$ | 22 | $W_{rgt_1}, W_{rgt_1}, U_{Rs}$ | 35 | $W_{rgt_2}, W_{rgt_2}, U_{Rst_2}$ |
| 10 | $O_{gt}, W_{rgt}, U_{rst}$ | 23 | $O_{gt_1}, W_{rgt_1}, U_{rs}$ | 36 | $O_{gt_2}, W_{rgt_2}, U_{rst_2}$ |
| 11 | $W_{rgt}$, $U_{rgt}$, $d_{st}$ | 24 | $W_{rgt_1}, U_{rgt_1}, d_{st}$ | 37 | $W_{rgt_2}, U_{rgt_2}, d_{st_2}$ |
| 12 | Inspection-I | 25 | Inspection -II | 38 | Inspection-III |

$$q_{01}(t) = 2\lambda e^{-(\alpha+2\lambda+\beta_1)t}, q_{02}(t) = q\alpha e^{-(\alpha+2\lambda+\beta_1)t},$$

$$q_{03}(t) = p\alpha e^{-(\alpha+2\lambda+\beta_1)t}, q_{0,12}(t) = \beta_1 e^{-(\alpha+2\lambda+\beta_1)t},$$

$$q_{10}(t) = g_1(t)e^{-(\lambda+\alpha)t}, q_{11}^{(4)}(t) = \frac{\lambda}{\lambda+\alpha}(1-e^{-(\lambda+\alpha)t})g_1(t)$$



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$$q_{12}^{(6)}(t)=\frac{q\alpha}{\lambda+\alpha}[1-e^{-(\lambda+\alpha)t}]g_1(t),$$
$$q_{13}^{(5)}(t)=p[e^{-\lambda t}-e^{-(\lambda+\alpha)t}]g_1(t)$$
$$q_{18}^{(5)}(t)=\lambda p[e^{-\lambda t}-e^{-(\lambda+\alpha)t}]\bar{G}_1(t),$$
$$q_{31}^{(7)}(t)=\lambda te^{-\lambda t}g_2(t), q_{39}^{(7)}(t)=\lambda^2te^{-\lambda t}\bar{G}_2(t)$$
$$q_{3,11}^{(7,9)}(t)=(1-e^{-\lambda t}-\lambda te^{-\lambda t})g_2(t),$$
$$q_{10,1}(t)=g_2(t)e^{-\lambda t}, q_{10,11}^{(9)}(t)=(1-e^{-\lambda t})g_2(t)$$
$$q_{1,10}^{(5,8)}=\frac{p}{\alpha+\lambda}[\alpha-(\alpha+\lambda)e^{-\lambda t}+\lambda e^{-(\alpha+\lambda)t}]g_1(t)$$
$$q_{20}(t)=g_2(t), q_{30}(t)=g_2(t)e^{-\lambda t}$$
$$q_{11,1}(t)=g_1(t), q_{12,13}(t)=\gamma_1 e^{-\gamma_1 t},$$
$$q_{13,14}(t)=2\lambda e^{-(\alpha+2\lambda+\beta_1)t}, q_{13,15}(t)=q\alpha e^{-(\alpha+2\lambda+\beta_1)t}$$
$$q_{13,16}(t)=p\alpha e^{-(\alpha+2\lambda+\beta_1)t},$$
$$q_{13,25}(t)=\beta_1 e^{-(\alpha+2\lambda+\beta_1)t}, q_{14,13}(t)=g_1(t)e^{-(\lambda+\alpha)t},$$
$$q_{14,14}^{(17)}(t)=\frac{\lambda}{\lambda+\alpha}(1-e^{-(\lambda+\alpha)t})g_1(t),$$
$$q_{14,15}^{(19)}(t)=\frac{q\alpha}{\lambda+\alpha}[1-e^{-(\lambda+\alpha)t}]g_1(t)$$
$$q_{14,16}^{(18)}(t)=p[e^{-\lambda t}-e^{-(\lambda+\alpha)t}]g_1(t),$$
$$q_{14,21}^{(18)}(t)=p[e^{-\lambda t}-e^{-(\lambda+\alpha)t}]\bar{G}_1(t)$$
$$q_{14,23}^{(18,21)}=\frac{p}{\lambda+\alpha}[\alpha-(\lambda+\alpha)e^{-\lambda t}+\lambda e^{-(\alpha+\lambda)t}]g_1(t)$$
$$q_{15,13}(t)=g_2(t), q_{16,13}(t)=g_2(t)e^{-\lambda t},$$
$$q_{16,14}^{(20)}(t)=\lambda te^{-\lambda t}g_2(t)$$
$$q_{16,22}^{(20)}(t)=\lambda^2te^{-\lambda t}\bar{G}_2(t),$$
$$q_{16,24}^{(20,22)}(t)=(1-e^{-\lambda t}-\lambda te^{-\lambda t})g_2(t)$$
$$q_{23,14}(t)=g_2(t)e^{-\lambda t}, q_{23,24}^{(22)}(t)=(1-e^{-\lambda t})g_2(t),$$
$$q_{24,14}(t)=g_1(t), q_{25,26}(t)=\gamma_2 e^{-\gamma_2 t}$$
$$q_{26,27}(t)=2\lambda e^{-(\alpha+2\lambda+\beta_1)t},$$
$$q_{26,28}(t)=q\alpha e^{-(\alpha+2\lambda+\beta_1)t},$$
$$q_{26,29}(t)=p\alpha e^{-(\alpha+2\lambda+\beta_1)t},$$
$$q_{27,28}^{(32)}(t)=\frac{q\alpha}{\lambda+\alpha}(1-e^{-(\lambda+\alpha)t})g_1(t),$$
$$q_{27,29}^{(31)}(t)=p[e^{-\lambda t}-e^{-(\lambda+\alpha)t}]g_1(t)$$
$$q_{26,38}(t)=\beta_1 e^{-(\alpha+2\lambda+\beta_1)t},$$
$$q_{27,26}(t)=g_1(t)e^{-(\lambda+\alpha)t},$$
$$q_{27,27}^{(30)}(t)=\frac{\lambda}{\lambda+\alpha}(1-e^{-(\lambda+\alpha)t})g_1(t)$$
$$q_{27,34}^{(31)}(t)=p[e^{-\lambda t}-e^{-(\lambda+\alpha)t}]\bar{G}_1(t)$$
$$q_{27,36}^{(31,34)}=\frac{p}{\lambda+\alpha}[\alpha-(\alpha+\lambda)e^{-\lambda t}+\lambda e^{-(\lambda+\alpha)t}]g_1(t)$$
$$q_{28,26}(t)=g_2(t), q_{29,26}(t)=g_2(t)e^{-\lambda t},$$
$$q_{29,27}^{(33)}(t)=\lambda te^{-\lambda t}g_2(t)$$
$$q_{29,35}^{(33)}(t)=\lambda^2te^{-\lambda t}\bar{G}_2(t),$$
$$q_{29,37}^{(33,35)}(t)=(1-e^{-\lambda t}-\lambda te^{-\lambda t})g_2(t)$$
$$q_{36,27}(t)=g_2(t)e^{-\lambda t}, q_{36,37}^{(35)}(t)=(1-e^{-\lambda t})g_2(t),$$
$$q_{37,27}(t)=g_1(t), q_{38,0}(t)=\gamma_3 e^{-\gamma_3 t}$$

The non -zero elements $p_{ij}$ are given as $p_{ij}=\lim_{s\to 0} q_{ij}^{*}(s)$.

The mean sojourn time ($\mu_i$) in the regenerative state i is defined as the time to stay in that state before transition to any other state. If T denotes the sojourn time in the regenerative state i, then

$$\mu_i=E(T)=\int_0^\infty P_r[T>t]dt,$$

Thus,

$$\mu_0=\int_0^\infty e^{-(2\lambda+\alpha+\beta_1)t}dt=,\mu_1=\int_0^\infty e^{-(\lambda+\alpha)t}\bar{G}_1(t),\mu_2=\int_0^\infty tg_2(t)dt$$
$$\mu_3=\int_0^\infty e^{-\lambda t}\bar{G}_2(t)dt,\mu_{10}=\int_0^\infty e^{-\lambda t}\bar{G}_2(t)dt,\mu_{11}=\int_0^\infty tg_1(t)dt$$
$$\mu_{12}=\int_0^\infty e^{-\gamma_1 t}dt=\frac{1}{\gamma_1},\mu_{13}=\int_0^\infty e^{-(2\lambda+\alpha+\beta_1)t}dt=\mu_0,$$
$$\mu_{14}=\mu_1,\mu_{15}=\mu_2\mu_{16}=\mu_3,\mu_{23}=\mu_{10},\mu_{24}=\mu_{11},$$
$$\mu_{25}=\frac{1}{\gamma_2},\mu_{26}=\mu_0,\mu_{27}=\mu_1,\mu_{28}=\mu_2$$
$$\mu_{29}=\mu_3,\mu_{36}=\mu_{10},\mu_{37}=\mu_{11},\mu_{38}=\frac{1}{\gamma_3}$$

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


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$$m_{ij} = \int_0^\infty t q_{ij} dt = -q_{ij}^{*'}(0)$$

Thus,

$$m_{01} + m_{02} + m_{03} + m_{0,12} = \mu_0$$

$$m_{10} + m_{11}^{(4)} + m_{12}^{(6)} + m_{13}^{(5)} + m_{18}^{(5)} = \frac{\lambda + q\alpha}{\lambda + \alpha}\mu_{11}$$

$$+\frac{p(1-g_1^*(\lambda))}{\lambda} - \frac{p\lambda}{\lambda+\alpha}\mu_1 = K_1(say)$$

$$m_{10} + m_{11}^{(4)} + m_{12}^{(6)} + m_{13}^{(5)} + m_{1,10}^{(5,8)} = \mu_{11}$$

$$m_{20} = \mu_2$$

$$m_{30} + m_{31}^{(7)} + m_{39}^{(7)} = \frac{1}{\lambda}\begin{bmatrix} 2 - g_2^*(\lambda) \\ -\lambda^2 \int_0^\infty t e^{-\lambda t} G_2(t) dt \end{bmatrix} = K_2(say)$$

$$m_{30} + m_{31}^{(7)} + m_{3,11}^{(7,9)} = \int_0^\infty t\left(1 + \lambda t + \frac{\lambda^2 t^2}{2}\right) e^{-\lambda t} g_2(t) dt = K_3(say)$$

$$m_{10,1} + m_{10,11}^{(9)} = \mu_2, m_{11,1} = \mu_{11}, m_{12,13} = \mu_{12},$$

$$m_{13,14} + m_{13,15} + m_{13,16} + m_{13,25} = \mu_0$$

$$m_{14,13} + m_{14,14}^{(17)} + m_{14,15}^{(19)} + m_{14,16}^{(18)} + m_{14,21}^{(18)} = K_1$$

$$m_{14,13} + m_{14,14}^{(17)} + m_{14,15}^{(19)} + m_{14,16}^{(18)} + m_{14,23}^{(18,21)} = \mu_{11},$$

$$m_{15,13} = \mu_2$$

$$m_{16,13} + m_{16,14}^{(20)} + m_{16,22}^{(20)} = K_2,$$

$$m_{16,13} + m_{16,14}^{(20)} + m_{16,24}^{(20,22)} = K_3$$

$$m_{23,14} + m_{23,24}^{(23)} = \mu_2, m_{24,14} = \mu_{11}$$

$$m_{25,26} = \frac{1}{\gamma_2} = \mu_{25}, m_{26,27} + m_{26,28}$$

$$+m_{26,29} + m_{26,38} = \mu_0$$

$$m_{27,26} + m_{27,27}^{(30)} + m_{27,28}^{(32)} + m_{27,29}^{(31)} + m_{27,34}^{(31)} = K_1$$

$$m_{27,26} + m_{27,27}^{(30)} + m_{27,28}^{(32)} + m_{27,29}^{(31)} + m_{27,36}^{(31,34)} = \mu_{11}$$

$$m_{28,26} = \mu_2, m_{29,26} + m_{29,27}^{(33)} + m_{29,35}^{(33)} = K_2$$

$$m_{29,26} + m_{29,27}^{(33)} + m_{29,37}^{(33,35)} = K_3,$$

$$m_{36,27} + m_{36,37}^{(35)} = \mu_2, m_{37,27} = \mu_{11}, m_{38,0} = \mu_{38}$$

## V. RELIABILITY AND MEAN TIME TO SYSTEM FAILURE

To determine the mean time to system failure (MTSF) of the system, we regard the failed state as absorbing states. Defining $\phi_i(t)$ as the cdf of first passage time from regenerative state i to failed state and making the probabilistic arguments we can obtain the recursive relation for $\phi_i(t)$. Then, the reliability of the system at time t is given by

R(t)=the inverse Laplace transform of $(1 - \phi_0^{**}(s)/s)$

and the mean time to system failure (MTSF) when the system starts from the state 0 is given by

$$T_0 = \lim_{s\to 0}\frac{1-\phi_0^{**}(s)}{s} = \frac{N}{D},$$

where $\phi_0^{**}(s)$ is the Laplace-Stieltjes Transform of $\phi_0(t)$, and

$$N = [(1 - p_{27,27}^{(30)} - p_{27,29}^{(31)} p_{29,27}^{(33)})(1 - p_{26,29}p_{29,26} - p_{26,28})$$
$$-(p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)} p_{29,26})(p_{26,27} + p_{26,29}p_{29,27})]$$
$$[(1 - p_{14,14}^{(17)} - p_{14,16}^{(18)} p_{16,14}^{(20)})(1 - p_{13,16}p_{16,13} - p_{13,15})$$
$$-(p_{14,13} + p_{14,16}^{(18)} p_{16,13} + p_{14,15}^{(19)})(p_{13,14} + p_{13,16}p_{16,14}^{(20)})]$$
$$[1 - p_{11}^{(4)} - p_{13}^{(5)} p_{31}^{(7)}]\mu_0 + [(1 - p_{27,27}^{(30)} - p_{27,29}^{(31)} p_{29,27}^{(33)})(1$$
$$-p_{26,29}p_{29,26} - p_{26,28}) - (p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)} p_{29,26})(p_{26,27}$$
$$+p_{26,29}p_{29,27})][(1 - p_{14,14}^{(17)} - p_{14,16}^{(18)} p_{16,14}^{(20)})$$
$$(1 - p_{13,16}p_{16,13} - p_{13,15}) - (p_{14,13} + p_{14,16}^{(18)} p_{16,13} + p_{14,15}^{(19)})$$
$$(p_{13,14} + p_{13,16}p_{16,14}^{(20)})](p_{01} + p_{03}p_{31}^{(7)})K_1$$
$$+[(1 - p_{27,27}^{(30)} - p_{27,29}^{(31)} p_{29,27}^{(33)})(1 - p_{26,29}p_{29,26}$$
$$-p_{26,28}) - (p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)} p_{29,26})(p_{26,27}$$
$$+p_{26,29}p_{29,27})][(1 - p_{14,14}^{(17)} - p_{14,16}^{(18)} p_{16,14}^{(20)})(1$$
$$-p_{13,16}p_{16,13} - p_{13,15}) - (p_{14,13} + p_{14,16}^{(18)} p_{16,13}$$
$$+p_{14,15}^{(19)})(p_{13,14} + p_{13,16}p_{16,14}^{(20)})][p_{02}(1 - p_{11}^{(4)}$$
$$-p_{13}^{(5)} p_{31}^{(7)}) + p_{12}^{(6)}(p_{01} + p_{03}p_{31}^{(7)})]\mu_2 + [(1 - p_{27,27}^{(30)} - p_{27,29}^{(31)}$$
$$p_{29,27}^{(33)})(1 - p_{26,29}p_{29,26} - p_{26,28}) - (p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}$$
$$p_{29,26})(p_{26,27} + p_{26,29}p_{29,27})][(1 - p_{14,14}^{(17)} - p_{14,16}^{(18)} p_{16,14}^{(20)})$$
$$(1 - p_{13,16}p_{16,13} - p_{13,15}) - (p_{14,13} + p_{14,16}^{(18)} p_{16,13} + p_{14,15}^{(19)})$$
$$(p_{13,14} + p_{13,16}p_{16,14}^{(20)})][p_{03}(1 - p_{11}^{(4)} - p_{13}^{(5)} p_{31}^{(7)})$$
$$+p_{13}^{(5)}(p_{01} + p_{03}p_{31}^{(7)})]K_2 + \mu_{12}[(1 - p_{27,27}^{(30)}$$
$$-p_{27,29}^{(31)} p_{29,27}^{(33)})(1 - p_{14,14}^{(17)} - p_{14,16}^{(18)} p_{16,14}^{(20)})$$

$$(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})p_{0,12}p_{13,25}(p_{26,38}+p_{26,29}p_{29,35}^{(33)})$$
$$+p_{0,12}p_{13,25}(p_{26,27}+p_{26,29}p_{29,27})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})$$
$$(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})(p_{27,34}^{(31)}+p_{27,29}^{(31)}p_{29,35}^{(33)})+[(1-p_{27,27}^{(30)}$$
$$-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{26,29}p_{29,26}-p_{26,28})-(p_{27,26}+p_{27,28}^{(32)}$$
$$+p_{27,29}^{(31)}p_{29,26})(p_{26,27}+p_{26,29}p_{29,27})]]p_{0,12}(1-p_{11}^{(4)}$$
$$-p_{13}^{(5)}p_{31}^{(7)})\{(p_{13,14}+p_{13,16}p_{16,14}^{(20)})(p_{14,21}^{(18)}+p_{14,16}^{(18)}p_{16,22}^{(18)})$$
$$+p_{13,16}p_{16,22}^{(20)}(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})\}]+[(1-p_{27,27}^{(30)}$$
$$-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})(1-p_{11}^{(4)}$$
$$-p_{13}^{(5)}p_{31}^{(7)})p_{0,12}p_{13,25}(p_{26,38}+p_{26,29}p_{29,35}^{(33)})+p_{0,12}(p_{26,38}$$
$$+p_{26,29}p_{29,35}^{(33)})+(p_{26,27}+p_{26,29}p_{29,27})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}$$
$$p_{16,14}^{(20)})(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})p_{0,12}(p_{27,34}^{(31)}+p_{27,29}^{(31)}p_{29,35}^{(33)})]$$
$$\mu_0+[(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{26,29}p_{29,26}-p_{26,28})$$
$$-(p_{27,26}+p_{27,28}^{(32)}+p_{27,29}^{(31)}p_{29,26})(p_{26,27}+p_{26,29}p_{29,27})]$$
$$(p_{0,12}p_{13,14}+p_{13,16}p_{16,14}^{(20)})(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})K_1$$
$$+\{(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{26,29}p_{29,26}$$
$$-p_{26,28})-(p_{27,26}+p_{27,28}^{(32)}+p_{27,29}^{(31)}p_{29,26})$$
$$(p_{26,27}+p_{26,29}p_{29,27})\}\{(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})p_{13,15}$$
$$+(p_{13,14}+p_{13,16}p_{16,14}^{(20)})p_{14,15}\}\{(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})(p_{01}+$$
$$p_{0,12}+p_{03}p_{31}^{(7)})-(p_{01}+p_{03}p_{31}^{(7)})(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})\}\mu_2$$
$$+[(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{26,29}p_{29,26}-p_{26,28})$$
$$-(p_{27,26}+p_{27,28}^{(32)}+p_{27,29}^{(31)}p_{29,26})(p_{26,27}+p_{26,29}p_{29,27})]$$
$$\{p_{13,14}+p_{13,16}-p_{13,16}p_{14,14}^{(17)}\}p_{0,12}(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})K_2$$
$$+(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})$$
$$(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})p_{0,12}p_{13,25}(p_{26,38}+p_{26,29}p_{29,35}^{(33)})$$
$$+p_{0,12}p_{13,25}(p_{26,27}+p_{26,29}p_{29,27})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})$$
$$(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})(p_{27,34}^{(31)}+p_{27,29}^{(31)}p_{29,35}^{(33)})\}\mu_{25}+(1-p_{27,27}^{(30)}$$
$$-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})$$
$$p_{0,12}p_{13,25}\mu_0+(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})(p_{26,27}+p_{26,29}p_{29,27})$$
$$(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})p_{0,12}p_{13,25}K_1$$
$$+[(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})p_{26,28}+(p_{26,27}+p_{26,29}p_{29,27})$$
$$p_{27,28}][\{(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})(1-p_{13,16}p_{16,13}-p_{13,15})$$
$$-(p_{14,13}+p_{14,16}^{(18)}p_{16,13}+p_{14,15}^{(19)})(p_{13,14}+p_{13,16}p_{16,14}^{(20)})\}$$
$$\{(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})(1-p_{02}-p_{03}p_{30})-(p_{10}+p_{13}^{(5)}p_{30}$$
$$+p_{12}^{(6)})(p_{01}+p_{03}p_{31}^{(7)})-(p_{03}p_{39}^{(7)}(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})$$
$$+(p_{18}+p_{13}p_{39})(p_{01}+p_{03}p_{31}^{(7)})\}+p_{0,12}(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})$$
$$\{(p_{13,14}+p_{13,16}p_{16,14}^{(20)})(p_{14,21}^{(18)}+p_{14,16}^{(18)}p_{16,20}^{(20)})$$
$$+p_{13,16}p_{16,20}^{(20)}(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})\}]\mu_2+p_{0,12}p_{13,25}$$
$$(1-p_{11}^{(4)}-p_{13}^{(5)}p_{31}^{(7)})(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})$$
$$[(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})p_{26,29}+(p_{26,27}$$
$$+p_{26,29}p_{29,27})p_{27,29}^{(31)}]K_2+(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})$$
$$(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})(1-p_{11}^{(4)}$$
$$-p_{13}^{(5)}p_{31}^{(7)})p_{0,12}p_{13,25}p_{26,38}\mu_{38}$$

and

$$D=[(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})(1-p_{26,29}p_{29,26}-p_{26,28})$$
$$-(p_{27,26}+p_{27,29}^{(31)}p_{29,26}+p_{27,28})(p_{26,27}+p_{26,29}p_{29,27}^{(33)})]$$
$$[(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})(1-p_{13,16}p_{16,13}-p_{13,15})-(p_{14,13}$$
$$+p_{14,16}^{(18)}p_{16,13}+p_{14,15}^{(19)})(p_{13,14}+p_{13,16}p_{16,14}^{(20)})][(1-p_{11}^{(4)}$$
$$-p_{13}^{(5)}p_3^{(7)})(1-p_{03}p_{30}-p_{02})-(p_{10}+p_{13}^{(5)}p_{30}+p_{12}^{(6)})$$
$$(p_{01}+p_{03}p_{31}^{(7)})]-p_{0,12}p_{13,25}p_{26,38}(1-p_{27,27}^{(30)}-p_{27,29}^{(31)}p_{29,27}^{(33)})$$
$$(1-p_{14,14}^{(17)}-p_{14,16}^{(18)}p_{16,14}^{(20)})(1-p_{11}^{(4)}-p_{13}^{(5)}p_3^{(7)})$$

## VI. AVAILABILITY AT FULL CAPACITY (ALL THE UNITS ARE WORKING)

Let us define $A_i(t)$ as the probability that system is up and working in full capacity at the instant t given that system entered regenerative state i at t=0. Using the arguments of the theory of regenerative process and Laplace transforms, the availability of the system is given by

$$A_0=\lim_{s\to 0}(sA_0^*(s))=\frac{N_1}{D_1}$$

where

$$N_1=3\mu_0 p_{0,12}^2[p_{10}+p_{12}^{(6)}+p_{13}^{(5)}p_{30}]^3$$

and

$$D_1=3p_{0,12}^2(p_{10}+p_{12}^{(6)}+p_{13}^{(5)}p_{30})^2[\{\mu_0+\mu_2 p_{02}$$
$$+\mu_{11}p_{03}p_{3,11}^{(7,9)}+\frac{1}{3}p_{0,12}(\mu_{12}+\mu_{25}$$
$$+\mu_{38})\}(p_{10}+p_{12}^{(6)}+p_{13}^{(5)}p_{30})+\{\mu_{11}+(p_{12}^{(6)}+p_{1,10}^{(5,8)})\mu_2$$
$$+\mu_{11}(p_{1,10}^{(5,8)}p_{10,11}^{(9)}+p_{13}^{(5)}p_{3,11}^{(7,9)})\}(p_{01}+p_{03}-p_{03}p_{30})$$
$$+K_3\{p_{03}(p_{10}+p_{12}^{(6)})+p_{13}^{(5)}(p_{01}+p_{03})\}]$$

Similarly, other measures of the system effectiveness have been obtained which are given as:

**Availability at Reduced Capacity** (one gas turbine and one steam turbine working) $(AR_0) = \frac{N_2}{D_1}$

**Availability in Single Cycle** (only one gas turbine working) $(A_0^{(s)}) = \frac{N_3}{D_1}$

**Expected Down time Excluding Failed State** $(DT_0) = \frac{N_4}{D_1}$

**Expected time for Minor Inspection** $(MI_0) = \frac{N_5}{D_1}$

**Expected time for Path Inspection** $(PI_0) = \frac{N_6}{D_1}$

**Expected time for Major Inspection** $(MJ_0) = \frac{N_7}{D_1}$

**Expected Busy Period Analysis for Repair** $(B_0) = \frac{N_8}{D_1}$

**Expected Number of Visits of the Repairman** $(V_0) = \frac{N_9}{D_1}$

where

$$N_2 = 3\mu_1(p_{01} + p_{03} - p_{03}p_{30})p_{0,12}^2(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})^2$$

$$N_3 = 3\mu_3 p_{0,12}^2(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})^2[(p_{01} + p_{03} - p_{03}p_{30})(p_{13}^{(5)} + p_{1,10}^{(5,8)}) + p_{03}(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})]$$

$$N_4 = [(p_{03}p_{3,11}^{(7,9)}\mu_{11} + p_{02}\mu_2 + p_{0,12}\mu_{12})(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30}) + (p_{01} + p_{03} - p_{03}p_{30})(p_{12}^{(6)}\mu_2 + p_{13}^{(5)}p_{3,11}^{(7,9)}\mu_{11} + p_{1,10}^{(5,8)}p_{10,11}^{(9)}\mu_{11})][p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}p_{29,26})p_{26,38}(p_{14,13} + p_{14,15}^{(19)} + p_{14,16}^{(18)}p_{16,13})p_{13,25}] + p_{0,12}(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})(p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}p_{29,26})p_{26,38}[(p_{14,13} + p_{14,15}^{(19)} + p_{14,16}^{(18)}p_{16,13})(p_{13,15}\mu_2 + p_{13,16}p_{16,24}^{(20,22)}\mu_{11} + p_{13,25}\mu_{25}) + (p_{13,14} + p_{13,16} - p_{13,16}p_{16,13})(p_{14,15}^{(19)}\mu_2 + p_{14,16}^{(18)}p_{16,24}^{(20,22)}\mu_{11} + p_{14,23}^{(18,21)}p_{23,24}^{(22)}\mu_{11})] + p_{0,12}p_{13,25}(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})(p_{14,13} + p_{14,15}^{(19)} + p_{14,16}^{(18)}p_{16,13})[(p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}p_{29,26})(p_{26,28}\mu_2 + p_{26,29}p_{29,37}^{(33,35)}\mu_{11} + p_{26,38}\mu_{38}) + (p_{26,27} + p_{26,29} - p_{26,29}p_{29,26})(p_{27,28}^{(32)}\mu_2 + p_{27,29}^{(31)}p_{29,37}^{(33,35)}\mu_{11} + p_{27,36}^{(31,34)}p_{36,37}^{(35)}\mu_{11})]$$

$$N_5 = p_{0,12}^3(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})^3\mu_{12}$$

$$N_6 = p_{0,12}^3(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})^3\mu_{25}$$

$$N_7 = p_{0,12}^3(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})^3\mu_{38}$$

$$N_8 = [(p_{02}\mu_2 + p_{03}\mu_2 + p_{03}p_{3,11}^{(7,9)}\mu_{11})(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})(p_{01} + p_{03} - p_{03}p_{30})(\mu_{11} + p_{12}^{(6)}\mu_2 + p_{13}^{(5)}\mu_2 + p_{13}^{(5)}p_{3,11}^{(7,9)}\mu_{11} + p_{1,10}^{(5,8)}\mu_2 + p_{1,10}^{(5,8)}p_{10,11}^{(9)}\mu_{11})][p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}p_{29,26})p_{26,38}(p_{14,13} + p_{14,15}^{(19)} + p_{14,16}^{(18)}p_{16,13})p_{13,25} + p_{0,12}(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})(p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}p_{29,26})p_{26,38}\{(p_{14,13} + p_{14,15}^{(19)} + p_{14,16}^{(18)}p_{16,13})(p_{13,15}\mu_2 + p_{13,16}\mu_2 + p_{13,16}p_{16,24}^{(20,22)}\mu_{11}) + (p_{13,14} + p_{13,16} - p_{13,16}p_{16,13})(\mu_{11} + p_{14,15}^{(19)}\mu_2 + p_{14,16}^{(18)}\mu_2 + p_{14,16}^{(18)}p_{16,24}^{(20,22)}\mu_{11} + p_{14,16}^{(18)}\mu_2 + p_{14,16}^{(18)}p_{16,24}^{(20,22)}\mu_{11} + p_{14,23}^{(18,21)}\mu_2 + p_{14,23}^{(18,21)}p_{23,24}^{(22)}\mu_{11})\}] + p_{0,12}p_{13,25}(p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30})(p_{14,13} + p_{14,15}^{(19)} + p_{14,16}^{(18)}p_{16,13})\{(p_{27,26} + p_{27,28}^{(32)} + p_{27,29}^{(31)}p_{29,26})(p_{26,28}\mu_2 + p_{26,29}\mu_2 + p_{26,29}\mu_2 + p_{26,29}p_{29,37}^{(33,35)}\mu_{11}) + (p_{26,27} + p_{26,29} - p_{26,29}p_{26,26})(\mu_{11} + p_{27,28}^{(32)}\mu_2 + p_{27,29}^{(31)}\mu_2 + p_{27,29}^{(31)}p_{29,37}^{(33,35)}\mu_{11} + p_{27,36}^{(31,34)}\mu_2 + p_{27,36}^{(31,34)}p_{36,37}^{(35)}\mu_{11})$$

$$N_9 = 3p_{0,12}^2[p_{10} + p_{12}^{(6)} + p_{13}^{(5)}p_{30}]^3$$

and $D_1$ is already specified.

## VII. COST-BENEFIT ANALYSIS

Expected profit incurred to the system is the excess of revenue over cost and in steady state is given by

$$PROFIT = C_0A_0 + C_{1R}AR_0 + C_{1S}AS_0 - C_2DT_0 - C_3MI_0 - C_4PI_0 - C_5MJ_0 - C_6B_0 - C_7V_0$$

$C_0$ = Revenue per unit uptime with full capacity.
$C_{1R}$ = Revenue per unit at reduced capacity.
$C_{1S}$ = Revenue per unit uptime in single cycle
$C_2$ = Loss per unit time for which the system is in down state (other than failed state)
$C_3$ = Cost per unit time for which the system is under minor inspection.
$C_4$ = Cost per unit time for which the system is undergone for path inspection.
$C_5$ = Cost per unit time for which the major inspection goes on.
$C_6$ = Cost per unit time for engaging the repairman for doing repair.
$C_7$ = Cost per visit of the repairman.

## VIII. RESULTS AND DISCUSSION

The following particular case is considered for numerical calculations

$$g_1(t) = \delta_1 e^{-\delta_1 t}, g_2(t) = \delta_2 e^{-\delta_2 t},$$

Various estimated values on the basis of gathered information are

$\lambda = 0.000023, \delta_1 = 0.042, \delta_2 = 0.04$

The assumed values are displayed on figures for graphs. The values of various measures of system effectiveness are obtained as:

Mean time to system failure=124651500000 hrs
Availability at full capacity ($A_0$) =0.968615
Availability at reduced capacity (one gas turbine and one steam turbine working) $(AR_0) = 0.001060$
Availability at single cycle (only one gas turbine working) $(A_0^{(s)}) = 0.000242$
Expected down time excluding failed state $(DT_0) = 0.30082$
Expected time for minor inspection $(MI_0) = 0.004805$
Expected time for path inspection $(PI_0) = 0.010621$
Expected time for major inspection $(MJ_0) = 0.060930$
Busy period analysis for repair $(B_0) = 0.034872$
Expected number of visits of the repairman $(V_0) = 0.000124$

Following conclusions have been drawn on the basis of graphs plotted for MTSF, Availability ($A_0$), Availability at reduced Capacity ($AR_0$), Availability in single cycle ($AS_0$) and profit with respect to failure rate of steam turbine ($\alpha$), Revenue per unit uptime with full Capacity ($C_0$), Revenue per unit uptime with reduced Capacity ($C_{1R}$) and Revenue per unit uptime in single Cycle ($C_{1S}$) for different values of probability of demand on higher rates (p) and loss during down time ($C_2$):

- MTSF gets decrease with the increase in the values of the failure rate ($\alpha$) of steam turbine. It has higher values for lower values of probability (p) of demand on higher rates.
- Availability at full capacity decreases with increase in the values of failure rate ($\alpha$) of steam turbine for different values of probability of demand on higher rates (p), there is negligible change in availability ($A_0$).
- Availability at reduced Capacity ($AR_0$) decreases with the increase in the values of failure rate ($\alpha$) of steam turbine. Also it has higher value for higher value of probability of demand on higher rate (p).
- Availability in single cycle ($AS_0$) increases with increase in the values of failure rate ($\alpha$) of steam turbine. Also it has higher value for higher value of probability of demand on higher rate (p).
- Availability $A_0$ decreases slightly as failure rate ($\alpha$) of steam turbines increases. However, $A_0$ is greater than $AS_0$, but if the failure rate ($\alpha$) is greater than 0.0800008 and other parametric values are $\lambda$=0.000023, $\beta_1$=0.0000625, $\delta_1$=0.042, $\delta_2$=0.04, $\gamma_1$=0.0042, $\gamma_2$=0.0019, $\gamma_3$=0.0014, p=0.5., $AS_0$ becomes higher than $A_0$.
- Availability $AR_0$ decreases slightly as failure rate ($\alpha$) increases and $AS_0$ increases as failure rate ($\alpha$) increases. However, $AR_0$ is greater than $AS_0$, but if the failure rate is greater than 0.00008744, $AS_0$ becomes higher than $AR_0$. Other parametric values taken here are as same as mentioned in the above point.
- Profit increases with increase in the values of probability of demand on higher rates (p). For $C_0$=50000, $C_{1S}$=1000000, $C_{1R}$=80000, $C_2$=500000, $C_3$=500, $C_4$=1000, $C_5$=1500, $C_6$=1250, $C_7$=10000, following interpretation can also be made:

(i) For p = 0.3, profit is positive or zero or negative according as failure rate $\alpha$ < or = or > 0.0022289, i.e. failure rate $\alpha$ should not be fixed greater than 0.0022289 to get the profit.
(ii) For p = 0.5, profit is positive or zero or negative according as failure rate $\alpha$ < or = or > 0.00291212, i.e. failure rate $\alpha$ should not be fixed greater than 0.00291212 to get the profit.
(iii) For p = 0.7, profit is positive or zero or negative according as failure rate $\alpha$ < or = or > 0.003762916, i.e. failure rate $\alpha$ should not be fixed greater than 0.003762916 to get the profit.

- Behaviour of profit w.r.t. revenue per unit uptime during at full Capacity ($C_0$) for different values of loss during down time ($C_2$) revealed that the profit increases with increase in the values of $C_0$. Also, when p=0.5, $C_{1S}$=1250000, $C_{1R}$=1000000, $C_3$=500, $C_4$=1000, $C_5$=1500, $C_6$=1250, $C_7$=10000

(i) For $C_2$ = 700000, profit is positive or zero or negative according as $C_0$ > or = or < 21181.85 i.e. $C_0$ should not be fixed less than 21181.85 to get the profit.
(ii) For $C_2$ = 725000, profit is positive or zero or negative according as $C_0$ > or = or < 22264.84 i.e. $C_0$ should not be fixed less than 22264.84 to get the profit.
(iii) For $C_2$ = 750000, profit is positive or zero or negative according as $C_0$ > or = or < 23347.83 i.e. $C_0$ should not be fixed less than 23347.83 to get the profit.

- Behaviour of profit w.r.t revenue per unit uptime during working at reduced Capacity ($C_{1R}$) for different values of loss during down time ($C_2$) exhibited that the profit increases with increase in the value of $C_{1R}$. Also, when p=0.5, $C_0$=1500000, $C_{1S}$=1000000, $C_3$=500, $C_4$=1000, $C_5$=1500, $C_6$=1250, $C_7$=10000

(i) For $C_2$ = 1760000, profit is positive or zero or negative according as $C_{1R}$ > or = or < 2962998.41 i.e. $C_{1R}$ should not be fixed less than 2962998.41 to get the profit.
(ii) For $C_2$ = 1760500, profit is positive or zero or negative according as $C_{1R}$ > or = or < 3086677.47 i.e. $C_{1R}$ should not be fixed less than 3086677.47 to get the profit.
(iii) For $C_2$ = 1761000, profit is positive or zero or negative according as $C_{1R}$ > or = or < 3210356.53 i.e. $C_{1R}$ should not be fixed less than 3210356.53 to get the profit.

- Behaviour of profit w.r.t. revenue per unit up time during working in single cycle ($C_{1S}$) for different values of loss during down time ($C_2$) showed that the profit increases with increase in the value of $C_{1S.}$ Moreover, if p=0.5, $C_0$=1500000, $C_{1R}$=1000000, $C_3$=500, $C_4$=1000, $C_5$=1500, $C_6$=1250, $C_7$=10000, then

(i) For $C_2$ = 1500000, profit is positive or zero or negative according as $C_{1S}$ > or = or < 706384.5 i.e. $C_{1S}$ should not be fixed less than 706384.5 to get the profit.

(ii) For $C_2$ = 1515000, profit is positive or zero or negative according as $C_{1S}$ > or = or < 723856.4 i.e. $C_{1S}$ should not be fixed less than 723856.4 to get the profit.

(iii) For $C_2$ = 1530000, profit is positive or zero or negative according as $C_{1S}$ > or = or < 741328.7 i.e. $C_{1S}$ should not be fixed less than 741328.7 to get the profit.

## IX. CONCLUDING REMARKS

The above remarks are based on the particular case taken up for computational work. However, if a stakeholder is interested in finding some other cut-off points related to the desired rates, costs and probabilities involved, he/she can use the equations obtained in this paper for various measures of system effectiveness. The particular case should be taken on the basis of data existed for the systems under consideration. And then, the lower/upper bounds can be obtained for the desired parameters putting the numerical values of various rates/costs experienced for the systems used by the stakeholders. The bounds so obtained for the desired parameters will definitely be helpful in taking important decisions so far as the reliability and the profitability of the system is concerned.

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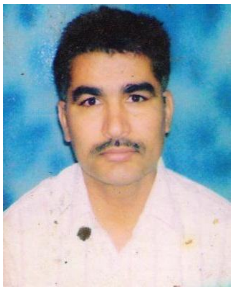

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