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STOCHASTIC BEHAVIOR OF A TWO UNIT SYSTEM WITH PARTIAL FAILURE AND FAULT DETECTION

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ABSTRACT

In the present paper we proposed and analyzed a two unit (identical units connected in parallel and both are in operative mode) operative system with the concept of repair to the partially failed unit and fault detection of the completely failed unit to decide whether the failed unit needs repair or replacement. The failure time of an operative unit to partial, partial failure to complete failure and operative to complete failure is assumed exponentially distributed with different parameters. The fault detection time, repair time of complete failure and replacement time are assumed a general distribution but different parameters. The reliability analysis of this model has been carried out by using regenerative point technique.

KEYWORDS

parallel, replacement, exponential and general.

INTRODUCTION

In the present study a repairable system which consists of two units viz. Main unit and Helping unit has been analyzed. Both the units are working and the main unit may fail either completely or partially or partially leading to complete failure whereas the helping unit is subjected to only complete failure with different types of failure rates. . However, there exist many practical situations wherein the operative unit fails partially and if the repair is provided to the partial failed unit, it may becomes operative. Also after the complete failure of a unit it is sent for fault detection that is to find out whether the repair is possible or not. If it is found to be repairable then it should sent for repair otherwise failed unit is replaced with a new unit. The concept of inspection and fault detection is widely used in literature, for describing the models, by several authors including Agarwal and Kumar [1], Agnihotri and Satsangi [2],[Mahmoud, et al [3], Malik [4], Naidu and Gopalan [5,6], Nakgawa [7,8] and Pour Darvish and Joorel [9].

In this model we consider a system composed of two identical units connected in parallel and both are in operative mode. The operative unit may fail partially or completely. However, a partially failed unit can also fail completely. The operative unit fails partially and if the repair is provided to the partial failed unit, it may becomes operative. Also after the complete failure of a unit it is sent for fault detection to decide whether the repair is possible or not. If it is found to be repairable then it should be sent for repair otherwise failed unit is replaced with a new unit. The probability that the failed unit goes for repair or replacement is fixed. The failure times of an operative unit to partial, partial failure to complete failure and operative to complete failure are assumed to be exponentially distributed with different parameters. The fault detection time, repair time of complete failure and replacement time are assumed a general distribution but different parameters.

NOTATIONS AND POSSIBLE STATES OF THE SYSTEM

O : Unit under operation.

O_{pr} : Unit failed partially and under repair.

O_{pw} : Unit waiting for repair after partial failure.

O_{F} : Unit under fault detection after its complete failure.

O_{Fw} : Unit waiting for fault detection after failure or all failure.

O_{r} : Failed unit under its repair.

O_{rep} : Failed unit under replacement.
O_{wrep} : Unit waiting for its replacement after complete failure.
α : Constant failure rate from operative to partially.
β : Constant failure rate from partial to complete.
γ : Constant failure rate from operative to complete.
δ : Constant repair rate of partial failed unit.
P : Prob. that failed unit goes for repair.
q (1-p) : Prob. that failed unit goes for replacement.
$F(.)$: Cdf of repair time distribution of fault detection.
$G(.)$: Cdf of repair time distribution of complete failure unit.
H(.) : Cdf of replacement unit.

Using these notations the various possible states of the system along with all possible transitions are presented in the Figure1.The states S_0, S_2, S_5 and S_7 are up states while $S_1, S_3, S_4, S_6, S_{12}$ and S_{13} are partially up states. The states S_8, S_9, S_{10}, S_{11} and S_{14} are down states. Further, all the states are regenerative states.

Possible States of the System: The system may be in one of the following state

$$S_0 \equiv [O, O] \qquad S_1 \equiv [O_{pr}, O] \qquad S_2 \equiv [O, O_F]$$

$$S_3 \equiv [O_{pr}, O_{Fw}] \qquad S_4 \equiv [O_{pr}, O_{pw}] \qquad S_5 \equiv [O, O_{rep}]$$

$$S_6 \equiv [O_{pw}, O_F] \qquad S_7 \equiv [O, O_r] \qquad S_8 \equiv [O_{Fw}, O_F]$$

$$S_9 \equiv [O_F, O_{rep}] \qquad S_{10} \equiv [O_r, O_{Fw}] \qquad S_{11} \equiv [O_r, O_{rep}]$$

$$S_{12} \equiv [O_{pw}, O_r] \qquad S_{13} \equiv [O_{pr}, O_{rep}] \qquad S_{14} \equiv [O_{wrep}, O_{rep}]$$

TRANSITION PROBABILITIES AND SOJOURN TIMES

The various steady state transition probabilities are as follows:

$$p_{01} = \frac{\alpha}{\alpha+\gamma} \qquad p_{02} = \frac{\gamma}{\alpha+\gamma} \qquad p_{14} = \frac{\alpha}{(\alpha+\beta+\delta)}$$

$$p_{25} = q\,\tilde{F}(\alpha+\gamma) \qquad p_{26} = \frac{\alpha}{(\alpha+\gamma)}\left[1-\tilde{F}(\alpha+\gamma)\right] \qquad p_{27} = p\,\tilde{F}(\alpha+\gamma)$$

$$p_{28} = \frac{\gamma}{(\alpha+\gamma)}\left[1-\tilde{F}(\alpha+\gamma)\right] \qquad p_{32} = p_{102} = p_{145} = 1 \qquad p_{41} = \frac{\delta}{\beta+\delta}$$

$$p_{43} = \frac{\beta}{\beta+\delta} \qquad p_{50} = \tilde{H}(\alpha+\gamma) \qquad p_{59} = \frac{\gamma}{(\alpha+\gamma)}\left[1-\tilde{H}(\alpha+\gamma)\right]$$

$$p_{5,13} = \frac{\alpha}{(\alpha+\gamma)}\left[1-\tilde{H}(\alpha+\gamma)\right] \qquad p_{68} = 1-\tilde{F}(\beta) \qquad p_{6,12} = p\tilde{F}(\beta)$$

$$p_{6,13} = q\tilde{F}(\beta) \qquad p_{70} = \frac{\delta}{(\alpha+\gamma+\delta)} \qquad p_{7,10} = \frac{\gamma}{(\alpha+\gamma+\delta)}$$

$$p_{7,12} = \frac{\alpha}{(\alpha+\gamma+\delta)} \qquad p_{89} = q \qquad p_{8,10} = p \qquad p_{92} = \int_o^\infty dH(t)\bar{F}(t)$$

$$p_{9,11} = p\int_o^\infty dF(t)\bar{H}(t) \qquad p_{9,14} = q\int_o^\infty dF(t)\bar{H}(t) \qquad p_{11,5} = \int_o^\infty dG(t)\bar{H}(t)$$

$$p_{11,7} = \int_o^\infty dH(t)\tilde{G}(t) \qquad p_{12,1} = \tilde{G}(\beta) \qquad p_{12,10} = \left[1-\tilde{G}(\beta)\right] \qquad p_{13,1} = \tilde{G}(\delta)$$

$$p_{13,5} = \left[1-\tilde{G}(\delta)\right] \qquad (1)$$

From these steady state probabilities the following relations can easily be verified:

$$p_{01}+p_{02}=1 \qquad p_{10}+p_{13}+p_{14}=1 \qquad p_{25}+p_{26}+p_{27}+p_{28}=1$$
$$p_{32}=p_{10,2}=p_{14,5}=1 \qquad p_{41}+p_{43}=1 \qquad p_{50}+p_{59}+p_{5,13}=1$$
$$p_{70}+p_{7,10}+p_{7,12}=1 \qquad p_{89}+p_{8,10}=1 \qquad p_{92}+p_{9,11}+p_{9,14}=1$$
$$p_{11,5}+p_{11,7}=1 \qquad p_{12,1}+p_{12,10}=1 \qquad p_{13,1}+p_{13,5}=1 \tag{2}$$

Mean Sojourn time

$$\mu_0=\frac{1}{\alpha+\gamma} \qquad \mu_1=\frac{1}{\alpha+\beta+\delta} \qquad \mu_2=\frac{1}{(\alpha+\gamma)}\left[1-\tilde{F}(\alpha+\gamma)\right]$$
$$\mu_3=\frac{1}{\delta} \qquad \mu_4=\frac{1}{\beta+\delta} \qquad \mu_5=\frac{1}{(\alpha+\gamma)}\left[1-\tilde{H}(\alpha+\gamma)\right]$$
$$\mu_6=\frac{1}{\beta}\left[1-\tilde{F}(\beta)\right] \qquad \mu_7=\frac{1}{\alpha+\gamma+\delta} \qquad \mu_8=1=\mu_{10}=\mu_{14}$$
$$\mu_9=\int_o^\infty \overline{F}(t)\overline{H}(t)dt \qquad \mu_{11}=\int_o^\infty \overline{G}(t)\overline{H}(t)dt \qquad \mu_{12}=\frac{1}{\beta}\left[1-\tilde{G}(\beta)\right]$$
$$\mu_{13}=\frac{1}{\delta}\left[1-\tilde{G}(\delta)\right] \tag{3}$$

MEAN TIME TO SYSTEM FAILURE

Let U_i be the random variable denoting time to system failure when the system starts from state S_i, $S_i \in E$ and let $\pi_i(t)=P[U_i \le t]$ be the cdf of time to system failure for the first time when it starts operation from state S_i. To determine the distribution function, $\pi_i(t)$ we regard the failed states S_8, S_9, S_{10}, S_{11} and S_{14} as absorbing states. Using basic probabilistic arguments, the recursive relations among $\pi_i(t)$ can be easily developed and taking L.T of the relations and solving for $\tilde{\pi}_0(s)$, we get

$$\tilde{\pi}_0(s)=\frac{N_1(s)}{D_1(s)} \tag{4}$$

where

$$\begin{aligned}N_1(s)=&\left[\tilde{Q}_{01}\tilde{Q}_{14}\left(\tilde{Q}_{32}\tilde{Q}_{41}\tilde{Q}_{13}+\tilde{Q}_{32}\tilde{Q}_{43}\right)+\left(1-\tilde{Q}_{14}\tilde{Q}_{41}\right)\left(\tilde{Q}_{01}\tilde{Q}_{13}\tilde{Q}_{32}+\tilde{Q}_{02}\right)\right]\\&\left[\begin{array}{l}\left(1-\tilde{Q}_{5,13}\tilde{Q}_{13,5}\right)\left(\tilde{Q}_{28}+\tilde{Q}_{26}\tilde{Q}_{28}+\tilde{Q}_{26}\tilde{Q}_{612}\tilde{Q}_{1210}+\tilde{Q}_{27}\tilde{Q}_{7,10}\tilde{Q}_{12,10}+\tilde{Q}_{27}\tilde{Q}_{7,10}\right)\\+\tilde{Q}_{25}\tilde{Q}_{59}+\tilde{Q}_{26}\tilde{Q}_{59}\tilde{Q}_{6,13}\end{array}\right]\\&\times\left(1-\tilde{Q}_{14}\tilde{Q}_{41}\right)\end{aligned}$$

and

$$\begin{aligned}D_1(s)=&\left(1-\tilde{Q}_{01}\tilde{Q}_{10}-\tilde{Q}_{14}\tilde{Q}_{41}\right)\\&\times\left\{\begin{array}{l}\left(1-\tilde{Q}_{5,13}\tilde{Q}_{13,5}\right)\left(1-\tilde{Q}_{14}\tilde{Q}_{41}\right)-\left(\tilde{Q}_{32}\tilde{Q}_{13}+\tilde{Q}_{14}\tilde{Q}_{32}\tilde{Q}_{43}\right)\\\left[\left(1-\tilde{Q}_{5,13}\tilde{Q}_{13,5}\right)\left(\tilde{Q}_{26}\tilde{Q}_{6,12}\tilde{Q}_{12,1}+\tilde{Q}_{27}\tilde{Q}_{7,12}\tilde{Q}_{12,1}\right)+\tilde{Q}_{25}\tilde{Q}_{5,13}\tilde{Q}_{13,1}+\tilde{Q}_{26}\tilde{Q}_{6,13}\tilde{Q}_{13,1}\right]\end{array}\right\}\\&-\left[\tilde{Q}_{01}\tilde{Q}_{14}\left(\tilde{Q}_{32}\tilde{Q}_{41}\tilde{Q}_{13}+\tilde{Q}_{32}\tilde{Q}_{43}\right)+\left(1-\tilde{Q}_{14}\tilde{Q}_{41}\right)\left(\tilde{Q}_{01}\tilde{Q}_{13}\tilde{Q}_{32}+\tilde{Q}_{02}\right)\right]\\&\times\left[\begin{array}{l}\left(1-\tilde{Q}_{14}\tilde{Q}_{41}\right)\left(\tilde{Q}_{26}\tilde{Q}_{50}\tilde{Q}_{13,5}\tilde{Q}_{6,13}+\tilde{Q}_{25}\tilde{Q}_{50}\right)+\left(1-\tilde{Q}_{5,13}\tilde{Q}_{13,5}\right)\\\left(\tilde{Q}_{27}\tilde{Q}_{70}-\tilde{Q}_{27}\tilde{Q}_{70}\tilde{Q}_{14}\tilde{Q}_{41}\tilde{Q}+\tilde{Q}_{10}\tilde{Q}_{26}\tilde{Q}_{6,12}\tilde{Q}_{12,1}+\tilde{Q}_{10}\tilde{Q}_{27}\tilde{Q}_{7,12}\tilde{Q}_{12,1}\right)\\+\tilde{Q}_{10}\tilde{Q}_{25}\tilde{Q}_{5,13}\tilde{Q}_{13,1}+\tilde{Q}_{10}\tilde{Q}_{26}\tilde{Q}_{6,13}\tilde{Q}_{13,1}\end{array}\right]\end{aligned}$$

(For the sake of simplicity the argument‘s’ has been omitted from $\tilde{Q}_{ij}(s)$)

and Using $\lim\limits_{s\to 0}\tilde{Q}_{ij}(s)\to p_{ij}$, and eq. (1) and eq. (2), we obtain the following limiting values of $N_1(s)$ and $D_1(s)$ on ‘s’ approaches to zero

$$N_1(0)=(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(p_{25}p_{59}+p_{26}p_{59}p_{13,5}p_{6,13})$$
$$+(1-p_{13,5}p_{5,13})(p_{28}+p_{26}p_{28}+p_{26}p_{6,12}p_{12,10}+p_{27}p_{7,10}+p_{27}p_{7,12}p_{12,10})$$
$$(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})$$

and

$$D_1(0)=(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(p_{25}p_{59}+p_{26}p_{59}p_{13,5}p_{6,13})$$
$$+(1-p_{13,5}p_{5,13})(p_{28}+p_{26}p_{28}+p_{26}p_{6,12}p_{12,10}+p_{27}p_{7,10}+p_{27}p_{7,12}p_{12,10})$$
$$(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41}) \tag{5}$$

On comparing the above expressions of $N_1(0)$ and $D_1(0)$, we observe that $N_1(0)=D_1(0)$ and thus $\tilde{\pi}_0(s)=1$ as $s\to 0,$ which implies that $\pi_0(t)$ is a proper cumulative distribution function.

Thus, Mean Time to System Failure (MTSF) when system starts operation with the entrance into S_0 is obtained as

$$E(T)=-\frac{d}{ds}\tilde{\pi}_0(o) = \frac{D_1'(0)-N_1'(0)}{D_1(0)} \tag{6}$$

where $N_1'(0)$ and $D_1^{'}(0)$ are the derivatives of the numerator and denominator of $\tilde{\pi}_0(s)$ at $s\to 0$.

To obtain the numerator of MTSF defined by (6), we use the following results:

$$m_{ij}=-\tilde{Q}_{ij}'(s)_{/}s=0 = \frac{d}{ds}\int_0^\infty e^{-st}dQ_{ij}(t)/_{s=0} \quad \text{and} \quad \sum_j m_{ij}=\mu_i$$

where m_{ij} is the mean elapsed time of the system in state S_i before transiting to state S_j.

Therefore, on arranging the coefficients of m_{ij}'s and also by using the above relations, the expression for $D_1'(0)-N_1'(0)$ can be written as:

$$D_1'(0)-N_1'(0)$$
$$=\mu_0(1-p_{14}p_{41})\left\{\begin{array}{l} p_{10}p_{25}p_{5,13}p_{13,1}+p_{10}p_{26}p_{13,1}p_{6,13} \\ +(1-p_{13,5}p_{5,13})(p_{10}p_{27}p_{7,12}p_{12,1}+p_{10}p_{26}p_{6,12}p_{12,1})+(1-p_{14}p_{41}) \\ \left[\begin{array}{l} p_{25}p_{50}+p_{25}p_{59}+p_{26}p_{50}p_{6,13}p_{12,10}+p_{26}p_{59}p_{6,13}p_{13,5}+(1-p_{13,5}p_{5,13}) \\ (p_{28}+p_{27}p_{70}+p_{26}p_{28}+p_{26}p_{6,12}p_{12,10}+p_{27}p_{7,10}+p_{27}p_{7,12}p_{12,10}) \end{array}\right] \end{array}\right\}$$
$$+\mu_1(1-p_{14}p_{41})\left[\begin{array}{l} (p_{01}+p_{26}p_{613}p_{121}+p_{27}p_{712}p_{121}) \\ (1-p_{135}p_{513})+p_{02}p_{25}p_{513}p_{131}+p_{02}p_{26}p_{613}p_{131} \end{array}\right]$$
$$+\mu_2(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(1-p_{5,13}p_{13,5})$$
$$+\mu_3(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{10}-p_{14}p_{41})$$
$$\times[p_{25}p_{513}p_{131}+p_{26}p_{613}p_{131}+(p_{26}p_{612}p_{121}+p_{27}p_{712}p_{121})(1-p_{513}p_{135})]$$
$$+\mu_3p_{01}(1-p_{10}-p_{14}p_{41})$$
$$\times\left[(1-p_{14}p_{41})\left[\begin{array}{l} p_{25}p_{50}+p_{26}p_{135}p_{50}p_{613}+p_{25}p_{59}+p_{26}p_{613}p_{59}p_{135}+ \\ (p_{27}p_{70}+p_{28}+p_{26}p_{68}+p_{26}p_{612}p_{1210}+p_{27}p_{710}+p_{27}p_{712}p_{1210})(1-p_{135}p_{513}) \end{array}\right]\right]$$
$$+\mu_4\ p_{14}(1-p_{10}-p_{14}p_{41})[p_{25}p_{513}p_{131}+p_{26}p_{613}p_{131}+(p_{26}p_{612}p_{121}+p_{27}p_{712}p_{121})(1-p_{513}p_{135})]$$

$$+\mu_4 p_{01}p_{14}\left[\begin{array}{l}(1-p_{14}p_{41})\left[\begin{array}{l}p_{25}p_{50}+p_{26}p_{135}p_{50}p_{613}+p_{25}p_{59}+p_{26}p_{613}p_{59}p_{135}+\\(p_{27}p_{70}+p_{28}+p_{26}p_{68}+p_{26}p_{612}p_{1210}+p_{27}p_{710}+p_{27}p_{712}p_{1210})\\\times(1-p_{135}p_{513})\end{array}\right]\\+p_{10}p_{25}p_{513}p_{131}+p_{10}p_{26}p_{613}p_{131}+(p_{10}p_{26}p_{612}p_{121}+p_{10}p_{27}p_{712}p_{121})\\\times(1-p_{135}p_{513})\\ \\ \\ \end{array}\right]$$

$$\begin{aligned}&+\mu_5(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(p_{25}+p_{26}p_{6,13}p_{13,5})\\&\quad+\mu_6(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(1-p_{5,13}p_{13,5})p_{26}\\&\quad+\mu_7(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(1-p_{5,13}p_{13,5})p_{27}\\&+\mu_{12}(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{135}p_{513})(1-p_{14}p_{41})(p_{26}p_{612}+p_{27}p_{712})\\&+\mu_{13}(1-p_{01}p_{10}-p_{14}p_{41})(1-p_{14}p_{41})(p_{25}p_{513}+p_{26}p_{613})\end{aligned} \tag{7}$$

Therefore, using (5) and (7) in (6), the mean time to system failure (MTSF) is obtained.

AVAILABILITY ANALYSIS

$A_i(t)$ is the probability that the system is in a up state at epoch't' given that initially it was in up state S_i. Using basic probabilistic arguments, the recursive relations among $A_i(t)$ can be easily developed and taking L.T of the relations and solving for $A_0^*(s)$ we get

$$A_0=\lim_{t\to\infty}A_0(t)=\lim_{s\to 0}sA_0^*(s)=\lim_{s\to 0}s\frac{N_2(s)}{D_2(s)} \tag{8}$$

which is an indeterminate form since the denominator of (8) becomes zero as $s\to 0$, which can easily be verified.

Therefore, on using L' Hospital's rule, the steady state availability, A_0 becomes

$$A_0 = \lim_{s\to 0}\frac{sN_2'(s)+N_2(s)}{D_2'(s)}=\frac{N_2(0)}{D_2'(0)} \tag{9}$$

Further on using the following relations:

$\lim_{s\to 0} q_{ij}^*(s)=q_{ij}^*(0)=p_{ij}$ and $-q_{ij}^{*'}(0)=m_{ij}$

also $Z_i^*(0)=\mu_i,\ i=0,\ 1,\ 2,\ 3,\ 4,\ 5,\ 6,\ 9$

The numerator and denominator of steady state availability of the system starting from state $S_0\ ,S_0\in E$, is thus becomes

$$\begin{aligned}N_2(0)=&[(K_0K_1+K_2K_{13})K_3+K_6(K_0K_4+K_4)]K_7+K_8K_3K_0\\&-[(K_{10}+K_{11}+K_{12})K_0+K_{13}K_{14}]K_3K_8-(K_{15}K_0+K_{16}K_{14})K_6K_8\end{aligned} \tag{10}$$

and

$$\begin{aligned}D_2'(0)=&\mu_0(1-p_{14}p_{41})[(K_{17}K_0+p_{10}K_{13})K_3+(K_{18}K_0+p_{10}K_{16})K_6]\\&+p_{01}\mu_1[K_3K_0-(K_{10}+K_{11}+K_{12})K_0K_3-K_3K_{13}K_{14}-(K_0K_{15}+K_{14}K_{16})K_6]\\&+K_7(K_3K_{13}+K_6K_{16})\mu_1+\mu_2[K_{19}(K_0K_{15}+K_{14}K_{16})+K_7(K_0K_{18}+p_{10}K_{16})]\\&+\mu_3(p_{13}+p_{14}p_{43})[(K_{17}K_0+p_{10}K_{13})K_3p_{01}+(K_{18}K_0+p_{10}K_{16})K_6p_{01}+K_{19}(K_3K_{13}+K_6K_{16})]\\&+\mu_4p_{14}[(K_{17}K_0+p_{10}K_{13})K_3p_{01}+(K_{18}K_0+p_{10}K_{16})K_6p_{01}+K_{19}(K_3K_{13}+K_6K_{16})]+\mu_5K_0K_6K_7\\&+\mu_6p_{26}K_3(p_{1210}K_0K_{19}+p_{121}K_{14}K_{19}+p_{10}p_{121}K_7)\\&+\mu_7K_0K_7(p_{26}p_{68}p_{89}p_{911}p_{117}K_3+p_{27}K_3+p_{28}p_{89}p_{911}p_{117}K_3+p_{59}p_{911}p_{117}K_6)\quad+\mu_8K_0K_3K_{19}(p_{26}p_{68}+p_{28})\\&+\mu_9K_0K_{19}(p_{26}p_{68}p_{89}K_3+p_{28}p_{89}K_3+p_{59}K_6)\end{aligned}$$

$$+\mu_{10}K_0K_{19}\begin{bmatrix} p_{26}p_{612}p_{1210}K_3+p_{26}p_{68}p_{810}K_3+K_3\left(p_{710}+p_{712}p_{1210}\right) \\ \times\left(p_{26}p_{68}p_{911}p_{117}+p_{28}p_{89}p_{911}p_{117}\right) \\ +p_{27}K_3\left(p_{710}+p_{1210}\right)+p_{28}p_{810}K_3+p_{59}p_{712}p_{911}p_{1210}K_6 \\ +p_{59}p_{710}p_{911}p_{117}K_6 \end{bmatrix}$$

$$+\mu_{11}\begin{bmatrix} p_{59}p_{911}\left[K_0K_{19}-\left(K_{10}+K_{11}+K_{12}\right)K_0K_{19}-K_{13}K_{14}K_{19}-\left(K_0K_{17}+p_{10}K_{13}\right)K_7\right] \\ +\left(p_{26}p_{68}p_{89}p_{911}+p_{28}p_{89}p_{911}\right)\left[K_{19}\left(K_0K_{15}+K_{14}K_{16}\right)+K_7\left(K_0K_{18}+p_{10}K_{16}\right)\right] \end{bmatrix}$$

$$+\mu_{12}K_0K_{19}\left[p_{27}K_3+p_{712}p_{911}p_{117}K_3\left(p_{26}p_{68}+p_{28}p_{89}\right)+p_{59}p_{712}p_{911}K_6\right]$$

$$+\mu_{13}\left[p_{26}p_{613}K_3\left(K_{14}K_{19}+p_{10}K_7\right)+p_{513}K_6K_{14}K_{19}\right]$$

$$+\mu_{14}\begin{bmatrix} p_{59}p_{914}\left[K_0K_{19}-\left(K_{10}+K_{11}+K_{12}\right)K_0K_{19}-K_{13}K_{14}K_{19}-\left(K_0K_{17}+p_{10}K_{13}\right)K_7\right] \\ +\left(p_{26}p_{68}p_{89}p_{914}+p_{28}p_{89}p_{914}\right)\left[K_{19}\left(K_0K_{15}+K_{14}K_{16}\right)+K_7\left(K_0K_{18}+p_{10}K_{16}\right)\right] \end{bmatrix}$$

(11)

where

$$K_1=\begin{bmatrix} \mu_2+p_{26}\mu_6+p_{26}p_{612}\mu_{12}+p_{26}p_{613}\mu_{13} \\ +\left(p_{26}p_{68}p_{89}p_{911}p_{117}+p_{27}+p_{28}p_{89}p_{911}p_{117}\right)\left(\mu_7+p_{712}\mu_{12}\right) \end{bmatrix}$$

$$K_0=\left(1-p_{14}p_{41}\right)$$

$$K_2=\left(\mu_1+\mu_5p_{14}+\mu_3p_{13}+\mu_3p_{14}p_{43}\right)$$

$$K_3=\left(1-p_{59}p_{911}p_{115}-p_{513}p_{135}-p_{59}p_{914}\right) \qquad K_4=\left(\mu_5+p_{513}\mu_{13}+p_{59}p_{911}p_{117}\mu_7+p_{712}\mu_{12}\right)$$

$$K_5=\left(p_{513}p_{131}+p_{712}p_{121}\right)\left(\mu_1+\mu_5p_{14}+\mu_3p_{13}+\mu_3p_{14}p_{43}\right)$$

$$K_6=\left[p_{25}+p_{26}p_{68}p_{89}\left(p_{914}+p_{911}p_{115}\right)+p_{613}p_{135}p_{26}+p_{28}p_{89}p_{914}p_{145}+p_{28}p_{89}p_{911}p_{115}\right]$$

$$K_7=\left[p_{01}p_{13}+p_{01}p_{14}p_{43}+p_{02}\left(1-p_{41}p_{14}\right)\right] \; K_8=\left(\mu_0-p_{14}p_{41}\mu_0+p_{01}\mu_1+p_{01}p_{14}\mu_4+p_{01}p_{13}\mu_3+p_{01}p_{14}p_{43}\mu_3\right)$$

$$K_{10}=\left(p_{26}p_{612}p_{1210}+p_{26}p_{68}p_{89}p_{92}+p_{26}p_{68}p_{810}\right)$$

$$K_{11}=\left(p_{26}p_{68}p_{911}p_{117}+p_{28}p_{89}p_{911}p_{117}\right)\left(p_{710}+p_{712}p_{1210}\right) \; K_{12}=\left(p_{27}p_{710}+p_{27}p_{1210}+p_{28}p_{89}p_{92}+p_{28}p_{810}\right)$$

$$K_{13}=\begin{pmatrix} p_{26}p_{612}p_{121}+p_{26}p_{613}p_{131}+ \\ p_{26}p_{68}p_{712}p_{121}p_{89}p_{911}p_{117}+p_{27}p_{712}p_{121}+p_{28}p_{712}p_{121}p_{89}p_{911}p_{117} \end{pmatrix}$$

$$K_{14}=\left(p_{13}+p_{14}p_{43}\right)$$

$$K_{15}=\left(p_{59}p_{92}+p_{59}p_{911}p_{712}p_{1210}+p_{59}p_{911}p_{117}p_{710}\right) \qquad K_{16}=\left(p_{513}p_{131}+p_{59}p_{911}p_{117}p_{712}p_{121}\right)$$

$$K_{17}=\left(p_{26}p_{68}p_{89}p_{911}p_{117}p_{70}+p_{27}p_{70}+p_{28}p_{89}p_{911}p_{117}p_{70}\right)$$

$$K_{18}=\left(p_{50}+p_{59}p_{911}p_{117}p_{70}\right)$$

$$K_{19}=\left(1-p_{14}p_{41}-p_{01}p_{10}\right)$$

BUSY PERIOD ANALYSIS

$B_i(t)$ is defined as the probability that the system having started from regenerative state $S_i, S_i \in E$ at time $t=0$ is under repair i.e is the repairman is busy. Using the definition of $B_i(t),\ i=0,1,2,3,\ldots,14$ the recursive relations among $B_i(t)$ can be easily developed, taking their Laplace transform and solving them for $B_0^*(s),$ the steady state probability that the system is under repair with repairman when system starts from state S_0, i.e. in the long-run the repairman, is given by

$$B_0=\lim_{t\to\infty}B_0(t)=\lim_{s\to 0}s\,B_0^*(s)=\lim_{s\to 0}s\,\frac{N_3(s)}{D_3(s)}$$

(12)

Since the denominator of (12) becomes zero as $s\to 0$, thus on using L' Hospital's Rule and the results $\lim_{s\to 0}q_{ij}^*(s)=q_{ij}^*(0)=p_{ij}$, and

$-q_{ij}^{*'}(0)=m_{ij}$ also the expression for B_0 becomes

$$B_0=\lim_{s\to 0}\frac{N_3(s)}{D_3'(s)}=\frac{N_3(0)}{D_3'(0)}$$

(13)

where

$$N_3(0) = p_{01}K_{25}\left[K_3K_0 - (K_{10}+K_{11}+K_{12})K_0K_3 + K_{13}K_{14}K_3 - (K_{15}K_0 + K_{16}K_{14})K_6\right]$$
$$+K_7K_0\left[\begin{array}{l} K_{20}K_3 + p_{25}K_{21} + p_{26}K_{22}K_3 + p_{26}p_{613}p_{135}K_{21} \\ +(p_{26}p_{68}p_{89} + p_{28}p_{89})(K_3K_{23} + K_{24}K_{21}) + K_{27}K_3 \end{array}\right]$$
$$+K_7K_{25}\left[\begin{array}{l} K_3K_{28} + p_{25}K_{16} + p_{26}(K_{26}K_3 + p_{68}p_{89}K_{16}K_{24} + p_{135}p_{613}K_{16}) \\ +K_3K_{28} + p_{28}p_{89}K_{16}K_{24} \end{array}\right] \quad (14)$$

The values K_0, K_3, K_6, K_7, K_{10}, K_{11}, K_{12}, K_{13}, K_{14}, K_{15} and K_{16} are already defined.

$$K_{20} = p_{27}(\mu_7 + p_{710}\mu_{10} + p_{712}\mu_{12} + p_{712}p_{1210}\mu_{10}) \; K_{21} = \mu_5 + p_{59}\mu_9 + p_{513}\mu_{13} + p_{59}p_{911}\mu_{11} + p_{59}p_{914}\mu_{14}$$
$$+ p_{59}p_{911}p_{117}(\mu_7 + p_{710}\mu_{10} + p_{712}\mu_{12} + p_{712}p_{1210}\mu_{10})$$
$$K_{22} = \mu_6 + p_{612}\mu_{12} + p_{612}p_{1210}\mu_{10} + p_{613}\mu_{13} + (\mu_8 + p_{810}\mu_{10})p_{68}$$
$$K_{23} = \mu_9 + p_{911}\mu_{11} + p_{914}\mu_{14} + p_{911}p_{117}(\mu_7 + p_{710}\mu_{10} + p_{712}\mu_{12} + p_{712}p_{1210}\mu_{10}) \; K_{24} = p_{911}p_{115} + p_{914}$$
$$K_{25} = \mu_1 + p_{13}\mu_3 + p_{14}\mu_4 + p_{14}p_{43}\mu_3$$
$$K_{26} = p_{612}p_{121} + p_{712}p_{911}p_{117}p_{121}p_{68}p_{89} + p_{131}p_{613}$$
$$K_{27} = p_{28}(\mu_8 + p_{810}\mu_{10})$$
$$K_{28} = p_{27}p_{712}p_{121} + p_{28}p_{89}p_{712}p_{911}p_{117}p_{121}$$

and $D_3'(0)$ is same as $D_2'(0)$, which is given by (11) .

GRAPHICAL REPRESENTATION OF MTSF

The repair time distributions of the complete failure of main unit, fault detection of main unit and replacement of failed unit of the system were assumed arbitrary while describing the system description. To study the behavior of its MTSF through graphical presentation, we assume that the repair time distributions of these three variables are also exponentially distributed with parameters λ_1, λ_2 and λ_3 respectively. To plot the graphs of MTSF of the system, we consider three different cases for the various values of the failure and repair rates. In the first case, we fixed the values of $\beta = \gamma = \delta = \lambda_1 = \lambda_2 = \lambda_3 = 0.30$ and different values of $\alpha,\ 0 < \alpha \le 1$. In the second case, $\beta = \gamma = \delta = \lambda_1 = \lambda_2 = \lambda_3 = 0.50$ and different values of $\alpha,\ 0 < \alpha \le 1$, while in the third case, $\beta = \gamma = \delta = \lambda_1 = \lambda_2 = \lambda_3 = 0.80$ and different values of $\alpha,\ 0 < \alpha \le 1$. The three sets of graphs of MTSF have been plotted and presented through Figure 2. From, this figure we observed that, in all cases, MTSF of the system decreases with increasing failure rate of partial failure of a unit.

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FIGURES

FIGURE 1: STATE TRANSITION DIAGRAM

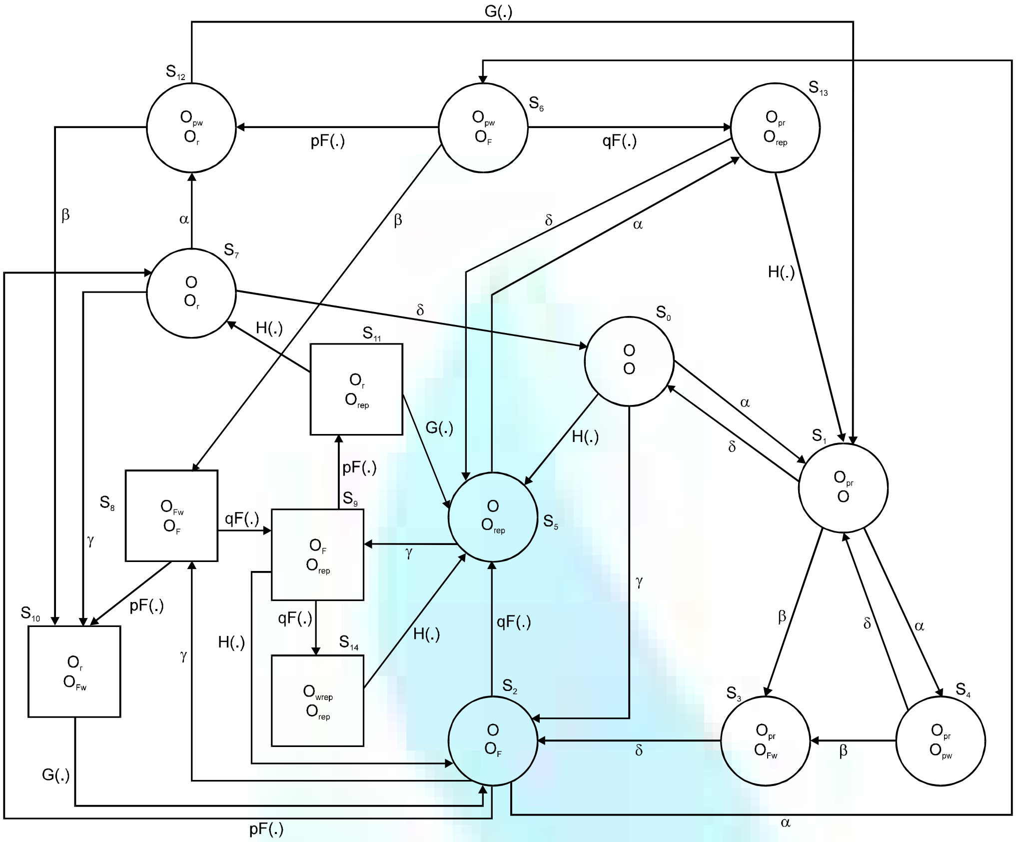
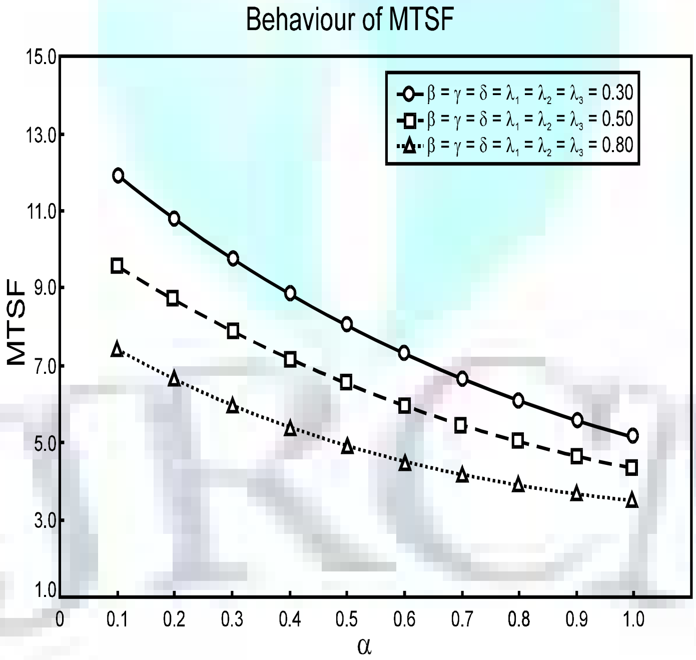


FIGURE 2



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