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Investigation of a Condensate system incorporating degrading and re-working: A Reliability approach

[1]Lalita Kthurya, [2]Amit Kumar,

[1&2] Department of Mathematics, School of Chemical Engineering and Physical Sciences, Lovely Professional University, Phagwara 144411, Punjab, India.

Email: amit.20445@lpu.co.in

Abstract

The purpose of this paper is to investigate the condensate system of a thermal power plant by taking its different sub units. For this purpose the different failures and repair of the system is analyzed to obtain the various states of the system in which it can appear during production. These states are depicted in a transition state diagram of the condensate system. Markov birth-death process is used to convert this transition state diagram in terms of a set of intro-differential equation (known as Chapman-Kolmogrov equation) which further solved by using Laplace transform and SVT for obtaining the measure of system effectiveness e.g. reliability, availability, MTTF, and profit function. The critical components are identified by doing sensitivity analysis for reliability.It asserts that the derived results play crucial role in system design and enhancing its performance.

Keywords: System effectiveness; Condensate system; Markov birth-death process; profit function; Sensitivity analysis;

1. Introduction

Investigation of various complex industrial systems for evaluating its different performance measures are the foremost concern of the industry personals for improving the performance/production of the same and to suggest the necessary change in system's structure/ configuration for betterment. In past many industrial systems are analysed by using different technique e.g. fuzzy approach, generating algorithm, mathematical modelling, signature analysis, Markov process [1], Gumbel-Hougaard family copula [2], [3], [4] etc.A steam power generation system is investigated by [5] by using probabilistic approach for finding its different performance indices. A hydro power plant is studied by Hosseini*et al.* [6]to obtain the annual energy for the same. In this study the authors also perform sensitivity analysis for finding the utmostacute components for the structure. Most of the research work regarding the analysis of the industrial system is based on the assumption that a repaired unit will works as new one but many time this situation did not match with the configuration of the system. This issue were taken by [7]. He investigated a system, with the supposition that a restored unit will not work in the same manner as new, for finding fineststrategy for the replacement of the units of the system to reduce its running cost. The effect of common cause

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failure with varying distributions for system's failures is analysed by Ram and Singh [8]. Kumar and Lata [9] discussed a condensate system using Fuzzy Markov Models. In this research they only restrict them self up to reliability of the system and did not find the rest of reliability characteristics. Garg [10] developed an approach for evaluating reliability of the industrial system by using Fuzzy Kolmogorov's differential equations. A biometric system with different components failure and repair by coverage factor is investigated by [11]. Suggestions are given for the improvement of the biometric system.The reliability characteristics of a hydroelectric power plant, by using coverage factor, are investigated by [12]. Kumar and Ram [13] developed a mathematical model for functioning of marine power plant using the Markov process and evaluated its reliability characteristics. The different trend in the field of reliability theory for the different engineering structures is presented by [14].

2. System Description

A condensate system is being studied by taking its various critical components including condenser, gland steam condenser, drain cooler, heater, deaerator and extraction pumps. All these components are arranged in a mixed configuration. The failure of a unit of its sub units leads the condensate system in a failed or degraded state. The system is modelled by using Markov process and then solved by using SVT along with Laplace transformation. The following Fig.1 gives the various possible state of the condensate system (according to different failure and repairs) in which it takes place in a time interval Δt.

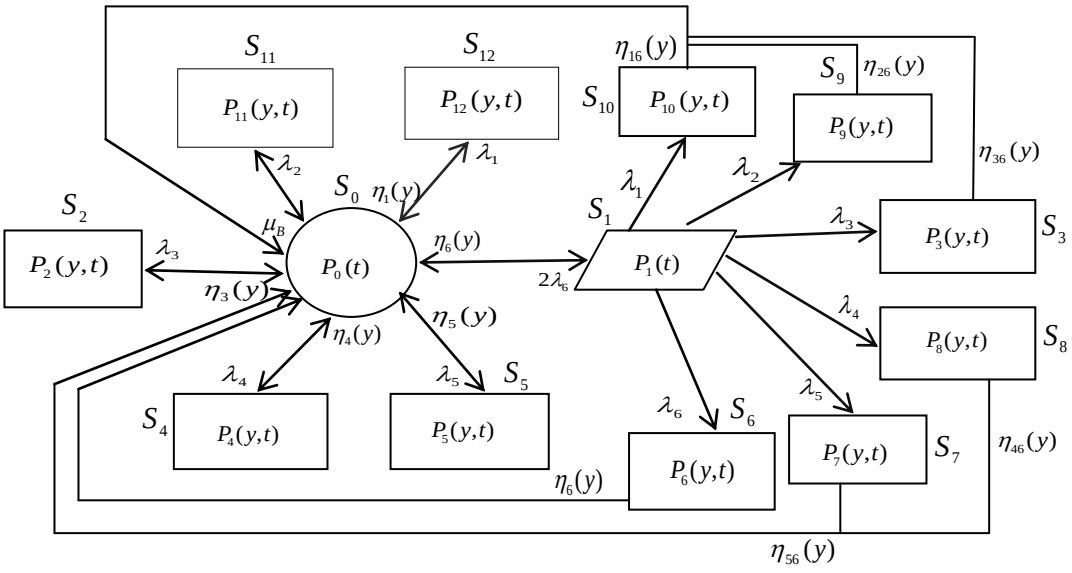


Fig. 1 Transition State Diagram

3. Assumptions

This section is consists of the assumption associated with the present paper.

- At an instant time t=0, the condensate system do not have any defect.
- After failure of a unit or component the condensate system transit to a degraded /failed state.

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- Maintenance team immediate attend the fled unit of the system.
- Simultaneous failure of any two or more than two unit is not possible.

4. Nomenclatures

The explanation of various notations and symbols that are used in present paper is given in Table 1.

t/s	*Time unit/ Laplace Transformation variable*
$P_i(t);\ i=0,1$	*State probability of the condensate system to be present in state* $S_i; i=0,1$ *respectively.*
$P_i(y,t);\ i=2,3,4,5,$ $6,7,8,9,10,11,12$	*State probability of the condensatesystem to be present in state* $S_i; i=2,3,4,5,6,7,8,9,10,11,12$ *respectively.*
$\overline{P}_i(s)$	*Laplace transform of* $P_i(t)$.
$\lambda_1/\lambda_2/\lambda_3/\lambda_4/\lambda_5/\lambda_6$	*Failure rate of condenser/ gland steam condenser/ drain cooler/heater/ deaerator/extraction pumps.*
$\eta_1(y)/\eta_2(y)/\eta_3(y)$ $/\eta_4(y)/\eta_5(y)/\eta_6(y)$	*Repair rate of condenser/ gland steam condenser/ drain cooler/heater/ deaerator/extraction pumps.*
$\eta_{16}(y)/\eta_{26}(y)/\eta_{36}(y)$ $/\eta_{45}(y)/\eta_{56}(y)$	*Simultaneous repair rate of condenser and extraction pump/ gland steam condenser and extraction pump/ drain cooler and extraction pump/ heaters and extraction pump/ deaerator and extraction pump.*
C_1/C_2	*The revenue and service cost of condensed system.*
$A(t)/R(t)$	*Availability/Reliability of the condensate system.*

5. Mathematical Formulation, Solution

The following set of intro-differential equation (known as Chapman-Kolmogrov equation) is generated by using the concept of Makov process and considering different failure/repairs.

$$\left(\frac{\partial}{\partial t}+\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+2\lambda_6\right)P_0(t)=\eta_6(y)P_1(t)+\int_0^\infty \eta_1(y)P_{12}(y,t)dy+\int_0^\infty \eta_2(y)P_{11}(y,t)dy++\int_0^\infty \eta_6(y)P_6(y,t)dy$$
$$+\int_0^\infty \eta_3(y)P_2(y,t)dy+\int_0^\infty \eta_4(y)P_4(y,t)dy+\int_0^\infty \eta_5(y)P_5(y,t)dy+\int_0^\infty \eta_{16}(y)P_{10}(y,t)dy+\int_0^\infty \eta_{26}(y)P_9(y,t)dy+\int_0^\infty \eta_{36}(y)P_3(y,t)dy$$
$$+\int_0^\infty \eta_{46}(y)P_8(y,t)dy+\int_0^\infty \eta_{56}(y)P_7(y,t)dy \qquad (1)$$

$$\left(\frac{\partial}{\partial t}+\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6+\eta_6(y)\right)P_1(t)=2\lambda_6 P_0(t) \qquad (2)$$

$$\left(\frac{\partial}{\partial y}+\frac{\partial}{\partial t}+\eta_i(y)\right)P_j(y,t)=0 \qquad (3)$$

where $i=1,2,3,4,5,6,16,26,36,46,56;$
$j=12,11,2,4,5,6,10,9,3,8,7;$ *indepdently*

Boundary conditions:

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$$P_k(0,t) = \lambda_l P_m(t) \qquad (4)$$

where $k = 12,11,2,4,5,6,10,9,3,8,7;$
$l = 1,2,3,4,5,6,1,2,3,4,5;$
$m = 0,0,0,0,0,1,1,1,1,1,1$ *independently*

Initial conditions:

$$P_i(t) = \begin{cases} 1; \ when i = t = 0 \\ 0; \ otherwise \end{cases} \qquad (5)$$

The set of equation (1)-(4), with the aid of Laplace transformation, can be rewritten as follows

$$(s + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + 2\lambda_6)\overline{P}_0(s) = 1 + \eta_6(y)\overline{P}_1(s) + \int_0^\infty \eta_1(y)\overline{P}_{12}(y,s)dy + \int_0^\infty \eta_2(y)\overline{P}_{11}(y,s)dy + + \int_0^\infty \eta_6(y)\overline{P}_6(y,s)dy$$
$$+ \int_0^\infty \eta_3(y)\overline{P}_2(y,s)dy + \int_0^\infty \eta_4(y)\,\overline{P}_4(y,s)dy + \int_0^\infty \eta_5(y)\overline{P}_5(y,s)dy + \int_0^\infty \eta_{16}(y)\overline{P}_{10}(y,s)dy + \int_0^\infty \eta_{26}(y)\overline{P}_9(y,s)dy +$$
$$\int_0^\infty \eta_{36}(y)\overline{P}_3(y,s)dy + \int_0^\infty \eta_{46}(y)\overline{P}_8(y,s)dy + \int_0^\infty \eta_{56}(y)\overline{P}_7(y,s)dy \qquad (6)$$

$$(s + \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5 + \lambda_6 + \eta_6(y))\overline{P}_1(s) = 2\lambda_6\,\overline{P}_0(s) \qquad (7)$$

$$\left(\frac{\partial}{\partial y} + s + \eta_i(y)\right)\overline{P}_j(y,s) = 0 \qquad (8)$$

where $i = 1,2,3,4,5,6,16,26,36,46,56;$
$j = 12,11,2,4,5,6,10,9,3,8,7;$ *indepdently*

Boundary conditions:

$$\overline{P}_k(0,s) = \lambda_l\,\overline{P}_m(s) \qquad (9)$$

where $k = 12,11,2,4,5,6,10,9,3,8,7;$
$l = 1,2,3,4,5,6,1,2,3,4,5;$
$m = 0,0,0,0,0,1,1,1,1,1,1$ *independently*

The various state probabilities of the condensate system is obtain by solving the above set of equation (6)-(10) as followings

$$\overline{P}_0(s) = 1 \Big/ \left(H_1 - H_2 - \frac{H_3.2\lambda_F}{H_4}\right); (10)$$

$$\overline{P}_1(s) = \frac{2\lambda_F}{H_4}\overline{P}_0(s) (11)$$

$$\overline{P}_2(y,s) = \frac{\lambda_3}{(s + \eta_3(y))}\overline{P}_0(s) (12)$$

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$$\overline{P}_3(y,s)=\frac{\lambda_3}{(s+\eta_{36}(y))}\overline{P}_0(s)\,(13)$$

$$\overline{P}_4(y,s)=\frac{\lambda_4}{(s+\eta_4(y))}\overline{P}_0(s)\,(14)$$

$$\overline{P}_5(y,s)=\frac{\lambda_5}{(s+\eta_5(y))}\overline{P}_0(s)\,(15)$$

$$\overline{P}_6(y,s)=\frac{\lambda_6}{(s+\eta_6(y))}\overline{P}_0(s)\,(16)$$

$$\overline{P}_7(y,s)=\frac{\lambda_5}{(s+\eta_{56}(y))}\overline{P}_0(s)\,(17)$$

$$\overline{P}_8(y,s)=\frac{\lambda_4}{(s+\eta_{46}(y))}\overline{P}_0(s)\,(18)$$

$$\overline{P}_9(y,s)=\frac{\lambda_2}{(s+\eta_{26}(y))}\overline{P}_0(s)\,(19)$$

$$\overline{P}_{10}(y,s)=\frac{\lambda_1}{(s+\eta_{16}(y))}\overline{P}_0(s)\,(20)$$

$$\overline{P}_{11}(y,s)=\frac{\lambda_2}{(s+\eta_2(y))}\overline{P}_0(s)\,(21)$$

$$\overline{P}_{12}(y,s)=\frac{\lambda_1}{(s+\eta_1(y))}\overline{P}_0(s)\,(22)$$

where $H_1=(s+\lambda_1++\lambda_2+\lambda_3+\lambda_4+\lambda_5+2\lambda_6)$

$$H_2=\left\{\frac{\lambda_1\eta_1(y)}{(s+\eta_1(y))}+\frac{\lambda_2\eta_2(y)}{(s+\eta_2(y))}+\frac{\lambda_3\eta_3(y)}{(s+\eta_3(y))}+\frac{\lambda_4\eta_4(y)}{(s+\eta_4(y))}+\frac{\lambda_5\eta_5(y)}{(s+\eta_5(y))}\right\};$$

$$H_3=\left\{\eta_6(y)+\frac{\lambda_1\eta_{16}(y)}{(s+\eta_{16}(y))}+\frac{\lambda_2\eta_{26}(y)}{(s+\eta_{26}(y))}+\frac{\lambda_3\eta_{36}(y)}{(s+\eta_{36}(y))}+\frac{\lambda_4\eta_{46}(y)}{(s+\eta_{46}(y))}+\frac{\lambda_5\eta_{56}(y)}{(s+\eta_{56}(y))}\right\};$$

$$H_4=(s+\lambda_1++\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6+\eta_6(y));$$

The system probability that it is available for functioning and not available for functioning is given by (23) and (24) respectively (From state transition diagram Fig. 1)

$$\overline{A}(s)=\overline{P}_0(s)+\overline{P}_1(s)\,(23)$$

$$\overline{P}_{down}(s)=\sum_{i=2}^{12}\overline{P}_i(y,s)\,(24)$$

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Now by using equation (10)-(22) in (36) and (37) then using inverse Laplace transformation of the obtained equation one can get the availability and failed state probability of the considered system.

6. Computation of Reliability indices

6.1 Availability

It is a measure of a system performance which tells about the probability regarding the availability of the system for its intent task. Here in the present paper equation (23) gives the numerical value of time dependent availability of the condensate system by taking $\lambda_1 = 0.006$, $\lambda_2 = 0.008$, $\lambda_3 = 0.003$, $\lambda_4 = 0.006$, $\lambda_5 = 0.003$, $\lambda_6 = 0.024$, and repair rates as one unit. Now taking inverse Laplace transformation of obtained equation author's get the availability of the condensate system as given in equation (25).

$$A(t) = -0.068901303e^{(-1.074000000t)} + 0.973663208 + 0.095238095e^{(-1.050000000t)} \quad (25)$$

The behaviour of the availability of the condensate system with time unit is given in Table 3 and Fig. 2.

Time t	**Availability** $A(t)$	**Time t**	**Availability** $A(t)$
0	1.000000000	7	0.9736869792
1	0.9834512251	8	0.9736718372
2	0.9772837471	9	0.9736663340
3	0.9749969080	10	0.9736643383
4	0.9741527200	11	0.9736636161
5	0.9738422963	12	0.9736633552
6	0.9737285391	13	0.9736632612

Table 3 Behaviour of the Condensate system Availability vs. Time *t*

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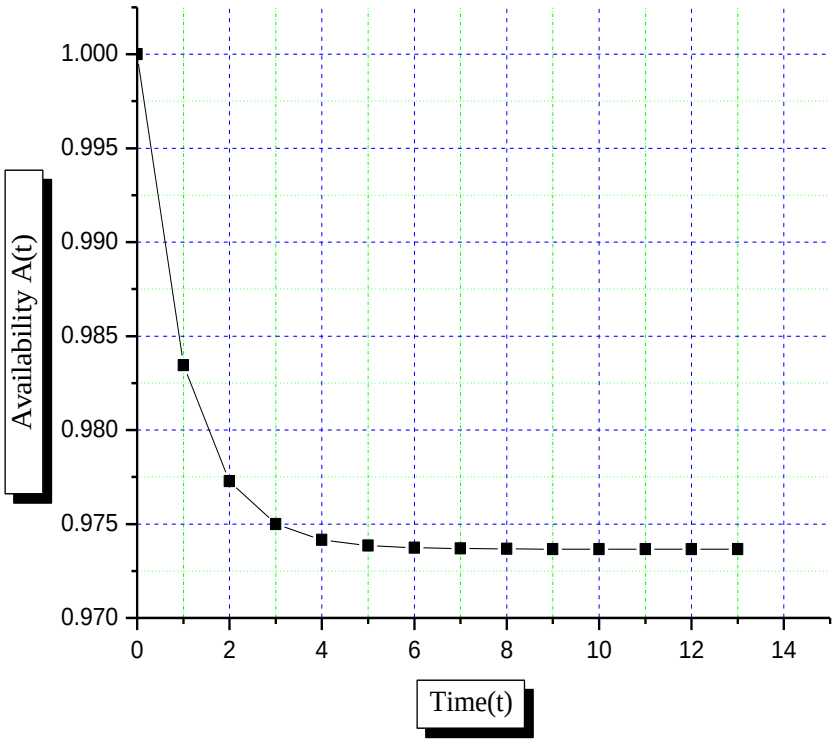


Fig.2 Behaviour of the Condensate system Availability vs. Time *t*

6.2 Reliability

The reliability of the associated model is obtained by using equation (23). The reliability expression is obtained (repair are taken as zero) as following

$$R(t) = e^{(-0.0740000000t)} + 4.e^{(-0.6200000000t)} \sinh(0.0120000000t) \quad (26)$$

The behaviour of the reliability of the condensate system with time unit is given in Table 4 and Fig. 3.

Time t	Reliability R(t)	Time t	Reliability R(t)
0	1.000000000	7	0.8136654005
1	0.9737871551	8	0.7874203540
2	0.9472437211	9	0.7614967920
3	0.9205005885	10	0.7359474038
4	0.8936740781	11	0.7108174327
5	0.8668672355	12	0.6861453860
6	0.8401710205	13	0.6619636881

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Table 4 Behaviour of the Condensate system Reliability vs. Time

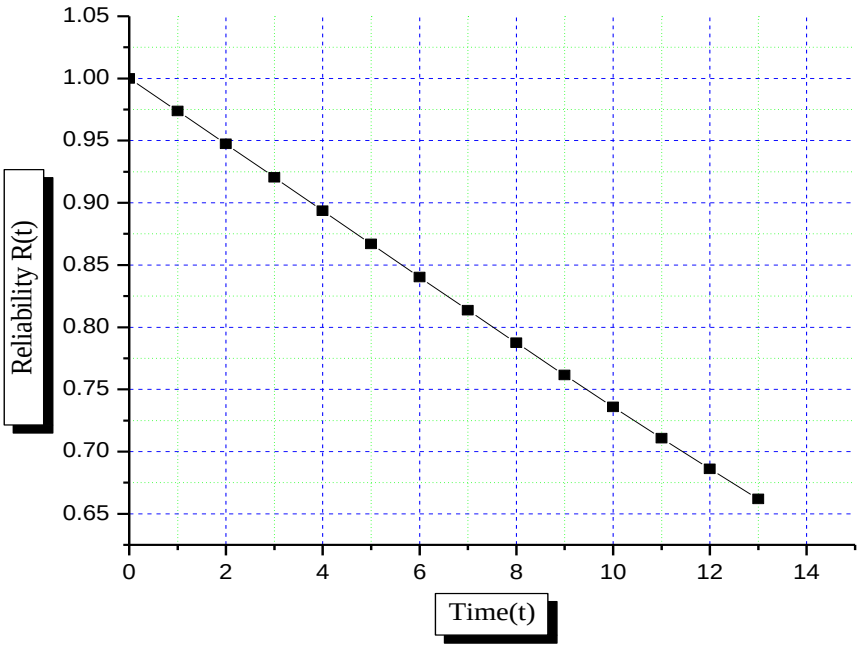


Fig.3 Behaviour of the Condensate system Availability vs. Time

6.3 MTTF

It is a system parameter which reflects about the mean failure of a system with regard of individual mean failures of its components. Mathematically it is calculated as given in equation (27).

$$MTTF = \int_0^t R(t)dt = \lim_{s\to 0} \bar{R}(s) \tag{27}$$

Now using equation (23) in (27), the MTTF of the Condensate is given by equation (28).

$$MTTF = \frac{1}{\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+\lambda_6} + \left\{1+\frac{2\lambda_6}{(\lambda_1+\lambda_2+\lambda_3+\lambda_4+\lambda_5+2\lambda_6)}\right\} \tag{28}$$

Finally the behaviour of Condensate system's MTTF is obtained as given in Table 5 and Fig. 4.

Failure rates	Condensate system's MTTF					
	λ_1	λ_2	λ_3	λ_4	λ_5	$\lambda_1,\lambda_2,\lambda_3,\lambda_4$ & λ_5
0.01	29.9145299	31.3765182	27.940220	29.914529	27.940220	39.8550724
0.02	24.1477272	25.1312828	22.798097	24.147727	22.798097	34.9143610
0.03	20.1323772	20.8333333	19.159058	20.132377	19.159058	30.3156146
0.04	17.1957671	17.7174413	16.464740	17.195767	16.464740	30.2156146
0.05	14.9657410	15.3673163	14.398909	14.965741	14.398909	26.5866209
0.06	13.2211538	13.5387488	12.770207	13.221153	12.770207	23.6006683

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Table 5 Behaviour of Condensate system's MTTF with variation in failures

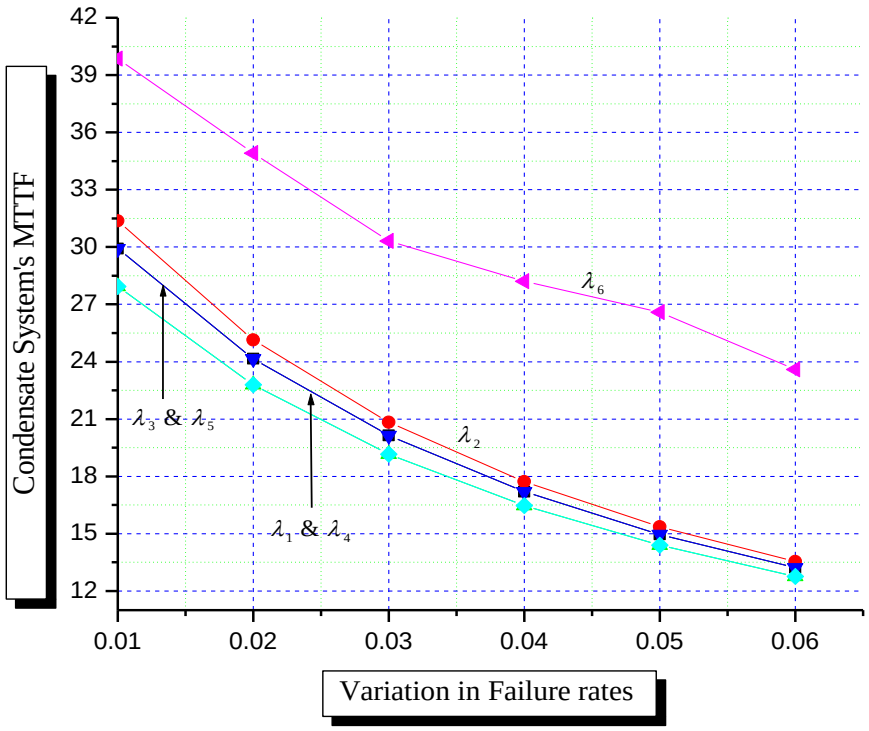


Fig.4 Behaviour of Condensate system's MTTF with respect to failure rates

6.4 Sensitivity Analysis

It is one of the important system performance measures tools which identify the impact of different components failure on overall system's performance. Basically it tells that which failure disturbs the performance of a system most and which affect least. Here in the present paper author have done sensitivity analysis for Condensate system's reliability.

6.4.1 Sensitivity analysis for system reliability

It is performed by using the concept of partial derivate in the system's reliability expression. The following Table 6 displays the variation in the reliability of the condensate system resulting from changes in its failure rates and time unit *t*. Fig. 5 given the behaviour of sensitivity analysis of the system for its reliability.

Time ***t***	$\frac{\partial R(t)}{\partial \lambda_1}$	$\frac{\partial R(t)}{\partial \lambda_2}$	$\frac{\partial R(t)}{\partial \lambda_3}$	$\frac{\partial R(t)}{\partial \lambda_4}$	$\frac{\partial R(t)}{\partial \lambda_5}$	$\frac{\partial R(t)}{\partial \lambda_6}$
0	0	0	0	0	0	0
1	-0.9737871	-0.97378716	-0.97378716	-0.97378716	-0.97378716	-0.0451155
2	-1.8944874	-1.89448744	-1.89448744	-1.89448744	-1.89448744	-0.1696252

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3	-2.7615017	-2.76150177	-2.76150177	-2.76150177	-2.76150177	-0.3587557
4	-3.5746963	-3.57469631	-3.57469631	-3.57469631	-3.57469631	-0.5995466
5	-4.3343361	-4.33433618	-4.33433618	-4.33433618	-4.33433618	-0.8806645

Table 6 Sensitivity for Condensate system's Reliability with Time *t*

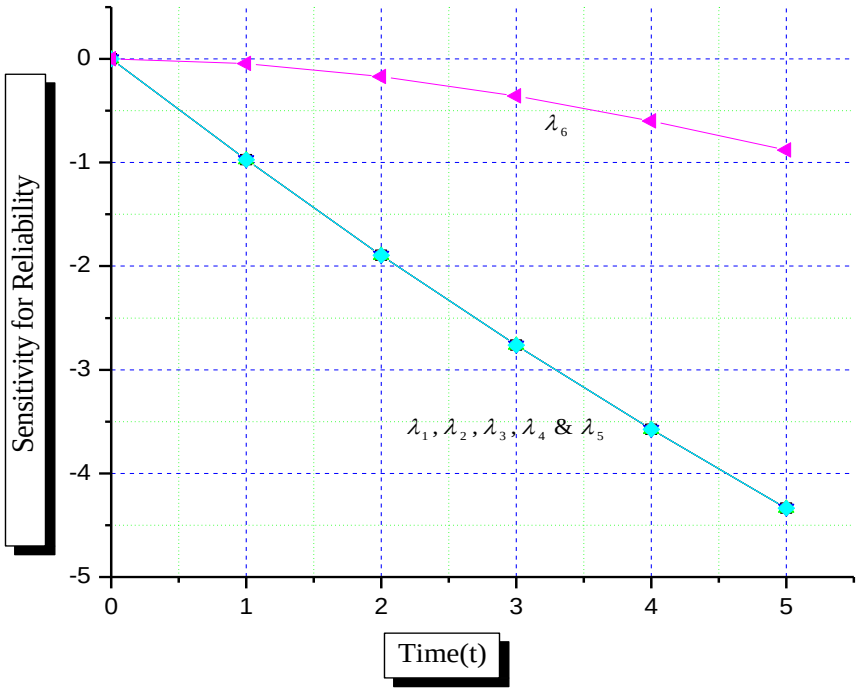


Fig. 5 Sensitivity for Condensate system's Reliability with Time *t*

7. Results, Discussion and Conclusion

A condensate system along with its different components namely condenser, drain cooler, grand steam condenser, heater, deaerator and extraction pump is investigated through Markov process and mathematical modelling for analysing its various reliability indices. The obtained results are depicted with the help of graphs. The availability of the condensate system is obtained as (from Fig. 2) 0.9736643383 and 0.9736632612 at ten and thirteen units of time respectively. Fig 3 reflects the behaviour of condensate system's reliability with time unit. It is observed the reliability of the system at ten units of time is 0.7359474038. The Condensate system's MTTF is reflected in Fig. 4. It is observed that the condensate system's MTTF is highest/least with respect to failure rate of extraction pump/drain cooler and deaerator. The sensitivity of condensate system's reliability with time is given in Fig. 5. It is observed from it the reliability of condensate system is approximately equally sensitive with all failures

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except failure of extraction pump. It asserts that the present research is beneficial for the management of the condensate system

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