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The Study of System Availability with Reboot Delay

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Abstract:

This paper extracts the availability of a warm standby system with reboot delay and switching failures. The system is studied under the assumption that the time-to-failure and the time to repair of the primary and standby units are exponentially and generally distributed, respectively. There is a possibility of failures during the switching from standby state to primary state. Reboot delay happens in this switching procedure of a standby unit to primary unit. The reboot time is assumed to be exponentially distributed. It is assumed that there is a significant probability of a switching failure. Primary and warm standby units can be considered to be repairable. Using the supplementary variable technique we develop the explicit expressions for the steady state availability.

Keywords: Availability; Switching failure; Warm standby units; Supplementary variable technique

1. Introduction:

Availability is used extensively in various field of engineering, such as production system, manufacturing system, parallel redundant system, multiprogramming system, and industrial system. An availability plan provides a strategy for availability control. Availability is concerned with the probabilistic mean values, probability distributions etc. one of the way increasing system availability is to allowed repair of primary unit as well as warm standby units. Rau (1970) has discussed in his book about the probability of several models in Systems Engineering. Ambuj and Stephen (1987) analyzed availability of computer systems. Tuteja and Gulshan (1992) considered cost benefits of two 4unit warm standby system with two server and different type of failure. Gupta and Rao (1996) gave interference model of M\G\1 machine with spare. Sarkar and Sarkar (2000) worked on availability of a system under faultless repair. Tern et al. (2004) explained availability of multicomponent systems with preventive maintenance. Parashar and Taneja (2007) evaluated reliability and profit of hot standby system with two types of repair facilities. Wang and Chen (2009) examined availability of three systems with reboot delay and switching failures. The system also worked with the assumption general repair times. Bieth et al. (2010) considered a system under arbitrary life with two repair persons.

Nakagawa (2011) gave different sources to analyze stochastic process for applications to reliability theory. Hajeeh (2012) discussed availability of a system with different repair. Levtin et al. (2013) optimized sequencing of a system with warm standbys. Yusuf (2015) evaluated availability of a repairable system with imperfect repairs and deterioration under. Kumar and Garg (2016) considered availability of series parallel system with help of soft computing technique. Devi, Kumar and Saini

(2017) analyzed non- identical unit system with weibull repair. Wang et al. (2018) examined cold-standby systems under periodic maintenance. Patowary et al. (2019) discussed modeling of microgrid system in hot standby mode. Yen et al. (2020) compared availability of systems with detection delay and general repair times. Lv (2021) worked on repairable system with one unreliable server and repair rate. Kanta and Chadhary (2024) used the idea of incomplete coverage probability to calculate a system's availability and probabilities. The availability of a warm standby system with a fault detection delay was covered by Kanta and Chadhary (2024). In their 2024 study, Kanta and Chadhary examined the costs of cold standby systems with common cause failures. The availability of a warm standby system with usual repair times was detailed by Kanta and Chadhary (2024). Gupta and Kumar (2025) analyzed an imperfect repairable system and obtained its availability.

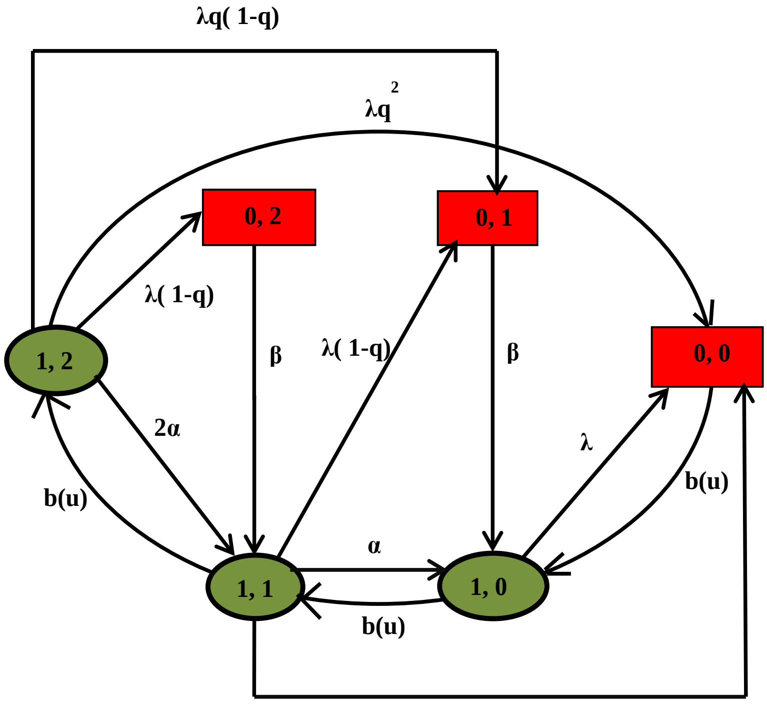
2. System Description:

In this study, a system is considered with reboot delay and switching failure. The system is studied under the statement that the time to failure and time to repair of the primary and standby units are exponentially and generally distributed. In this system, standby units work as warm standby units, whenever, primary unit is failed. There is a possibility of failures during the switching from standby unit to primary unit. It is expected that there exists a significant probability q of switching failure in the system. In the system, let us assume that reboot delay happens throughout the switching process of a standby unit to a primary unit. The reboot times are supposed to be exponentially dispersed with parameter β. The primary and standby units are considered to be repairable. The times to repair of the units of the system are random variables (i.i.d.) which having the distribution B (u) ($u \geq 0$) with a probability density function b (u) ($u \geq 0$), and mean repair time b_1. U is the remaining repair time for failed unit under repair such a supplementary variable. The system has one primary unit and two standby units with failure rate λ and α respectively. It has six states. Three states are operable states and three states are failed states. States (1,2), (1,1) & (1,0) are operable states while states (0,2), (0,1) & (0,0) are failed states.

3. Notation:

M (t): Number of primary units in the system, (initially).
N (t): Number of warm standby unit in the system.
U (t): Lasting repair time for the unit being repaired.
β: Reboot delay rate.
λ: Failure rate of primary unit in the system.
α: Failure rate of a warm standby in the system.
$P_{m,n}$ (t): Probability that at time t, where m and n are operating and warm standby units respectively. Where m = 0, 1 & n = 0, 1, 2.
b (u): Probability density functions for repair distribution.

4. The **STATE TRANSITION DIAGRAM** is as follows:



5. System Equation:

The differential difference equations of each state are as following.

$$P'_{1,2}(t) = -(\lambda + 2\alpha)P_{1,2}(t) + P_{1,1}(0,t) \quad (1)$$

$$P'_{0,2}(t) = -\beta P_{0,2}(t) + \lambda(1-q)P_{1,2}(t) \quad (2)$$

$$\left(\frac{\partial}{\partial t} - \frac{\partial}{\partial u}\right)P_{1,1}(u,t) = -(\lambda + \alpha)P_{1,1}(u,t) + 2\alpha P_{1,2}(u,t) + \beta P_{0,2}(u,t) + b(u)P_{1,0}(u,t) \quad (3)$$

$$P'_{0,1}(t) = -\beta P_{0,1}(t) + \lambda q(1-q)P_{1,2}(t) + \lambda(1-q)P_{1,1}(t) \quad (4)$$

$$\left(\frac{\partial}{\partial t} - \frac{\partial}{\partial u}\right)P_{1,0}(u,t) = -\lambda P_{1,0}(u,t) + \alpha P_{1,1}(u,t) + \beta P_{0,1}(u,t) + b(u)P_{0,0}(u,t) \quad (5)$$

$$\left(\frac{\partial}{\partial t} - \frac{\partial}{\partial u}\right)P_{0,0}(u,t) = \lambda q^2 P_{1,2}(u,t) + \lambda q P_{1,1}(u,t) + \lambda P_{1,0}(u,t) \quad (6)$$

From equation (1) - (6), we get the following steady state equation.

$$0 = -(\lambda + 2\alpha)P_{1,2} + P_{1,1}(0) \quad (7)$$

$$-\frac{\partial}{\partial u}P_{1,1}(u) = -(\lambda + \alpha)P_{1,1}(u) + 2\alpha P_{1,2}(u) + \beta P_{0,2}(u) + b(u)P_{1,0}(0) \quad (8)$$

$$-\frac{\partial}{\partial u}P_{1,0}(u) = -\lambda P_{1,0}(u) + \alpha P_{1,1}(u) + \beta P_{0,1}(u) + b(u)P_{0,0}(0) \tag{9}$$

$$-\frac{\partial}{\partial u}P_{0,0}(u,t) = \lambda q^2 P_{1,2}(u,t) + \lambda q P_{1,1}(u,t) + \lambda P_{1,0}(u) \tag{10}$$

$$0 = -\beta P_{0,2}(t) + \lambda(1-q)P_{1,2} \tag{11}$$

$$0 = -\beta P_{0,1} + \lambda q(1-q)P_{1,2} + \lambda(1-q)P_{1,1} \tag{12}$$

Where two state (0, 2) and (0, 1) incur a reboot delay with same mean 1/β. In steady state, we define.

$$P_{0,2}(u) = b(u)P_{0,2} \tag{13}$$

$$P_{1,2}(u) = b(u)P_{1,2} \tag{14}$$

$$P_{0,1}(u) = b(u)P_{0,1} \tag{15}$$

Further we define,

$$B^*(S) = \int_0^\infty e^{-su}dB(u) = \int_0^\infty e^{-su}b(u)du \tag{16}$$

$$P^*_{m,n}(S) = \int_0^\infty e^{-su}P_{m,n}(u)d(u) \tag{17}$$

$$P_{m,n} = P^*_{m,n}(0) = \int_0^\infty P_{m,n}(u)du \tag{18}$$

$$\int_0^\infty e^{-su}\frac{d}{du}P_{m,n}(u)du = SP^*_{m,n}(S) - P_{m,n}(0) \tag{19}$$

From equations (7), (11) and (12), we have.

$$P_{1,1}(0) = (\lambda + 2\alpha)P_{1,2} \tag{20}$$

$$P_{0,2} = \frac{\lambda(1-q)}{\beta}P_{1,2} \tag{21}$$

$$P_{0,1} = \frac{\lambda q(1-q)}{\beta}P_{1,2} + \frac{\lambda(1-q)}{\beta}P_{1,1} \tag{22}$$

Taking the Laplace – Stieltjes transformation of equation (8) - (10) by using equation (13) - 15) we have.

$$(\lambda + \alpha - s)P^*_{1,1}(s) = (\lambda(1-q) + 2\alpha)B^*(s)P_{1,2} + B^*(s)P_{1,0}(0) - P_{1,1}(0) \tag{23}$$

$$(\lambda - s)P^*_{1,0}(s) = \alpha P^*_{1,1}(s) + \beta B^*(s)P_{0,1} + B^*(s)P_{0,0}(0) - P_{1,0}(0) \tag{24}$$

$$-sP^*_{0,0}(s) = \lambda P^*_{1,0}(s) + \lambda q P^*_{1,1}(s) + \lambda q^2 B^*(s)P_{1,2} - P_{0,0}(0) \tag{25}$$

Now setting S = λ+α and S = 0 in equation (23) and using equation (20).

$$P_{1,0}(0) = \frac{\lambda q B^*(\lambda+\alpha) + (\lambda+2\alpha)\left[1 - B^*(\lambda+\alpha)\right]}{B^*(\lambda+\alpha)}P_{1,2} \tag{26}$$

$$P_{1,1}^{*}(0)=\frac{(\lambda+2\alpha)\left[1-B^{*}(\lambda+\alpha)\right]}{(\lambda+\alpha)B^{*}(\lambda+\alpha)}P_{1,2} \tag{27}$$

Putting again S = λ in equation (23) and using equation (26), we have.

$$P_{1,1}^{*}(\lambda)=\frac{(\lambda+2\alpha)\left[B^{*}(\lambda)-B^{*}(\lambda+\alpha)\right]}{\alpha B^{*}(\lambda+\alpha)}P_{1,2} \tag{28}$$

Now setting S = λ in equation (24).

$$P_{0,0}(0)=\frac{P_{1,0}(0)-\alpha P_{1,1}^{*}(\lambda)-\beta B^{*}(\lambda)P_{0,1}}{B^{*}(\lambda)} \tag{29}$$

We get after substituting equations (22), (26) and (28) into equation (29).

$$P_{0,0}(0)=\frac{1}{B^{*}(\lambda)}\left[\lambda q+\frac{(\lambda+2\alpha)\{1-B^{*}(\lambda)\}}{B^{*}(\lambda+\alpha)}\right]P_{1,2}+\left[-\lambda(1-q)\left\{q+\frac{(\lambda+2\alpha)\{1-B^{*}(\lambda+\alpha)\}}{(\lambda+\alpha)B^{*}(\lambda+\alpha)}\right\}\right]P_{1,2} \tag{30}$$

Put S = 0 in equation (25),

$$\lambda P_{1,0}^{*}(0)=P_{0,0}(0)-\lambda q P_{1,1}^{*}(0)+\lambda q^{2}P_{1,2} \tag{31}$$

Substituting equations (27) & (30) into equation (31).

$$P_{1,0}^{*}(0)=\left[\frac{q(1-B^{*}(\lambda))}{B^{*}(\lambda)}+\frac{(\lambda+2\alpha)(1-B^{*}(\lambda))}{\lambda B^{*}(\lambda)B^{*}(\lambda+\alpha)}-\frac{(\lambda+2\alpha)\{1-B^{*}(\lambda+\alpha)\}}{(\lambda+\alpha)B^{*}(\lambda+\alpha)}\right]P_{1,2} \tag{32}$$

Now differentiating equation (23) - (25) with respect to S and after this we put S = 0 in the obtained result then we have. Where $b_1=-B^{*(1)}(0)$ denotes mean repair time.

$$P_{1,1}^{*}(0)=(\lambda+\alpha)P_{1,1}^{*(1)}(0)+b_1\{[\lambda(1-q)+2\alpha]P_{1,2}+P_{1,0}(0)\} \tag{33}$$

$$P_{1,0}^{*}(0)=\lambda P_{1,0}^{*(1)}(0)-\alpha P_{1,1}^{*(1)}(0)+b_1[P_{0,0}(0)+\beta P_{0,1}] \tag{34}$$

$$P_{0,0}^{*}(0)=-\lambda P_{1,0}^{*(1)}(0)-\lambda q P_{1,1}^{*(1)}(0)+b_1\lambda q^{2}P_{1,2} \tag{35}$$

We get on substituting equations (26) and (27) into equation (33).

$$P_{1,1}^{*(1)}(0)=\frac{1}{(\lambda+\alpha)}\frac{(\lambda+2\alpha)}{B^{*}(\lambda+\alpha)}\left[\frac{\{1-B^{*}(\lambda+\alpha)\}}{(\lambda+\alpha)B^{*}}-b_1\right]P_{1,2} \tag{36}$$

We obtain the following equation after substituting equations (34) and (36) into equation (35).

$$P_{0,0}^{*}(0)=\left[\begin{array}{l}-\dfrac{q\{1-B^{*}(\lambda)\}}{B^{*}(\lambda)}+\dfrac{\lambda(1-q)(\lambda+2\alpha)\{1-B^{*}(\lambda+\alpha)\}}{(\lambda+\alpha)^{2}B^{*}(\lambda+\alpha)}+b_1\dfrac{(\lambda+2\alpha)(\lambda q+\alpha)}{(\lambda+\alpha)B^{*}(\lambda+\alpha)}\\ +\dfrac{(\lambda+2\alpha)\{1-B^{*}(\lambda)\}}{B^{*}(\lambda)B^{*}(\lambda+\alpha)}\left\{b_1-\dfrac{1}{\lambda}\right\}+\dfrac{\lambda q b_1}{B^{*}(\lambda)}+\lambda q^{2}\end{array}\right] \tag{37}$$

Now using the normalizing condition

$$P_{1,2}+P_{1,1}^{*}(0)+P_{1,0}^{*}(0)+P_{0,0}^{*}(0)+P_{0,2}+P_{0,1}=1 \tag{38}$$

We can compute $P_{1,2}$. We assume that two reboot delay state (0, 2) and (0, 1) are system down states. Then we get the availability A_V.

$$A_v = P_{1,2} + P_{1,1}^{*}(0) + P_{1,0}^{*}(0) \tag{39}$$

Now substituting (27) and (32) into equation (39), we get.

$$A_v = \left[1 + \frac{1 - B^{*}(\lambda)}{B^{*}(\lambda)}\left\{q + \frac{(\lambda + 2\alpha)}{\lambda B^{*}(\lambda + \alpha)}\right\}\right]P_{1,2} \tag{40}$$

6. Special cases for A_V :

In this work, we determine three repair time distributions; Exponential, Gamma and Uniform distribution respectively. The expressions of availability are as following.

I. Exponential repair time: This case consists of mean repair time set as $b_1 = 1/\mu$, where μ is the repair rate. We have the following values by taking Laplace transformation.

$$B^{*}(\lambda) = \frac{\mu}{\lambda + \mu} \tag{41}$$

$$B^{*}(\lambda + \alpha) = \frac{\mu}{\lambda + \mu + \alpha} \tag{42}$$

$$A_{VM} = \left[1 + \frac{\lambda}{\mu}\left\{q + \frac{(\lambda + 2\alpha)(\lambda + \alpha + \mu)}{\lambda\mu}\right\}\right]P_{1,2} \tag{43}$$

II. Gamma repair time distribution: This repair time has Gamma distribution with parameter r. We set the mean repair time set as $b_1 = 1/\mu$. After taking Laplace transformation we obtain the following results.

$$B^{*}(\lambda) = \left(\frac{r\mu}{\lambda + r\mu}\right)^{r} \tag{44}$$

$$B^{*}(\lambda + \alpha) = \left(\frac{r\mu}{\lambda + \alpha + r\mu}\right)^{r} \tag{45}$$

$$A_{V(Gam(r))} = \left[1 + \frac{\left\{(\lambda + r\mu)^{r} - (r\mu)^{r}\right\}}{(r\mu)^{r}}\left\{q + \frac{(\lambda + 2\alpha)(\lambda + \alpha + r\mu)^{r}}{\lambda (r\mu)^{r}}\right\}\right]P_{1,2} \tag{46}$$

III. Uniform repair time distribution: In this case, repair time has a uniform distribution over the time interval [a, b]. We set b_1= (a + b)/2 which is mean repair time. We obtain following values after taking Laplace transformation.

$$B^{*}(\lambda) = \frac{e^{-a\lambda} - e^{-b\lambda}}{\lambda(b - a)} \tag{47}$$

$$B^*(\lambda+\alpha)=\frac{e^{-a(\lambda+\alpha)}-e^{-b(\lambda+\alpha)}}{(\lambda+\alpha)(b-a)} \tag{48}$$

$$A_{V[U(a,b)]}=\left[1+\frac{\{\lambda(b-a)-(e^{-a\lambda}-e^{-b\lambda})\}}{(e^{-a\lambda}-e^{-b\lambda})}\left\{q+\frac{(\lambda+2\alpha)(\lambda+\alpha)(b-a)}{(e^{-a(\lambda+2\alpha)}-e^{-b(\lambda+2\alpha)})}\right\}\right]P_{1,2} \tag{49}$$

7. Comparison of Availability:

In this study, three types of repair time distributions as exponential, gamma and uniform are used.The values of different parameter are set as following.

$\frac{1}{\lambda}=1000$ days; $\frac{1}{\alpha}=2000$ days; $\frac{1}{\mu}=10$ days; $\frac{1}{\delta}=\frac{10}{24}$ days; $\frac{1}{q}=20$ days

i.e. $\lambda = 0.001, 0.0001, 0.00001$; $\alpha = 0.0005$; $\mu = 0.1$; $\delta = 2.4$; $q = 2.4$

In the following three cases α, μ and δ are keep fixed. We see variation in λ.

Case a: The value of λ vary from 0.001 to 0.01.
Case b: The value of λ vary from 0.0001 to 0.001.
Case c: The value of λ vary from 0.00001 to 0.0001.

The comparisons of availability with numerical results are given as following in tables 1-3.

λ	α	β	μ	q	A_{VM}	$A_{VGamma(r)}$	$A_{VU(a,b)}$
0.001	0.0005	2.4	0.1	0.05	0.998960009	0.998961157	0.998961482
0.002	0.0005	2.4	0.1	0.05	0.997625971	0.9976261	0.997626031
0.003	0.0005	2.4	0.1	0.05	0.995912519	0.995904434	0.995901652
0.004	0.0005	2.4	0.1	0.05	0.993832816	0.993804818	0.993795541
0.005	0.0005	2.4	0.1	0.05	0.991399808	0.991336062	0.991315136

0.006	0.0005	2.4	0.1	0.05	0.988626236	0.988507117	0.988468113
0.007	0.0005	2.4	0.1	0.05	0.985524643	0.985327077	0.985262382
0.008	0.0005	2.4	0.1	0.05	0.982107382	0.981805174	0.981706079
0.009	0.0005	2.4	0.1	0.05	0.97838662	0.977950766	0.977807561
0.01	0.0005	2.4	0.1	0.05	0.974374347	0.973773336	0.9735754

Table 1

λ	α	β	μ	q	A_{VM}	$A_{VGamma(r)}$	$A_{VU(a,b)}$
0.001	0.0005	1	0.1	0.05	0.998380338	0.99838147	0.99838179
0.001	0.0005	2	0.1	0.05	0.998877158	0.998878303	0.998878627
0.001	0.0005	3	0.1	0.05	0.999042874	0.999044024	0.99904435
0.001	0.0005	4	0.1	0.05	0.999125753	0.999126905	0.999127231
0.001	0.0005	5	0.1	0.05	0.999175486	0.999176641	0.999176967
0.001	0.0005	6	0.1	0.05	0.999208645	0.9992098	0.999210127
0.001	0.0005	7	0.1		0.999232331	0.999233487	0.999233814

				0.05			
0.001	0.0005	8	0.1	0.05	0.999250097	0.999251253	0.99925158
0.001	0.0005	9	0.1	0.05	0.999263914	0.999265071	0.999265398
0.001	0.0005	10	0.1	0.05	0.999274969	0.999276126	0.999276453

Table 2

λ	α	β	μ	q	A_{VM}	$A_{VGamma(r)}$	$A_{VU(a,b)}$
0.001	0.0005	2.4	0.1	0.01	0.998993525	0.99899119	0.998990426
0.001	0.0005	2.4	0.1	0.02	0.998987957	0.998986493	0.998986001
0.001	0.0005	2.4	0.1	0.03	0.998980514	0.998979921	0.998979701
0.001	0.0005	2.4	0.1	0.04	0.998971198	0.998971475	0.998971528
0.001	0.0005	2.4	0.1	0.05	0.998960009	0.998961157	0.998961482
0.001	0.0005	2.4	0.1	0.06	0.998946948	0.998948966	0.998949563
0.001	0.0005	2.4	0.1	0.07	0.998932015	0.998934904	0.998935773
0.001	0.0005	2.4	0.1		0.998915212	0.998918971	0.998920112

				0.08			
0.001	0.0005	2.4	0.1	0.09	0.998896539	0.998901168	0.998902581
0.001	0.0005	2.4	0.1	0.1	0.998875996	0.998881496	0.998883181

Table 3

8. Interpretation of the results:

In this study, we analyzed the availability of a warm standby system incorporating key real-world complexities such as reboot delay**,** switching failures**,** and generally distributed repair times**.** By modeling the system with one primary unit and two warm standby units, and by classifying the system into six distinct states, we were able to capture the system's behavior under various failures and repair scenarios. Using the supplementary variable technique**,** we developed explicit expressions for the steady-state availability of the system. The model accommodates exponential failure and reboots times, along with general repair time distributions, making it flexible and applicable to a wide range of practical systems. The analysis highlights the significant impact of switching failure probability and reboot delay on system availability. As such, these factors should be carefully considered in the design and maintenance planning of standby systems to ensure high reliability and reduced downtime. This work provides a strong analytical foundation for further research into more complex or larger-scale systems, including those with multiple standby levels, varying repair priorities, or different standby policies (e.g., cold or hot standby).

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