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Reliability analysis of captive power plant system where the working of standby unit depends on connecting unit

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ABSTRACT

Captive power plants usually operate parallel to the gridline to overcome the losses associated with power failures. While the connectivity of the power plant and gridline highly depends on the functioning of the electrical breaker. This study reveals the importance of connecting device breakers in a captive power plant to operate the system at full or reduced capacity and safer it from reverse feeding. Using semi-Markov processes reliability model is developed for steam turbine generators interconnected with gridline by an electric breaker. The expressions are formed for reliability measures like mean time to system failure, availability, busy period, and profit using regenerative point techniques. Also, these measures are evaluated numerically using an actual dataset belonging to a captive power plant. Graphical plotting shows a decline in profit with increasing the failure rates of turbine generators, gridline, and working probability of breaker. The revenue per unit uptime of the system is forecasted to get productive profit with different failure rates of the power generator.

1. Introduction

Every production industry focus on ancillary activities for making a flexible and reliable power supply for the industry. These activities play a crucial role in decreasing operating costs for the system. Also, it necessitates the concept of redundancy for power sources available for industry. Parashar and Taneja (2007) and Mathew et al. (2010) have worked on different types of redundant systems. Huang and Xu (2010) formed a closed-form expression to evaluate the lifetime reliability of k out of n load-sharing redundant systems. Rizwan et al. (2013) presented a reliability analysis of a seven-unit desalination plant with shutdown during the winter season. Various authors like Singh and Taneja (2014) and Naithani et al. (2017) have worked on the performance enhancement of the system subjected to different constraints. Sharma and Kaur (2016) have studied a two-unit standby system with an essential unit generator that increased its availability. Taneja and Prasad (2020) have carried out the reliability analysis for three-unit gas turbine power generating system with FCFS repair priority, where the system goes downstate when the turbine fails. Rajesh and Prasad (2018) have given the provision of redundancy in power-generating turbines. Bhardwaj et al. (2021) studied the MTSF and profit analysis of a redundant system having an unstable switch. But, the literature on reliability doesn't have a single attempt on the reliability of devices connecting redundant electrical sources. Observing this gap in literature present research elevates the importance of the reliability of electrical breakers.

Present paper concentrate on the profit analysis of the captive power plant of National Fertilizer Limited, Bathinda, India where the working of the grid-line depends on breakers on turbine failures. The system consists of two Steam Turbine Generators (STGs), gridlines (GL), and breakers. Initially, as shown in Fig. 1, the system fully functions on two steam turbine generators where the grid-line is on standby mode. On failure of any one of the STG, the breaker interconnects the supply of the grid line and for a small amount of time system goes to a halt state. But if the breaker fails, the safety relays would cut-off load from operating STG leading to system failure. If the breaker operates successfully on the grid failure, the system works at reduced capacity on one STG. Moreover, the breaker cuts off the connection with the gridline to prevent the reverse feeding of electricity that damages the steam turbine generators. Using the data in Table 1, various system

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measures such as Meantime to system failure, Availability, Busy period of a repairman, number of repairs, and profit analysis have been calculated numerically in Table 2 and presented graphically (Figs. 2-5) using semi-Markov processes and regenerative point techniques assuming the following assumptions.

1.1. Assumptions

- Failure times are assumed to follow an exponential distribution.
- Units work as well as new after every repair.
- Among two steam turbine generators repair priority is given to the recently failed unit.
- In case of breaker failure, it is repaired immediately among all units.
- In case of failure of two steam turbine generators and gridline, repair priority is given to gridline.

2. Nomenclature and model description

λ_1: Constant failure rate of identical units steam turbine generators.
λ_2: Constant failure rate of gridline.
p: The probability that breaker will work.
q: The probability that breaker fails to shift the load.
β: Rate with breaker shifts the load.
$G_1(t)$, $g_1(t)$: c.d.f. and p.d.f. of repair time of Steam Turbine generators.
$G_2(t)$, $g_2(t)$: c.d.f. and p.d.f. of repair time of gridline.
$G_3(t)$, $g_3(t)$: c.d.f. and p.d.f. of repair time of breakers.

2.1. Symbols for the states of the system

Si: States of the system with number *i*.
ST_O, P_O: Steam turbine generators, gridline in the operating state.
BKs, *BKo*: Breaker is in the standby state, Breaker is in the operating state.
STr, *Pr*, *BKr*: STG, gridline, and breaker are under repair.
P_R: Gridline under repair from the previous state.
STwr, *Pwr*: Failed Units Steam turbine generators and gridline waiting for repair.
P_S: Gridline in Standby state.

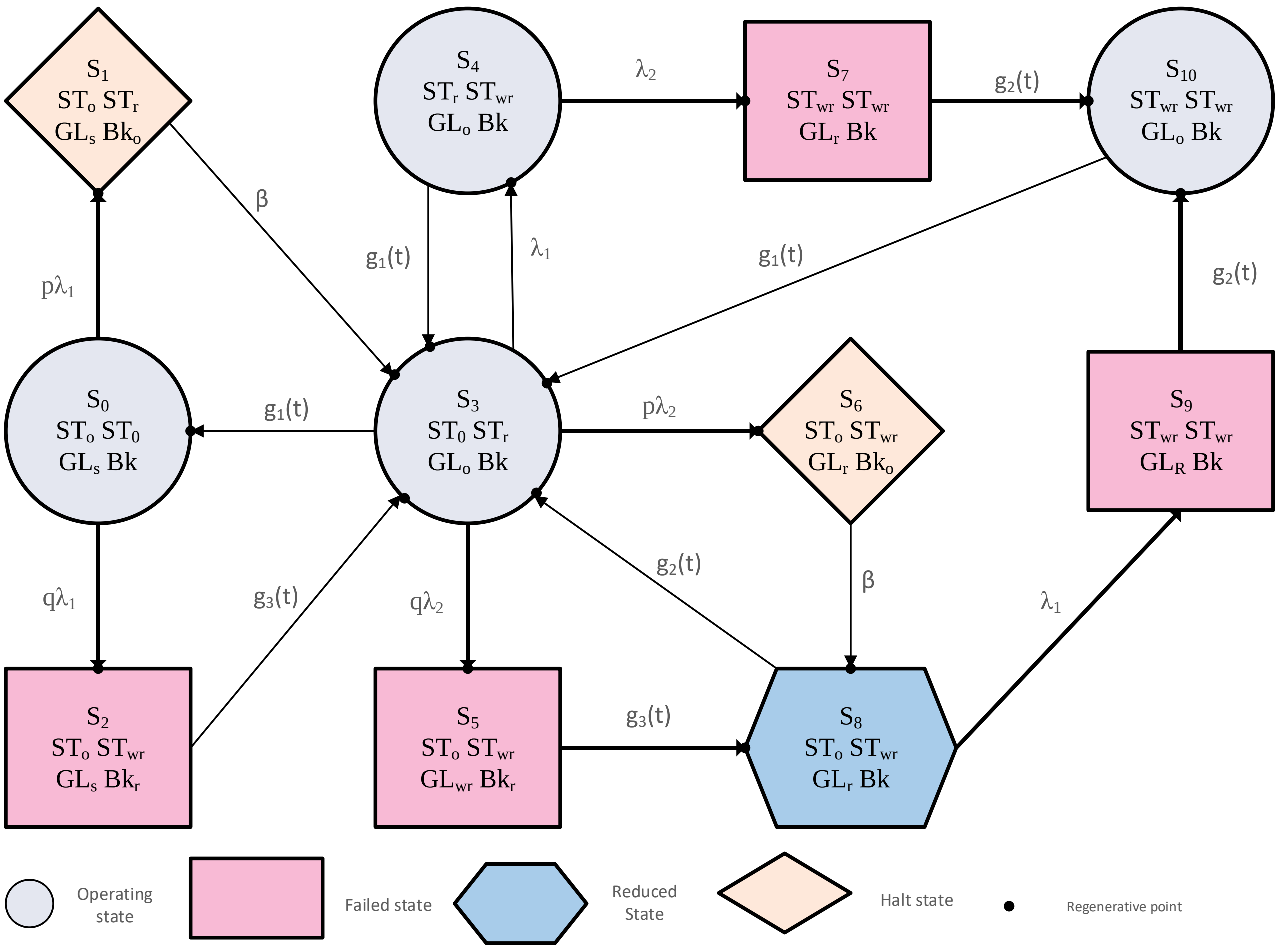

Fig. 1: State transition diagram

2.2. Transition probabilities

The State Transition Diagram is as shown in Fig. 1. the epochs of entry into the states S_0, S_1, S_2, S_3, S_4, S_5, S_6, S_7, S_8, S_{10} are regenerative points so these are regenerative states, and states S_2, S_5, S_9 are failed state.

$$dQ_{01}(t) = p\lambda_1 e^{-(\lambda_1)t}\,dt$$
$$dQ_{02}(t) = q\lambda_1 e^{-(\lambda_1)t}\,dt$$

$dQ_{13}(t) = \beta e^{-(\beta)t}dt$
$dQ_{23}(t) = g_3(t)dt$
$dQ_{30}(t) = e^{-(\lambda_1+\lambda_2)t}\, g_1(t)dt$
$dQ_{34}(t) = \lambda_1 e^{-(\lambda_1+\lambda_2)t}\,\overline{G_1(t)}dt$
$dQ_{35}(t) = q\lambda_2 e^{-(\lambda_1+\lambda_2)t}\,\overline{G_1(t)}dt$
$dQ_{36}(t) = p\lambda_2 e^{-(\lambda_1+\lambda_2)t}\,\overline{G_1(t)}dt$
$dQ_{43}(t) = e^{-(\lambda_2)t}g_1(t)dt$
$dQ_{47}(t) = \lambda_2 e^{-(\lambda_2)t}\,\overline{G_1(t)}dt$
$dQ_{58}(t) = g_3(t)dt$
$dQ_{68}(t) = \beta e^{-(\beta)t}dt$
$dQ_{7,10}(t) = g_2(t)dt$
$dQ_{83}(t) = e^{-(\lambda_1)t}g_2(t)dt$
$dQ_{89}(t) = \lambda_1 e^{-(\lambda_1)t}\,\overline{G_2(t)}dt$
$dQ_{8,10}^{(9)}(t) = [\lambda_1 e^{-(\lambda_1)t}©1]\overline{G_2(t)}dt$
$dQ_{10,3}(t) = g_1(t)dt$

The non-zero elements *pij's* are given as:

$p_{01} = p$
$p_{02} = q$
$p_{13} = p_{23} = 1$
$p_{30} = g_1^*(\lambda_1 + \lambda_2)$
$p_{35} = q\dfrac{\lambda_2}{(\lambda_1 + \lambda_2)}[1 - g_1^*(\lambda_1 + \lambda_2)]$
$p_{36} = p\dfrac{\lambda_2}{(\lambda_1 + \lambda_2)}[1 - g_1^*(\lambda_1 + \lambda_2)]$
$p_{34} = \dfrac{\lambda_2}{(\lambda_1 + \lambda_2)}[1 - g_1^*(\lambda_1 + \lambda_2)]$
$p_{43} = g_1^*(\lambda_2)$
$p_{47} = 1 - g_1^*(\lambda_2)$
$p_{58} = p_{68} = 1$
$p_{7,10} = p_{10,3} = 1$
$p_{83} = g_2^*(\lambda_2)$

The state transition probabilities can be verified in the way that:

$p_{01} + p_{02} + p_{03} = 1$
$p_{30} + p_{35} + p_{36} + p_{34} = 1$
$p_{43} + p_{47} = 1$
$p_{83} + p_{89} = 1$
$p_{83} + p_{8,10}^{(9)} = 1$

and the mean sojourn time μ_i corresponding to regenerative state $'i'$ is given as:

$\mu_0 = \frac{1}{\lambda_1}$
$\mu_1 = \frac{1}{\beta}$
$\mu_2 = -g_3^{*'}(0)$
$\mu_3 = \frac{1}{\lambda_1+\lambda_2}[1 - g_1^*(\lambda_1 + \lambda_2)]$
$\mu_4 = \frac{1}{\lambda_2}[1 - g_1^*(\lambda_2)]$
$\mu_5 = -g_3^{*'}(0)$
$\mu_6 = \dfrac{1}{\beta}$
$\mu_7 = -g_2^{*'}(0)$
$\mu_8 = \dfrac{1}{\lambda_1}[1 - g_2^*(\lambda_1)]$
$\mu_7 = -g_2^{*'}(0)$

The unconditional mean time required by the system to transit from state $'i'$ to any regenerative state $'j'$ when time is counted from the epoch of entrance in the state $'i'$ is mathematically stated as:

$$m_{ij} = \int_a^b t\,dQ_{ij}(t) = -q_{ij}^{*'}(0)$$

So we have,

$m_{01} + m_{02} = \mu_0$
$m_{13} = \mu_1$
$m_{23} = \mu_2$
$m_{30} + m_{34} + m_{35} + m_{36} = \mu_3$
$m_{43} + m_{47} = \mu_4$
$m_{58} = \mu_5$
$m_{68} = \mu_6$
$m_{7,10} = \mu_7$
$m_{83} + m_{89} = \mu_8$
$m_{83} + m_{8,10}^{(9)} = k_8$
$m_{10,3} = \mu_{10}$

where,

$$k_8 = \int_0^\infty t g_2(t)dt \tag{1}$$

2.3. Mean time to system failure

The mean time to system failure is determined by considering the failed states as absorbing states. The mean time to system failure (MTSF), when the system starts from the initial state *So*, is given by,

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

Using L' Hospital Rule and putting the value of $\phi_0^{**}(s)$ we have,

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

where,

$$N = \mu_0(1 - p_{34}p_{43})$$

and,

$$D = 1 - p_{34}p_{43}$$

2.4. Availability at full capacity

Using the theory of regenerative processes, the availability at full capacity AF_0 of the system is given by,

$$AF_0 = \lim_{s\to 0}\left(sA_0^*(s)\right) = \frac{N_1}{D_1}$$

where,

$$N_1 = \mu_1 p_{30} + \mu_3 + \mu_4 p_{34} + \mu_{10}[p_{34}p_{8,10}^{(9)}(p_{35} + p_{36})]$$

and,

$$D_1 = \mu_0 p_{30} + \mu_1 p_{01}p_{30} + \mu_2 p_{02}p_{30} + \mu_3 + \mu_4 p_{34} + \mu_5 p_{35} + \mu_6 p_{36} + \mu_7 p_{47}p_{34} + k_8(p_{35} + p_{36}) + \mu_{10}[p_{47}p_{34} + p_{8,10}^{(9)}(p_{35} + p_{36})] \tag{2}$$

where k_8 is already specified in Eq. 1.

2.5. Availability at reduced capacity

Using the theory of regenerative processes, the availability at reduced capacity AF_0 of the system is given by,

$$AR_0 = \lim_{s\to 0}\left(sA_0^*(s)\right) = \frac{N_2}{D_1}$$

where,

$$N_2 = \mu_8(p_{35} + p_{36})$$

and D_1 is already specified in Eq. 2.

2.6. Busy period analysis of repairman

Using the theory of regenerative processes, a busy period analysis of a repairman is given by,

$$B_0 = \lim_{s\to 0}\left(sB_0^*(s)\right) = \frac{N_3}{D_1}$$

where,

$$N_3 = \mu_1 p_{01} p_{30} + \mu_2 p_{02} p_{30} + \mu_3 + \mu_4 p_{34} + \mu_5 p_{35} + \mu_6 p_{36} + \mu_7 p_{47} p_{34} + k_8(p_{35} + p_{36})$$

and D_1 is already specified in Eq. 2.

2.7. Expected number of repairs

Using the theory of regenerative processes, expected number of repairs are given by,

$$V_0 = \lim_{s\to 0}(sV_0^{**}(s)) = \frac{N_4}{D_1}$$

where, $N_4 = p_{30}$ and D_1 is already specified in Eq. 2.

2.8. Profit analysis

The expected total profit incurred to the system in steady-state is given by,

$$P_F = C_0 AF_0 + C_1 AR_0 - C_2 B_0 - C_3 V_0$$

C_0 = revenue per unit up time at full capacity.
C_1 = revenue per unit up time at reduced capacity.
C_2 = cost per unit time when the repairman is busy.
C_3 = cost per repair.

2.9. Particular cases

The following specific cases are considered for Graphical representation, where repair times are distributed exponentially. Let us assume that $g_1(t)=\alpha_1 e^{-\alpha_1(t)}$, $g_2(t)=\alpha_2 e^{-\alpha_2(t)}$, $g_3(t)=\alpha_3 e^{-\alpha_3(t)}$ and remaining distributions same as in the general case. Therefore, we have:

$$p_{01} = p \qquad p_{02} = q$$
$$p_{30} = \frac{\alpha_1}{(\lambda_1+\lambda_2+\alpha_1)} \qquad p_{34} = \frac{\lambda_1}{(\lambda_1+\lambda_2+\alpha_1)}$$
$$p_{35} = q\frac{\lambda_2}{(\lambda_1+\lambda_2+\alpha_1)} \qquad p_{36} = p\frac{\lambda_2}{(\lambda_1+\lambda_2+\alpha_1)}$$
$$p_{43} = \frac{\alpha_1}{(\lambda_2+\alpha_1)} \qquad p_{47} = \frac{\lambda_2}{(\lambda_2+\alpha_1)}$$
$$p_{8,10}^{(9)} = \frac{\lambda_1}{(\lambda_2+\alpha_1)} \qquad \mu_0 = \frac{1}{(\lambda_1)}$$
$$\mu_2 = \mu_5 = \frac{1}{(\alpha_3)} \qquad \mu_3 = \frac{1}{(\lambda_1+\lambda_2+\alpha_1)}$$
$$\mu_4 = \frac{1}{(\lambda_2+\alpha_1)} \qquad \mu_6 = \frac{1}{(\beta_1)}$$
$$\mu_7 = k_8 = \frac{1}{(\alpha_2)} \qquad \mu_8 = \frac{1}{(\lambda_1+\alpha_2)}$$
$$\mu_{10} = \frac{1}{(\alpha_1)}$$

Table 1: Various rates calculated from the data gathered from Industry

Failure rate of STG (λ_1)	0.00043/hour
Failure rate of Gridline (λ_2)	0.00043/hour
Probability that generator will work (p)	0.87
Repair rate of STG (α_1)	0.0065/hour
Repair rate of Gridline (α_2)	0.34/hour
Revenue per unit uptime of the system (C_0)	1462990 INR.
Revenue per unit up time at reduced capacity of the system (C_1)	1028997 INR.

Table 2: Various reliability measures calculated for the system

Meantime to System Failure	148 hours
Availability of System at full capacity	0.998698/hour
Availability of System at Reduced Capacity	0.001144/hour
Busy Period of Repairman	0.065217/hour
Expected number of Repairs	0.000402/hour

3. Results and discussion

Fig. 2 reveals the behavior of MTSF w.r.t. failure rate of steam turbine generator (λ_1) for different values of the failure rate of gridline (λ_2). The MTSF curve lowers with a hike in the failure rate of the generator (λ_1). It has lowered values for the raising failure rates of the grid line. Fig. 3 interpreted that the profit decreases with increasing the failure rate of the STG and gives greater values for lesser values of the failure rate of the gridline. Fig. 4 interpreted that the profit increases as the probability of working of the breaker (connecting unit) increases and gives greater values for lesser values of the failure rate of the steam turbine generator (STG). Fig. 5 interpreted that the profit increases with increasing the cost per unit uptime of the system and decreases when the failure rate of the generator increases.

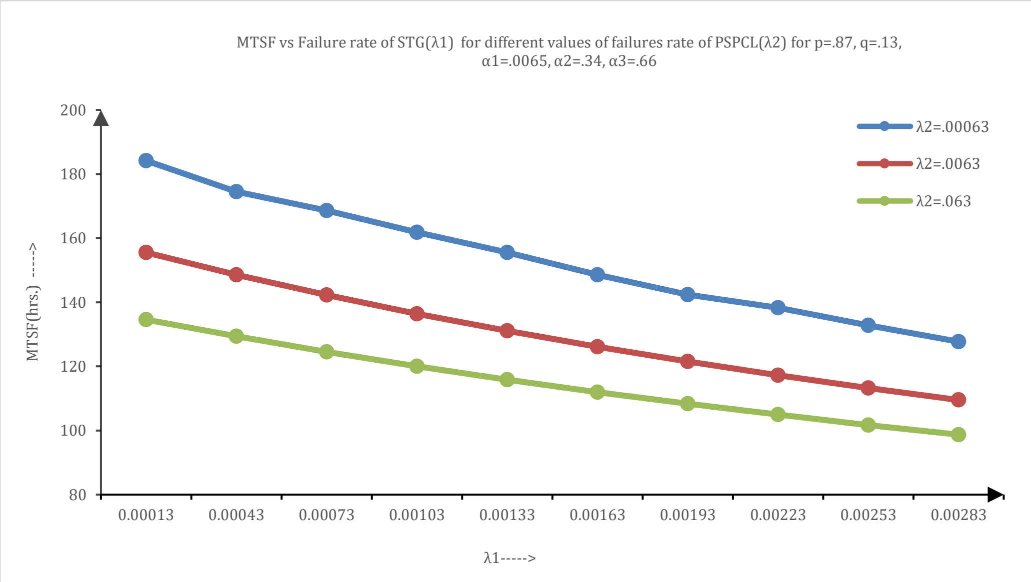

Fig. 2: MTSF

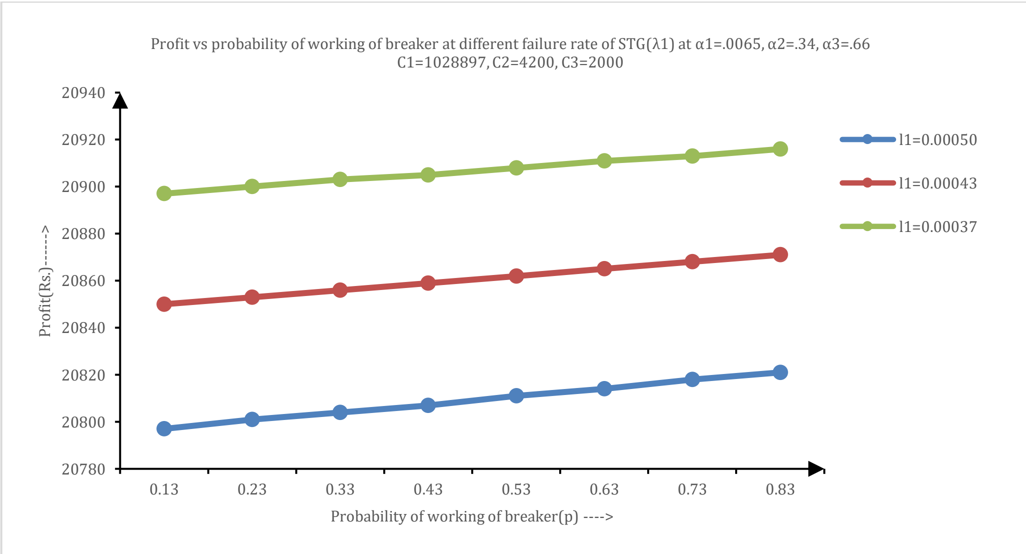

Fig. 3: Profit vs. failure rate of STG

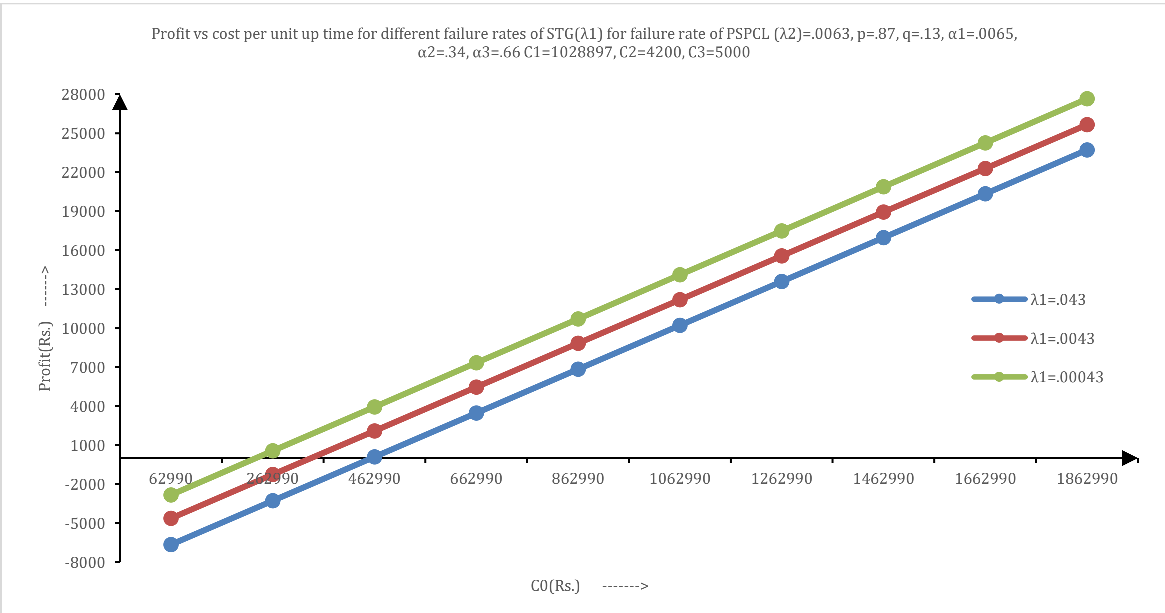

Fig. 4: Profit vs. prob. of working of breaker

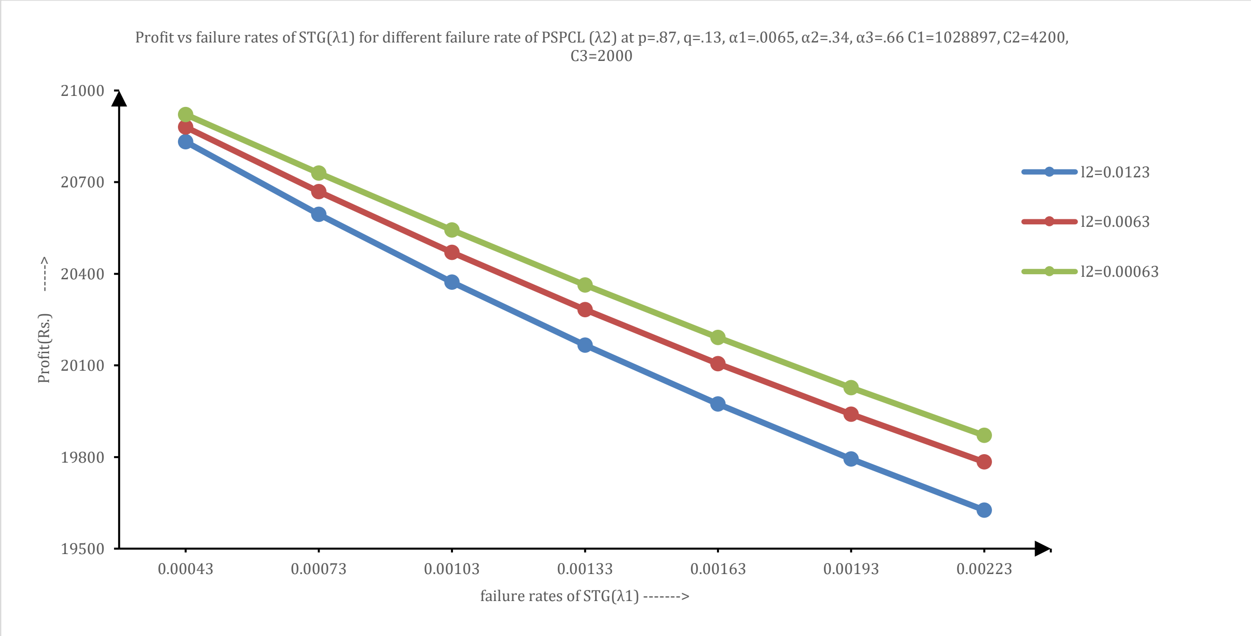

Fig. 5: Profit vs. cost per unit uptime of system

4. Conclusion

The above-discussed model reveals the reliability behavior of the system working on two steam turbine generators connected to a gridline with the help of a breaker. The availability, as well as profit procured by the system, varies inversely to the failure rate of the STG. Also, the system functions adequately when the breaker successfully connects the gridline to the system. The engineers and system designers can use the proposed model and calculations performed in Table 3 in the same way for their industries. The expressions developed can be used to find out the practical reliability of similar mechanism-type systems.

Table 3: Profit vs. revenue per unit up-time for variation in the failure rate of STG

Failure rate of STG (per hour)	Revenue per unit up time (Rs.)	Profit (Rs)
λ1 = .043	C0 < or = or >457895	Negative (Loss) or Zero or Positive respectively
λ1 = .0043	C0 < or = or >338807	Negative (Loss) or Zero or Positive respectively
λ1 = .00043	C0 < or = or >230680	Negative (Loss) or Zero or Positive respectively

Compliance with ethical standards

Conflict of interest

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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