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Availability Measures for 4-Component system by using Markov Process

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ABSTRACT

Availability depends on both reliability and maintainability. To predict system availability, both the failure and repair probability must be considered. Markov process is employed to build the Mathematical models of reliability and availability for the repairable systems. In this paper, availability is computed for repairable system consisting of 4-components by using Markov process.

Key words: Availability, Reliability, Maintainability, Probability, Markov process.

1. INTRODUCTION

Markov analysis is a powerful modeling technique with strong application in reliability and availability analysis. Markov model consists of comprehensive representations of possible chains of events i.e., transition with systems which, in the case of reliability and availability analysis, correspond to sequences of failures and repair.

Reliability as the probability of a system performing its intended function under stated conditions without failure for a given period of time [1]. Availability is the probability that a component or system is performing its required function at a given time (t) when used under stated operating conditions [2]. It differs from reliability in that availability is the probability that the component is currently in a non-failure state even though it may have previously failed and have been restored to its normal operating conditions. Therefore system availability can never be less than system reliability. Availability may be the preferred measure when the system or component can be restored since it accounts for both failures and repairs.

Vijayalaxmi Dharwd and S.B.Karjagi [3] studied Modelling and analysis of generation system based on Markov process with case study. Xiaoquan Li et al [4] has described Reliability analysis based on Markov process for repairable systems. M.A.EI-Damcese and N.S.Temraz [5] have estimated Availability and reliability measures for multi state system by using Markov reward model. Upasana, Neetu Gupta and Yogesh Kumar Goyal [6] have been discussed Availability function using Markov modelling with application of soft ware

on matrix method. M.A. El-Dameese and N.S. Temraz [7] studied analysis for a parallel repairable system with different failure modes. Neama Salah Youssef Temraz [8] discussed availability and reliability analysis for dependent system with load-sharing and degradation facility.

2. MATHEMATICAL MODEL

2.1. 4-component system, if at least 3-components are good and one back up unit.

Consider 4-component system with three primary units in series and one back up unit that can replace either of the primary units. 4-component system can have $2^4 = 16$ states. The failure rates are $\lambda_1, \lambda_2, \lambda_3, \lambda_4^- \,\&\, \lambda_4$ for components 1,2,3,4 on standby, and 4 on-line, respectively and the repair rate is μ. The transition rate diagram is given below.

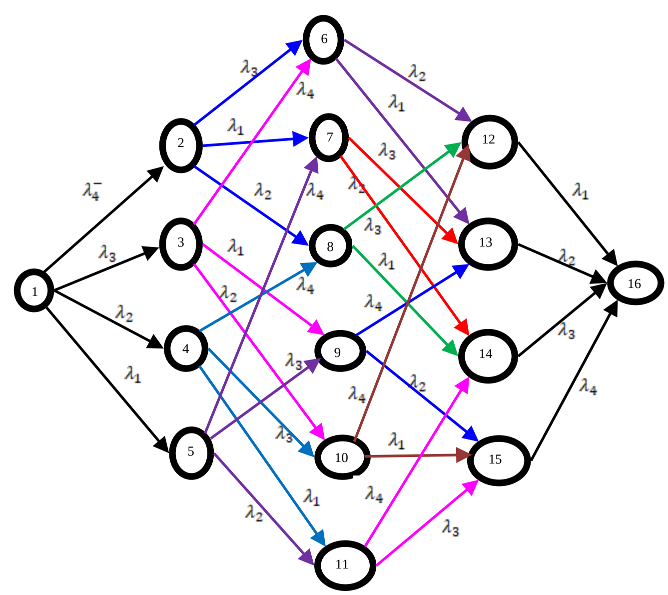

Figure 1: Rate diagram for a four –component system

Table 1: State definition for four component system

State	Component 1	Component 2	Component 3	Component 4
1	Good	Good	Good	Standby
2	Good	Good	Good	Failed
3	Good	Good	Failed	Good
4	Good	Failed	Good	Good
5	Failed	Good	Good	Good
6	Good	Good	Failed	Failed
7	Failed	Good	Good	Failed
8	Good	Failed	Good	Failed
9	Failed	Good	Failed	Good
10	Good	Failed	Failed	Good
11	Failed	Failed	Good	Good
12	Good	Failed	Failed	Failed
13	Failed	Good	Failed	Failed
14	Failed	Failed	Good	Failed
15	Failed	Failed	Failed	Good
16	Failed	Failed	Failed	Failed

From the state definitions, the reliability

$$R(t) = P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t)$$

$$R(t) = \sum_{j=1}^{5} P_j(t)$$

The state equations are

$$\frac{dP_1(t)}{dt} = \left(1 - (\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4^-)\right)P_1(t) + \mu P_2(t) + \mu P_3(t) + \mu P_4(t) + \mu P_5(t)$$

$$\frac{dP_2(t)}{dt} = \lambda_4^- P_1(t) + \left(1 - (\lambda_1 + \lambda_2 + \lambda_3 + \mu)\right)P_2(t) + \mu P_6(t) + \mu P_7(t) + \mu P_8(t)$$

$$\frac{dP_3(t)}{dt} = \lambda_3 P_1(t) + \left(1 - (\lambda_4 + \lambda_1 + \lambda_2 + \mu)\right)P_3(t) + \mu P_6(t) + \mu P_9(t) + \mu P_{10}(t)$$

$$\frac{dP_4(t)}{dt} = \lambda_2 P_1(t) + \left(1 - (\lambda_4 + \lambda_3 + \lambda_1 + \mu)\right)P_4(t) + \mu P_8(t) + \mu P_{10}(t) + \mu P_{11}(t)$$

$$\frac{dP_5(t)}{dt} = \lambda_1 P_1(t) + \left(1 - (\lambda_4 + \lambda_3 + \lambda_2 + \mu)\right)P_5(t) + \mu P_7(t) + \mu P_9(t) + \mu P_{11}(t)$$

$$\frac{dP_6(t)}{dt} = \lambda_3 P_2(t) + \lambda_4 P_3(t) + \left(1 - (\lambda_2 + \lambda_1 + 2\mu)\right)P_6(t) + \mu P_{12}(t) + \mu P_{13}(t)$$

$$\frac{dP_7(t)}{dt} = \lambda_1 P_2(t) + \lambda_4 P_5(t) + \left(1 - (\lambda_2 + \lambda_3 + 2\mu)\right)P_7(t) + \mu P_{13}(t) + \mu P_{14}(t)$$

$$\frac{dP_8(t)}{dt} = \lambda_4 P_4(t) + \lambda_2 P_2(t) + \left(1 - (\lambda_3 + \lambda_1 + 2\mu)\right)P_8(t) + \mu P_{12}(t) + \mu P_{14}(t)$$

$$\frac{dP_9(t)}{dt} = \lambda_1 P_3(t) + \lambda_3 P_5(t) + \left(1 - (\lambda_4 + \lambda_2 + 2\mu)\right)P_9(t) + \mu P_{13}(t) + \mu P_{15}(t)$$

$$\frac{dP_{10}(t)}{dt} = \lambda_2 P_3(t) + \lambda_3 P_4(t) + \left(1 - (\lambda_4 + \lambda_1 + 2\mu)\right)P_{10}(t) + \mu P_{12}(t) + \mu P_{15}(t)$$

$$\frac{dP_{11}(t)}{dt} = \lambda_1 P_4(t) + \lambda_2 P_5(t) + \left(1 - (\lambda_4 + \lambda_3 + 2\mu)\right)P_{11}(t) + \mu P_{14}(t) + \mu P_{15}(t)$$

$$\frac{dP_{12}(t)}{dt} = \lambda_2 P_6(t) + \lambda_3 P_8(t) + \lambda_4 P_{10}(t) + \left(1 - (\lambda_1 + 3\mu)\right)P_{12}(t) + \mu P_{16}(t)$$

$$\frac{dP_{13}(t)}{dt} = \lambda_1 P_6(t) + \lambda_3 P_7(t) + \lambda_4 P_9(t) + \left(1 - (\lambda_2 + 3\mu)\right)P_{13}(t) + \mu P_{16}(t)$$

$$\frac{dP_{14}(t)}{dt} = \lambda_2 P_7(t) + \lambda_1 P_8(t) + \lambda_4 P_{11}(t) + \left(1 - (\lambda_3 + 3\mu)\right)P_{14}(t) + \mu P_{16}(t)$$

$$\frac{dP_{15}(t)}{dt} = \lambda_2 P_9(t) + \lambda_1 P_{10}(t) + \lambda_3 P_{11}(t) + \left(1 - (\lambda_4 + 3\mu)\right)P_{15}(t) + \mu P_{16}(t)$$

$$\frac{dP_{16}(t)}{dt} = \lambda_1 P_{12}(t) + \lambda_2 P_{13}(t) + \lambda_3 P_{14}(t) + \lambda_4 P_{15}(t) - 3\mu P_{16}(t)$$

The repair capability is involved, the transition matrix is modified as follows, with the last row replacing a redundant equation and representing the equation

$$\sum_{i=1}^{16} P_i(t) = 1$$

The transition matrix is

$$T = \begin{bmatrix}
a & \mu & \mu & \mu & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_4^- & b & 0 & 0 & 0 & \mu & \mu & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_3 & 0 & c & 0 & 0 & \mu & 0 & 0 & \mu & \mu & 0 & 0 & 0 & 0 & 0 & 0 \\
\lambda_2 & 0 & 0 & d & 0 & 0 & 0 & \mu & 0 & \mu & \mu & 0 & 0 & 0 & 0 & 0 \\
\lambda_1 & 0 & 0 & 0 & e & 0 & \mu & 0 & \mu & 0 & \mu & 0 & 0 & 0 & 0 & 0 \\
0 & \lambda_3 & \lambda_4 & 0 & 0 & f & 0 & 0 & 0 & 0 & 0 & \mu & \mu & 0 & 0 & 0 \\
0 & \lambda_1 & 0 & 0 & \lambda_4 & 0 & g & 0 & 0 & 0 & 0 & 0 & \mu & \mu & 0 & 0 \\
0 & \lambda_2 & 0 & \lambda_4 & 0 & 0 & 0 & h & 0 & 0 & 0 & \mu & 0 & \mu & 0 & 0 \\
0 & 0 & \lambda_1 & 0 & \lambda_3 & 0 & 0 & 0 & i & 0 & 0 & 0 & \mu & 0 & \mu & 0 \\
0 & 0 & \lambda_2 & \lambda_3 & 0 & 0 & 0 & 0 & 0 & j & 0 & \mu & 0 & 0 & \mu & 0 \\
0 & 0 & 0 & \lambda_1 & \lambda_2 & 0 & 0 & 0 & 0 & 0 & k & 0 & 0 & \mu & \mu & 0 \\
0 & 0 & 0 & 0 & 0 & \lambda_2 & 0 & \lambda_3 & 0 & \lambda_4 & 0 & l & 0 & 0 & 0 & \mu \\
0 & 0 & 0 & 0 & 0 & \lambda_1 & \lambda_3 & 0 & \lambda_4 & 0 & 0 & 0 & m & 0 & 0 & \mu \\
0 & 0 & 0 & 0 & 0 & 0 & \lambda_2 & \lambda_1 & 0 & 0 & \lambda_4 & 0 & 0 & n & 0 & \mu \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_2 & \lambda_1 & \lambda_3 & 0 & 0 & 0 & o & \mu \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & -3\mu \\
1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1
\end{bmatrix}$$

Where

$a = -(\lambda_1 + \lambda_2 + \lambda_3 + \lambda_4^-)$,
$b = -(\lambda_1 + \lambda_2 + \lambda_3 + \mu)$,
$c = -(\lambda_1 + \lambda_2 + \lambda_4 + \mu)$,
$d = -(\lambda_4 + \lambda_3 + \lambda_1 + \mu)$,
$e = -(\lambda_2 + \lambda_3 + \lambda_4 + \mu)$,
$f = -(\lambda_1 + \lambda_2 + 2\mu)$,
$g = -(\lambda_2 + \lambda_3 + 2\mu)$,
$h = -(\lambda_1 + \lambda_3 + 2\mu)$,

$i = -(\lambda_2 + \lambda_4 + 2\mu),$
$j = -(\lambda_1 + \lambda_4 + 2\mu),$
$k = -(\lambda_3 + \lambda_4 + 2\mu),$
$l = -(\lambda_1 + 3\mu),$
$m = -(\lambda_2 + 3\mu),$
$n = -(\lambda_3 + 3\mu),$
$o = -(\lambda_4 + 3\mu)$

2.2. 4-component system, if at least 2-components are good and two back up units.

In a similar method 4-component system with two primary units in series and two back up units that can replace either of the primary units. 4-component system can have $2^4 = 16$ states. The failure rates are $\lambda_1,\lambda_2,\lambda_3^-,\lambda_3,\lambda_4^-$ & λ_4 for components 1, 2, 3 on standby,3on-line,4 on standby, and 4 on-line, respectively and the repair rate is μ.

Table 2: State definition for four component system

State	Component 1	Component 2	Component 3	Component 4
1	Good	Good	Standby	Standby
2	Good	Good	Good	Failed
3	Good	Good	Failed	Good
4	Good	Failed	Good	Good
5	Failed	Good	Good	Good
6	Good	Good	Failed	Failed
7	Failed	Good	Good	Failed
8	Good	Failed	Good	Failed
9	Failed	Good	Failed	Good
10	Good	Failed	Failed	Good
11	Failed	Failed	Good	Good
12	Good	Failed	Failed	Failed
13	Failed	Good	Failed	Failed
14	Failed	Failed	Good	Failed
15	Failed	Failed	Failed	Good
16	Failed	Failed	Failed	Failed

From the state definitions, the reliability

$$R(t) = P_1(t) + P_2(t) + P_3(t) + P_4(t) + P_5(t) + P_6(t) + P_7(t) + P_8(t) + P_9(t) + P_{10}(t) + P_{11}(t)$$

$$R(t) = \sum_{j=1}^{11} P_j(t)$$

The state equations are

$$\frac{dP_1(t)}{dt} = (1 - (\lambda_1 + \lambda_2 + \lambda_3^- + \lambda_4^-))P_1(t) + \mu P_2(t) + \mu P_3(t) + \mu P_4(t) + \mu P_5(t)$$

$$\frac{dP_2(t)}{dt} = \lambda_4^- P_1(t) + (1 - (\lambda_1 + \lambda_2 + \lambda_3^- + \mu))P_2(t) + \mu P_6(t) + \mu P_7(t) + \mu P_8(t)$$

$$\frac{dP_3(t)}{dt} = \lambda_3 P_1(t) + (1 - (\lambda_4 + \lambda_1 + \lambda_2 + \mu))P_3(t) + \mu P_6(t) + \mu P_9(t) + \mu P_{10}(t)$$

$$\frac{dP_4(t)}{dt} = \lambda_2 P_1(t) + (1 - (\lambda_4 + \lambda_3 + \lambda_1 + \mu))P_4(t) + \mu P_8(t) + \mu P_{10}(t) + \mu P_{11}(t)$$

$$\frac{dP_5(t)}{dt} = \lambda_1 P_1(t) + (1 - (\lambda_4 + \lambda_3 + \lambda_2 + \mu))P_5(t) + \mu P_7(t) + \mu P_9(t) + \mu P_{11}(t)$$

$$\frac{dP_6(t)}{dt} = \lambda_3 P_2(t) + \lambda_4 P_3(t) + (1 - (\lambda_2 + \lambda_1 + 2\mu))P_6(t) + \mu P_{12}(t) + \mu P_{13}(t)$$

$$\frac{dP_7(t)}{dt} = \lambda_1 P_2(t) + \lambda_4 P_5(t) + (1 - (\lambda_2 + \lambda_3 + 2\mu))P_7(t) + \mu P_{13}(t) + \mu P_{14}(t)$$

$$\frac{dP_8(t)}{dt} = \lambda_4 P_4(t) + \lambda_2 P_2(t) + (1 - (\lambda_3 + \lambda_1 + 2\mu))P_8(t) + \mu P_{12}(t) + \mu P_{14}(t)$$

$$\frac{dP_9(t)}{dt} = \lambda_1 P_3(t) + \lambda_3 P_5(t) + (1 - (\lambda_4 + \lambda_2 + 2\mu))P_9(t) + \mu P_{13}(t) + \mu P_{15}(t)$$

$$\frac{dP_{10}(t)}{dt} = \lambda_2 P_3(t) + \lambda_3 P_4(t) + (1 - (\lambda_4 + \lambda_1 + 2\mu))P_{10}(t) + \mu P_{12}(t) + \mu P_{15}(t)$$

$$\frac{dP_{11}(t)}{dt} = \lambda_1 P_4(t) + \lambda_2 P_5(t) + (1 - (\lambda_4 + \lambda_3 + 2\mu))P_{11}(t) + \mu P_{14}(t) + \mu P_{15}(t)$$

$$\frac{dP_{12}(t)}{dt} = \lambda_2 P_6(t) + \lambda_3 P_8(t) + \lambda_4 P_{10}(t) + (1 - (\lambda_1 + 3\mu))P_{12}(t) + \mu P_{16}(t)$$

$$\frac{dP_{13}(t)}{dt} = \lambda_1 P_6(t) + \lambda_3 P_7(t) + \lambda_4 P_9(t) + (1 - (\lambda_2 + 3\mu))P_{13}(t) + \mu P_{16}(t)$$

$$\frac{dP_{14}(t)}{dt} = \lambda_2 P_7(t) + \lambda_1 P_8(t) + \lambda_4 P_{11}(t) + (1 - (\lambda_3 + 3\mu))P_{14}(t) + \mu P_{16}(t)$$

$$\frac{dP_{15}(t)}{dt} = \lambda_2 P_9(t) + \lambda_1 P_{10}(t) + \lambda_3 P_{11}(t) + (1 - (\lambda_4 + 3\mu))P_{15}(t) + \mu P_{16}(t)$$

$$\frac{dP_{16}(t)}{dt} = \lambda_1 P_{12}(t) + \lambda_2 P_{13}(t) + \lambda_3 P_{14}(t) + \lambda_4 P_{15}(t) - 3\mu P_{16}(t)$$

The repair capability is involved, the transition matrix is modified as follows, with the last row replacing a redundant equation and representing the equation

$$\sum_{i=1}^{16} P_i(t) = 1$$

The transition matrix is

$$T=\begin{bmatrix} a & \mu & \mu & \mu & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_4^- & b & 0 & 0 & 0 & \mu & \mu & \mu & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_3^- & 0 & c & 0 & 0 & \mu & 0 & 0 & \mu & \mu & 0 & 0 & 0 & 0 & 0 & 0 \\ \lambda_2 & 0 & 0 & d & 0 & 0 & 0 & \mu & 0 & \mu & \mu & 0 & 0 & 0 & 0 & 0 \\ \lambda_1 & 0 & 0 & 0 & e & 0 & \mu & 0 & \mu & 0 & \mu & 0 & 0 & 0 & 0 & 0 \\ 0 & \lambda_3 & \lambda_4 & 0 & 0 & f & 0 & 0 & 0 & 0 & 0 & \mu & \mu & 0 & 0 & 0 \\ 0 & \lambda_1 & 0 & 0 & \lambda_4 & 0 & g & 0 & 0 & 0 & 0 & 0 & \mu & \mu & 0 & 0 \\ 0 & \lambda_2 & 0 & \lambda_4 & 0 & 0 & 0 & h & 0 & 0 & 0 & \mu & 0 & \mu & 0 & 0 \\ 0 & 0 & \lambda_1 & 0 & \lambda_3 & 0 & 0 & 0 & i & 0 & 0 & 0 & \mu & 0 & \mu & 0 \\ 0 & 0 & \lambda_2 & \lambda_3 & 0 & 0 & 0 & 0 & 0 & j & 0 & \mu & 0 & 0 & \mu & 0 \\ 0 & 0 & 0 & \lambda_1 & \lambda_2 & 0 & 0 & 0 & 0 & 0 & k & 0 & 0 & \mu & \mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda_2 & 0 & \lambda_3 & 0 & \lambda_4 & 0 & l & 0 & 0 & 0 & \mu \\ 0 & 0 & 0 & 0 & 0 & \lambda_1 & \lambda_3 & 0 & \lambda_4 & 0 & 0 & 0 & m & 0 & 0 & \mu \\ 0 & 0 & 0 & 0 & 0 & 0 & \lambda_2 & \lambda_1 & 0 & 0 & \lambda_4 & 0 & 0 & n & 0 & \mu \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_2 & \lambda_1 & \lambda_3 & 0 & 0 & 0 & o & \mu \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & \lambda_1 & \lambda_2 & \lambda_3 & \lambda_4 & -3\mu \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

$a=-(\lambda_1+\lambda_2+\lambda_3^-+\lambda_4^-)$,
$b=-(\lambda_1+\lambda_2+\lambda_3^-+\mu)$,
$c=-(\lambda_1+\lambda_2+\lambda_4+\mu)$,
$d=-(\lambda_4+\lambda_3+\lambda_1+\mu)$,
$e=-(\lambda_2+\lambda_3+\lambda_4+\mu)$,
$f=-(\lambda_1+\lambda_2+2\mu)$,
$g=-(\lambda_2+\lambda_3+2\mu)$,
$h=-(\lambda_1+\lambda_3+2\mu)$,
$i=-(\lambda_2+\lambda_4+2\mu)$,
$j=-(\lambda_1+\lambda_4+2\mu)$,
$k=-(\lambda_3+\lambda_4+2\mu)$,
$l=-(\lambda_1+3\mu)$,
$m=-(\lambda_2+3\mu)$,
$n=-(\lambda_3+3\mu)$,
$o=-(\lambda_4+3\mu)$

3. NUMERICAL RESULTS

Let
$\lambda_1=0.01,\ \lambda_2=0.02,\ \lambda_3=0.03, \lambda_3^-=0.03,$
$\lambda_4=0.04,\ \lambda_4^-=0.004\ \ and\ \ \mu=0.1.$

Then $T=$

$$\begin{bmatrix} -0.064 & 0.1 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.004 & -0.16 & 0 & 0 & 0 & 0.1 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.03 & 0 & -0.17 & 0 & 0 & 0.1 & 0 & 0 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.02 & 0 & 0 & -0.18 & 0 & 0 & 0 & 0.1 & 0 & 0.1 & 0.1 & 0 & 0 & 0 & 0 & 0 \\ 0.01 & 0 & 0 & 0 & -0.19 & 0 & 0.1 & 0 & 0.1 & 0 & 0.1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0.03 & 0.003 & 0 & 0 & -0.23 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0.1 & 0 & 0 & 0 \\ 0 & 0.01 & 0 & 0 & 0.003 & 0 & -0.25 & 0 & 0 & 0 & 0 & 0 & 0.1 & 0.1 & 0 & 0 \\ 0 & 0.02 & 0 & 0.003 & 0 & 0 & 0 & -0.24 & 0 & 0 & 0 & 0.1 & 0 & 0.1 & 0 & 0 \\ 0 & 0 & 0.01 & 0 & 0.03 & 0 & 0 & 0 & -0.26 & 0 & 0 & 0 & 0.1 & 0 & 0.1 & 0 \\ 0 & 0 & 0.02 & 0.03 & 0 & 0 & 0 & 0 & 0 & -0.25 & 0 & 0.1 & 0 & 0 & 0.1 & 0 \\ 0 & 0 & 0 & 0.01 & 0.02 & 0 & 0 & 0 & 0 & 0 & -0.27 & 0 & 0 & 0.1 & 0.1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0.02 & 0 & 0.03 & 0 & 0.003 & 0 & -0.31 & 0 & 0 & 0 & 0.1 \\ 0 & 0 & 0 & 0 & 0 & 0.01 & 0.03 & 0 & 0.003 & 0 & 0 & 0 & -0.32 & 0 & 0 & 0.1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0.02 & 0.01 & 0 & 0 & 0.003 & 0 & 0 & -0.33 & 0 & 0.1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.02 & 0.01 & 0.03 & 0 & 0 & 0 & -0.34 & 0.1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}$$

Where $P=T^{-1}b$ with $P^t=[P_1,P_2,P_3,\dots,P_{16}]$ &
$b^t=[0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,1]$

Using Mat lab, the solution is

$P_1=0.5229, P_2=0.0598, P_3=0.1375, P_4=0.0916, P_5=0.0457, P_6=0.0373,$
$P_7=0.0126, P_8=0.0250, P_9=0.0132, P_{10}=0.0264, P_{11}=0.0088, P_{12}=0.0085,$
$P_{13}=0.0043, P_{14}=0.0029, P_{15}=0.0026, P_{16}=0.0009.$

4-component system, if at least 3-components are good and one back up unit steady state availability is

$$A=P_1+P_2+P_3+P_4+P_5=0.8575.$$

4-component system, if at least 2-components are good and two back up units steady state availability is

$$A=P_1+P_2+P_3+P_4+P_5+P_6+P_7+P_8+P_9+P_{10}+P_{11}=0.9808.$$

4. CONCLUSION

Steady state availability has been computed for repairable system consisting of 4-components by using Markov process when at least three components are good, and one back up unit and at least two components are good, and two back up units.

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