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Reliability Estimation Of Wind Turbines Through Markov Modelling

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Abstract:
The Reliability of Wind Turbines plays an important role in electricity generation. The Markov Technique has been widely used to evaluate the Reliability of complex systems with multiple failure modes. In this study, Laplace Transform is employed on a repairable four-state (One operational state and three failure state) Markov model to determine the probability of the system. The failure rate and repair rate of the components of Wind Turbines have been analysed over time and the Reliability of Wind Turbines have been effectively evaluated. This study confirms that the proposed approach can derive a set of Probabilistic values and Reliability of the repairable four state system.

Keywords: Failure Rate, Repair Rate, Reliability, Markov Processes.

1 Introduction:

In recent years of fast- growing technology, everybody is interested to buy a system which is more reliable, that is, the system which works as per expectation. Hence it is the prime responsibility of the system engineers to develop a reliable system and also to enhance the techniques to improve the Reliability of the system. As a result, the researchers have also been succeeded in framing the guidelines for improving the Reliability of the system.

This Reliability technology has also been used in number of industries for satisfying operation. In this paper, using Markov Chain, the Chapman Kolmogorov equation for four states namely one operational state and three failure states have been used. Then Laplace Transform is applied on these probability equations and hence solved using Crammers' rule. Then finally, Inverse Laplace Transform have been applied to find the solution of the probabilities at all four state and hence Reliability is arrived for the four state probabilities.

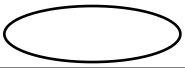
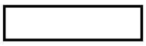
Many scholars have evaluated the Reliability from a qualitative and quantitative prospectus. Chao et al [1] applied the Markov Structure to analyse the Reliability of large systems which is connected in series. Yadav et al [13] have done a Markov approach for the calculation of of Reliability an availability of a four-unit repairable system. Kalaiarasi et al [3] developed the formula for Reliability of the system with four elements.Chopra et al [4] used Gumbel-Hougaard Family Copula to find the Reliability of two dissimilar units Parallel systems. Rathi et al [6] have considered a parallel-cold standby system of pairwise identical four units and calculated the Reliability of that system. Saritha et al [7] have derived the Availability Measures for 4-Component system by using Markov Process. Carroll et al [9] derived Failure rate, repair time and unscheduled O&M cost analysis of offshore Wind Turbines. Guarda Brauning et al and Zhu [10],[11] have evaluated the Reliability, Failure rate and repair time analysis of offshore Wind Turbines. Li et al [12] applied Reliability improvement technique to enhance the system Reliability and Availability of safety critical systems, or operational impact systems in the railroad and mass transit industry.

This work contributes to the evaluation of the Reliability value of system with four state which is connected in series. In this evaluation, we have the following assumptions:

- The system could be repaired.

- Failure and repair rates are statistically independent.
- The system follows the exponential distribution.

2 Notations and Descriptions:

Notations	Descriptions
λ_i	Failure rate of three components, i=1,2,3
μ_i	Repair rate of three components, i=1,2,3
$P_0(t)$	Probability of the system, at operating state
$P_i(t)$	Probability of the system, at failure state, i=1,2,3
s	Laplace Transform variable
	The system in operating state
	The system in Failed state
R(t)	Reliability of the system

The Transition State Diagram of the system with one operational state and three different failure state is as follows:

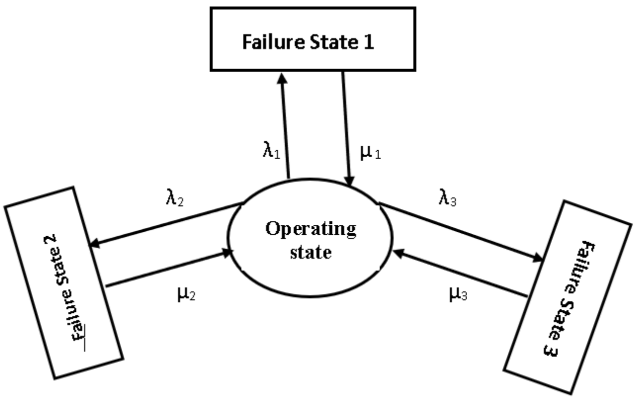


Figure 1: Transition State diagram of the system

The Transition Probability Matrix of the system with one operational state and three different failure state is as follows:

$$\begin{bmatrix} P_0(t+\Delta t) \\ P_1(t+\Delta t) \\ P_2(t+\Delta t) \\ P_3(t+\Delta t) \end{bmatrix} = \begin{bmatrix} 1-(\lambda_1+\lambda_2+\lambda_3)\Delta t & \mu_1\Delta t & \mu_2\Delta t & \mu_3\Delta t \\ \lambda_1\Delta t & 1-\mu_1\Delta t & 0 & 0 \\ \lambda_2\Delta t & 0 & 1-\mu_2\Delta t & 0 \\ \lambda_3\Delta t & 0 & 0 & 1-\mu_2\Delta t \end{bmatrix} \begin{bmatrix} P_0(t) \\ P_1(t) \\ P_2(t) \\ P_3(t) \end{bmatrix}$$

$$P_0(t+\Delta t) = [1-(\lambda_1+\lambda_2+\lambda_3)\Delta t]P_0(t) + \mu_1\Delta t P_1(t) + \mu_2\Delta t P_2(t) + \mu_3\Delta t P_3(t)]$$

$$P_1(t+\Delta t) = \lambda_1\Delta t P_0(t) + (1-\mu_1\Delta t)P_1(t)$$

$$P_2(t+\Delta t) = \lambda_2\Delta t P_0(t) + (1-\mu_2\Delta t)P_2(t)$$

$$P_3(t+\Delta t) = \lambda_3\Delta t P_0(t) + (1-\mu_3\Delta t)P_3(t)$$

Taking limit $\Delta t \to 0$, we get the following set of differential equations for each state:

$$P_0'(t) = \lim_{\Delta t\to 0}\frac{P_0(t+\Delta t)-P_0(t)}{\Delta t} = -(\lambda_1+\lambda_2++\lambda_3)P_0(t) + \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_3(t)$$

$$P_1'(t)=\lim_{\Delta t\to 0}\frac{P_1(t+\Delta t)-P_1(t)}{\Delta t}=\lambda_1 P_0(t)-\mu_1 P_1(t)$$
$$P_2'(t)=\lim_{\Delta t\to 0}\frac{P_2(t+\Delta t)-P_2(t)}{\Delta t}=\lambda_2 P_0(t)-\mu_2 P_2(t)$$
$$P_3'(t)=\lim_{\Delta t\to 0}\frac{P_3(t+\Delta t)-P_3(t)}{\Delta t}=\lambda_3 P_0(t)-\mu_3 P_3(t)$$

Applying the Laplace Transform for derivatives $L\left[f^{'}(t)\right]=sL[f(t)]-f(0),$ we get

$$sP_0(s)-P_0(0)=-(\lambda_1+\lambda_2+\lambda_3)P_0(s)+\mu_1P_1(s)+\mu_2P_2(s)++\mu_3P_3(s)$$
$$sP_1(s)-P_1(0)=\lambda_1P_0(s)-\mu_1P_1(s)$$
$$sP_2(s)-P_2(0)=\lambda_2P_0(s)-\mu_2P_2(s)$$
$$sP_3(s)-P_3(0)=\lambda_3P_0(s)-\mu_3P_3(s)$$

$$\begin{bmatrix} s+\lambda_1+\lambda_2+\lambda_3 & -\mu_1 & -\mu_2 & -\mu_3 \\ -\lambda_1 & s+\mu_1 & 0 & 0 \\ -\lambda_2 & 0 & s+\mu_2 & 0 \\ -\lambda_3 & 0 & 0 & s+\mu_3 \end{bmatrix}\begin{bmatrix} P_0(s) \\ P_1(s) \\ P_2(s) \\ P_3(s)\end{bmatrix}=\begin{bmatrix} P_0(0) \\ P_1(0) \\ P_2(0) \\ P_2(0)\end{bmatrix}$$

Using Crammar's Rule, we determine the value of $P_0(s),P_1(s),P_2(s)$ and $\mathrm{P}_3(\mathrm{s})$ as follows,

$$\Delta=\begin{vmatrix} s+\lambda_1+\lambda_2+\lambda_3 & -\mu_1 & -\mu_2 & -\mu_3 \\ -\lambda_1 & s+\mu_1 & 0 & 0 \\ -\lambda_2 & 0 & s+\mu_2 & 0 \\ -\lambda_3 & 0 & 0 & s+\mu_3 \end{vmatrix}$$
$$=\left(s+\lambda_1+\lambda_2+\lambda_3\right)\left(s+\mu_1\right)\left(s+\mu_2\right)\left(s+\mu_3\right)-\mu_1\lambda_1\left(s+\mu_2\right)\left(s+\mu_3\right)$$
$$-\mu_2\lambda_2\left(s+\mu_1\right)\left(s+\mu_3\right)-\mu_3\lambda_3\left(s+\mu_1\right)\left(s+\mu_2\right)$$
$$=s(s-a)(s-b)(s-c)$$

Where $a=-(\lambda_1+\mu_1),b=-(\lambda_2+\mu_2),c=-(\lambda_3+\mu_3)$ are the roots of the equations,

$$\Delta_0=\begin{vmatrix} 1 & -\mu_1 & -\mu_2 & -\mu_3 \\ 0 & s+\mu_1 & 0 & 0 \\ 0 & 0 & s+\mu_2 & 0 \\ 0 & 0 & 0 & s+\mu_3 \end{vmatrix}$$
$$=(s+\mu_1)(s+\mu_2)(s+\mu_3)$$
$$P_0(s)=\frac{\Delta_0}{\Delta}=\frac{(s+\mu_1)(s+\mu_2)(s+\mu_3)}{s(s-a)(s-b)(s-c)}$$

Using partial fractions,

$$P_0(s)=\frac{A_1}{s}+\frac{A_2}{s-a}+\frac{A_3}{s-b}+\frac{A_3}{s-c}$$

$$A_1=\frac{\mu_1\mu_2\mu_3}{-abc} \qquad A_2=\frac{(a+\mu_1)(a+\mu_2)(a+\mu_3)}{a(a-b)(a-c)}$$
$$A_3=\frac{(b+\mu_1)(b+\mu_2)(b+\mu_3)}{b(b-a)(b-c)} \qquad A_4=\frac{(c+\mu_1)(c+\mu_2)(c+\mu_3)}{c(c-a)(c-b)}$$

Applying Inverse Laplace Transform and replacing for a,b,c

$$P_0(t)=\frac{\mu_1\mu_2\mu_3}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$
$$+\frac{\lambda_1[\mu_2-(\lambda_1+\mu_1)][\mu_3-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$
$$+\frac{\lambda_3[\mu_1-(\lambda_3+\mu_3)][\mu_2-(\lambda_3+\mu_3)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$
$$+\frac{\lambda_2[\mu_1-(\lambda_2+\mu_2)][\mu_3-(\lambda_2+\mu_2)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

Similarly solving for $P_1(s),P_2(s),P_3(s)$

$$\Delta_1=\begin{vmatrix} s+\lambda_1+\lambda_2+\lambda_3 & 1 & -\mu_2 & -\mu_3 \\ -\lambda_1 & 0 & 0 & 0 \\ -\lambda_2 & 0 & s+\mu_2 & 0 \\ -\lambda_3 & 0 & 0 & s+\mu_3 \end{vmatrix}$$
$$=\lambda_1(s+\mu_2)(s+\mu_3)$$
$$P_1(s)=\frac{\Delta_1}{\Delta}=\frac{\lambda_1(s+\mu_2)(s+\mu_3)}{s(s-a)(s-b)(s-c)}$$

Applying Inverse Laplace Transform,

$$P_1(t)=\frac{\lambda_1\mu_2\mu_3}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$
$$-\frac{\lambda_1[\mu_2-(\lambda_1+\mu_1)][\mu_3-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$
$$+\frac{\lambda_1\lambda_2[\mu_3-(\lambda_2+\mu_2)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$
$$+\frac{\lambda_1\lambda_3[\mu_2-(\lambda_3+\mu_3)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

$$\Delta_2=\begin{vmatrix} s+\lambda_1+\lambda_2+\lambda_3 & -\mu_1 & 1 & -\mu_3 \\ -\lambda_1 & s+\mu_1 & 0 & 0 \\ -\lambda_2 & 0 & 0 & 0 \\ -\lambda_3 & 0 & 0 & s+\mu_3 \end{vmatrix}$$
$$=(s+\mu_1)\lambda_2(s+\mu_3)$$
$$P_2(s)=\frac{\Delta_2}{\Delta}=\frac{(s+\mu_1)\lambda_2(s+\mu_3)}{s(s-a)(s-b)(s-c)}$$

Applying Inverse Laplace Transform

$$P_2(t)=\frac{\lambda_2\mu_1\mu_3}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$
$$+\frac{\lambda_1\lambda_2[\mu_3-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$
$$-\frac{\lambda_2[\mu_1-(\lambda_2+\mu_2)][\mu_3-(\lambda_2+\mu_2)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$

$$+\frac{\lambda_2\lambda_3[\mu_1-(\lambda_3+\mu_3)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

$$\Delta_3=\begin{vmatrix} s+\lambda_1+\lambda_2+\lambda_3 & -\mu_1 & -\mu_2 & 1 \\ -\lambda_1 & s+\mu_1 & 0 & 0 \\ -\lambda_2 & 0 & s+\mu_2 & 0 \\ -\lambda_3 & 0 & 0 & 0 \end{vmatrix}=(s+\mu_1)(s+\mu_2)\lambda_3$$

$$P_3(s)=\frac{\Delta_3}{\Delta}=\frac{(s+\mu_1)(s+\mu_2)\lambda_3}{s(s-a)(s-b)(s-c)}$$

$$P_3(t)=\frac{\lambda_3\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$

$$+\frac{\lambda_1\lambda_3[\mu_2-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$

$$+\frac{\lambda_2\lambda_3[\mu_1-(\lambda_2+\mu_2)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$

$$-\frac{\lambda_3[\mu_1-(\lambda_3+\mu_3)][\mu_2-(\lambda_3+\mu_3)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

Reliability of the system is given by

$$R(t)=P_0(t)+P_1(t)+P_2(t)+P_3(t)$$

$$=\frac{\mu_1\mu_2\mu_3}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$

$$+\frac{\lambda_1[\mu_2-(\lambda_1+\mu_1)][\mu_3-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$

$$+\frac{\lambda_3[\mu_1-(\lambda_3+\mu_3)][\mu_2-(\lambda_3+\mu_3)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$

$$+\frac{\lambda_2[\mu_1-(\lambda_2+\mu_2)][\mu_3-(\lambda_2+\mu_2)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

$$+\frac{\lambda_1\mu_2\mu_3}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$

$$-\frac{\lambda_1[\mu_2-(\lambda_1+\mu_1)][\mu_3-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$

$$+\frac{\lambda_1\lambda_2[\mu_3-(\lambda_2+\mu_2)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$

$$+\frac{\lambda_1\lambda_3[\mu_2-(\lambda_3+\mu_3)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

$$+\frac{\lambda_2\mu_1\mu_3}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$

$$+\frac{\lambda_1\lambda_2[\mu_3-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$

$$-\frac{\lambda_2[\mu_1-(\lambda_2+\mu_2)][\mu_3-(\lambda_2+\mu_2)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$

$$+\frac{\lambda_2\lambda_3[\mu_1-(\lambda_3+\mu_3)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$
$$+\frac{\lambda_3\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)(\lambda_3+\mu_3)}$$
$$+\frac{\lambda_1\lambda_3[\mu_2-(\lambda_1+\mu_1)]}{(\lambda_1+\mu_1)[(\lambda_2+\mu_2)-(\lambda_1+\mu_1)][(\lambda_3+\mu_3)-(\lambda_1+\mu_1)]}e^{-(\lambda_1+\mu_1)t}$$
$$+\frac{\lambda_2\lambda_3[\mu_1-(\lambda_2+\mu_2)]}{(\lambda_2+\mu_2)[(\lambda_1+\mu_1)-(\lambda_2+\mu_2)][(\lambda_3+\mu_3)-(\lambda_2+\mu_2)]}e^{-(\lambda_2+\mu_2)t}$$
$$-\frac{\lambda_3[\mu_1-(\lambda_3+\mu_3)][\mu_2-(\lambda_3+\mu_3)]}{(\lambda_3+\mu_3)[(\lambda_1+\mu_1)-(\lambda_3+\mu_3)][(\lambda_2+\mu_2)-(\lambda_3+\mu_3)]}e^{-(\lambda_3+\mu_3)t}$$

In this research article, we evaluate the Reliability analysis of Wind Turbines. Wind Turbines are tall and huge machine which converts the kinetic energy of wind into Mechanical energy which is then transformed into Electrical Energy. In these recent years, the Wind Turbines are most essential for its application. Hence the Reliability of Wind Turbine should be analysed more specifically. Here we have taken three most common failures, namely Gearbox and Bearings failure, Blade damage and Generator and Electrical failures. We assume the following notations to find the Reliability of Wind Turbines in 25 years (analysed for each 5 years):

- λ_1 and μ_1 are failure rate and repair rate of Gearbox and Bearings
- λ_2 and μ_2 are failure rate and repair rate of Blades
- λ_3 and μ_3 are failure rate and repair rate of Generators.

Time (for each 5 year)	**Failure Rate**	**Repair Rate**	$P_0(t)$	$P_1(t)$	$P_2(t)$	$P_3(t)$	$R(t)$
t=1	λ_1=0.1 λ_2=0.2 λ_3=0.3	μ_1=0.5 μ_2=0.6 μ_3=0.7	0.37739	0.00604	0.39086	0.16439	0.93868
t=2	λ_1=0.2 λ_2=0.3 λ_3=0.4	μ_1=0.4 μ_2=0.5 μ_3=0.6	0.46616	0.033025	0.17958	0.2167	0.89546
t=3	λ_1=0.3 λ_2=0.4 λ_3=0.5	μ_1=0.3 μ_2=0.4 μ_3=0.5	0.41235	0.150405	0.01621	0.1745	0.75347
t=4	λ_1=0.4 λ_2=0.5 λ_3=0.6	μ_1=0.2 μ_2=0.3 μ_3=0.4	0.3045	0.08557	0.10541	0.0909	0.58640
t=5	λ_1=0.5 λ_2=0.6 λ_3=0.7	μ_1=0.1 μ_2=0.2 μ_3=0.3	0.19597	0.06252	0.03248	0.00975	0.30072

Table 1: Reliability of the Wind Turbine

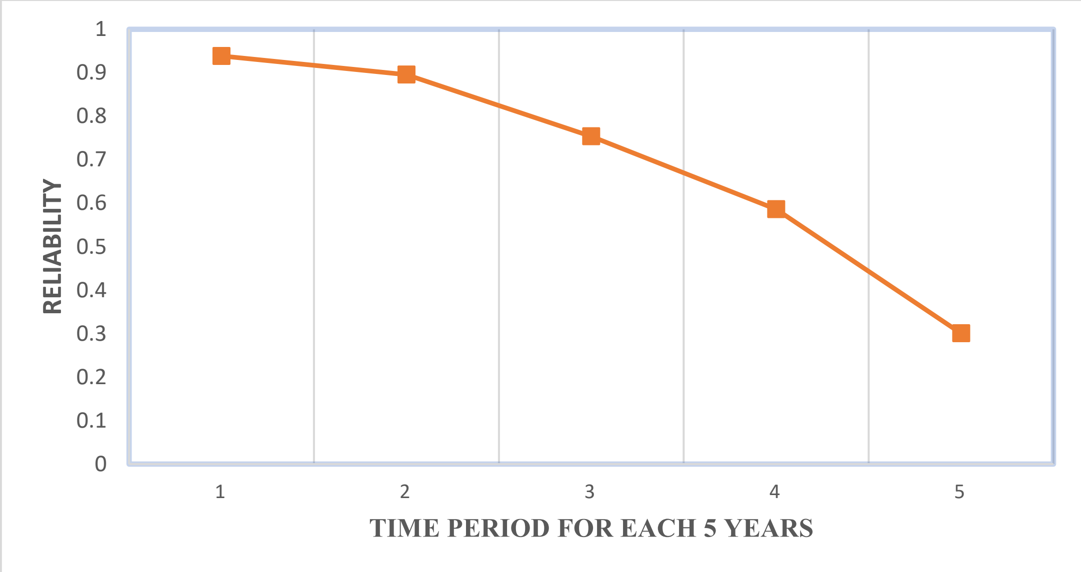


Figure 2: Reliability curve of the Wind Turbines

The table and the graph reveal that as the time increases the Reliability value decreases. Hence the failures of Gearbox and Bearings, Blade damage & Generator and Electrical systems could decrease the Reliability of Wind Turbines.

3 Conclusion

This study highlights the calculation of probability of the system at one operating state and at three failure state using which the Reliability of the system has been evaluated. Based on the Failure rates and repair rates of Wind Turbines, quantitative evaluation of Reliability have been done for the period of twenty-five years. On analysing this case study, we conclude that Gearbox and Bearings failure, Blade damage and Generator and Electrical failure could decrease Reliability of the Wind Turbines. Hence periodical maintenances and a better planning of services may increase the Reliability.

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