Operational availability analysis of generators in steam turbine power plants

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Abstract

The main aim of this study is to explore the availability and profitability of generators, which are key units of steam turbine power plants, considering exponential failure and arbitrary repair time distributions. A Markov birth–death process and supplementary variable technique are used to evaluate system effectiveness measures. Such a generator mainly consists of seven repairable components arranged in a series configuration. A stochastic model of the generator is developed, and the Chapman–Kolmogorov differential difference equation of the system derived. Finally, the results for the steady-state availability and profitability of the system are obtained for a particular case that will be helpful to system designers to enhance the performance of plants to some extent.

Keywords Generator · Steam turbine power plant · Markov birth–death process · Availability · Chapman–Kolmogorov differential difference equations

1 Introduction

As populations exhibit rapid growth, the consumption of electricity by domestic and commercial clients is increasing, with corresponding increasing expectations regarding the energy that power plants can produce. The main aim of any power plant is to maximize its capacity, which is only possible if it can remain operative with high availability. Successful operation of steam turbine power plants depends on successful functioning of its subsystems. In the current age, due to the complexity of such systems and fundamental issues, power plants face many operational challenges and cannot achieve excellent performance. The performance of any plant depends upon the reliability of its components. Through the use of highly reliable subunits/components and perfect maintenance, higher availability can be achieved. Failure is an unavoidable circumstance but can be avoided for some time by implementing reliability improvement techniques. Some of the main causes of power plant failure include poor maintenance, lack of good operators,

inadequate testing, etc., resulting in random system failures and subsequent unavailability. It thus becomes necessary to conduct maintenance of even well-designed components from time to time. Management always wishes to achieve high reliability but with low investment. The main aim of the present study is to determine the most critical component which contributes significantly to the operational availability and profitability of such systems. A Markov birth–death process and supplementary variable technique are used in the system analysis. The data associated with failure and repair rates, expenditure, and revenue are taken arbitrarily based on discussions with maintenance personnel at a plant situated in the central part of India. Sabouhia et al. [1] recommended the consideration of all failure and repair rates as exponentially distributed. Thereafter, for different combinations of failure and repair rates of subsystems, the availability and profitability of the system are analyzed, and their variation recorded. Such information on the variation of availability can be applied to identify the most sensitive subsystems, based on which proper maintenance

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policies could be planned to improve the performance of the system.

This manuscript is organized into five sections, including this introductory part. A detailed literature review is presented in Sect. 2. A system description, notation, and state transition diagram are provided in Sect. 3. The stochastic analysis is described in Sect. 4, while the numerical analysis and conclusions are given in the final section.

2 Literature review

Cox [2] first coined the term “supplementary variable technique” and obtained reliability measures for a non-Markovian system. Kumar et al. [3] used a Markov birth–death process to depict the steady-state behavior of a desulfurization system, while Arora and Kumar [4] adopted this methodology for availability analysis of steam and power generation systems. In that work, the failure and repair rates of all subsystems were considered to be exponentially distributed. Furthermore, the derived results could be used to formulate maintenance policies for the system. A detailed introduction to reliability and maintainability theories was presented in Ebeling [5]. Billinton and Allan [6] explained the tools and theories used in reliability evaluation of engineering systems. Gupta and Tewari [7] and Tewari et al. [8] focused on simulation modeling of thermal power plants. In all this published work, all the subsystems were considered to be single complex systems. Carazas et al. [9] developed a stochastic model for heat recovery steam generators to determine the availability of the system. Heat recovery steam generators (HRSGs) are extensively used in thermal power plants. HRSGs installed in combined-cycle power plants have been studied as a case study for reliability analysis. Balagurusamy [10] explained some basic concepts of reliability theory that are useful for system analysis, including quality, probability, Laplace transforms, failure curves, various hazard models, and redundancy. A 210-MW coal-fired thermal power plant situated in the eastern region of India was analyzed as a case study by Adhikarya et al. [11]. Reliability, availability, and maintainability (RAM) analysis of the plant was carried out in order to propose the maintenance time of the plant to enhance its availability and performance and ensure a proper power supply. Various other system characteristics such as mean time to failure (MTTF) and the cost–benefit tradeoff for single- and two-unit systems have been extensively studied by many researchers such as Singh et al. [12], Kumar et al. [13], Kumari et al. [14], Kumar and Saini [15], and Saini and Kumar [16]. Devi et al. [17] developed a model for a coal-fired power plant to mitigate the risk of unexpected failures, reduce the overall costs of production, evaluate the availability index using a Markov birth–death process, and identify the most critical unit of each subsystem. It was suggested that, by adopting the developed model, the reliability of the plant

could be increased. Suleiman et al. [18], Aggarwal et al. [19], Okafor et al. [20], Sabouhia et al. [1], Agarwal et al. [21], and Niwas and Garg [22, 24] studied various complex industrial systems, including some used in power plants, under different assumptions and provided recommendations to enhance their performance. Kadyan and Kumar [23] designed and analyzed a stochastic model for refining a system in the sugar industry and simplified it using the supplementary variable technique. Savsar [25] carried out an analysis of the Sabiya Power Plant in Kuwait, which has 8 steam turbines and 13 gas turbine stations. A simulation model was used to analyze the effects of different maintenance policies on the availability of these stations. Recently, Kumar and Saini [26] developed a fuzzy reliability model for a marine power plant and analyzed the availability of the system using membership functions. Dahiya et al. [27] developed and analyzed an A-Pan crystallization system used in the sugar industry. However, componentwise analysis of power plants has not been carried out so far in literature. Therefore, an effort is made herein to derive an expression for generators in power plants using a birth–death process and the supplementary variable technique.

3 System description, notation, and assumptions

3.1 System description

A unit used to convert mechanical into electric energy is termed a generator. Steam turbines are one source of such mechanical energy. With the help of a generator, this mechanical energy can be converted into electrical energy. A generator consists of the following main components:

3.1.1 Subsystem A (housing)

This subsystem consists of one unit. This is where the generators are kept safely and securely for operation. Carelessness by staff while handling the protection of the generator or its improper structure can lead to failure of the housing.

3.1.2 Subsystem B (bearing)

A bearing is a component used between two parts that allows rotational or linear movement and reduces the friction between them, thus enhancing their performance and saving energy. This subsystem consists of one unit. A series of bearings are positioned to transfer the relative motion of the moving parts in the system. This helps reduce friction caused by rotation and reduce wear and tear. There are many possible reasons for the failure of bearings, including improper lubrication, contamination, improper mounting,

misalignment, corrosion, fatigue (spalling), overheating, excessive loads, improper storage and handling, etc.

3.1.3 Subsystem C (stator)

This subsystem consists of one unit. A stator is the static component of a rotary system with large copper windings, found in electric generators. Energy passes through the stator to the rotating component of the system. The rotating magnetic field is converted into an electric current by the stator. When a generator is subjected to adverse operating conditions—electrical, mechanical, or environmental—the life of the stator winding can be drastically shortened.

3.1.4 Subsystem D (cooling system)

This subsystem consists of two cooling units, one operative and the other on cold standby. Generators have numerous conductors. When current flows through them, they produce heat. To decrease the danger of destruction, this heat must be appropriately removed from the system to avoid the rapid loss in the windings. This heat can be removed using many types of cooling system, including air-cooled systems, liquid-cooled systems, hydrogen-cooled systems, etc. Better cooling systems help to address this issue and reduce the requirement for maintenance. Failure of the cooling system may occur due to an improper coolant level, breakdown of the insulation in the coil, lack of cooling tower maintenance, etc.

3.1.5 Subsystem E (rotor)

This subsystem consists of one unit. The rotor is the chief rotating component of a generator. It generates the magnetic field in the generator. The rotor windings of generators can suffer damage due to deficiencies in their design, manufacture abnormalities, improper operating conditions, etc.

3.1.6 Subsystem F (exciter)

This subsystem consists of one unit only. The process for producing a magnetic field from an electric current is called excitation. Failure of the exciter can be caused by several factors, such as power supply outage, short circuits in the excitation windings, failure of the voltage regulator, etc.

3.1.7 Subsystem G (protection)

This subsystem consists of one unit only. Protection is used to keep the generator safe from various types of mechanical and electrical stress. Failure of such protection may occur

due to internal faults and abnormal operating conditions such as overload, overvoltage, loss of synchronization, etc.

3.2 Notations

A, B, C, D, E, F, G

D_1

a, b, c, d, d_1, e, f, g

$S_i (1 \leq i \leq 14)$

$\alpha_i (1 \leq i \leq 7)$

$\beta_i(x) (1 \leq i \leq 7)$

$p_0(t)$

$p_i(x, t) (0 \leq i \leq 14)$

Specifies that the system is operating at full capacity

Specifies that the system is in a failure state

Specifies that the units are operating at full capacity

Indicates that unit D is operating in the cold standby state

Represent failed units

Represent the different states

Parameters of the exponential distributions of the random variables describing the failure rate of subsystems A, B, C, D, E, F, G , respectively

Parameter of the exponential distribution of the random variables describing the repair rate of subsystems A, B, C, D, E, F, G , respectively

Probability that the system is operating at full capacity at the initial time t

Probability of reaching the i th position at time t with an intervening repair time x

3.3 Assumptions

The present study is performed under the following set of assumptions:

- The failure rate of all the subsystems follows an exponential distribution while the repair rates follow an arbitrary distribution.
- All the random variables are independent of one another.
- Two or more failure cannot happen at same time.
- A permanent repairman is assigned to the system and is always present in the plant. Also, repairs and switches are perfect.

4 Stochastic modeling of the system

Using simple probabilistic concepts, a Markov birth–death process, and the supplementary variable technique, the Chapman–Kolmogorov differential–difference equations can be derived based on the state transition diagram shown in Fig. 1:

$$\begin{aligned}
 p_0(t + \Delta t) = & (1 - \alpha_1 \Delta t - \alpha_2 \Delta t - \alpha_3 \Delta t - \alpha_4 \Delta t - \alpha_5 \Delta t \\
 & - \alpha_6 \Delta t - \alpha_7 \Delta t) p_0(t) + \int_0^\infty \beta_1(x) p_1(x, t) \Delta t dx \\
 & + \int_0^\infty \beta_2(x) p_2(x, t) \Delta t dx + \int_0^\infty \beta_3(x) p_3(x, t) \Delta t dx \\
 & + \int_0^\infty \beta_4(x) p_4(x, t) \Delta t dx + \int_0^\infty \beta_5(x) p_5(x, t) \Delta t dx \\
 & + \int_0^\infty \beta_6(x) p_6(x, t) \Delta t dx + \int_0^\infty \beta_7(x) p_7(x, t) \Delta t dx.
 \end{aligned}$$

Dividing both sides by Δt yields (Fig. 2)

$$\begin{aligned}
 \frac{p_0(t + \Delta t) - p_0(t)}{\Delta t} = & (-\alpha_1 - \alpha_2 - \alpha_3 - \alpha_4 - \alpha_5 - \alpha_6 - \alpha_7) p_0(t) \\
 & + \int_0^\infty \beta_1(x) p_1(x, t) dx + \int_0^\infty \beta_2(x) p_2(x, t) dx \\
 & + \int_0^\infty \beta_3(x) p_3(x, t) dx + \int_0^\infty \beta_4(x) p_4(x, t) dx \\
 & + \int_0^\infty \beta_5(x) p_5(x, t) dx + \int_0^\infty \beta_6(x) p_6(x, t) dx \\
 & + \int_0^\infty \beta_7(x) p_7(x, t) dx.
 \end{aligned}$$

As $\Delta t \rightarrow 0$,

$$\begin{aligned}
 \lim_{\Delta t \rightarrow 0} \frac{p_0(t + \Delta t) - p_0(t)}{\Delta t} = & (-\alpha_1 - \alpha_2 - \alpha_3 - \alpha_4 - \alpha_5 - \alpha_6 - \alpha_7) p_0(t) \\
 & + \int_0^\infty \beta_1(x) p_1(x, t) dx + \int_0^\infty \beta_2(x) p_2(x, t) dx + \int_0^\infty \beta_3(x) p_3(x, t) dx \\
 & + \int_0^\infty \beta_4(x) p_4(x, t) dx + \int_0^\infty \beta_5(x) p_5(x, t) dx \\
 & + \int_0^\infty \beta_6(x) p_6(x, t) dx + \int_0^\infty \beta_7(x) p_7(x, t) dx,
 \end{aligned}$$

Fig. 1 Configuration diagram

Fig. 2 State change diagram of a generator in a steam turbine power plant

$$\begin{aligned}
&\Rightarrow \frac{dp_0}{dt} + (\alpha_1 + \alpha_2 + \alpha_3 + \alpha_4 + \alpha_5 + \alpha_6 + \alpha_7)p_0(t) \\
&= \int_0^\infty \beta_1(x)p_1(x,t)dx + \int_0^\infty \beta_2(x)p_2(x,t)dx \\
&+ \int_0^\infty \beta_3(x)p_3(x,t)dx + \int_0^\infty \beta_4(x)p_4(x,t)dx \\
&+ \int_0^\infty \beta_5(x)p_5(x,t)dx + \int_0^\infty \beta_6(x)p_6(x,t)dx \\
&+ \int_0^\infty \beta_7(x)p_7(x,t)dx \Rightarrow \frac{dp_0}{dt} + \sum_{i=1}^7 \alpha_i p_0(t) \\
&= \sum_{i=1}^7 \int_0^\infty \beta_i(x)p_i(x,t)dx \Rightarrow \left(\frac{d}{dt} + u_0\right)p_0(t) \\
&= f_0 \text{ where } u_0 = \sum_{i=1}^7 \alpha_i \text{ and } f_0 = \sum_{i=1}^7 \int_0^\infty \beta_i(x)p_i(x,t)dx.
\end{aligned} \quad (1)$$

Similarly,

$$p_1(x + \Delta x, t + \Delta t) = \alpha_1 \Delta t p_0(t) + 1 - \beta_1(x) \Delta x p_1(x, t). \quad (2)$$

Differentiating Eq. (2) with respect to x and t partially, we get

$$\Rightarrow \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta_1(x)\right)p_1(x, t) = \alpha_1 p_0(t). \quad (3)$$

Similarly, we can obtain

$$\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta_i(x)\right)p_i(x, t) = \alpha_i p_0(t); \quad i = 2, 3, 5, 6, 7 \quad (4)$$

and

$$\begin{aligned}
p_4(x + \Delta x, t + \Delta t) &= (1 - \alpha_1 \Delta t - \alpha_2 \Delta t - \alpha_3 \Delta t - \alpha_4 \Delta t - \alpha_5 \Delta t - \alpha_6 \Delta t - \alpha_7 \Delta t)(1 - \beta_4(x) \Delta t) \\
&+ p_4(x, t) + \alpha_4 \Delta t p_0(t) + \beta_1(x) \Delta x p_8(x, t) + \beta_2(x) \Delta x p_9(x, t) + \beta_3(x) \Delta x p_{10}(x, t) \\
&+ \beta_4(x) \Delta x p_{11}(x, t) + \beta_5(x) \Delta x p_{12}(x, t) + \beta_6(x) \Delta x p_{13}(x, t) + \beta_7(x) \Delta x p_{14}(x, t).
\end{aligned} \quad (5)$$

Differentiating Eq. (5) with respect to x and t partially, we get

$$\begin{aligned}
&\Rightarrow \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta_4(x) + \sum_{i=1}^7 \alpha_i\right)p_4(x, t) = \alpha_4 p_0(t) + \beta_1(x)p_8(x, t) + \beta_2(x)p_9(x, t) + \beta_3(x)p_{10}(x, t) \\
&+ \beta_4(x)p_{11}(x, t) + \beta_5(x)p_{12}(x, t) + \beta_6(x)p_{13}(x, t) + \beta_7(x)p_{14}(x, t) \\
&\Rightarrow \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta_4(x) + u_0\right)p_4(x, t) = f_1(x, t),
\end{aligned} \quad (6)$$

where

$$\begin{aligned}
f_1(x, t) &= \beta_1(x)p_8(x, t) + \beta_2(x)p_9(x, t) + \beta_3(x)p_{10}(x, t) \\
&+ \beta_4(x)p_{11}(x, t) + \beta_5(x)p_{12}(x, t) \\
&+ \beta_6(x)p_{13}(x, t) + \beta_7(x)p_{14}(x, t).
\end{aligned}$$

Similarly,

$$p_8(x + \Delta x, t + \Delta t) = \alpha_1 \Delta t p_4(x, t) + (1 - \beta_1(x) \Delta x)p_8(x, t). \quad (7)$$

Differentiating Eq. (7) with respect to x and t partially, we get

$$\Rightarrow \left(\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta_1(x)\right)p_8(x, t) = \alpha_1 p_4(x, t). \quad (8)$$

Similarly,

$$\begin{aligned}
&\left(\frac{\partial}{\partial x} + \frac{\partial}{\partial t} + \beta_i(x)\right)p_j(x, t) = \alpha_i p_4(t); \\
&i = 2, 3, 4, 5, 6, 7 \text{ and } j = 9, 10, 11, 12, 13, 14.
\end{aligned} \quad (9)$$

The boundary conditions are given as

$$\begin{aligned}
p_1(0, t) &= \alpha_1 p_0(t) & p_2(0, t) &= \alpha_2 p_0(t) & p_3(0, t) &= \alpha_3 p_0(t) \\
p_4(0, t) &= \alpha_4 p_0(t) & p_5(0, t) &= \alpha_5 p_0(t) & p_6(0, t) &= \alpha_6 p_0(t) \\
p_7(0, t) &= \alpha_7 p_0(t) & p_8(0, t) &= \alpha_1 p_4(t) & p_9(0, t) &= \alpha_2 p_0(t) \\
p_{10}(0, t) &= \alpha_3 p_0(t) & p_{11}(0, t) &= \alpha_4 p_0(t) & p_{12}(0, t) &= \alpha_5 p_0(t) \\
p_{13}(0, t) &= \alpha_6 p_0(t) & p_{14}(0, t) &= \alpha_7 p_0(t),
\end{aligned} \quad (10)$$

while the initial conditions are given as

$$\begin{aligned}
p_0(0) &= 1 \\
p_i(0) &= 0; i = 1 \text{ to } 14.
\end{aligned} \quad (11)$$

Equations (1) (3), (4), (6), (8), and (9) together with the boundary and initial condition constitute a set of Chapman–Kolmogorov differential difference equations. For a specific case, to illustrate the importance of the results for

the availability and profitability of the system, we assume that the repair rates follow an exponential distribution. Then, the above sets of equations and boundary and initial conditions reduce to the following:

$$\left(\frac{d}{dt} + u_0\right)p_0(t) = \beta_1 p_1(t) + \beta_2 p_2(t) + \beta_3 p_3(t) + \beta_4 p_4(t) + \beta_5 p_5(t) + \beta_6 p_6(t) + \beta_7 p_7(t), \quad (12)$$

$$\left(\frac{d}{dt} + \beta_i\right)p_i(t) = \alpha_i p_0(t); \quad i = 1, 2, 3, 5, 6, 7, \quad (13)$$

$$\left(\frac{d}{dt} + u_0 + \beta_4\right)p_4(t) = \alpha_4 p_0(t) + \beta_1 p_8(t) + \beta_2 p_9(t) + \beta_3 p_{10}(t) + \beta_4 p_{11}(t) + \beta_5 p_{12}(t) + \beta_6 p_{13}(t) + \beta_7 p_{14}(t), \quad (14)$$

$$\sum_{i=0}^{14} p_i = 1$$

$$\Rightarrow p_0 = \left[1 + \frac{\alpha_1}{\beta_1} + \frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_5}{\beta_5} + \frac{\alpha_6}{\beta_6} + \frac{\alpha_7}{\beta_7} + \frac{\alpha_1 \alpha_4}{\beta_1 \beta_4} + \frac{\alpha_2 \alpha_4}{\beta_2 \beta_4} + \frac{\alpha_3 \alpha_4}{\beta_3 \beta_4} + \frac{\alpha_4^2}{\beta_4^2} + \frac{\alpha_4 \alpha_5}{\beta_4 \beta_5} + \frac{\alpha_4 \alpha_6}{\beta_4 \beta_6} + \frac{\alpha_4 \alpha_7}{\beta_4 \beta_7}\right]^{-1} \quad (20)$$

$$\Rightarrow p_0 = \left[1 + \left(1 + \frac{\alpha_4}{\beta_4}\right)\left(\frac{\alpha_1}{\beta_1} + \frac{\alpha_2}{\beta_2} + \frac{\alpha_3}{\beta_3} + \frac{\alpha_4}{\beta_4} + \frac{\alpha_5}{\beta_5} + \frac{\alpha_6}{\beta_6} + \frac{\alpha_7}{\beta_7}\right)\right]^{-1}.$$

$$\left(\frac{d}{dt} + \beta_i\right)p_j(t) = \alpha_i p_4(t); \quad i = 1, 2, 3, 4, 5, 6, 7; \quad j = 8, 9, 10, 11, 12, 13, 14, \quad (15)$$

and the initial conditions are given as

$$p_0(0) = 1 \quad (16)$$

$$p_i(0) = 0; i = 1 \text{ to } 14.$$

The steady-state probabilities and longtime availability of the system can be obtained by taking $\frac{d}{dt} = 0$ as $t \rightarrow \infty$, $p_i(t) = p_i$ in Eqs. (12), (13), (14), (15), and (16), yielding

$$\beta_1 p_8 = \alpha_1 p_4 \quad \beta_2 p_9 = \alpha_2 p_4 \quad \beta_3 p_{10} = \alpha_3 p_4 \quad \beta_4 p_{11} = \alpha_4 p_4$$

$$\beta_5 p_{12} = \alpha_5 p_4 \quad \beta_6 p_{13} = \alpha_6 p_4 \quad \beta_7 p_{14} = \alpha_7 p_4 \quad p_j = \frac{\alpha_j}{\beta_j} p_4; \quad i = 1, 2, 3, 4, 5, 6, 7; \quad j = 8, 9, 10, 11, 12, 13, 14, \quad (17)$$

$$\beta_1 p_1 = \alpha_1 p_0 \quad \beta_2 p_2 = \alpha_2 p_0 \quad \beta_3 p_3 = \alpha_3 p_0 \quad \beta_5 p_5 = \alpha_5 p_0$$

$$\beta_6 p_6 = \alpha_6 p_0 \quad \beta_7 p_7 = \alpha_7 p_0 \quad p_j = \frac{\alpha_j}{\beta_j} p_0; \quad j = 1, 2, 3, 5, 6, 7. \quad (18)$$

Solving the above set of equations simultaneously, the probability of being in states S_1 to S_{14} in terms of p_0 is obtained as

$$p_1 = \frac{\alpha_1}{\beta_1} p_0 \quad p_2 = \frac{\alpha_2}{\beta_2} p_0 \quad p_3 = \frac{\alpha_3}{\beta_3} p_0$$

$$p_4 = \frac{\alpha_4}{\beta_4} p_0 \quad p_5 = \frac{\alpha_5}{\beta_5} p_0 \quad p_6 = \frac{\alpha_6}{\beta_6} p_0$$

$$p_7 = \frac{\alpha_7}{\beta_7} p_0 \quad p_8 = \frac{\alpha_1}{\beta_1} p_4 = \frac{\alpha_1 \alpha_4}{\beta_1 \beta_4} p_0 \quad p_9 = \frac{\alpha_2 \alpha_4}{\beta_2 \beta_4} p_0 \quad (19)$$

$$p_{10} = \frac{\alpha_3 \alpha_4}{\beta_3 \beta_4} p_0 \quad p_{11} = \frac{\alpha_4^2}{\beta_4^2} p_0 \quad p_{12} = \frac{\alpha_4 \alpha_5}{\beta_4 \beta_5} p_0$$

$$p_{13} = \frac{\alpha_4 \alpha_6}{\beta_4 \beta_6} p_0 \quad p_{14} = \frac{\alpha_4 \alpha_7}{\beta_4 \beta_7} p_0.$$

Using the normalizing condition $\sum_{i=0}^{14} p_i = 1$, the following expressions are obtained

The steady-state availability of the system can then be obtained as

$$A_v = p_0 + p_4 \Rightarrow A_v = p_0 + \frac{\alpha_4}{\beta_4} p_0 \Rightarrow A_v = \left(1 + \frac{\alpha_4}{\beta_4}\right) p_0. \quad (21)$$

4.1 Profitability analysis

Let K_1 be the total revenue per unit uptime of the system and K_2 the total repair cost. Then, the profit according to the system model in steady state can be obtained using the equation

$$\text{Profit} = K_1 A_v - K_2$$

By considering, $K_1 = 5000$ and $K_2 = 500$.

$$\text{So, Profit} = [5000 \left[\left(1 + \frac{\alpha_4}{\beta_4}\right) p_0 \right] - 500. \quad (22)$$

4.2 Numerical and graphical results

Numerical results illustrating the effect of the failure and repair rates on the availability and profitability of the generator in the steam turbine power plant are

Table 1 Effect of variation of failure rate on system availability w.r.t. failure rate α_2

α_2	$\alpha_1 = 0.0003$	$\alpha_1 = 0.003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$
$\downarrow$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.002$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$
	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$	$\alpha_4 = 0.09$	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$
	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.007$	$\alpha_5 = 0.007$	$\alpha_5 = 0.0007$
	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.0075$	$\alpha_6 = 0.00075$
	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.001$
0.005	0.93349	0.888692	0.913591	0.877496	0.861142	0.865334	0.899888
0.006	0.929153	0.884761	0.909436	0.873663	0.85745	0.861606	0.895858
0.007	0.924857	0.880864	0.90532	0.869863	0.85379	0.85791	0.891863
0.008	0.920599	0.877002	0.90124	0.866096	0.85016	0.854245	0.887903
0.009	0.916381	0.873173	0.897197	0.862362	0.846562	0.850612	0.883979
0.01	0.912202	0.869377	0.89319	0.85866	0.842993	0.84701	0.880089
0.011	0.90806	0.865614	0.889219	0.854989	0.839455	0.843438	0.876233
0.012	0.903956	0.861884	0.885283	0.851349	0.835947	0.839896	0.872411
0.013	0.899888	0.858186	0.881382	0.847741	0.832467	0.836383	0.868622
0.014	0.895858	0.854519	0.877515	0.844163	0.829016	0.8329	0.864866

Table 2 Effect of variation of failure rate on profitability of system w.r.t. failure rate α_2 . Effect of variation of failure rates of subsystems on profitability of system

α_2	$\alpha_1 = 0.0003$	$\alpha_1 = 0.003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$	$\alpha_1 = 0.0003$
$\downarrow$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.002$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$	$\alpha_3 = 0.0006$
	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$	$\alpha_4 = 0.09$	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$	$\alpha_4 = 0.009$
	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.007$	$\alpha_5 = 0.0007$	$\alpha_5 = 0.0007$
	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.00075$	$\alpha_6 = 0.0075$	$\alpha_6 = 0.00075$
	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.0002$	$\alpha_7 = 0.001$
0.005	4634.195	4387.808	4524.749	4326.23	4236.281	4259.334	4449.387
0.006	4610.343	4366.185	4501.9	4305.148	4215.975	4238.831	4427.217
0.007	4586.711	4344.753	4479.259	4284.249	4195.843	4218.504	4405.245
0.008	4563.297	4323.509	4456.821	4263.531	4175.882	4198.35	4383.468
0.009	4540.097	4302.45	4434.585	4242.991	4156.089	4178.367	4361.884
0.01	4517.109	4281.574	4412.547	4222.628	4136.464	4158.554	4340.489
0.011	4494.33	4260.879	4390.706	4202.439	4117.004	4138.908	4319.282
0.012	4471.757	4240.363	4369.057	4182.422	4097.706	4119.427	4298.26
0.013	4449.387	4220.022	4347.6	4162.575	4078.569	4100.109	4277.421
0.014	4427.217	4199.855	4326.331	4142.895	4059.59	4080.952	4256.762

presented in Tables 1, 2, 3, and 4. The system availability and profitability are obtained w.r.t. to the failure rate (α_2) of subsystem B, i.e., the bearing, by varying its value to $\alpha_2 = 0.005, 0.006, 0.007, 0.008, 0.009, 0.010, \dots, 0.014$, while the failure and repair rates of the other subsystems are taken as follows:

$$\alpha_1 = 0.0003, \alpha_3 = 0.0006, \alpha_4 = 0.009, \alpha_5 = 0.0007, \\ \alpha_6 = 0.00075, \alpha_7 = 0.0002, \beta_1 = 0.05, \beta_2 = 0.02, \\ \beta_3 = 0.06, \beta_4 = 0.3, \beta_5 = 0.07, \beta_6 = 0.08, \beta_7 = 0.02.$$

The availability of the system is calculated using the above parameter values based on Eq. (21), and the results are presented in Table 1. It can be easily observed that the availability of the system decreases by approximately 4.5% as the failure rate α_1 is increased from 0.0003 to 0.003. Similarly, the availability of the system decreases by approximately 2.13%, 6%, 7.75%, 7.3%, and 3.6% as the failure rate α_3 is increased from 0.0006 to 0.002, α_4 from 0.009 to 0.09, α_5 from 0.0007 to 0.007, α_6 from 0.00075 to 0.0075, and α_7 from 0.0002 to 0.001, respectively (Figs. 3, 4).

Table 3 Effect of variation of repair rate on system availability w.r.t. repair rate β_2

β_2	$\beta_1 = 0.05$	$\beta_1 = 0.1$	$\beta_1 = 0.05$	$\beta_1 = 0.05$	$\beta_1 = 0.05$	$\beta_1 = 0.05$	$\beta_1 = 0.05$
$\downarrow$	$\beta_3 = 0.06$	$\beta_3 = 0.06$	$\beta_3 = 0.3$	$\beta_3 = 0.06$	$\beta_3 = 0.06$	$\beta_3 = 0.06$	$\beta_3 = 0.06$
	$\beta_4 = 0.3$	$\beta_4 = 0.3$	$\beta_4 = 0.3$	$\beta_4 = 1.2$	$\beta_4 = 0.3$	$\beta_4 = 0.3$	$\beta_4 = 0.3$
	$\beta_5 = 0.07$	$\beta_5 = 0.07$	$\beta_5 = 0.07$	$\beta_5 = 0.07$	$\beta_5 = 0.7$	$\beta_5 = 0.07$	$\beta_5 = 0.07$
	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 1.0$	$\beta_6 = 0.08$
	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.2$
0.2	0.93349	0.936112	0.940514	0.934203	0.941399	0.941067	0.941399
0.3	0.940809	0.943471	0.947943	0.941533	0.948843	0.948505	0.948843
0.4	0.944511	0.947195	0.951702	0.945241	0.952609	0.952269	0.952609
0.5	0.946747	0.949443	0.953972	0.94748	0.954883	0.954541	0.954883
0.6	0.948243	0.950948	0.955491	0.948979	0.956405	0.956062	0.956405
0.7	0.949315	0.952026	0.956579	0.950052	0.957495	0.957152	0.957495
0.8	0.95012	0.952836	0.957397	0.950859	0.958314	0.95797	0.958314
0.9	0.950747	0.953467	0.958034	0.951487	0.958953	0.958608	0.958953
1	0.95125	0.953972	0.958544	0.95199	0.959464	0.959119	0.959464

Table 4 Effect of variation of repair rate on profitability of system w.r.t. repair rate β_2

β_2	$\beta_1 = 0.05$	$\beta_1 = 0.1$	$\beta_1 = 0.05$	$\beta_1 = 0.05$	$\beta_1 = 0.05$	$\beta_1 = 0.05$	$\beta_1 = 0.05$
$\downarrow$	$\beta_3 = 0.06$	$\beta_3 = 0.06$	$\beta_3 = 0.3$	$\beta_3 = 0.06$	$\beta_3 = 0.06$	$\beta_3 = 0.06$	$\beta_3 = 0.06$
	$\beta_4 = 0.3$	$\beta_4 = 0.3$	$\beta_4 = 0.3$	$\beta_4 = 1.2$	$\beta_4 = 0.3$	$\beta_4 = 0.3$	$\beta_4 = 0.3$
	$\beta_5 = 0.07$	$\beta_5 = 0.07$	$\beta_5 = 0.07$	$\beta_5 = 0.07$	$\beta_5 = 0.7$	$\beta_5 = 0.07$	$\beta_5 = 0.07$
	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 0.08$	$\beta_6 = 1.0$	$\beta_6 = 0.08$
	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.02$	$\beta_7 = 0.2$
0.2	4634.195	4648.613	4672.825	4638.118	4677.695	4675.868	4677.695
0.3	4674.447	4689.093	4713.688	4678.432	4718.635	4716.779	4718.635
0.4	4694.811	4709.573	4734.362	4698.828	4739.349	4737.478	4739.349
0.5	4707.107	4721.938	4746.846	4711.142	4751.856	4749.976	4751.856
0.6	4715.336	4730.214	4755.202	4719.384	4760.228	4758.342	4760.228
0.7	4721.23	4736.142	4761.186	4725.287	4766.224	4764.333	4766.224
0.8	4725.659	4740.597	4765.683	4729.724	4770.73	4768.836	4770.73
0.9	4729.109	4744.067	4769.187	4733.179	4774.24	4772.344	4774.24
1	4731.873	4746.846	4771.993	4735.947	4777.051	4775.153	4777.051
1.1	4734.136	4749.122	4774.291	4738.214	4779.353	4777.454	4779.353

Fig. 3 Effect of variation of failure rates on system availability w.r.t. failure rate α_2

Fig. 4 Effect of variation of failure rates on profitability of system w.r.t. failure rate β_2

The profitability of the system is calculated using the above dataset, and the results are presented in Table 2. It can be easily observed that the profitability of the system decreases by approximately 5.34% as the failure rate α_1 is increased from 0.0003 to 0.003. Similarly, the profit of the system decreases by approximately 2.36%, 6.65%, 8.59%, 8.09%, and 4% when the failure rate α_3 is increased from 0.0006 to 0.002, α_4 from 0.009 to 0.09, α_5 from 0.0007 to 0.007, α_6 from 0.00075 to 0.0075, and α_7 from 0.0002 to 0.001, respectively.

The system availability and profitability are obtained w.r.t to the repair rate (β_2) of subsystem B, i.e., the bearing, by varying its value to $\beta_2 = 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1$ with a constant value of the failure rate $\alpha_2 = 0.005$. The failure and repair rates of the other subsystems are taken as follows:

$$\alpha_1 = 0.0003, \alpha_3 = 0.0006, \alpha_4 = 0.009, \alpha_5 = 0.0007, \\ \alpha_6 = 0.00075, \alpha_7 = 0.0002, \beta_1 = 0.05, \beta_3 = 0.06, \\ \beta_4 = 0.3, \beta_5 = 0.07, \beta_6 = 0.08, \beta_7 = 0.02.$$

The availability of the system is calculated using the above parameter values, and the results are presented in Table 3. It is observed that the availability of the system increases by approximately 0.28% as the repair rate β_1 is increased from 0.05 to 0.1. Similarly, the availability of the system increases by approximately 0.75%, 0.08%, 0.85%, 0.81%, and 0.85% as the repair rate β_3 is increased from 0.06 to 0.3, β_4 from 0.3 to 1.2, β_5 from 0.07 to 0.7, β_6 from 0.08 to 1, and β_7 from 0.02 to 0.2, respectively (Figs. 5, 6).

The profitability of the system is calculated using the fixed set of values, and the results are presented in Table 4.

Fig. 5 Effect of variation of repair rates on system availability w.r.t. repair rate β_2

Fig. 6 Effect of variation of repair rates on profitability of system w.r.t. repair rate β_2

It is observed that the profitability of the system increases by approximately 0.31% as the repair rate β_1 is increased from 0.05 to 0.1. Similarly, the profitability of the system increases by approximately 0.83%, 0.08%, 0.94%, 0.90%, and 0.94% as the repair rate β_3 is increased from 0.06 to 0.3, β_4 from 0.3 to 1.2, β_5 from 0.07 to 0.7, β_6 from 0.08 to 1, and β_7 from 0.02 to 0.2, respectively.

5 Discussion

In steam turbine power plants, hardware failures are physical failures and occur randomly. These physical failures may result from burn-in, wear-out, degradation, and improper allocation of redundant units in the design phase of the plant. The physical components involved in failure of steam turbine power plants include the HRSG subsystem, turbine, condenser, cooling tower, auxiliary cooling subsystem, and generator [1]. The availability of a system is defined as the probability that the system is available for use as and when required. It is expressed as $MTBF/(MTBF + MTTR)$, where MTBF is the mean time before failure and MTTR is the mean time to repair. Okafor et al. [20] used a Markovian approach considering constant failure and repair rates for all subsystems, revealing that the availability decreased rapidly over time. Carazas et al. [9] analyzed the heat recovery steam generators used in thermal power plants using fault tree and failure mode and effects analysis (FMEA) approaches. The failure and repair distributions were identified, and maintenance strategies proposed. Many studies have been carried out on thermal power plants, but the generators used in steam turbine power plants have not been discussed so far. A stochastic model is proposed herein to enhance the availability of such plants. The results illustrate that, by controlling the

failure rates and increasing the repair rate of subsystems, the system availability can be enhanced. The proposed model predicts an availability of 95.94% for a certain set of values of various parameters. The analysis reveals that the failure rate of the rotor strongly affects the availability of the generator.

5.1 Conclusions

The suggested stochastic model can be used to support system designers, as it provides information about the availability and performance of generator units for steam turbine power plants. Tables 1, 2, 3, and 4 present the numerical results for the availability and profitability with respect to the failure and repair rates. The availability and profitability are strongly influenced by the failure rates of the components, as seen in Table 1. The rotor and cooling system are the most sensitive components of the generator, and their failure rates have the greatest influence. The reliability ranges from 2.13% to 7.75% as the failure rates of various components are changed. The profitability varies from 2.36% to 8.59% with respect to the failure rate changes. A change of 8.59% in the profitability is observed if the failure rate of the cooling system increases. Overall, among the considered components, the rotor has minimum availability whereas the influence of the cooling system is greatest according to the results obtained on variation of its failure rate. Therefore, subsystems D and E are the most critical and their failure rates must be effectively controlled for smooth and long-term operation of the generator with greater profitability and long-time availability. These results will also be helpful for system designers when planning the maintenance schedules of such plants. Although the proposed system model for generators provides very significant results, it also suffers

from some limitations, including the use of exponential failure and repair rates and the lack of consideration of simultaneous failures as well as goodness-of-fit analysis of the system availability based on data collected under experimental conditions.

5.2 Future work

In future work, the following issues could be considered:

- Arbitrary distributions for the failure rates of all the sub-systems, e.g., Weibull or Gamma
- Simultaneous occurrence of two or more failures
- Goodness-of-fit testing for the availability based on data for the time to repair and time between failures collected from maintenance records from a plant

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflicts of interest.

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