Malaya Journal of Matematik, Vol. 9, No. 1, 829-835, 2021

https://doi.org/10.26637/MJM0901/0146

Availability estimation of nuclear reactor with standby generators by employing pre-emptive resume repair policy

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Abstract
In this paper, the authors have studied about availability estimation of nuclear power generation plants. If any of the subsystems stops working, then the whole system gets fail. Pre-emptive resume policy has been used for repair purposes, for failures follow exponential time distribution, whereas all repairs follow general time distribution. The system under consideration is non- Markovian the supplementary variable technique has been used for the mathematical formulation of the model. Laplace transforms are being utilized to solve mathematical equations. Some particulate cases and asymptotic behavior of the system have also been derived to improve the model's practical importance. The expression for the availability function has been computed. A numerical problem, together with its graphical representation, has been appended in the end to highlight actual results.

Keywords
Nuclear reactor, generation plants.

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Article History: Received **21** January **2021**; Accepted **19** March **2021**

Contents

1. Introduction

More than 16% of the world's electricity is generated by nuclear energy, over from all sources worldwide in 1960.

A nuclear reactor produces and controls energy release from splitting the atoms of uranium and plutonium elements. In a reactor of atomic energy, the energy produced by heat is used to produce steam from atoms' continuous fission in the fuel. The steam is used to supply electricity to turbines (as in most fossil fuel plants). Most types of reactors have several components:

Fuel: Uranium oxide (UO2) pellets are generally arranged to form fuel rods in tubes. In fuel units, the rods are positioned in the core reactor.

Moderator: This material slows down the released neutrons from fission to cause more split. It is often water, but perhaps heavy water or graphite.

Control rods: These are made of cadmium, hafnium, or boron neutron-adsorbing material that is inserted or removed from the core to control or to stop the reaction rate. (The use of other neutron absorbers for secondary shutdown systems, usually in the primary refrigeration system).

Coolant: The heat from the core will be delivered through a liquid or gas. The moderator also operates as a coolant in light-water reactors.

Pressure vessel or pressure tubes: Usually a full steel vessel that contains the reactor core and the coolant/coolant, but it

can also be several tubes that hold the fuel and transport the coolant via the moderator.
Steam generator: Part of the cooling system used to produce steam for the turbine with heat from the reactor.
The nuclear reactor system configuration has been shown in fig-1(a), (b), respectively. The entire plant was divided into four subsystems: A, B, C, and D.

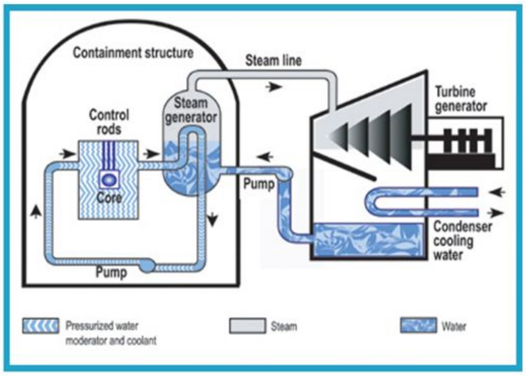

Fig-1(a): Nuclear Reactor

Subsystem A is a reactor vessel that generates heat energy by splitting atoms. This energy is transmitted via coolant to the B subsystem. This B subsystem is a heat exchanger that transforms the heat into vapor. Now this steam is moving to the C subsystem, a turbine. This subsystem C, connected to the generator (subsystem D), generates electrical energy for turning the turbine. Lastly, the generator can store electrical energy for further use. In this model, the authors have taken one redundant standby generator. So, subsystem D has two standby redundant units and. If any of its subsystems stop working, the entire system will fail. For repair purposes, pre-emptive resume policies were adopted. All failures are exponential, while all repairs follow the overall time distribution. State- transition diagram has been shown in fig-1(c).

2. Preliminaries

2.1 List of notations

α_i	:	The ith subsystem's failure rate, where $i = A, B, C$, and D.
$(1-\beta)$	:	The failure rate of switching device S.
δ	:	Repair rate of switching device S.
$\mu_i(j)\Delta$	:	The first order probability that i^{th} subsystem can be repaired in the time interval $(j, j+\Delta)$ conditioned that it was not repaired j, when $i = A, B, C$, and D; $j = x, y, z$, and m
$P_0(t)$	:	Pr{ at time t, the system is all operable }
$P_{D_1}(n,t)\Delta$	:	Pr{ at time t, the system is operable with standby D -unit while online D -unit has failed already }. Elapsed repair time lies in the interval $(n, n+\Delta)$.
$P_i(j,t)\Delta$	:	Pr{ at time t, the system has failed due to failure of i th subsystem }. Elapsed repair time lies in the interval $(j, j+\Delta)$, where $i = A, B, C, D$ and $j = x, y, z, m$, respectively.
$P_{D_{1i}}(j,t)\Delta$	:	Pr{ at time t, the system has failed due to failure of i th subsystem while one-D-unit has failed already }. Elapsed repair time for i^{th} subsystem lies in the interval $(j, j+\Delta)$, where $i = A, B, C$, and $j = x, y, z$, respectively.
$P_{D_i i}(j,m,t)\Delta$	:	Pr{ at time t, the system has failed due to failure of 1^{th} subsystem while one-D-unit has failed already }. Elapsed repair time for i^{th} subsystem lies in the interval $(j, j+\Delta)$, and for the $D-1$ unit, it lies between $(m, m+\Delta)$, where $i = A, B, C$ and $j = x, y, z$ respectively.
$P_{D_1 S}(t)$	:	Pr{ at time t, the system has failed due to failure of switching device S while one D-unit has failed already}
$\bar{F}(s)$	:	Laplace transform $(L.T.)$ of function $F(t)$
$S_i(t)$	:	$\mu_i(j)\exp\cdot - \int \mu_i(j)dj\}\forall i$ and j.

2.2 Assumptions

According to this model, the following are some assumptions:

(i) At time t = 0, all the system is new and operable with full efficiency.

(ii) The switching device used for the online standby generator is imperfect.

(iii) All the failures follow exponential time distribution, and nothing can fail from a failed state.

(iv) All repairs follow the general distribution of time and are perfect.

(v) Pre-emptive resumption policy has been implemented for repair purposes.

(vi) Repair to subsystem D can be given only when both the generators become fail. Otherwise, repair facilities are always available.

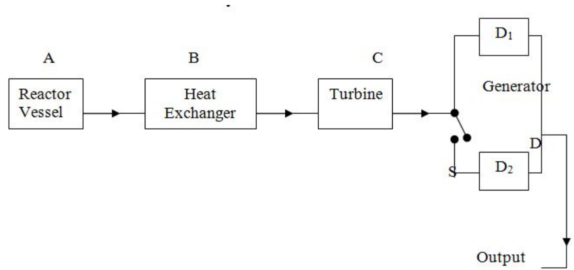

Fig-1(b): System Configuration

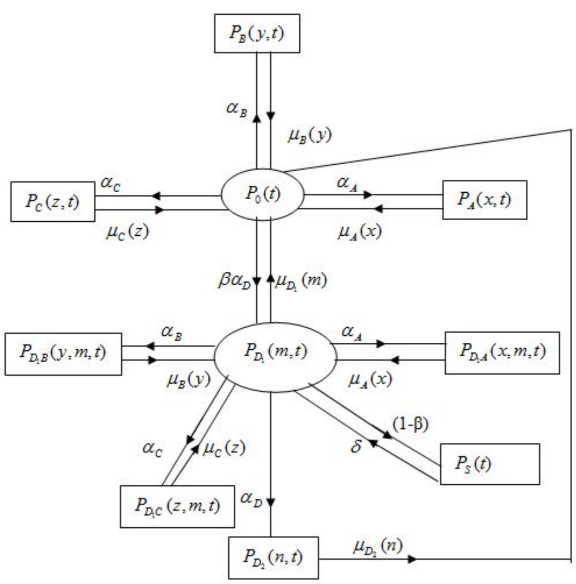

Fig-1(c): Transition-state diagram

3. Formulation of mathematical model

By using probability consideration and limiting procedure, we obtain the following set of difference-differential equations, which is continuous in time, discrete in space, and governing the behavior of the considered system:

$$\left[\frac{d}{dt}+\alpha_A+\alpha_B+\alpha_C+\beta\alpha_D\right]P_0(t) = \int_0^\infty P_A(x,t)\mu_A(x)dx+\int_0^\infty P_B(y,t)\mu_B(y)dy + \int_0^\infty P_C(z,t)\mu_C(z)dz+\int_0^\infty P_D(m,t)\mu_{D_1}(m)dm + \int_0^\infty P_{D_2}(n,t)\mu_{D_2}(n)dn \quad (3.1)$$

$$\left[\frac{\partial}{\partial j}+\frac{\partial}{\partial t}+\mu_i(j)\right]P_i(j,t)=0, \quad (3.2)$$

$\forall$, $i=A,B,C$ and $j=x,y,z$ respectively

$$\left[\frac{\partial}{\partial m}+\frac{\partial}{\partial t}+\alpha_A+\alpha_B+\alpha_C+\alpha_D+(1-\beta) +\mu_Q(m)\right]P_{D_1}(m,t) = \int_0^\infty P_{D_iA}(x,m,t)\mu_A(x)dx + \int_0^\infty P_{D_1B}(y,m,t)\mu_B(y)dy + \int_0^\infty P_{D_LC}(z,m,t)\mu_C(z)dz \quad (3.3)$$

$$\left[\frac{\partial}{\partial j}+\frac{\partial}{\partial t}+\mu_i(j)\right]P_{D_i i}(j,m,t)=0 \quad (3.4)$$

For $i=A,B,C$ and $j=x,y,z$ respectively

$$\left[\frac{d}{dt}+\delta\right]P_S(t)=(1-\beta)P_{D_1}(t) \quad (3.5)$$

$$\left[\frac{\partial}{\partial n}+\frac{\partial}{\partial t}+\mu_{D_2}(n)\right]P_{D_2}(n,t)=0 \quad (3.6)$$

Boundary conditions are:

$$P_i(0,t)=\alpha_i P_0(t) \quad ,\forall i=A,B,C \quad (3.7)$$

$$P_{D_1}(0,t)=\delta\mathscr{P}_S(t)+\beta\alpha_D P_0(t) \quad (3.8)$$

$$P_{D_1}(0,m,t)=\alpha_i P_{D_1}(m,t), \quad \forall i=A,B,C \quad (3.9)$$

$$P_{D_2}(0,t)=\alpha_D P_{D_1}(t) \quad (3.10)$$

Initial conditions are:

$$P_0(0)=1, \quad \text{otherwise zero} \quad (3.11)$$

3.1 Solution of the model

Taking Laplace transforms of equations (3.1) through (3.10) subjected to initial conditions (3.11), we obtain

$$[s+\alpha_A+\alpha_B+\alpha_C+\beta\alpha_D]\bar{P}_0(s) = 1+\int_0^\infty \bar{P}_A(x,s)\mu_A(x)dx+\int_0^\infty \bar{P}_B(y,s)\mu_B(y)dy + \int_0^\infty \bar{P}_C(z,s)\mu_C(z)dz+\int_0^\infty \bar{P}_{D_1}(m,s)\mu_{D_1}(m)dm + \int_0^\infty \bar{P}_{D_2}(n,s)\mu_{D_2}(n)dn \quad (3.12)$$

$$\left[\frac{\partial}{\partial j}+s+\mu_i(j)\right]\bar{P}_i(j,s)=0, \tag{3.13}$$

$\forall i=A,B,C$ and $j=x,y,z$ respectively.

$$\left[\frac{\partial}{\partial m}+s+\alpha_A+\alpha_B+\alpha_C+\alpha_D+(1-\beta)+\mu_{D_1}(m)\right]\bar{P}_{D_1}(m,s) \\ =\int_0^\infty \bar{P}_{D_iA}(x,m,s)\mu_A(x)dx \\ +\int_0^\infty \bar{P}_{D_1B}(y,m,s)\mu_B(y)dy+\int_0^\infty \bar{P}_{D_1C}(z,m,s)\mu_C(z)dz \tag{3.14}$$

$$\left[\frac{\partial}{\partial j}+s+\mu_i(j)\right]\bar{P}_{D_ii}(j,m,s)=0 \tag{3.15}$$

For $i=A,B,C$ and $j=x,y,z$ respectively

$$[s+\delta]\bar{P}_s(s)=(1-\beta)\bar{P}_{D_1}(s)$$
$$\left[\frac{\partial}{\partial n}+s+\mu_{D_2}(n)\right]\bar{P}_{D_2}(n,s)=0$$
$$\bar{P}_i(0,s)=\alpha_i\bar{P}_0(s)\quad,\quad\forall i=A,B,C$$
$$\bar{P}_{D_1}(0,s)=\delta\bar{P}_s(s)+\beta\alpha_D\bar{P}_0(s)$$
$$\bar{P}_{D_ii}(0,m,s)=\alpha_i\bar{P}_{D_1}(m,s),\quad\forall i=A,B \text{ and } C$$
$$\bar{P}_{D_2}(0,s)=\alpha_D\bar{P}_{D_1}(s)$$

Now integrating equation (3.13) with the help of boundary conditions (3.18), we get

$$\bar{P}_i(j,s)=\alpha_i\bar{P}_0(s)\exp\left\{-sj-\int\mu_i(j)dj\right\}$$

integrating this again w.r.t. j from 0 to ∞, we obtain

$$\bar{P}_i(s)=\alpha_i\bar{P}_0(s)\frac{1-\bar{S}_i(s)}{s}$$

or,

$$\bar{P}_i(s)=\alpha_i\bar{P}_0(s)D_i(\ s),\ \text{where } i=A,B \text{ and } C \tag{3.16}$$

Simplifying (3.16), we get

$$\bar{P}_s(s)=\frac{(1-\beta)\bar{P}_{D_l}(s)}{(s+\delta)} \tag{3.17}$$

Integrating equation (3.17) subjected to (3.21), we get

$$\bar{P}_{D_2}(n,s)=\alpha_D\bar{P}_{D_1}(s)\exp\left\{-sn-\int\mu_{D_2}(n)dn\right\} \tag{3.18}$$

$$\Rightarrow \bar{P}_{D_2}(s)=\alpha_D\bar{P}_{D_1}(s)D_{D_2}(\ s) \tag{3.19}$$

Now solving (3.15) with the help of (3.20), we obtain

$$\bar{P}_{D_ii}(j,m,s)=\alpha_i\bar{P}_{D_1}(m,s)\exp\left\{-sj-\int\mu_i(j)dj\right\}$$
$$\Rightarrow \bar{P}_{D_ii}(m,s)=\alpha_i\bar{P}_{D_1}(m,s)D_i(\ s)$$

$$\Rightarrow \bar{P}_{D_ii}(s)=\alpha_i\bar{P}_{D_1}(s)D_i(\ s), \tag{3.20}$$

where $i=A,B$ and C. Simplifying equation (3.14) with the help of relevant expressions, we get

$$\left[\frac{\partial}{\partial m}+s+\alpha_A+\alpha_B+\alpha_C+\alpha_D+(1-\beta)+\mu_{D_1}(m)\right]\bar{P}_{D_1}(m,s) \\ =\left[\alpha_A\bar{S}_A(s)+\alpha_B\bar{S}_B(s)+\alpha_C\bar{S}_C(s)\right]\bar{P}_{D_1}(m,s) \\ \Rightarrow\left[\frac{\partial}{\partial m}+s+s\alpha_AD_A(s)+s\alpha_BD_B(s)+s\alpha_CD_C(s)+\alpha_D \\ +(1-\beta)+\mu_{D_1}(m)\right]\bar{P}_{D_1}(m,s)=0$$

Integrating this subject to boundary condition (3.19), we obtain

$$\bar{P}_{D_1}(m,s)=\bar{P}_{D_1}(0,s)\exp\left\{-Am-\int\mu_{D_1}(m)dm\right\}$$
$$\Rightarrow \bar{P}_{D_1}(s)=\bar{P}_{D_1}(0,s)D_{D_1}(A)$$
$$\Rightarrow \bar{P}_{D_1}(s)=\left|\beta\alpha_D\bar{P}_0(s)+\delta\overline{P_s}(s)\right|D_{D_1}(A)$$
$$=\left[\beta\alpha_D\bar{P}_0(s)+\delta\frac{(1-\beta)\bar{P}_{D_1}(s)}{(s+\delta)}\right]D_{D_1}(A)$$
$$\text{or, }\bar{P}_{D_1}(s)=\frac{\beta\alpha_D\bar{P}_0(s)D_{D_1}(A)(s+\delta)}{(s+\beta\delta)}$$

where

$$A=s\left[1+\alpha_AD_A(s)+\alpha_BD_B(s)+\alpha_CD_C(s)\right]+\alpha_D+(1-\beta)$$

$$\text{or, }\bar{P}_{D_1}(s)=B(s)\bar{P}_0(s) \tag{3.21}$$

In last, simplifying equation (3.12) with the help of relevant expressions, one may obtain:

$$\bar{P}_0(s)=\frac{1}{E(s)}$$

Thus, finally, we obtained the following L.T. of various transition-state probabilities of fig-1(c), in terms of $E(s)$

$$\bar{P}_0(s)=\frac{1}{E(s)} \tag{3.22}$$
$$\bar{P}_i(s)=\frac{\alpha_iD_i(s)}{E(s)},\quad i=A,B,\text{ and } C \tag{3.23}$$
$$\bar{P}_{D_i}(s)=\frac{B(s)}{E(s)} \tag{3.24}$$
$$\bar{P}_{D_ii}(s)=\frac{\alpha_iB(s)D_i(s)}{E(s)},\quad i=A,B \text{ and } C \tag{3.25}$$
$$\bar{P}_S(s)=\frac{(1-\beta)B(s)}{(s+\delta)E(s)} \tag{3.26}$$
$$\text{and }\bar{P}_{D_2}(s)=\frac{\alpha_DB(s)D_{D_2}(s)}{E(s)} \tag{3.27}$$
$$\text{where,}B(s)=\frac{\beta\alpha_DD_{D_1}(A)(s+\delta)}{(s+\beta\delta)} \tag{3.28}$$
$$A=s\left[1+\alpha_AD_A(s)+\alpha_BD_B(s)+\alpha_CD_C(s)\right] \\ +\alpha_D+(1-\beta) \tag{3.29}$$

$$E(s) = A - (1-\beta)(1+\alpha_D) - \alpha_D \bar{S}_{D_2}(s)B(s) - \left[\beta\alpha_D + \frac{\delta(1-\beta)B(s)}{s+\delta}\right]\bar{S}_{D_1}(A)$$

It is interesting to note here that

$$\text{Sum of equations (3.27) through (3.32)} = \frac{1}{s} \tag{3.30}$$

3.2 Long-run behaviour of the system

Using Abel's lemma, viz; $\lim_{t\to\infty} P(t) = \lim_{s\to\infty} s\bar{P}(s) = P$ (say), provided the limit on left exists, in equations (3.27) through (3.32), we obtain the following long-run behavior of the considered system:

$$P_0 = \frac{1}{E'(0)} \tag{3.31}$$

$$P_i = \frac{\alpha_i M_i}{E'(0)}, \quad \forall i = A, B, \text{ and } C \tag{3.32}$$

$$P_{D_i} = \frac{B(0)}{E'(0)} \tag{3.33}$$

$$P_{D,i} = \frac{\alpha_i B(0) M_i}{E'(0)}, \quad \forall i = A, B \text{ and } C \tag{3.34}$$

$$P_S = \frac{(1-\beta)B(0)}{\delta E'(0)} \tag{3.35}$$

$$\text{and } P_{D_2} = \frac{\alpha_D B(0) M_{D_2}}{E'(0)} \tag{3.36}$$

where,

$$B(0) = \alpha_D D_{D_1}(A_0)$$
$$A_0 = \alpha_D + (1-\beta)$$
$$E'(0) = \left[\frac{d}{ds}E(s)\right]_{s-0}$$
$$M_i = -\bar{S}_i'(0) = \text{ Mean time to repair } i^{th} \text{ failure.}$$

3.3 Particular cases

Case (i) When all repairs follow exponential time distribution
Setting $\bar{S}_i(j) = \frac{\mu_i}{(j+\mu_i)} \forall i$ and j, in equations (3.27) through (3.32), we obtain the following L.T of probabilities of states of fig-1(c) in this case:

$$\bar{P}_0(s) = \frac{1}{E_1(s)}$$
$$\bar{P}_i(s) = \frac{\alpha_i}{E_1(s)(s+\mu_i)}, \quad \forall i = A, B, \text{ and } C$$
$$\bar{P}_{D_1}(s) = \frac{B_1(s)}{E_1(s)}$$
$$\bar{P}_{D_i i}(s) = \frac{\alpha_i B_1(s)}{E_1(s)(s+\mu_i)} \quad \forall i = A, B, \text{ and } C$$
$$\bar{P}_s(s) = \frac{(1-\beta)B_1(s)}{(s+\delta)E_1(s)}$$
$$\text{and } \bar{P}_{D_2}(s) = \frac{\alpha_D B_1(s)}{E_1(s)(s+\mu_{D_2})}$$
$$\text{where, } B_1(s) = \frac{\beta\alpha_D(s+\delta)}{(s+\beta\delta)(A_1+\mu_{D_1})}$$

$$A_1 = s\left[1 + \frac{\alpha_A}{s+\mu_A} + \frac{\alpha_B}{s+\mu_B} + \frac{\alpha_C}{s+\mu_C}\right] + \alpha_D + (1-\beta)$$
$$E_1(s) = A_1 - (1-\beta)(1+\alpha_D) - \frac{\alpha_D B_1(s)\mu_{D_2}}{(s+\mu_{D_2})} - \left[\beta\alpha_D + \frac{\delta(1-\beta)B_1(s)}{(s+\delta)}\right]\frac{\mu_{D_1}}{A_1+\mu_{D_1}}$$

Case (ii): When switching device S is perfect.
In this case, $P_S(0) = 0$ and put $\beta = 1$ in equations (3.27) through (3.32), we can obtain the required results.

3.4 Reliability and M.T.T.F. of the system

We have from equation (3.27)

$$\bar{R}(s) = \frac{1}{s+\alpha_A+\alpha_B+\alpha_C+\beta\alpha_D}$$

Taking inverse L. T., we obtain

$$R(t) = \exp\{-(\alpha_A+\alpha_B+\alpha_C+\beta\alpha_D)t\} \tag{3.37}$$

Also,

$$M\cdot T\cdot T\cdot F = \lim_{s\to 0} R(s) = \frac{1}{\alpha_A+\alpha_B+\alpha_C+\beta\alpha_D} \tag{3.38}$$

3.5 Availability of considered system

We have from equations (3.27) and (3.29)

$$\bar{P}_{up}(s) = \frac{1}{s+\alpha_A+\alpha_B+\alpha_C+\beta\alpha_D}\left[1 + \frac{\beta\alpha_D}{s+\alpha_A+\alpha_B+\alpha_C+\alpha_D+(1-\beta)}\right]$$

Inverting this, we obtain

$$P_{up}(t) = \left[1 + \frac{\beta \alpha_D}{(1+\alpha_D)(1-\beta)}\right] e^{-(\alpha_A+\alpha_s+\alpha_c+\beta\alpha_D)t} \tag{3.39}$$

$$- \frac{\beta \alpha_D}{(1+\alpha_D)(1-\beta)} e^{-(\alpha_d+\alpha_s+\alpha_c+\alpha_D+1-\beta)t} \tag{3.40}$$

Also,

$$P_{\text{down}}(t) = 1 - P_{\text{up}}(t) \tag{3.41}$$

4. Numerical Illustration

For a numerical example, let us consider the values: $\alpha_A = 0.02, \alpha_B = 0.03, \alpha_C = 0.06, \alpha_D = 0.08, \beta = 0.6$ and $t = 0, 1, 2, \ldots, 10$ Using these values in equations (53), (54), and (55), we compute the table- 1,2, and 3 , respectively. The corresponding graphs have been shown in fig-2, 3, and 4 respectively.

5. Results and discussion

Table-1 gives the values of reliability function for different values of time t. Its graph has been drawn in fig-2. Analysis of table-1 and fig-2 reveals that the considered system's reliability decreases slowly as we make an increase in the value of time t. Table- 2 gives the values of M.T.T.F. w.r.t. switching rate β. Its graph has been shown in fig-3. Examination of table-2 and fig-3 yields that M.T.T.F. decreases approximately in a consistent manner as we increase the value of βt.
Table- 3 computes the values of the considered system's availability function w.r.t. time t, and its graph has been shown in fig-4. This fig-4 indicates that the system's availability decreases catastrophically initially, and afterthat, it decreases smoothly. It is also noted that there are no sudden jumps in $R(t), M.T.T.F.$, and $P_{up}(t)$ values.

Table-1

Time t	Reliability R(t)
0	1
1	0.85385
2	0.729059
3	0.622507
4	0.531528
5	0.453845
6	0.387515
7	0.33088
8	0.282522
9	0.241231
10	0.205975

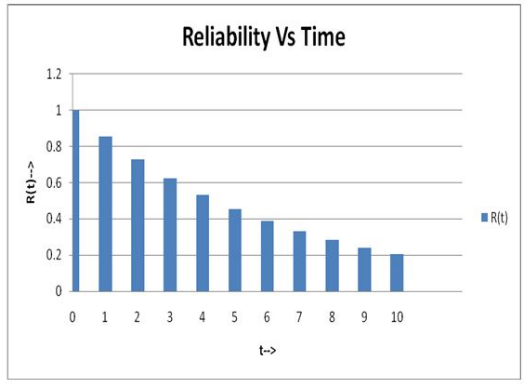

Fig 2.

Table-2

Switching Rate	M.T.T.F.
0	9.090909
0.1	8.474576
0.2	7.936508
0.3	7.462687
0.4	7.042254
0.5	6.666667
0.6	6.329114
0.7	6.024096
0.8	5.747126
0.9	5.494505
1	5.263158

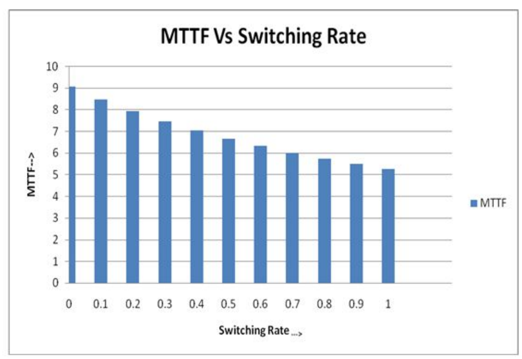

Fig 3.

Table-3

Time t	Availability P_{up} (t)
0	1
1	0.887127
2	0.775919
3	0.672744
4	0.58009
5	0.498452
6	0.427345
7	0.365854
8	0.312919
9	0.267483
10	0.228555

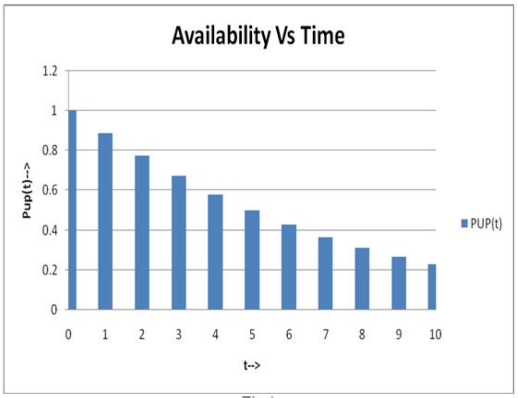

Fig 4.

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ISSN(P):2319 − 3786
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