AVAILABILITY OF A SYSTEM SUBJECTED TO COMMON CAUSE AND HUMAN ERROR FAILURES: COMPARISON OF REPAIR TIME DISTRIBUTION

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ABSTRACT: *Availability analysis can be used in research and development to evaluate the performance of new systems technologies and components. In the context of three unit series parallel system availability analysis can help to evaluate the reliability and availability of the system, identify the most critical components and sub systems, optimize the system configuration and maintenance strategies and assess the risk of system failures and develop strategies. This paper presents the availability analysis of a three unit series parallel system subjected to common cause and human error failures. A general method for the system steady state availability or limiting availability of the system is developed when failed system repair times are gamma distributed.*

KEYWORDS: **Reliability, Availability, Three unit series parallel systems, Common cause failures, Human error failures.**

1.INTRODUCTION:

The reliability evaluation of two component stand by systems, series and parallel systems, have been studied by many authors under different assumptions . In reality the systems under the consideration may not be modeled as series or parallel systems. For example, if we consider a human system, the heart and the kidneys should function properly for the human being to survive (assuming the remaining parts of the body are all operative). However this cannot be modeled as a simple series or parallel system comprising two sub systems with one or two components in each sub-system While the heart does appear as a single component in the first sub-system , the second sub - system representing the kidneys will have to be represented by two components , each one corresponding to one of the two kidneys . This is necessitated by the fact that the proper functioning of any one of the two kidneys ensures the survival of the human being. The system may therefore by modeled as a series – parallel system as shown in fig. 1.

Fig1: series – parallel system

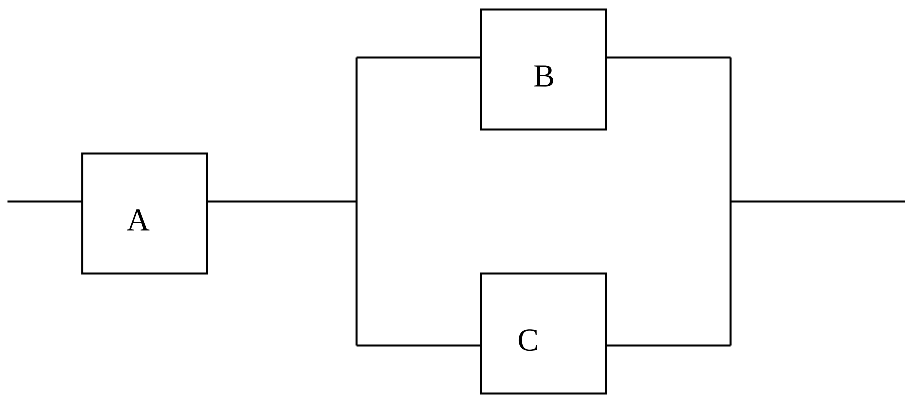


Fig 1

Here the components A, B and C are statistically independent, i.e., the failure of one component does not affect the failure or otherwise of the other two components. The other examples of series – parallel systems are

1. A CPU connected to two parallel I/O ports.
2. A Multiplexer connected to a pair of terminals.
3. A Stabilizer powered by two alternative sources.

In this paper we consider a three unit series parallel system and we study the availability analysis of the system is subjected to common cause and human error failures.

2. ASSUMPTIONS AND NOTATIONS:

we consider three models of a three unit series-parallel system consisting of the units A , B and C which is in functioning state only , when A is functioning and either B or C are in functioning state , and we assume that the system is subjected to common cause and human error failures.

ASSUMPTIONS

At any time epoch 't' the system can be in one of the following eight states.

0 $\rightarrow$ The state of the system with all the three components functioning state.

1 $\rightarrow$ The state of the system with the component A and one of the components B or C is in functioning state.

2 $\rightarrow$ The failed state of the system corresponding to the failure of A from the State '0'

3 $\rightarrow$ The failed state of the system due to the failure of the component A from state 1.

4 $\rightarrow$ The failure state of the system corresponding to the failure of both the components B and C while A is functioning.

5 → The failed state of the system due to human error from state '0'.

6 → The failed state of the system due to common cause.

7 → The failed state of the system due to common cause of failure of A and B

NOTATIONS :

t = Time

S = Laplace transform variable

λ = Constant failure rate of the units A and B.

λ_{C_1} = Constant common cause failure rate of the system from the state '0'

λ_h = Constant human error failure rate of the system

λ_{C_2} = Constant common cause failure rate of the system from state 1.

λ_A = Constant failure rate of the unit A

λ_{AB} = Common failure rate of A and B

μ = Constant repair rate of a unit

μ_1 = Constant repair rate of the system from the state 4.

μ_2 = Constant repair rate of the system from the failed state 3.

μ_{AB} = Common repair rate of A and B.

$P_K(x,t)$ = Probability density (with respect to repair time) that the failed system is in state K and has an elapsed repair time of x for K = 5,6.

$\mu_k(x)$, $q_k(t)$ = Repair rate and probability density function of repair time irrespectively when the failed system is in state k and has an elapsed repair time of x for k = 5,6.

β = The shape parameter of the Gamma probability density function.

3.ANALYSIS

With the above notations the transition diagram of the system is given by

Fig 2: Transition diagram

μ_2

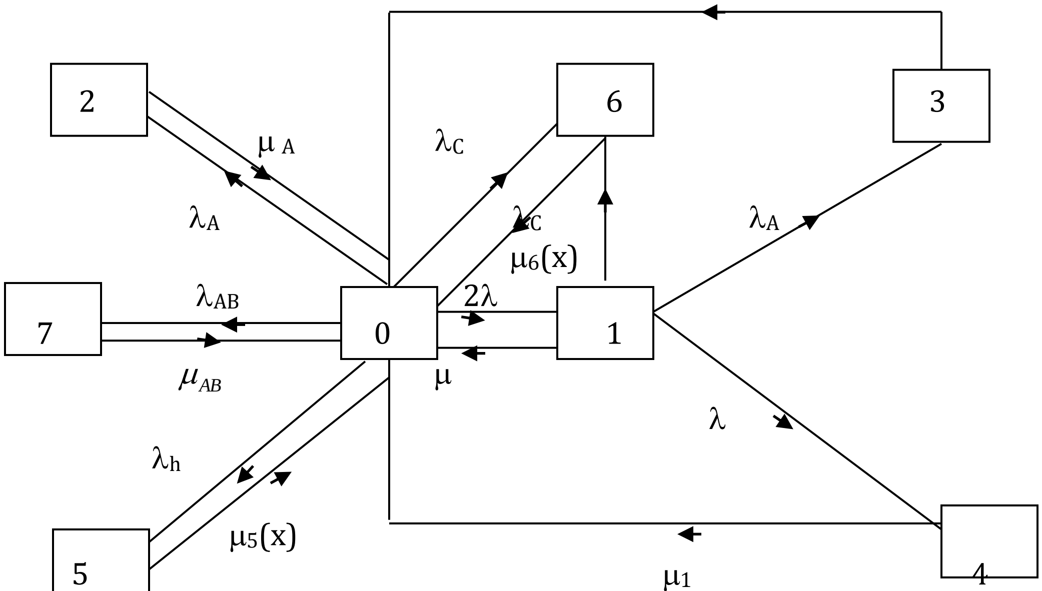


Fig 2: Transition diagram

The system of integro differential equations associated with this model are given by

$$\frac{dP_0(t)}{dt} + (2\lambda + \lambda_{c_1} + \lambda_A + \lambda_h + \lambda_{AB})\ P_0(t) = \mu\, P_1(t) + \mu_A\, P_2(t) + \mu_2\, P_3(t) + \mu_1\, P_4(t) +$$

$$\mu_{AB} P_7(t) + \int_0^\infty P_5(x,t)\,\mu_5(x)\,dx + \int_0^\infty P_6(x,t)\,\mu_6(x)\,dx \qquad 1$$

$$\frac{dP_1(t)}{dt} + (\mu + \lambda_A + \lambda + \lambda_{c_2})\ P_1(t) = 2\lambda\, P_0(t) \qquad 2$$

$$\frac{dP_2(t)}{dt} + \mu_A\ P_2(t) = \lambda_A\, P_0(t) \qquad 3$$

$$\frac{dP_3(t)}{dt} + \mu_2\ P_3(t) = \lambda_A\, P_1(t) \qquad 4$$

$$\frac{dP_4(t)}{dt} + \mu_1\ P_4(t) = \lambda\, P_1(t) \qquad 5$$

$$\frac{dP_7(t)}{dt} + \mu_{AB} P_7(t) = \lambda_{AB} P_0(t) \quad 6$$

$$\left[\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \mu_5(x)\right] P_5(x,t) = 0 \quad 7$$

$$\left[\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \mu_6(x)\right] P_6(x,t) = 0 \quad 8$$

$$P_5(0,t) = \lambda_h P_0(t) \quad 9$$

$$P_6(0,t) = \lambda_{c_1} P_0(t) + \lambda_{c_2} P_1(t) \quad 10$$

The initial conditions are given by

$P_0(0) = 1$ and $p_j(0) = 0$ for $j = 1,2,3,4,7$

$P_k(x,0) = 0$ for $K = 5,6$.

Using Laplace Transformations the above equations reduces to

$$SP_0(S) - 1 + (2\lambda + \lambda_{c_1} + \lambda_A + \lambda_h + \lambda_{AB}) P_0(S) = \mu P_1(S) + \mu_A P_2(S) + \mu_2 P_3(S) + \mu_1 P_4(S) + \mu_{AB} P_7(S) + \int_0^\infty P_5(x,S)\mu_5(x)dx + \int_0^\infty P_6(x,S)\mu_6(x)dx \quad 11$$

$$SP_1(S) + (\mu + \lambda_A + \lambda + \lambda_{c_2}) P_1(S) = 2\lambda P_0(S) \quad 12$$

$$SP_2(S) + \mu_A P_2(S) = \lambda_A P_0(S) \quad 13$$

$$SP_3(S) + \mu_2 P_3(S) = \lambda_A P_1(S) \quad 14$$

$$SP_4(S) + \mu_1 P_4(S) = \lambda P_1(S) \quad 15$$

$$SP_7(S) + \mu_{AB} P_7(S) = \lambda_{AB} P_0(S) \quad 16$$

$$\left[\frac{\partial}{\partial x} + S + \mu_5(x)\right] P_5(x,S) = 0 \quad 17$$

$$\left[\frac{\partial}{\partial x} + S + \mu_6(x)\right] P_6(x,S) = 0 \quad 18$$

$$P_5(0,S) = \lambda_h P_0(S) \quad 19$$

$$P_6(0,S) = \lambda_{c_1} P_0(S) + \lambda_{c_2} P_1(S) \quad 20$$

From equations 12 to 16

$$P_1(S) = \frac{2\lambda\ P_0(S)}{S+\lambda+\lambda_{c_2}+\mu+\lambda_A}$$

$$P_2(S) = \frac{\lambda_A P_0(S)}{S+\mu_A}$$

$$P_3(S) = \frac{\lambda_A P_1(S)}{S+\mu_2} = \frac{2\lambda\lambda_A P_0(S)}{(S+\mu_2)(S+\lambda+\lambda_{c_2}+\mu+\lambda_A)}$$

$$P_4(S) = \frac{\lambda P_1(S)}{S+\mu_1} = \frac{2\lambda^2}{(S+\mu_1)(S+\lambda+\lambda_{c_2}+\mu+\lambda_A)} P_0(S)$$

$$P_7(S) = \frac{\lambda_{AB}}{S+\mu_{AB}} P_0(S)$$

From equations.11

$$SP_0(S) - 1 + (2\lambda + \lambda_{c_1} + \lambda_A + \lambda_h + \lambda_{AB})\ P_0(S) = \frac{2\lambda\ \mu}{S+\lambda+\lambda_{C_2}+\mu+\lambda_A} P_0(S) +$$

$$\frac{\mu_A \lambda_A P_0(S)}{S+\mu_A} + \frac{2\lambda^2 \mu_1}{(S+\mu_1)(S+\lambda+\lambda_{c_2}+\mu+\lambda_A)} P_0(S)$$

$$+ \frac{2\lambda\lambda_A \mu_2}{(S+\mu_2)(S+\lambda+\lambda_{c_2}+\mu+\lambda_A)} P_0(S) + \frac{\mu_{AB}\lambda_{AB}}{S+\mu_{AB}} P_0(S)$$

$$+ \int_0^\infty P_5(x,S)\, \mu_5(x)\, dx + \int_0^\infty P_6(x,S)\, \mu_6(x)\, dx$$

From equation 17

$$\frac{\partial}{\partial x} P_5(x,S) = -(S+\mu_5(x)) P_5(x,S)$$

$$\Rightarrow \frac{\frac{\partial}{\partial x} P_5(x,S)}{P_5(x,S)} = -(S+\mu_5(x))$$

Integrating we obtain

$$\left[\log P_5(x,s)\right]_0^x = -Sx - \int_0^x \mu_5(x)dx$$

$$\frac{\left[\log P_5(x,s)\right]}{\left[\log P_5(0,s)\right]} = -Sx - \int_0^x \mu_5(x)dx$$

$$\frac{P_5(x,s)}{P_5(0,s)} = e^{-sx-\int_0^x \mu_5(x)dx}$$

$$\Rightarrow P_5(x,s) = P_5(0,s)e^{-sx-\int_0^x \mu_5(x)dx}$$

$$= \lambda_h e^{-sx-\int_0^x \mu_5(x)dx} P_0(S) \quad 21$$

Again from equations 18 we obtain

$$P_6(x,S) = P_6(0,S)e^{-sx-\int_0^x \mu_6(x)dx} = \left[\lambda_{c_1} + \frac{2\lambda\lambda_{c_2}}{S+\lambda_A+\lambda+\lambda_{c_2}+\mu}\right]P_0(S)e^{-sx-\int_0^x \mu_6(x)dx}$$

22

From equation 11. we have

$$SP_0(S) -1 + (2\lambda + \lambda_{c_1} + \lambda_A + \lambda_h + \lambda_{AB})\ P_0(S) = \frac{2\lambda\ \mu}{S+\lambda+\lambda_{C_2}+\mu+\lambda_A}P_0(S) +$$

$$\frac{\mu_A\lambda_A P_0(S)}{S+\mu_A} + \frac{2\lambda^2\mu_1}{(S+\mu_1)(S+\lambda+\lambda_{c_2}+\mu+\lambda_A)}P_0(S) +$$

$$\frac{2\lambda\lambda_A\mu_2}{(S+\mu_2)(S+\lambda+\lambda_{c_2}+\mu+\lambda_A)}P_0(S) + \frac{\mu_{AB}\lambda_{AB}}{S+\mu_{AB}}P_0(S) +$$

$$\int_0^\infty \lambda_h e^{-sx-\int_0^x \mu_5(x)dx} P_0(S)\ \mu_5(x)\, dx\ +$$

$$\int_0^\infty \left[\lambda_{c_1} + \frac{2\lambda\lambda_{c_2}}{S+\lambda_A+\lambda+\lambda_{c_2}+\mu}\right] P_0(S)\,\mu_6(x) e^{-sx-\int_0^x \mu_6(x)dx}\, dx$$

$$\Rightarrow SP_0(S) - 1 + A_6 P_0(S) = \frac{A_7}{S+A_1}P_0(S) + \frac{A_8}{S+A_2}P_0(S) + \frac{A_9}{(S+A_1)(S+A_3)}P_0(S)$$

$$+\frac{A_{10}}{(S+A_1)(S+A_4)}P_0(S) + \frac{A_{11}}{S+A_5}P_0(S) + \lambda_h P_0(S) q_5(S) + \left[\lambda_{c_1} + \frac{2\lambda\lambda_{c_2}}{S+A_1}\right] P_0(S)\, q_6(S)$$

on simplification we obtain

$$P_0(S) = \frac{(S+A_1)(S+A_2)(S+A_3)(S+A_4)(S+A_5)}{Q(S)} \qquad 23$$

Where $Q(S) = S^6 + S^5 A_{16} + S^4 A_{17} + S^3 A_{18} + S^2 A_{19} + S\, A_{20} + A_{21}$

$- \lambda_h\, q_5(S)\ (S^5 + S^4 A_{22} + S^3 A_{23} + S^2 A_{24} + S\, A_{25} + A_{26})$

$-q_6(S)\ (S^5 A_{27} + S^4 A_{28} + S^3 A_{29} + S^2 A_{30} + S\, A_{31} + A_{32})$ and A_1 to A_{32} are constants

$$q_k(S) = \int_0^\infty e^{-sx} q_k(x)dx$$

$$q_k(x) = \mu_5(x) e^{-\int_0^x \mu_5(x)dx} \qquad \text{for } K = 5,\ 6$$

From the equation 21

$$P_i(S) = \int_0^\infty P_i(x,S)dx\, 2 \quad \text{we obtain}$$

$$P_5(S) = \int_0^\infty P_5(x,S)dx$$

$$= \lambda_h P_0(S) \int_0^\infty e^{-sx} e^{-\int_0^x \mu_5(x)dx} dx$$

$$= \lambda_h P_0(S) \left[\left(\frac{e^{-sx} e^{-\int_0^x \mu_5(x)dx}}{-S} \right)_0^\infty - \int_0^\infty e^{-\int_0^x \mu_5(x)dx} (-\mu_5(X))_0^X \frac{e^{-sx}}{-S} dx \right]$$

$$= \lambda_h P_0(S) \left[\frac{1}{S} - \frac{1}{S} \int_0^\infty e^{-sx} \mu_5(X) e^{-\int_0^x \mu_5(x)dx} dx \right]$$

$$= \frac{\lambda_h P_0(S)}{S}(1 - q_5(S))$$

Similarly from the equation 22 we get

$$P_6(S) = \int_0^\infty P_6(x,S)dx = \left[\lambda_{C_1} + \frac{2\lambda\lambda_{C_2}}{S + A_1} \right] \frac{1 - q_6(S)}{S} P_0(S)$$

As a special case we assume that the repair time distribution of the failed system will follow Gamma distribution with shape parameter β. In this case one has

$$q_5(x) = \frac{\mu_5 (\mu_5 x)^{\beta - 1} e^{-\mu_5 x}}{\gamma(\beta)}; t \geq 0, \beta > 0 \qquad 24$$

and

$$q_6(x) = \frac{\mu_6 (\mu_6 x)^{\beta - 1} e^{-\mu_6 x}}{\gamma(\beta)}; t \geq 0, \beta > 0 \qquad 25$$

(I). We assume that the shape parameter $\beta = 1$. In this case the repair rate of the failed system is constant and its repair times are exponentially distributed. Hence we have

$$q_5(x) = \mu_5 e^{-\mu_5 x} \qquad 26$$

$$q_6(x) = \mu_6 e^{-\mu_6 x} \qquad 27$$

Taking Laplace transforms we obtain

$$q_5(S) = \frac{\mu_5}{S+\mu_5} \quad \text{and} \quad q_6(S) = \frac{\mu_6}{S+\mu_6}$$

substituting these results into equation 2.3.23 we obtain

$$p_0(S) = \frac{N_0(S)}{SD_0(S)} \qquad 28$$

Where $N_0(S) = S^7 + B_1 S^6 + B_2 S^5 + B_3 S^4 + B_4 S^3 + B_5 S^2 + B_6 S + B_7$

$D_0(S) = S^7 + B_8 S^6 + B_9 S^5 + B_{10} S^4 + B_{11} S^3 + B_{12} S^2 + B_{13} S + B_{14}$

Similarly,

$$P_1(S) = \frac{(S+\mu_5)(S+\mu_6)}{SD_0(S)} N_1(S) \qquad 29$$

$$P_2(S) = \frac{(S+\mu_5)(S+\mu_6)}{SD_0(S)} N_2(S) \qquad 30$$

$$P_3(S) = \frac{(S+\mu_5)(S+\mu_6)}{SD_0(S)} N_3(S) \qquad 31$$

$$P_4(S) = \frac{(S+\mu_5)(S+\mu_6)}{SD_0(S)} N_4(S) \qquad 32$$

$$P_5(S) = \frac{(S+\mu_6)}{SD_0(S)} N_5(S) \qquad 33$$

$$P_6(S) = \frac{(S+\mu_5)}{SD_0(S)} N_6(S) \qquad 34$$

$$P_7(S) = \frac{(S+\mu_5)(S+\mu_6)}{SD_0(S)} N_7(S) \qquad 35$$

where

$N_1(S) = 2\lambda\,(S+A_2)\,(S+A_3)\,(S+A_4)\,(S+A_5)$

$N_2(S) = \lambda_A\,(S+A_1)\,(S+A_3)\,(S+A_4)\,(S+A_5)$

$N_3(S) = 2\lambda\lambda_A\,(S+A_2)\,(S+A_3)\,(S+A_5)$

$N_4(S) = 2\lambda^2\,(S+A_2)\,(S+A_4)\,(S+A_5)$

$N_5(S) = \lambda_h\,(S+A_1)\,(S+A_2)\,(S+A_3)\,(S+A_4)\,(S+A_5)$

$N_6(S) = [(S+A_1)\,\lambda_{c_1} + 2\lambda\,\lambda_{c_2}]\,(S+A_2)\,(S+A_3)\,(S+A_4)\,(S+A_5)$

$N_7(S) = \lambda_{AB}\,(S+A_1)\,(S+A_2)\,(S+A_3)\,(S+A_4)$

If S_i, $1 \le i \le 7$ are the real roots of the equation $D_0(s) = 0$ then from the equation 28 and 29 we obtain

$$P_0(t) = G_1 + G_2 e^{S_1 t} + G_3 e^{S_2 t} + G_4 e^{S_3 t} + G_5 e^{S_4 t} + G_6 e^{S_5 t} + G_7 e^{S_6 t} + G_8 e^{S_7 t}$$

And

$$P_1(t) = G_9 + G_{10} e^{S_1 t} + G_{11} e^{S_2 t} + G_{12} e^{S_3 t} + G_{13} e^{S_4 t} + G_{14} e^{S_5 t} + G_{15} e^{S_6 t} + G_{16} e^{S_7 t}$$

Here the time dependent availability $A_v(t)$ of the system is given by

$A_v(t) = P_0(t) + P_1(t)$

$$= (G_1 + G_9) + (G_2 + G_{10}) e^{S_1 t} + (G_3 + G_{11}) e^{S_2 t} + (G_4 + G_{12}) e^{S_3 t}$$

$$+ (G_5 + G_{13}) e^{S_4 t} + (G_6 + G_{14}) e^{S_5 t} + (G_7 + G_{15}) e^{S_6 t} + (G_8 + G_{16}) e^{S_7 t}$$

Limiting availability (steady state) A_v of the system is given by

$$A_v = \underset{t \to \infty}{lt} A_v(t) = (G_1 + G_9)$$

(ii) We assume that the shape parameter $\beta = 2$

In this case repair time distribution is Erlangian and its repair rates become time-dependent. In this case one has

$$q_5(x) = \mu_5^2 x\, e^{-\mu_5 x} \quad \text{and}$$

$$q_6(x)=\mu_6^2 x e^{-\mu_6 x}$$

Taking Laplace Transforms we obtain

$$q_5(s)=\frac{\mu_5^2}{(s+\mu_5)^2} \quad \text{and} \quad q_6(s)=\frac{\mu_6^2}{(s+\mu_6)^2}$$

Substitute these expressions in 2.3.23

$$P_0(s)=\frac{NR_0(s)}{sDR_0(s)} \qquad 36$$

where

$$NR_0(s)=s^9+s^8B_{16}+s^7B_{17}+s^6B_{18}+s^5B_{19}+s^4B_{20}+s^3B_{21}+s^2B_{22}+s^1B_{23}+\ B_{24}$$

$$DR_0(s)=s^9+s^8B_{25}+s^7B_{26}+s^6B_{27}+s^5B_{28}+s^4B_{29}+s^3B_{30}+s^2B_{31}+s^1B_{32}+\ B_{33}$$

where B_1 to B_{33} are constants

Similarly

$$P_1(S)=\frac{2\lambda}{S+A_1}P_0(S)$$

$$\Rightarrow P_1(S)=\frac{(S+\mu_5)^2(S+\mu_6)^2}{SDR_0(S)}NR_1(S) \qquad 37$$

$$P_2(S)=\frac{\lambda_A}{S+\mu_A}P_0(S)$$

$$\Rightarrow P_2(S)=\frac{(S+\mu_5)^2(S+\mu_6)^2}{SDR_0(S)}NR_2(S) \qquad 38$$

$$P_3(S)=\frac{\lambda_A}{S+\mu_2}P_1(S)$$

$$\Rightarrow P_3(S)=\frac{(S+\mu_5)^2(S+\mu_6)^2}{SDR_0(S)}NR_3(S) \qquad 39$$

$$P_4(S) = \frac{\lambda}{s+\mu_1} P_1(S)$$

$$\Rightarrow P_4(S) = \frac{(S+\mu_5)^2 (S+\mu_6)^2}{SDR_0(S)} NR_4(S) \quad 40$$

$$P_7(S) = \frac{\lambda_{AB}}{S+\mu_{AB}} P_0(S)$$

$$\Rightarrow P_7(S) = \frac{(S+\mu_5)^2 (S+\mu_6)^2}{SDR_0(S)} NR_7(S) \quad 41$$

$$P_5(S) = \frac{\lambda_h}{S} P_0(S)(1-q_5(S))$$

$$\Rightarrow P_5(S) = \frac{(S+2\mu_5)(S+\mu_6)^2}{SDR_0(S)} NR_5(S) \quad 42$$

$$P_6(S) = [\lambda_{c_1} + \frac{2\lambda_{c_2}\lambda}{S+A_1}] \frac{(1-q_6(S))}{S} P_0(S)$$

$$\Rightarrow P_6(S) = \frac{(S+2\mu_6)(S+\mu_5)^2}{SDR_0(S)} NR_6(S) \quad 43$$

where $NR_1(S) = 2\lambda\lambda(+ A_2)(S+A_3)(S+A_4)(S+A_5) = N_1(S)$

$$NR_2(S) = \lambda_A (S+A_1)(S+A_3)(S+A_4)(S+A_5) = N_2(S)$$

$$NR_3(S) = 2\lambda\lambda_A (S+A_2)(S+A_3)(S+A_5) = N_3(S)$$

$$NR_4(S) = 2\lambda^2 (S+A_2)(S+A_4)(S+A_5) = N_4(S)$$

$$NR_5(S) = \lambda_h (S+A_1)(S+A_2)(S+A_3)(S+A_4)(S+A_5) = N_5(S)$$

$$NR_6(S) = [\lambda_{c_1} (S+A_1) + 2\lambda\lambda_{c_2}](S+A_2)(S+A_3)(S+A_4)(S+A_5) = N_6(S)$$

$$NR_7(S) = \lambda_{AB} (S+A_1)(S+A_2)(S+A_3)(S+A_4) = N_7(S)$$

For real roots s_i,i=1..9 of the equation $DR_0(s)=0$ from equations and

We obtain

$$P_0(t) = H_1 + H_2 e^{S_1 t} + H_3 e^{S_2 t} + H_4 e^{S_3 t} + H_5 e^{S_4 t} + H_6 e^{S_5 t} + H_7 e^{S_6 t} + H_8 e^{S_7 t} + H_9 e^{S_8 t} + H_{10} e^{S_9 t}$$

$$P_1(t) = H_{11} + H_{12} e^{S_1 t} + H_{13} e^{S_2 t} + H_{14} e^{S_3 t} + H_{15} e^{S_4 t} + H_{16} e^{S_5 t} + H_{17} e^{S_6 t} + H_{18} e^{S_7 t} + H_{19} e^{S_8 t} + H_{20} e^{S_9 t}$$

where H_1 to H_{20} are constants

Here the time dependent availability $A_V(t)$ of the system is given by

$$A_V(t) = P_0(t) + P_1(t)$$

$$= \begin{array}{l} (H_1 + H_{11}) + (H_2 + H_{12}) e^{S_1 t} + (H_3 + H_{13}) e^{S_2 t} + (H_4 + H_{14}) e^{S_3 t} \\ + (H_5 + H_{15}) e^{S_4 t} + (H_6 + H_{16}) e^{S_5 t} + (H_7 + H_{17}) e^{S_6 t} + (H_8 + H_{18}) e^{S_7 t} \\ + (H_9 + H_{19}) e^{S_8 t} + (H_{10} + H_{20}) e^{S_9 t} \end{array}$$

Limiting Availability (steady state) A_V of the system is given by

$$A_V = \underset{t \to \infty}{\mathrm{lt}} A_V(t) = H_1 + H_{11}$$

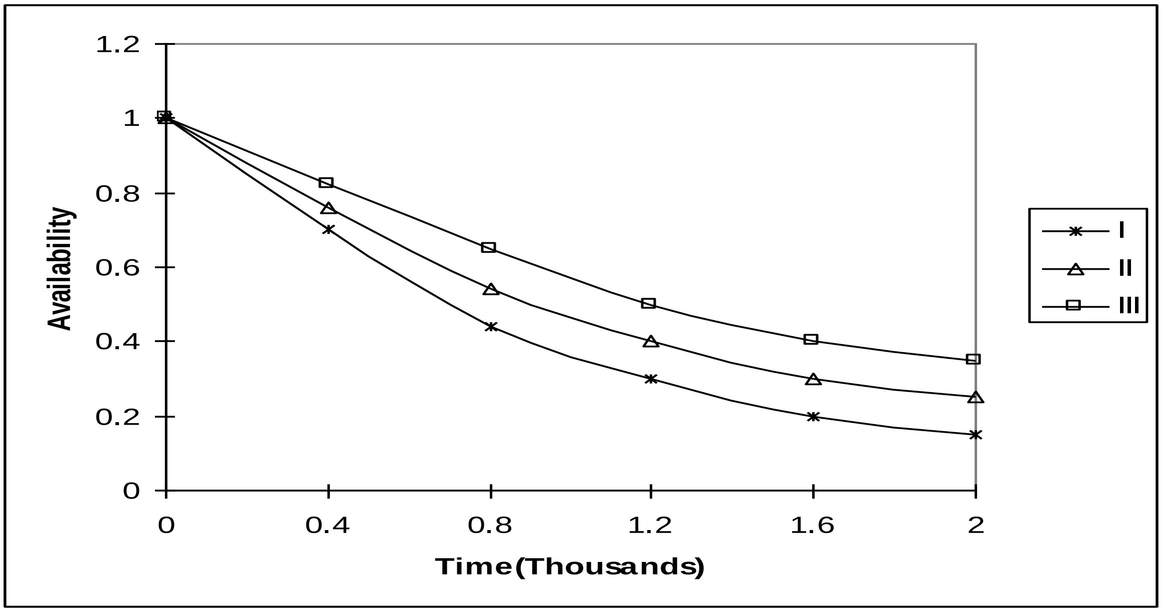
DISCUSSION

The Availability curve is plotted in figure 3. From these graph we observe that

1 The Availability of the system decreases with time; Availability of the system decreases more rapidly for $\beta = 2$ that $\beta = 1$.

2 As the human error increases, the Availability of the system decreases.

Fig 3: Availability curve



I II III

λ_h = 0.0005 0.0003 0.0001

Fig.3

$\lambda = 0.0002$ $\mu = 0.00$ $\lambda_A = 0.0($ $\mu_A = 0.0003$ $\lambda_{C_1} = \lambda_{C_2} = 0.0($ $\mu_1 = \mu_2 = 0.0($

$\mu_5 = \mu_6 = 0.00001$ $\lambda_{AB} = 0.0001$ $\mu_{AB} = 0.0003$

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