Reliability Assessment of AC Power Supply of a Nuclear Reactor Model

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Abstract

The reliability is defined as the probability that a system (item) will perform a specified function under specified operational and environment condition, at specified time. The assessment of reliability benefits the interconnected operation which led to increasing interest in efficient reliability evaluation methods, so any reliability analysis of system must be based on precisely defined concepts. Markov method technique used to assess time based reliability, which are very important data to the engineers and designers for designing and developing any system to ensure that the system will operate satisfactorily and does not loss its essential function when operating and applying on the AC power supply of a nuclear reactor.

الخلاصة

الوثوقية هي احتمالية ضمان تجهيز المستهلك بالقدرة دون انقطاع عند شروط معينة وعند فترة زمنية محددة إن حساب الوثوقية يفيد في الأنظمة المعقدة المتشابكة وفي هذه الحالة نحتاج إلى طرائق دقيقه جدا لحساب الوثوقية مبنية على أسس علميه مدروسة .

استعمال تقنيةِ طريق ماركوف لتَقييم الوقتِ علي أساس الوثوقية و توفر رسمي ثابت للبياناتَ وهي مهمةَ جداً للمهندسين والمصممين لتَصميم وتَطوير أيّ نظام لضمان اشتغال بشكل مرضي وبدون خسارةُ وظيفتُها الضروريةُ عندما تشتغل وتسلط على AC المجهز للقدرة للمفاعل النووي .

Introduction

For many years, considerable importance has been given to system reliability, especially when designing engineering systems for use in aerospace, defense, conventional and nuclear power generation and transmission line. Furthermore, the field of reliability has reached the point where it has branched out into various specialized (-Japan Nuclear Cycle Development Institute,2000).

In reconfigurable systems, two basic reconfiguration strategies occur, the degradation and replacement with spares, the critical factor often becomes the effectiveness of the dynamic reconfiguration process; the techniques that are used to identify the faulty component and the methods that are used to repair the system vary greatly and can lead to complex reliability models. It is necessary to model such systems by using a powerful modeling technique like Markov methods analysis and Markov Modeling technique(Hassan, 2007).

The Fast Breeder reactor may be designed to fission with fast neutrons, but these fast reactors must be more compact than thermal reactors so that fast neutrons may produce fissions quickly before they are absorbed or moderated by surrounding materials shown in Figure (1). They are designed with structural materials that are poor absorbers and moderators of neutrons, such as stainless steel. The core of a fast reactor must contain a fissionable fuel of about 20% enrichment to compensate for the lowered probability of fissioning with high energy neutrons (Electricite de France, 2000).

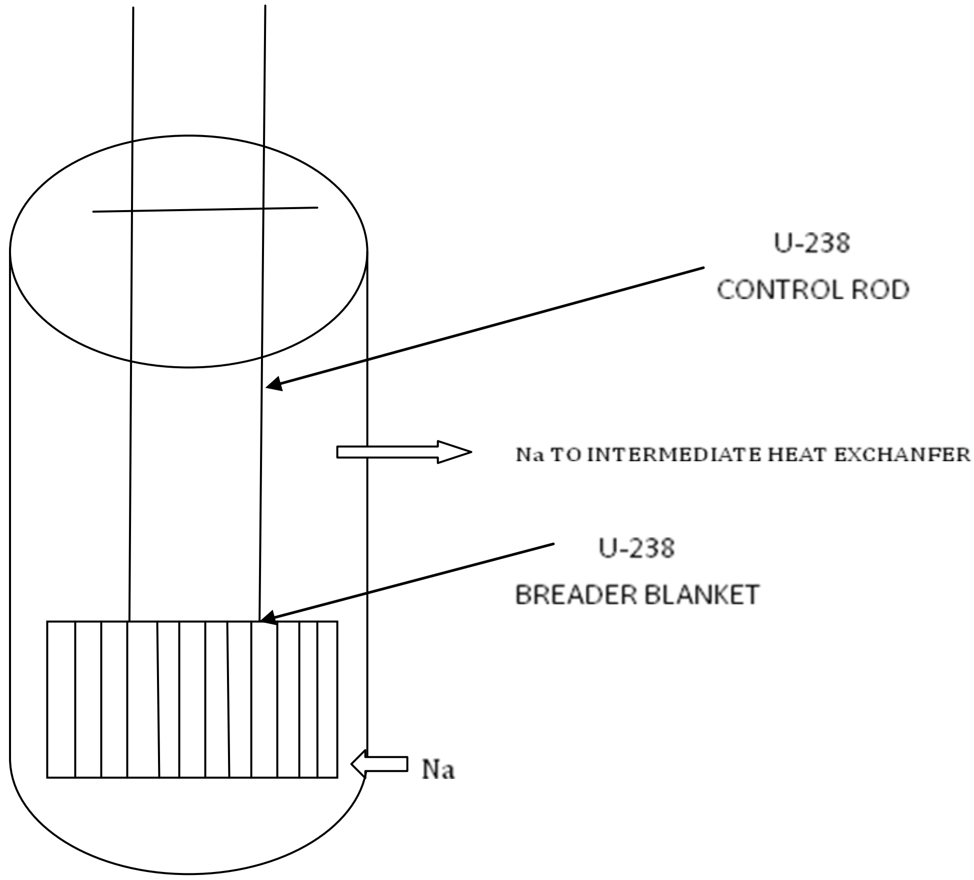

Figure (1) Fast breeder reactor

The Markov Method:

Markov modeling is another technique that is widely used for reliability analysis of complex reliability systems. It is easy to construct and is flexible in the type of systems their behavior it can model (Hassan, 2007) .

A system in markov model is looking to be in one of several states. One possible state, for example, is that , in which all the units composing the system are operating. Another possible state is that in which one unit has failed but the other units continue to operate. The main assumption in markov process model is that the probability of a system will submit a transition from one state to another state depending only on the current state of the system and not on any previous states the system may have experienced (AL-Rawi, *et al.*, 2003).

Markov process is a function of system X and the time of observant t. The four kinds of models arise because both X and t may be either discrete or continuos random variables, resulting in four combinations. If the model is discrete in both state and time, then, the model is generally called a Markov chain model or a discrete-state discrete-time model. If the model is discrete in state and continuos in time, the model is called a Markov process. The two other types of models involve a continues-state variable(Gupta ,2004).

The following assumptions are necessary in order to apply the markov model solution (Ftaiet, , 2000).

1. Failure and restoration rates are constant, not time dependent.
2. Events are independent of one another.
3. All equipment is as designed to be up, down, or in standby at t=0.
4. All states are mutually exclusive.
5. The probability of being in any state at any given point in time depends only on the immediately previous state

To illustrate the general representation of Markov process analysis for a system with s-independent units, we consider a parallel system with three units, each of which will be in one of two states, operating or failing(AL-Rawi, *et al.,* 2003) .

The system state is then defined as be in one of the 2n possible combinations of operating and failed units. For the thee-unit system resulting eight system states shown in table (1) (AL-Rawi, *et al.*, 2003):

Table (1) Case Study of the Markov method

State	Unit 1	Unit 2	Unit 3
1	1	1	1
2	1	1	0
3	1	0	0
4	1	0	1
5	0	1	1
6	0	0	1
7	0	1	0
8	0	0	0

Since the three units are in parallel (redundant), only state number 8-result in failure of whole system.

To assess system availability, all the possible evolutions of the system have to be taken into account, so, the Markov diagram can be used without any modifications and the transition matrix [A] that corresponding to this diagram will be (AL-Rawi, *et al.*, 2003) :

$$A=\begin{bmatrix}
-\begin{pmatrix}\lambda_1+\lambda_2\\+\lambda_3\end{pmatrix} & \mu_3 & \mu_2 & \mu_1 & 0 & 0 & 0 & 0\\
\lambda_3 & -\begin{pmatrix}\mu_3+\lambda_1\\+\lambda_2\end{pmatrix} & 0 & 0 & \mu_2 & \mu_1 & 0 & 0\\
\lambda_2 & 0 & -\begin{pmatrix}\mu_2+\lambda_1\\+\lambda_3\end{pmatrix} & 0 & \mu_3 & 0 & \mu_1 & 0\\
\lambda_1 & 0 & 0 & -\begin{pmatrix}\mu_1+\lambda_2\\+\lambda_3\end{pmatrix} & 0 & \mu_3 & \mu_2 & 0\\
0 & \lambda_2 & \lambda_3 & 0 & -\begin{pmatrix}\mu_2+\mu_3\\+\lambda_1\end{pmatrix} & 0 & 0 & \mu_1\\
0 & \lambda_1 & 0 & \lambda_3 & 0 & -\begin{pmatrix}\mu_1+\mu_3\\+\lambda_2\end{pmatrix} & 0 & \mu_2\\
0 & 0 & \lambda_1 & \lambda_2 & 0 & 0 & -\begin{pmatrix}\mu_1+\mu_2\\+\lambda_3\end{pmatrix} & \mu_3\\
0 & 0 & 0 & 0 & \lambda_1 & \lambda_2 & \lambda_3 & -\begin{pmatrix}\mu_1+\mu_2\\+\mu_3\end{pmatrix}
\end{bmatrix}$$

Where

λ =Failure Rate in (hr-1)

μ =Repair Rate in (hr-1)

And the sum of the elements of each column is zero, this is a feature of Markov matrix. This matrix deals with the differential equations of the form :

$$\frac{d}{dt}\mathrm{P}(t) = \mathrm{A.P}(t)\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

This equation can be written as**(AL-Rawi, *et al.*, 2003)**:

•

$$[\mathrm{P}_s^{\bullet}(t)\} = [A][\mathrm{P}_s(t)]\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where:

[Ps(t)]= is the column vector of the system probability function (availability) that consist of **(AL-Rawi, *et al.*, 2003)**:

$$[\mathrm{P}_s(t)] = \begin{bmatrix}\mathrm{P}_1(t)\\ \mathrm{P}_2(t)\\ \mathrm{P}_3(t)\\ \mathrm{P}_4(t)\end{bmatrix}$$

The solution of equation (2) beginning with an initial condition represented by the probability of zero for each state matrix unless given one to the first state **(AL-Rawi, *et al.*, 2003)** shown in figure (2) .

[P(0)]= the initial or boundary conditions column vector which contains the probabilities to be in any state i at time. t=0, where in our example i =1,2,3,4.

The method used to solve equation (2) is the state space solution of differential equations to resolve the set of differential equations that rated to the problem under study and by using computer programs in Matlab system (Gupta ,2004) .

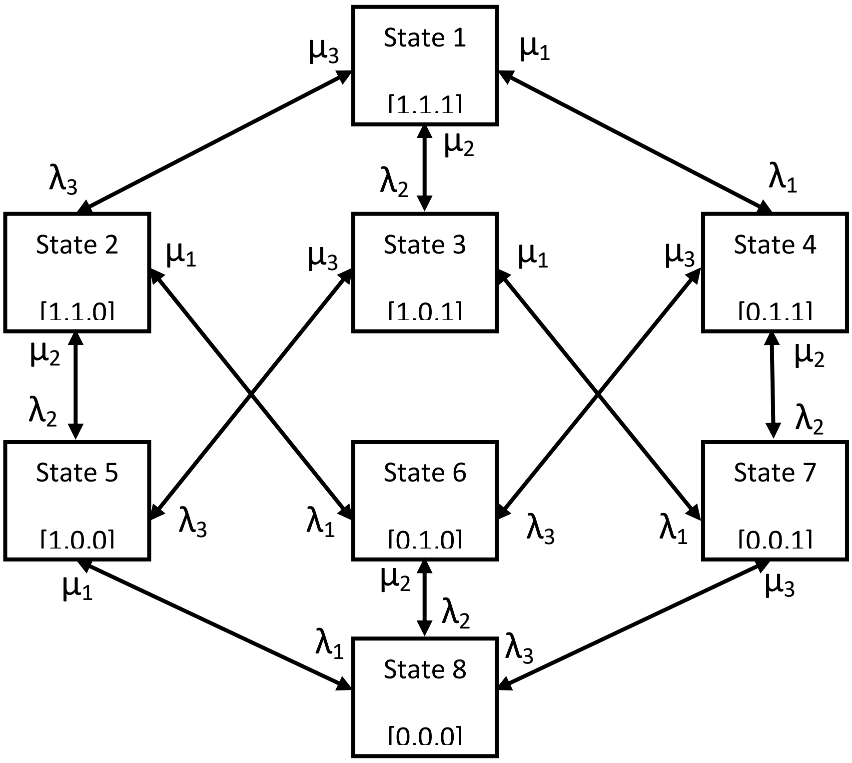

Figure (2) 3-Unit State Space Model

The following set of differential equations describes the system behavior:

$$\frac{dP_1(t)}{dt} = -(\lambda_1 + \lambda_2 + \lambda_3)P_1(t) + \mu_3 P_2(t) + \mu_2 P_3(t) + \mu_1 P_4(t) \quad (3)$$

$$\frac{dP_2(t)}{dt} = -(\mu_1 + \lambda_2 + \lambda_3)P_4(t) + \lambda_1 P_1(t) + \mu_3 P_6(t) + \mu_2 P_7(t) \quad (4)$$

$$\frac{dP_3(t)}{dt} = -(\mu_2 + \lambda_1 + \lambda_3)P_3(t) + \lambda_2 P_1(t) + \mu_3 P_5(t) + \mu_1 P_7(t) \quad (5)$$

$$\frac{dP_4(t)}{dt} = -(\mu_1 + \lambda_2 + \lambda_3)P_4(t) + \lambda_1 P_1(t) + \mu_3 P_6(t) + \mu_2 P_7(t) \quad (6)$$

$$\frac{dP_5(t)}{dt} = -(\mu_2 + \mu_3 + \lambda_1)P_5(t) + \lambda_2 P_2(t) + \lambda_3 P_3(t) + \mu_1 P_8(t) \quad (7)$$

$$\frac{dP_6(t)}{dt} = -(\mu_1 + \mu_3 + \lambda_2)P_6(t) + \lambda_1 P_2(t) + \lambda_3 P_4(t) + \mu_2 P_8(t) \quad (8)$$

$$\frac{dP_7(t)}{dt} = -(\mu_1 + \mu_2 + \lambda_3)P_7(t) + \lambda_1 P_3(t) + \lambda_2 P_4(t) + \mu_3 P_8(t) \quad (9)$$

$$\frac{dP_8(t)}{dt} = -(\mu_1 + \mu_2 + \mu_3)P_8(t) + \lambda_1 P_5(t) + \lambda_2 P_6(t) + \mu_3 P_7(t) \quad (10)$$

The whole information is contained in the diagram:

All the possible states of the system.

All the possibilities of the jumping (transition) from state to another one.

This diagram allows one to find directly the matrix [A]. to avoid any ambiguity and going to use the following rotation:

aij : transition from j to i. this element is ith row jth column. Using the diagram, it is easy to determine each aij.

aii : is equal to the sum with minus sign of all the arrows leaving state i.

aij : is equal to the value of the arrow going from state j to state i.

then it is very easy to draw the Markov diagram and to determine the matrix [A]. So the matrix [A] for our example becomes [10]:

For a series system, parallel redundant system, and 2-out of 3- parallel system, the state to be combined for system success and failure are:

series system	Success = State 1
	Failure = State 2, 3, 4, 5, 6, 7, 8
Parallel Redundant System	Success = State 1, 2, 3, 4, 5, 6, 7
	Failure = State 8
2-out of 3- parallel system0	Success = State 1, 2, 3, 4
	Failure = State 5, 6, 7 8

The basic concepts of evaluating the time dependent state probabilities of Markov process uses differential equation and solution by eign value method.

Eign Value Method [6]

If the matrix A is decomposed as

$A=VDV^{-1}$…………………………………………………………..(11)

Where V,D are the Eign vector and Eign value matrix respectively, then the matrix exponential e^{At} satisfies

$e^{At}=V e^{Dt} V^{-1}$ …...……………………………………….…….(12)

All methods for computation of e^{At} which employ a decomposition of the form (12) involve two conflicting objectives:

Making the matrix D which is a diagonal matrix so that e^{Dt} is easy to compute.

Making the matrix V well conditioned so that the error in computing $V e^{Dt} V^{-1}$ becomes small. The using of Eign value method puts the emphasis on the first objective.

The main purpose of the programs is to perform the following tasks:

Systematic building up of transition rate matrix.

Solution of set of first differential equation by Neural Program.

Evaluation of state frequency and duration by applying the following equation:

Let f_i be state frequency, in the long run f_i equals the reciprocal of the mean cycle time, that is:

$f_i=1/T_{ci}$……………………………………………………………...(13)

Where Tci is the mean cycle time, and is given by

$Tci=Ti+Ti'$……..…………………………………………………..…..(14)

Where Ti is the mean duration of stay in state I, and that of the stay outside i, is Ti′. The state frequency, in terms of state probability and Ti, is given below:

$fi=pi/Ti$…….……………………………………………………..….(15)

Next fi, mean duration Ti, and transition rates in the system will be related as:

$fij=\lambda ij\ pi$ ………………………………………………………………..(16)

where fij is defined as the expected number of direct transfers from i to j per unit time, λij is the transition rate between state i and j.

$fi =\sum_{i\neq j} fij$………………………………………………………….(17)

Then

$fi =pi\sum_{i\neq j} \lambda ij$………………………………………………………….(18)

And

$Ti=1/\sum_{i\neq j} \lambda ij$ ………………………………………………………….(19)

Markov method calculations tend be very lengthy even for this simple component system. As the number of components increases, the calculations become more lengthy. While Fault Tree analysis depends on System chart and theoretical calculations without computer program lead to increase in the error in solution. Therefore it is preferable to use Path Tracing method for reliability calculations of transmission and distribution systems because it is uses the computer program at high accuracy degree.

Result

This search presents the mathematical model of a powerful reliability analysis tool which is Markov method analysis .The reliability and availability indices produced by the reliability analysis program using the mathematical model of Markov analysis. The results of reliability program represent the change of probability of each state of the system over time as shown in Figures (3.a to 3.j). from the result of the first state that is shown in Figure (3.a) when the entire four power sources are available, the value of reliability in this state is high and starts with probability of success (1) at time zero which indicates a certainty of success and this probability value decreases very slowly over operation time (taken as 106 hours), this means that the probability of being in state (1) is high and that the system is very reliable.

Conversely, the probability of being in the other states of the system increases over time as shown in Figures (3.b to 3.i), but the results show that the probability values of being in any state other than state (1) remains small. The results of reliability also give the system unreliability (state 10) as shown in Figure (3.j), which is considered as an absorbing state in the reliability study, this value of unreliability (Q) is ($6.12731367391261\times10^{-4}$) at time (106 hours) and since the reliability and unreliability are mutually exclusive, R(t) = 1-Q, this reflects a high reliability of the system reached (0.99938726863259).

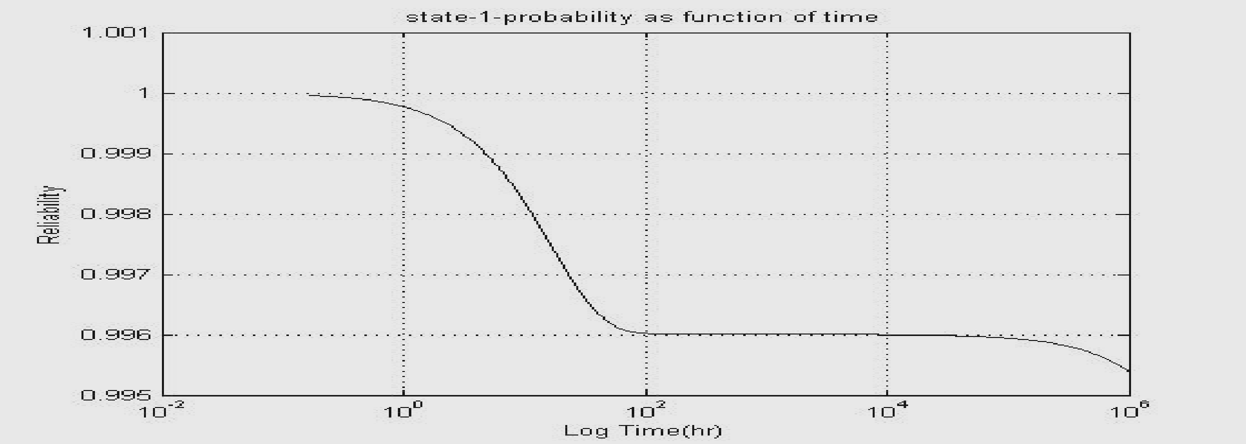

Figure (3.a) Probability Values of State -1- from Reliability Study

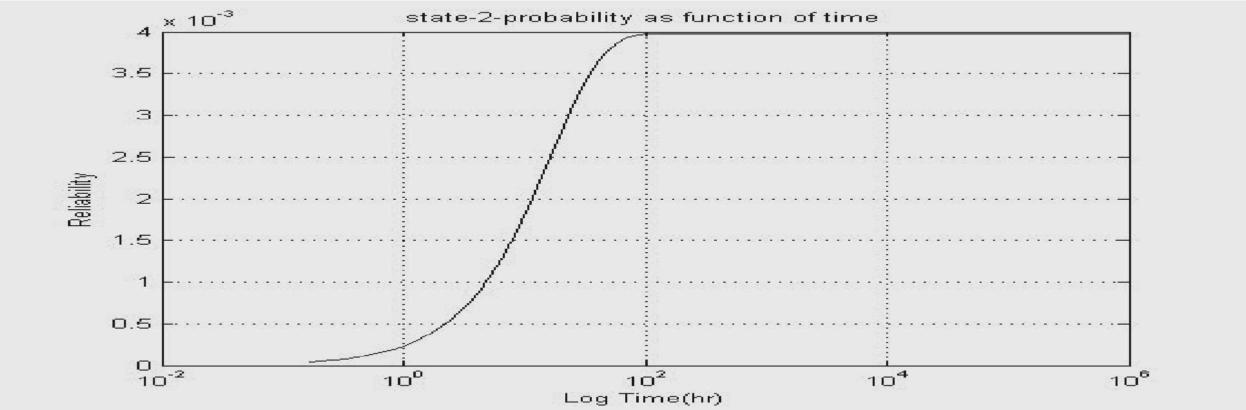

Figure (3.b) Probability Values of State -2- from Reliability Study

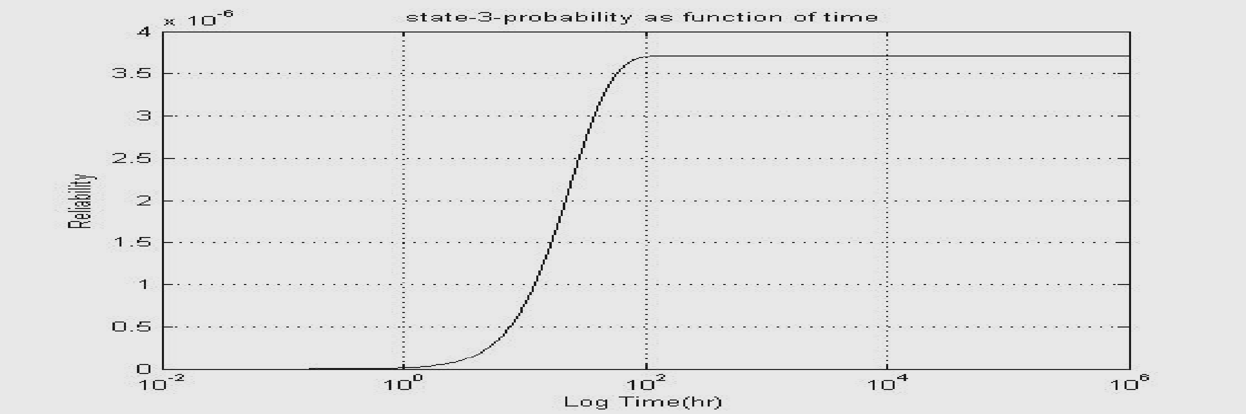

Figure (3.c) Probability Values of State -3- from Reliability Study

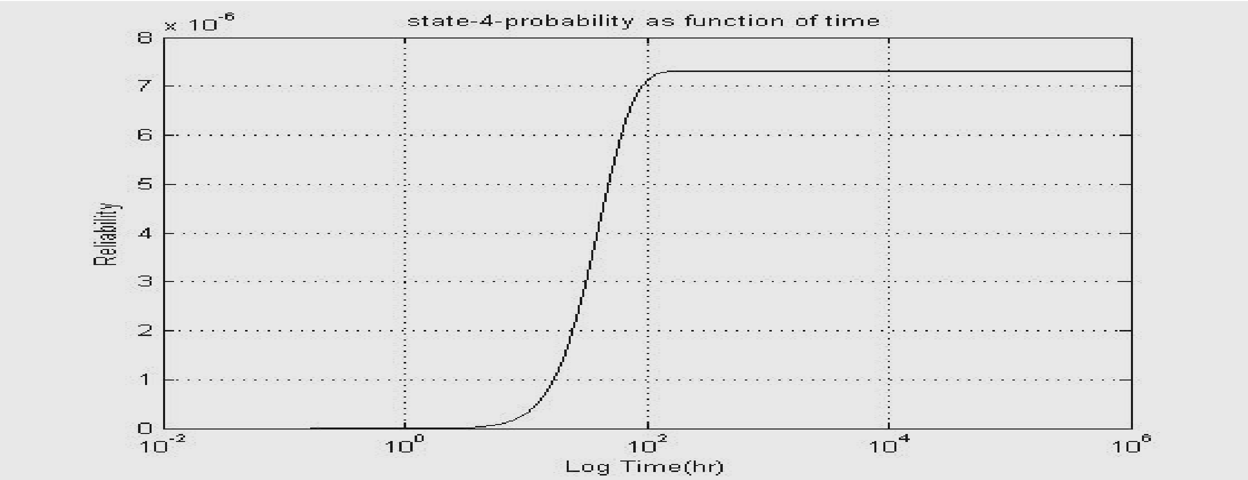

Figure (3. d) Probability Values of State -4 from Reliability Study

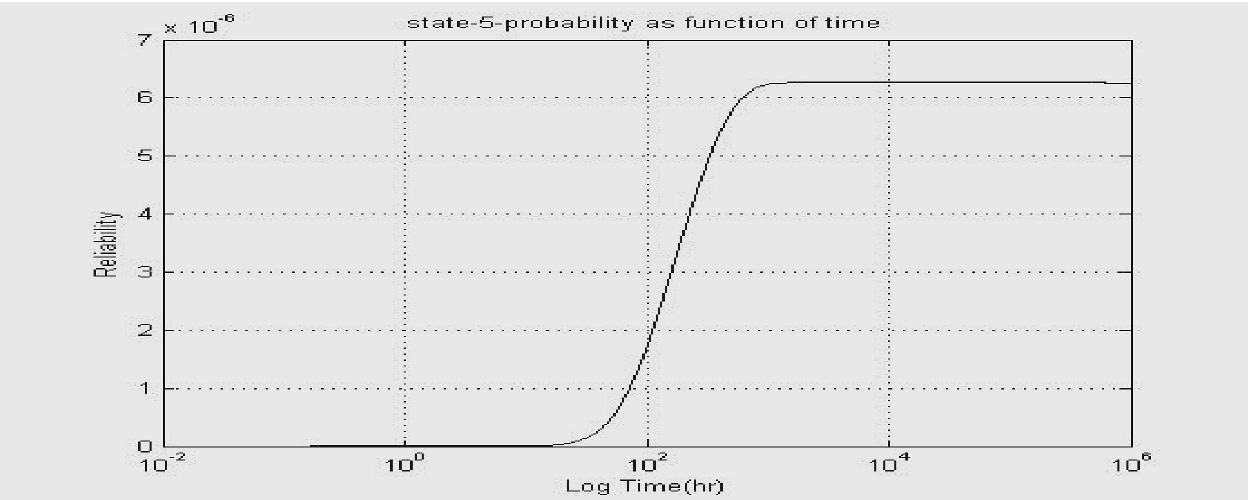

Figure (3.e) Probability Values of State -5- from Reliability Study

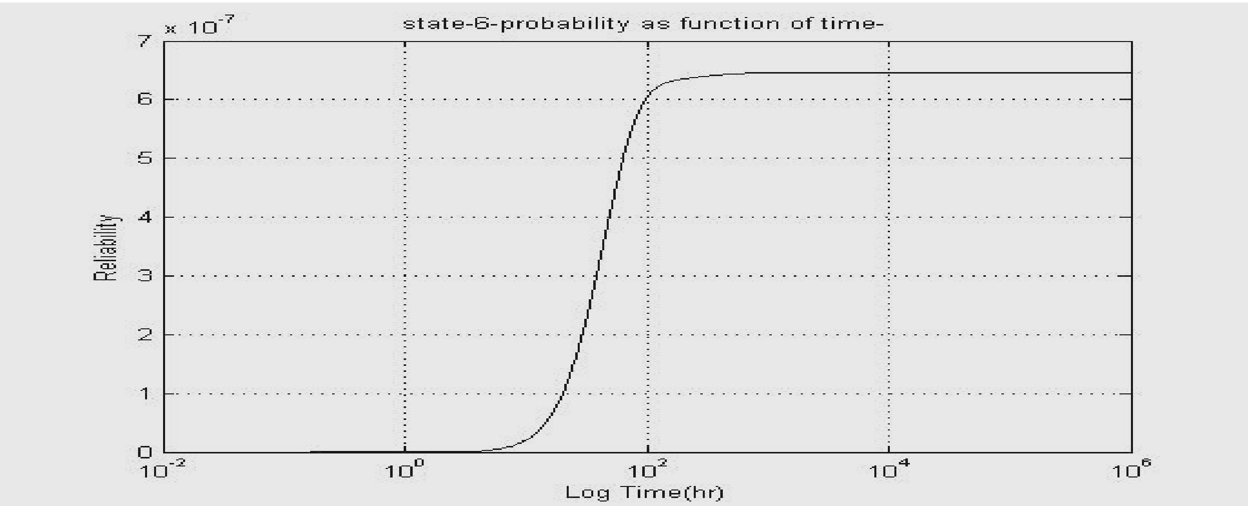

Figure (3.f) Probability Values of State -6- from Reliability Study

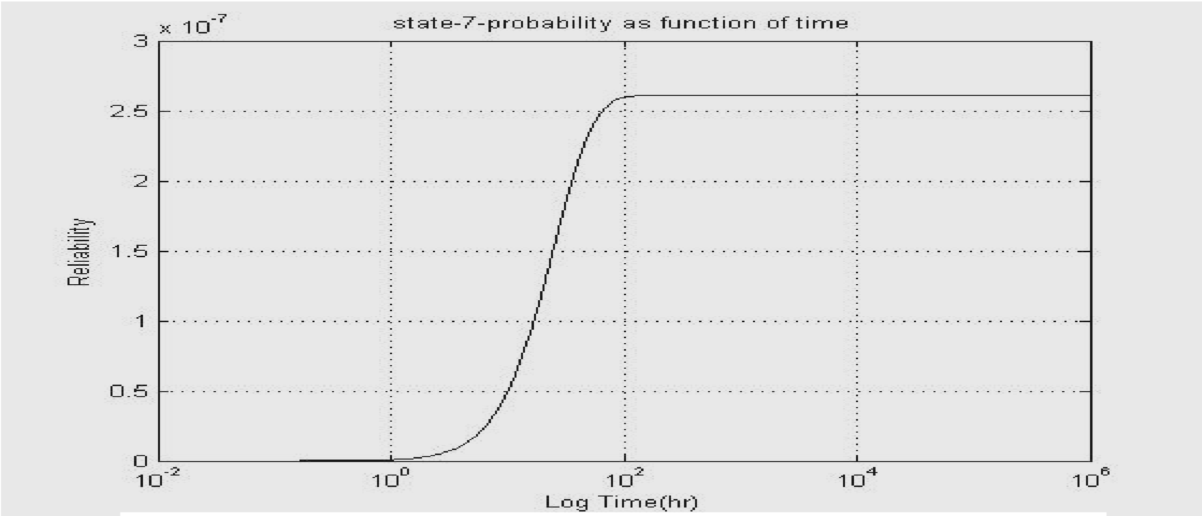

Figure (3.g) Probability Values of State -7- from Reliability Study

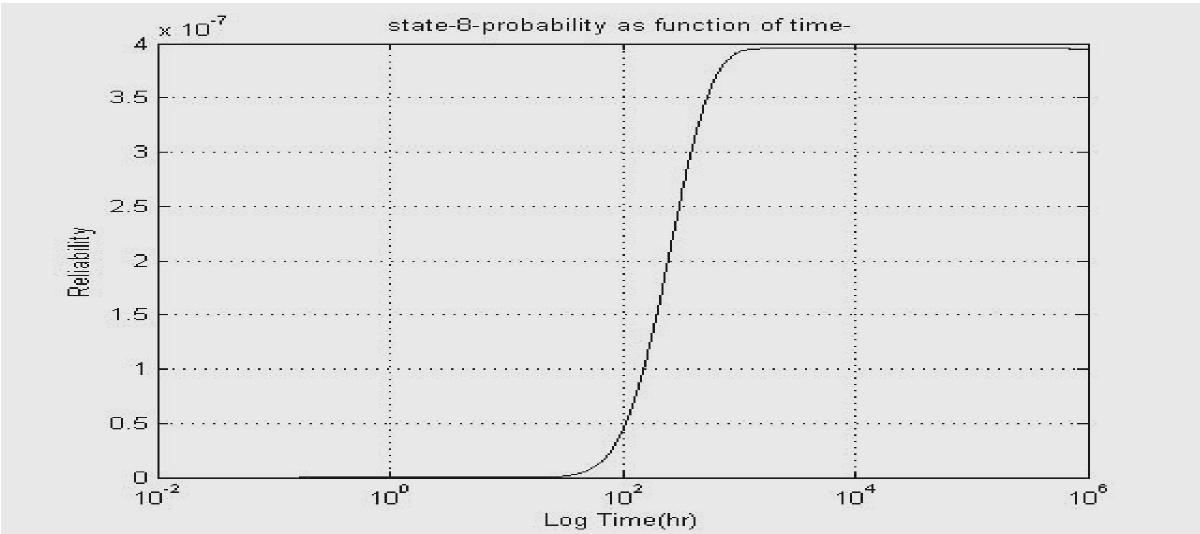

Figure (3.h) Probability Values of State -8- from Reliability Study

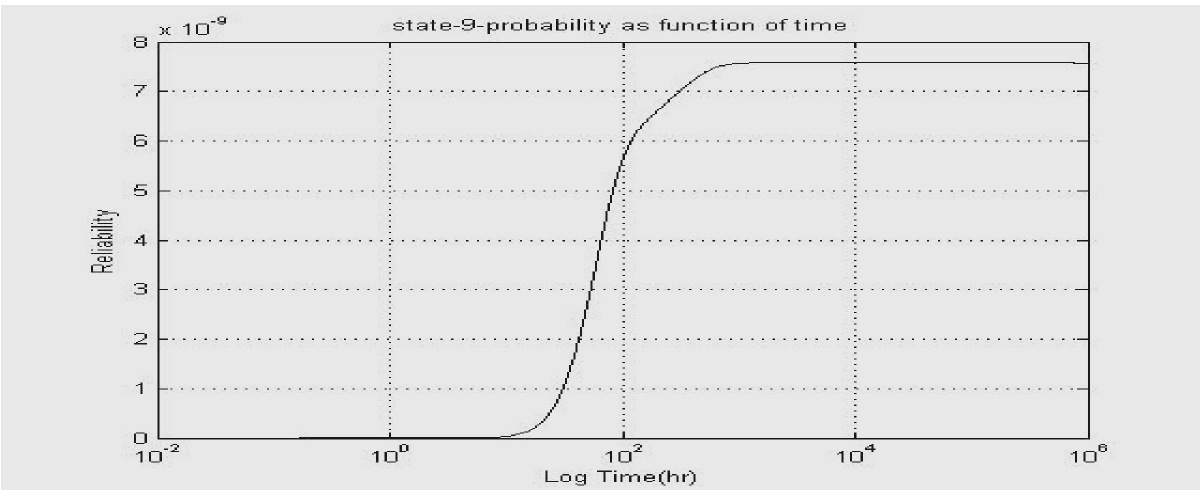

Figure (3.i) Probability Values of State -9- from Reliability Study

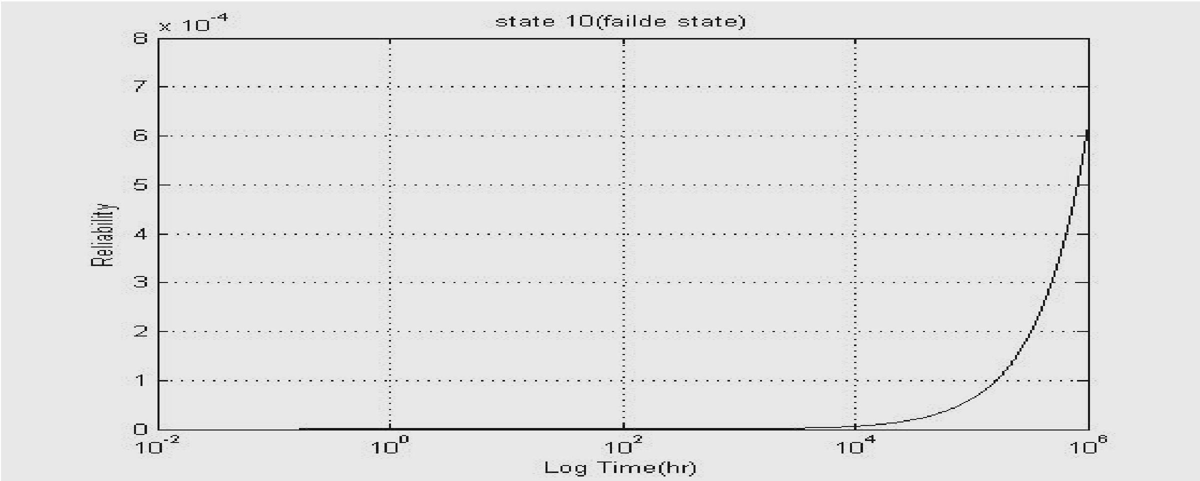

Figure (3.j) State -10- System Unreliability

The results of the reliability, availability and outage rate are listed in Table (2).

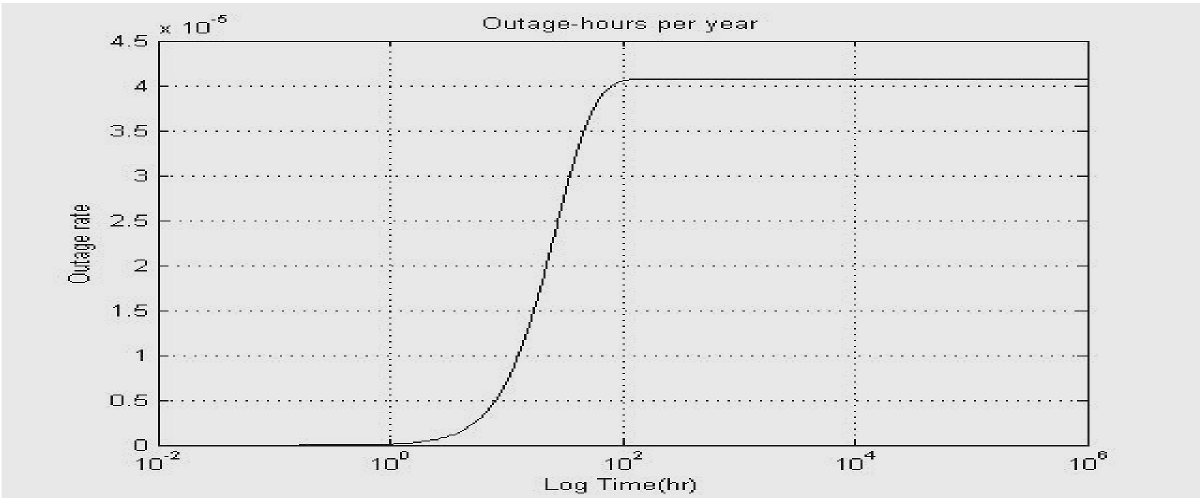

Figure (4) Outage –Rate per Year

Table (2) Reliability and Outage Rate of AC Power Supply

Time (hour)	System Reliability	Outage Rate /year
100	0.99999995056440	4.04927405358856×10-5
1000	0.99999939900014	4.07598320734082×10-5
10000	0.99999388263965	4.07599577104082×10-5
20000	0.99998775338553	4.07599577104082×10-5
30000	0.99998162416817	4.07599577104082×10-5
50000	0.99996936584698	4.07599577104082×10-5
100000	0.99993872070180	4.07599577104082×10-5
150000	0.99990807649355	4.07599577104082×10-5
250000	0.99984679089522	4.07599577104082×10-5
500000	0.99969359333578	4.07599577104082×10-5
1000000	0.99938726863259	4.07599577104082×10-5

Discussion and Conclusion

The following summarizes the general conclusions that could be deduced this work:-

1- Markov method approach has shown a great flexibility in modeling different types of systems because it describes both the failure of an item and its subsequent repair and it develops the probability of an item being in a given state, as a function of the sequence through which the item has traveled.

2- The entire system of AC power supply shows high reliability performance for very long operational time, this is due to redundant construction that includes the two standby diesels and the low failure rates of the components of the system.

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