Reliability and Maintainability Investigation of Generator in Steam Turbine Power Plant using RAMD analysis

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Abstract. Generator is key unit of steam turbine power plant which is used to convert mechanical energy into electrical energy. This energy is further used for completing the requirement generated by various sectors of country. Generator is one of the most important component of steam turbine power plant configured with seven subsystems in series configuration. So, it is necessary to ensure its smooth functioning which is attain by the proper functioning of its subcomponents. It is important to increase operational availability of subsystem. Hence, present study is proposed to investigate various reliability measures of generator used in STP through RAMD approach at component level. For this purpose, mathematical models using Markovian birth death process have been developed for all subsystems of generator. These models are very helpful in reliability, maintainability, and availability analysis of generators. RAMD analysis will play significant role in this direction. This will help to find critical component of system so that proper maintenance strategies can be proposed. It is assumed that all failure and repair rates associated with each component followed exponential distribution and adequate repair facility always remains available with system. Various system performance measures like reliability function, maintainability function, dependability function and steady state availability for different components as well as system have been evaluated. The numerical results have been derived to highlight the importance of study.

Keywords: Generator, Availability, Dependability, Dependability ratio.

1. Introduction
In present scenario most of the industries are facing crises. Due to lack of well-trained human resources and development of technology industries moving towards automation. For smooth functioning of any industry, electricity is foremost requirement. Power plants are the biggest source of electricity. But electricity cost is still a challenge in front of management. Economic burden increase as the electricity prices goes up. So it is important to produce more and more electricity from power plants with greater efficiency and with low cost. This efficiency can be achieved by the smooth functioning and increasing reliability of subsystem of power plants and is guaranteed by time-to-time availability and proper maintenance of system. Reliability theory provides us a structure to establish proper system designs, optimize its operating availability and formulate proper maintenance policies. It is required that maintenance manager should be aware about most critical component and its time-to-time maintenance strategy. RAMD is one of the methods which help in achieving this goal. This
helps to identify the most critical component among all of them and to ensure that they have proper maintenance policies. A lot of work has been done so far to improve reliability of industrial systems. Van Casteren et al. (2000) performed performance tests in electrical power systems using Weibull Markovian method. Arora et al. (2007) studied a particular problem to optimize resource allocation in the thermal power plant. The coal handling process has been analyzed through complex programming. The operational availability evaluation has been done to increase the efficiency of the system. Ebeling (2008) suggested various techniques to test reliability and availability of systems with varying failure and repair rates. Fytiti and Zabaniotou (2008) worked on different methodologies to maintain the sewage treatment plants. Tsarouhas et al. (2009) used best fitted distribution of failure and repair rates to investigate reliability, availability, and maintainability of strudel production line. Carazas et al. (2009) suggested a methodology for the assessment of performance measures of gas turbine power plant. Carazas et al. (2010) provided a performance model for availability evaluation for HRSGs system built in a combined cycle power plant. Komal and Kumar (2010) estimate various reliability measures by utilizing conventional lambda-tau approach. Kumar et al. (2010) used genetic algorithms to maximize the quality of a fertilizer plant’s CO shift conversion process. Seadi and Lukehurst (2012) carried out work in the direction of reliability analysis of fluid digestate from biogas plants. Garg and Sharma (2012) built up a two-stage approach namely particle swarm optimization to optimize the various repair and failure parameters using statistical measures mean, standard deviation, and coefficient of variation. Adhikari et al. (2012) done a comparative study of a coal-fired thermal power station in eastern India which focused on efficiency, stability and availability of plant. Bachmann (2015) revealed about sustainable biogas production in municipal wastewater treatment plans. Aggarwal et al. (2015) made various choices of failure and repair rates of fertilizer plant’s subsystem to calculate long-run availability, reliability and mean time between failures. Corvaro et al. (2017) developed a technique for evaluating reciprocating compressor output with the aid of efficiency, availability, maintenance and taking failure and repair rates as exponentially distributed. Tsarouhas (2018) analyzed quality of the wine packaging production line using the RAMD methodology. Saini et al. (2019) used RAMD approach to identify evaporation system’s performance parameters in the sugar industry and made system reliability sensitivity analysis. Gupta et al. (2020) carried out operational availability analysis of generators in steam turbine power plants. Kumar et al. (2020) performed reliability and maintainability analysis of power generating unit of sewage treatment plant.

In present study, an effort has been made to analyze the reliability characteristics of generator in steam turbine power plant at component level. Fundamental concepts of reliability theory and Markovian birth–death process have been used to explore the system. The paper consists four sections, including present introductory section. System description, and assumptions are explained in section second. RAMD analysis is performed in section 3. Finally, section 4 is devoted to conclusion and implication of the results.

2. System description and assumptions

2.1 List of notations and definitions

- System is working with full capacity
- System is in failure state
- A, B, C, D, E, F and G represent states at which subsystem is working with full capacity
- a, b, c, d, e, f and g represent states at which subsystem is failed
B, D, represent states at which subsystem B and D is in cold standby state respectively
\[ \alpha_i, \quad i = 1, 2, 3, 4, 5, 6, 7 \]  
Failure rate of subsystem A, B, C, D, E, F and G respectively
\[ \eta_i, \quad i = 1, 2, 3, 4, 5, 6, 7 \]  
Repair rate of subsystems A, B, C, D, E, F and G respectively
\[ P_i; \quad i = 0, 1, 2 \]  
Probability that system is in initial state with full capacity  

Steady state probability that the system is in \( i^{th} \) state
\[ f(x) = \begin{cases} \lambda e^{-\lambda x} &; 0 \leq x \leq \infty \\ 0 &; otherwise \end{cases} \]  
probability density function of exponential distribution
\[ R(t) = P(T > t) = \int_0^\infty f(x)dx \]  
Reliability function

\[ \text{Availability function} = \frac{\text{Life time}}{\text{total time}} = \frac{\text{Life time}}{\text{Life time + Repair time}} = \frac{MTBF}{MTBF + MTTR} \]  
(2)

\[ M(t) = P(T \leq t) = 1 - e^{\left(\frac{-t}{MTTR}\right)} \]  
Maintainability function

\[ MTBF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\alpha t}dt = \frac{1}{\alpha} \]  
Mean Time Between Failures

\[ MTTR = \frac{1}{\eta} \]  
Mean Time to repair

\[ \eta = \text{repair rate} ; \quad \alpha = \text{failure rate} \]  
(6)

\[ d = \frac{\eta}{\alpha} = \frac{MTBF}{MTTR} \]  
Dependability ratio

\[ D_{\min} = 1 - \left( \frac{1}{d - 1} \right) \left( e^{-\text{ind} / d - 1} - e^{-\text{ind} / d - 1} \right) \]  
(8)

2.2. System description

In this section, a brief description of Generator in steam turbine power plant has been given. A unit that is used for conversion of mechanical energy into electric energy is termed as generator. Generator mainly consists of seven components namely housing, bearing, stator, cooling system, rotor, exciter and protection. All components are arranged in series configuration. The pictorial representation of components is in fig 2.1.
2.2.1. Subsystem A (Housing)

It consists of one unit of housing. The failure of this unit tends to complete system failure as it is connected to the following unit in sequence.

2.2.2. Subsystem B (Bearing)

It consists of two sets of bearing, one in operative and other in cold standby. The failure rate of both the units are same and failure of both units tends to system failure. This unit also connected in sequence with subsequent units.

2.2.3. Subsystem C (Stator)

It consists of one unit of stator. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

2.2.4. Subsystem D (Cooling System)

It consists of two sets of cooling system, one is operative and other is in cold standby. The failure rate of both the units are same and failure of both units tends to system failure.

2.2.5. Subsystem E (Rotor)

It consists of one unit of rotor. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

2.2.6. Subsystem F (Exciter)

It consists of one set of exciter. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

2.2.7. Subsystem G (Protection)

It consists of one set of protection. This unit's failure causes complete system failure as it is connected to the following unit in sequence.

2.3. Assumptions

- The failure rates and repair rates of each subsystem follows exponential distribution.
- The failure and repair rates are statistically independent to each other.
- There are no simultaneous failures among the subsystem.
- There are sufficient repair and replacement facilities. Repairmen always present in plant and performance wise repaired system is as good as new.
- The switchover devices used for standby subsystems are perfect.

3. RAMD analysis of the system

In this section, mathematical models have been developed for all subsystems of the generator using Markov birth death process and Chapman Kolmogorov differential equations for each of the sub-systems have been derived. The rates of failure and repair of each subsystem has been considered exponentially distributed as shown in table 3.1. For each subsystem, a transition diagram has been depicted. In each subsystem, after solving respective Chapman Kolmogorov differential equations in steady state and using normalizing conditions, various performance measures of the subsystem such as maintainability, availability, reliability, mean time to failure (MTTF), mean time to repair (MTTR) and dependability ratio have been obtained.

| Subsystem | Failure Rates ($\alpha$) | Repair rates ($\eta$) |
|-----------|--------------------------|----------------------|
| $S_1$     | $\alpha_1 = 0.005$       | $\eta_1 = 0.65$      |
| $S_2$     | $\alpha_2 = 0.009$       | $\eta_2 = 1.25$      |
The RAMD indices for subsystems of generator of STPP are computed as:

3.1. RAMD indices for subsystem $S_1$

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

$$P_0'(t) = -\alpha_3 P_0(t) + \eta_3 P_1(t) \quad \ldots(9)$$

$$P_1'(t) = \alpha_4 P_0(t) - \eta_3 P_1(t) \quad \ldots(10)$$

Under steady state, equation 9 and 10 reduces to

$$P_1 = \frac{\alpha_4}{\eta_3} P_0 \quad \ldots(11)$$

Now, using normalization condition

$$P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\alpha_4}{\eta_3} P_0 = 1 \Rightarrow P_0 = \frac{\eta_3}{\eta_3 + \alpha_4} \quad \ldots(12)$$

Now, by using equations (1-5, 7-8 & 12) important system performance measures have been derived and appended in table-4.

3.2. RAMD indices for subsystem $S_2$

This subsystem has single unit working at a time only but with one cold standby unit. Failure of both leads to complete system failure. The transition diagram and Chapman Kolmogorov differential equations associated with it are given as
\[ P_0(t) = -\alpha_2 P_0(t) + \eta_2 P_1(t) \]  
\[ P_1(t) = \alpha_2 P_1(t) - (\alpha_2 + \eta_2) P_1(t) + \eta_2 P_2(t) \]  
\[ P_2(t) = \alpha_2 P_1(t) - \eta_2 P_2(t) \]  
\( \text{ ...(15) } \)

Under steady state, equation 13,14 and 15 reduces to

\[ P_1 = \frac{\alpha_2}{\eta_2} P_0 \]  
\[ P_2 = \frac{\alpha_2^2}{\eta_2} P_0 \]  
\( \text{ ...(16) } \) and  
\( \text{ ...(17) } \)

Now, using normalization condition:

\[ P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\alpha_2}{\eta_2} P_0 + \frac{\alpha_2^2}{\eta_2^2} P_0 = 1 \Rightarrow P_0 = \frac{1}{1 + \frac{\alpha_2}{\eta_2} + \frac{\alpha_2^2}{\eta_2^2}} \]  
\( \text{ ...(18) } \)

Now, by using equations (1-5, 7-8 & 18) important system performance measures have been derived and appended in table-4.

### 3.3. RAMD indices for subsystem S_3

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

\[ P_0(t) = -\alpha_3 P_0(t) + \eta_3 P_1(t) \]  
\[ P_1(t) = \alpha_3 P_1(t) - \eta_3 P_1(t) \]  
\( \text{ ...(19) } \) and  
\( \text{ ...(20) } \)

Under steady state, equation 19 and 20 reduces to

\[ P_1 = \frac{\alpha_3}{\eta_3} P_0 \]  
\( \text{ ...(21) } \)

Now, using normalization condition:

\[ P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\alpha_3}{\eta_3} P_0 = 1 \Rightarrow P_0 = \frac{\eta_3}{\eta_3 + \alpha_3} \]  
\( \text{ ...(22) } \)

Now, by using equations (1-5, 7-8 & 22) important system performance measures have been derived and appended in table-4.

### 3.4. RAMD indices for subsystem S_4

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

\[ P_0(t) = -\alpha_4 P_0(t) + \eta_4 P_1(t) \]  
\[ P_1(t) = \alpha_4 P_1(t) - \eta_4 P_1(t) \]  
\( \text{ ...(21) } \)

Now, using normalization condition:

\[ P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\alpha_4}{\eta_4} P_0 = 1 \Rightarrow P_0 = \frac{\eta_4}{\eta_4 + \alpha_4} \]  
\( \text{ ...(22) } \)

Now, by using equations (1-5, 7-8 & 22) important system performance measures have been derived and appended in table-4.
This subsystem has single unit working at a time only but with one cold standby unit. Failure of both leads to complete system failure. The transition diagram and Chapman Kolmogorov differential equations associated with it are given as:

\[ P_0(t) = -\alpha_4 P_0(t) + \eta_4 P_1(t) \]  \hspace{1cm} \text{(23)}

\[ P_1(t) = \alpha_4 P_0(t) - (\alpha_4 + \eta_4) P_1(t) + \eta_4 P_2(t) \]  \hspace{1cm} \text{(24)}

\[ P_2(t) = \alpha_4 P_1(t) - \eta_4 P_2(t) \]  \hspace{1cm} \text{(25)}

Under steady state, equation 23, 24 and 25 reduces to

\[ P_1 = \frac{\alpha_4}{\eta_4} P_0 \]  \hspace{1cm} \text{(26)}

\[ P_2 = \frac{\alpha_4^2}{\eta_4^2} P_0 \]  \hspace{1cm} \text{(27)}

Now, using normalization condition:

\[ P_0 + P_1 + P_2 = 1 \Rightarrow P_0 + \frac{\alpha_4}{\eta_4} P_0 + \frac{\alpha_4^2}{\eta_4^2} P_0 = 1 \Rightarrow P_0 = \left(1 + \frac{\alpha_4}{\eta_4} + \frac{\alpha_4^2}{\eta_4^2}\right)^{-1} \]  \hspace{1cm} \text{(28)}

Now, by using equations (1-5, 7-8 & 28) important system performance measures have been derived and appended in table-4.

3.5. RAMD indices for subsystem S

3.6. RAMD indices for subsystem S
This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

\[ P_6(t) = -\alpha_6 P_0(t) + \eta_6 P_1(t) \]  
\[ P_1(t) = \alpha_6 P_0(t) - \eta_6 P_1(t) \]  

Under steady state, equation 33 and 34 reduces to

\[ P_1(t) = \frac{\alpha_6}{\eta_6} P_0(t) \]  

Now, using normalization condition

\[ P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\alpha_6}{\eta_6} P_0 = 1 \Rightarrow P_0 = \frac{\eta_6}{\eta_6 + \alpha_6} \]  

Now, by using equations (1-5, 7-8 & 36) important system performance measures have been derived and appended in table-4.

### 3.7 RAMD indices for subsystem S_7

This subsystem has single unit only. Failure of it leads to complete system failure. The transition diagram and Chapman - Kolmogorov differential equations associated with it is given as:

\[ P_7(t) = -\alpha_7 P_0(t) + \eta_7 P_1(t) \]  
\[ P_1(t) = \alpha_7 P_0(t) - \eta_7 P_1(t) \]  

Under steady state, equation 37 and 38 reduces to

\[ P_1(t) = \frac{\alpha_7}{\eta_7} P_0(t) \]  

Now, using normalization condition

\[ P_0 + P_1 = 1 \Rightarrow P_0 + \frac{\alpha_7}{\eta_7} P_0 = 1 \Rightarrow P_0 = \frac{\eta_7}{\eta_7 + \alpha_7} \]  

Now, by using equations (1-5, 7-8 & 40) important system performance measures have been derived and appended in table-4.

### 3.8 System reliability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system reliability of the generator is determined by
The variation in reliability with respect to different time instant is compiled in table 2.

Table 2: Variation of reliability of subsystems with time

| Time (in months) | R_{S1}(t) | R_{S2}(t) | R_{S3}(t) | R_{S4}(t) | R_{S5}(t) | R_{S6}(t) | R_{S7}(t) | R_{Sys}(t) |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|
| 0                | 1.00000   | 1.00000   | 1.00000   | 1.00000   | 1.00000   | 1.00000   | 1.00000   | 1.00000    |
| 10               | 0.95123   | 0.83527   | 0.97045   | 0.84366   | 0.93239   | 0.98020   | 0.96464   | 0.57350    |
| 20               | 0.90484   | 0.69768   | 0.94176   | 0.71177   | 0.86936   | 0.96079   | 0.93053   | 0.32890    |
| 30               | 0.86071   | 0.58275   | 0.91393   | 0.60050   | 0.81058   | 0.94176   | 0.89763   | 0.18862    |
| 40               | 0.81873   | 0.48675   | 0.88692   | 0.50662   | 0.75578   | 0.92312   | 0.86589   | 0.10818    |
| 50               | 0.77880   | 0.40657   | 0.86071   | 0.42741   | 0.70469   | 0.90484   | 0.83527   | 0.06204    |
| 60               | 0.74082   | 0.33960   | 0.83527   | 0.36059   | 0.65705   | 0.88692   | 0.80574   | 0.03558    |
| 70               | 0.70469   | 0.28365   | 0.81058   | 0.30422   | 0.61263   | 0.86936   | 0.77724   | 0.02040    |
| 80               | 0.67032   | 0.23693   | 0.78663   | 0.25666   | 0.57121   | 0.85214   | 0.74976   | 0.01170    |
| 90               | 0.63763   | 0.19790   | 0.76338   | 0.21654   | 0.53259   | 0.83527   | 0.72325   | 0.00671    |
| 100              | 0.60653   | 0.16530   | 0.74082   | 0.18268   | 0.49659   | 0.81737   | 0.69768   | 0.00385    |

3.9 System availability

All seven subsystems are connected through one another in sequence. Any one of the failure leads to complete failure of the system. The overall system availability of the generator is determined by

\[ A_{Sys} = A_{S1} \times A_{S2} \times A_{S3} \times A_{S4} \times A_{S5} \times A_{S6} \times A_{S7} \]

\[ = 0.908613 \] \hspace{1cm} ...(42)

3.10 System maintainability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system maintainability of the generator determined by

\[ M_{Sys}(t) = M_{S1}(t) \times M_{S2}(t) \times M_{S3}(t) \times M_{S4}(t) \times M_{S5}(t) \times M_{S6}(t) \times M_{S7}(t) \]

\[ = (1 - e^{-0.65t}) \times (1 - e^{-2.5t}) \times (1 - e^{-0.75t}) \times (1 - e^{-1.9t}) \times (1 - e^{-0.18t}) \times (1 - e^{-0.09t}) \times (1 - e^{-0.45t}) \]

\[ = 1 - e^{-0.0169t} \] \hspace{1cm} ...(43)

The variation in maintainability with respect to different time instant is compiled in table 3.

Table 3: Variation of maintainability of subsystems with time

| Time (in months) | M_{S1}(t) | M_{S2}(t) | M_{S3}(t) | M_{S4}(t) | M_{S5}(t) | M_{S6}(t) | M_{S7}(t) | M_{Sys}(t) |
|------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|------------|
| 0                | 0.00000   | 0.00000   | 0.00000   | 0.00000   | 0.00000   | 0.00000   | 0.00000   | 0.00000    |
3.11 System dependability

All seven subsystems are connected through one another in sequence. Just one failure leads to complete failure of the system. The overall system dependability of the generator is determined by

\[ D_{\text{min(Sys)}} = D_{\text{min(S1)}} \times D_{\text{min(S2)}} \times D_{\text{min(S3)}} \times D_{\text{min(S4)}} \times D_{\text{min(S5)}} \times D_{\text{min(S6)}} \times D_{\text{min(S7)}} \]

\[ = 0.913978 \quad \ldots(44) \]

The summarized form of all the RAMD indices computed above for all the subsystems of cooling tower is given in table 4 which is as follows

| RAMD indices of subsystems | Subsystem S1 | Subsystem S2 | Subsystem S3 | Subsystem S4 | Subsystem S5 | Subsystem S6 | Subsystem S7 | System |
|----------------------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------|
| Reliability                | \( e^{-0.015t} \) | \( e^{-0.018t} \) | \( e^{-0.003t} \) | \( e^{-0.017t} \) | \( e^{-0.007t} \) | \( e^{-0.002t} \) | \( e^{-0.0036t} \) | \( e^{-0.0556t} \) |
| Maintainability            | \( 1 - e^{-0.65t} \) | \( 1 - e^{-2.5t} \) | \( 1 - e^{-0.75t} \) | \( 1 - e^{-1.9t} \) | \( 1 - e^{-0.18t} \) | \( 1 - e^{-0.09t} \) | \( 1 - e^{-0.45t} \) | \( 1 - e^{-0.0169t} \) |
| Availability              | 0.992366     | 0.992852     | 0.996016     | 0.991132     | 0.962567     | 0.978261     | 0.992064     | 0.908613 |
| MTBF                       | 200.0000     | 55.5556      | 333.3333     | 58.8235      | 142.8571     | 500.0000     | 277.7777     | 1568.3472 |
| MTTR                       | 1.538462     | 0.400000     | 1.333333     | 0.526316     | 5.555556     | 11.111111    | 2.222222     | 22.686999 |
| Dependability              | 0.992593     | 0.993053     | 0.996088     | 0.991426     | 0.965899     | 0.979620     | 0.992306     | 0.913978 |
| Dependability ratio        | 130.0000     | 138.8889     | 250.0000     | 111.7647     | 25.7143      | 45.0000      | 125.0000     |        |

Table 5: Variation in reliability of system due to variation in failure rate of subsystem 1

| System | Subsystem 1 |
|--------|-------------|
| Time (in months) | \( \alpha_t=0.002 \) | \( \alpha_t=0.006 \) | \( \alpha_t=0.002 \) | \( \alpha_t=0.006 \) |
| 0      | 1.000000    | 1.000000    | 1.000000    | 1.000000    |
| Time (in months) | $\beta_2=0.005$ | $\beta_2=0.015$ | $\beta_2=0.005$ | $\beta_2=0.015$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0               | 1.000000        | 1.000000        | 1.000000        | 1.000000        |
| 10              | 0.621263        | 0.508648        | 0.904837        | 0.740818        |
| 20              | 0.385968        | 0.258722        | 0.818731        | 0.548812        |
| 30              | 0.239788        | 0.131598        | 0.740818        | 0.406570        |
| 40              | 0.148972        | 0.066937        | 0.670320        | 0.301194        |
| 50              | 0.092551        | 0.034047        | 0.606531        | 0.223130        |
| 60              | 0.057498        | 0.017318        | 0.548812        | 0.165299        |
| 70              | 0.035722        | 0.008809        | 0.496585        | 0.122456        |
| 80              | 0.022193        | 0.004481        | 0.449329        | 0.090718        |
| 90              | 0.013787        | 0.002279        | 0.406570        | 0.067206        |
| 100             | 0.008566        | 0.001159        | 0.367879        | 0.049787        |

Table 6  Variation in reliability of system due to variation in failure rate of subsystem 2

| Time (in months) | $\beta_3=0.0008$ | $\beta_3=0.0075$ | $\beta_3=0.0008$ | $\beta_3=0.0075$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0               | 1.000000        | 1.000000        | 1.000000        | 1.000000        |
| 10              | 0.586255        | 0.548263        | 0.992032        | 0.927743        |
| 20              | 0.343695        | 0.300592        | 0.984127        | 0.860708        |
| 30              | 0.201493        | 0.164804        | 0.976286        | 0.798516        |
| 40              | 0.118126        | 0.090356        | 0.968507        | 0.740818        |

Table 7  Variation in reliability of system due to variation in failure rate of subsystem 3
| Time (in months) | $\beta_4=0.002$ | $\beta_4=0.05$ | $\beta_4=0.002$ | $\beta_4=0.05$ |
|-----------------|----------------|----------------|----------------|----------------|
| 50              | 0.069252       | 0.049539       | 0.960789       | 0.687289       |
| 60              | 0.040599       | 0.027160       | 0.953134       | 0.637628       |
| 70              | 0.023802       | 0.014891       | 0.945539       | 0.591555       |
| 80              | 0.013954       | 0.008164       | 0.938005       | 0.548812       |
| 90              | 0.008181       | 0.004476       | 0.930531       | 0.509156       |
| 100             | 0.004796       | 0.002454       | 0.923116       | 0.472367       |

Table 8  Variation in reliability of system due to variation in failure rate of subsystem 4

| Time (in months) | $\beta_5=0.0025$ | $\beta_5=0.015$ | $\beta_5=0.0025$ | $\beta_5=0.015$ |
|-----------------|----------------|----------------|----------------|----------------|
| 0               | 1.000000       | 1.000000       | 1.000000       | 1.000000       |
| 10              | 0.653116       | 0.250074       | 0.960789       | 0.367879       |
| 20              | 0.426561       | 0.062537       | 0.923116       | 0.135335       |
| 30              | 0.278594       | 0.015639       | 0.886920       | 0.049787       |
| 40              | 0.181954       | 0.003911       | 0.852144       | 0.018316       |
| 50              | 0.118837       | 0.000978       | 0.818731       | 0.006738       |
| 60              | 0.077615       | 0.000245       | 0.786628       | 0.002479       |
| 70              | 0.050691       | 0.000061       | 0.755784       | 0.000912       |
| 80              | 0.033107       | 0.000015       | 0.726149       | 0.000335       |
| 90              | 0.021623       | 0.000004       | 0.697676       | 0.000123       |
| 100             | 0.014122       | 0.000001       | 0.670320       | 0.000045       |

Table 9  Variation in reliability of system due to variation in failure rate of subsystem 5
Table 10   Variation in reliability of system due to variation in failure rate of subsystem 6

| Time (in months) | β₆=0.09 | β₆=0.006 | β₆=0.09 | β₆=0.006 |
|------------------|---------|----------|---------|----------|
| 0                | 1.000000| 1.000000 | 1.000000| 1.000000 |
| 10               | 0.237877| 0.551011 | 0.406570| 0.941765 |
| 20               | 0.056586| 0.303613 | 0.165299| 0.886920 |
| 30               | 0.013460| 0.167294 | 0.067206| 0.835270 |
| 40               | 0.003202| 0.092181 | 0.027324| 0.786628 |
| 50               | 0.000762| 0.050793 | 0.011109| 0.740818 |
| 60               | 0.000181| 0.027987 | 0.004517| 0.697676 |
| 70               | 0.000043| 0.015421 | 0.001836| 0.657047 |
| 80               | 0.000002| 0.004682 | 0.000304| 0.582748 |
| 100              | 0.000001| 0.002580 | 0.000123| 0.548812 |

Table 11   Variation in reliability of system due to variation in failure rate of subsystem 7

| Time (in months) | β₇=0.0008 | β₇=0.0075 | β₇=0.0008 | β₇=0.0075 |
|------------------|-----------|-----------|-----------|-----------|
| 0                | 1.000000  | 1.000000  | 1.000000  | 1.000000  |
| 10               | 0.589783  | 0.551563  | 0.992032  | 0.927743  |
| 20               | 0.347844  | 0.304221  | 0.984127  | 0.860708  |
| 30               | 0.205153  | 0.167797  | 0.976286  | 0.798516  |
| 40               | 0.120996  | 0.092551  | 0.968507  | 0.740818  |
| 50               | 0.071361  | 0.051047  | 0.960789  | 0.687289  |
| 60               | 0.042088  | 0.028156  | 0.953134  | 0.637628  |
| 70               | 0.024823  | 0.015530  | 0.945539  | 0.591555  |
| 80               | 0.014640  | 0.008566  | 0.938005  | 0.548812  |
| 90               | 0.008634  | 0.004724  | 0.930531  | 0.509156  |
| 100              | 0.005092  | 0.002606  | 0.923116  | 0.472367  |

4. Discussion and conclusion

For a particular case, reliability analysis of various subsystems and system has been performed by assigning numerical values appended in Table 1. All subsystems reliability and
maintenance behaviors have been shown in Tables 2 and 3. Table 4 comprises all other RAMD measures. From the numerical analysis mentioned in table 2, it is revealed that after 50 months of operation system’s reliability only remains 0.10818. It happened due to the least reliable subsystems bearing and cooling system. It is recommended in this situation that more attention should be given to less performers and proper maintenance strategies planned to enhance their reliability. Tables 5, 6, 7, 8, 9, 10 and 11 showed the reliability behavior of different subsystems with respect to time as well as variation in their failure rates. Bearing and cooling system are most critical, highly sensitive and require special attention to improve the reliability of the generator. From the above discussion, it is inferred that if maintenance personal properly monitor the failure rates of the bearing and cooling system by proper maintenance policies, it surely improve the efficiency of the generator and its working hours.

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