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GAS TURBINE POWER PLANT PERFORMANCE EVALUATION UNDER KEY FAILURES

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Abstract

Compression and combustion are two important functions of a gas turbine power plant. It is generally used to drive generators and works as a combinatorial plant with conventional steam boilers. The most significant and valuable fact of the gas turbine power plant is that it requires air instead of water to generate electricity. The main components of gas turbine power plant are compressor, combustor, turbine and auxiliaries such as starting device, lubricant pump, fuel system, etc. In this paper, the authors have assumed the different types of component failure such as compressor, combustor, turbine, auxiliaries and human failure with some other auxiliary's failures and determined the different reliability characteristics of gas turbine power plant by using supplementary variable techniques, Laplace transformation and Markov process. Some numerical examples on the basis of past research are also developed for the practical utility of the plant.

Keywords: Gas turbine system, sensitivity analysis, combustion.

1. Introduction

The gas turbine is widely applicable in the several fields such as aviation, power generation, oil and gas industry, and marine propulsion due to various specific reasons. The main advantage of gas turbine power plant is well suited for peak load service. The working medium of gas turbine power plant is a permanent gas. A conventional gas turbine power plant consists of turbines, a compressor mounted on the same shaft or coupled to the turbine, a combustor and auxiliaries such as lubricant pump, oil system, etc. The working fluid is compressed in a compressor, which is rotary in general, multistage type. Heat energy is added to the compressed fluid in the chamber and this high energy fluid send to the turbine at high temperature and pressure, then turbine generates power through a generator. Some part of the generated power is consumed in driving the compressor

Nomenclatures

t	Time scale
s	Laplace transforms variable.
$P_0(t)$	Probability at time t in state 0.
$P_i(t)$	Probability at time t in i^{th} state; i=1, 2, 3,4
$P_j(x,t)$	Probability density function that the system is in j^{th} state and has an elapsed repair time of x; j=5,6,7,8
S_0	Good state
S_1, S_2, S_3, S_4	Degraded state
S_5, S_6, S_7, S_8	Failed state
Greek Symbols	
λ_G / λ_{GT} / λ_{CP} / λ_{CB} / λ_{NF} / λ_{NZ} / λ_H	Failure rate of generator / gas turbine / compressor / combustor / availability of fuel / nozzle / human error.
μ	Repair rate from failed state to good state.

and accessories, and the rest is utilized in electrical energy. In the gas turbine power plant, compressed air and fuel are burned at high temperature to produce the hot gases. These hot gases move through blades in the turbine to spin quickly. The spinning turbine converts the mechanical energy into electrical energy by using a generator.

Many researchers have done a lot of work in the field of power generation through the gas turbine. Pittaluga et al. [1] studied on heavy duty gas turbine plant and aerothermodynamics simulation using *Simulink* and presented a physical simulator for predicting the off design and dynamic behavior of a single shaft heavy duty gas turbine plant suitable for gas steam combined cycles. In that work, a nonlinear mathematical model is constructed, this is based on the lumped parameter approach and constructed a set of first order differential and algebraic equations. The authors also presented some dynamic responses of the simulated plant, furnished with a proportional integral speed regulator. Pilavachi [2] described power generation with gas turbine systems and combined heat and power, and gave an overview of power generation with gas turbine and combined heat and power systems. They also presented the European Union strategy for developing gas turbine and combined heat and power systems. The main targets are a reduction of the overall costs and the development of above 40 kW bio massed fired systems. Costamagna et al. [3] studied the design and part load performance of a hybrid system based on a solid oxide fuel cell reactor and a micro gas turbine, and discussed the influence of the reactor layout, the current density, the air utilization factor, the cell operating temperature, etc., and also analyzed the different micro gas turbine rotational speed control system, fixed and variable, and presented the design and off design models of a recuperated micro gas turbine. Li [4] discussed the performance analysis based gas turbine diagnostics and the gas turbine fault diagnostics. The author explained the different models used in gas turbine diagnostics. Lunghi et al. [5] discussed the analysis and optimization of hybrid MCFC gas turbine plants and analyzed a parametric performance evaluation of a hybrid molten carbonate fuel cell (MCFC) indirect heated gas turbine and the methodology to define new operating conditions. Jolly and Wadhwa [6] studied the reliability, availability and maintainability of high precision special purpose manufacturing machines, by collecting the data and analyzed the performance of machines, and concluded that the machines have high availability and good reliability but poor maintainability.

Carazas and De Souza [7 - 9]; De Souza et al. [10] have done very much work in the field of power plant and studied the availability analysis of heat recovery steam generators and gas turbine used in many plants such as combined cycle thermos-electric power plants, gas turbine power plant, thermal power plant and combined-cycle gas and steam turbine power plant. The authors presented a method for reliability and availability evaluation of heat recovery steam generator installed in combined cycle thermo-electric power station and considered two identical heat recovery steam generators installed in the same power plant, and used Weibull distribution for reliability calculations. The authors also described that the maintenance policy of gas turbines is based on five or six year cycle. During the first two years some basic preventive tasks are performed annually. In the middle of the cycle, a more complex inspection is performed and then basic tasks are performed annually. The authors also discussed a method for analysis of two F series gas turbines and showed that one presenting 99% and the other 96% availability. The authors studied that the turbine two presented almost twice the numbers of failures of turbine 1 and conclude that after 48000 operating hours, the gas turbines are submitted to a major maintenance.

Hooshmand et al. [11] studied the power system reliability enhancement by using power formers and investigated the installation effect of generators on the power system reliability by considering four different cases of the network with conventional generators and showed that the use of power formers in power systems has significant advantages and the reliability parameters were improved. Ahmadi and Dincer [12] discussed the thermodynamic and exergo environmental analysis and multi objective optimization of a gas turbine power plant by using the genetic algorithm to optimize the two important objective functions. The first objective function was the cycle exergy efficiency and the other ones were total cost rate of the plant including investment cost. Obodeh and Esabunor [13] studied the reliability assessment of WRPC gas power station and analyzed the reliability on the basis of five year failure database. They analyzed the comparison of minimum and maximum failure rate of the gas turbine 1 and gas turbine 2, and suggested training and retraining of technical personnel. Verma et al. [14] described a fuzzy fault tree approach for analyzing the fuzzy reliability of a gas power plant and construct a fault tree on the basis of the failure modes for the components of gas a power plant. The authors also constructed a probability expression of the failure of the gas power plant in terms of the minimal cut set. Sarkara et al. [15] discussed the reliability assessment of Rukhia gas turbine power plant in Tripura and analyzed the reliability indices on the basis of five and half year failure database. The authors also presented a comparative study and suggested that tedious preventive maintenance must be well scheduled and more regular.

Schobeiri and Nikparto [16] compared a numerical study of aerodynamics and heat transfer on transitional flow around a highly loaded turbine blade and flow separation using RANS, URANS and LES. They investigated the boundary layer development and heat transfer along the suction and pressure surfaces of a highly loaded turbine blade with separation. For this comparative study, they used different numerical methods such as Reynolds Averaged Navier-Stokes based Solvers

(RANS), Unsteady Reynolds Averaged Navier-Stokes equations (URANS) and Large Eddy Simulation (LES). They compared the different experimental and numerical results. Schobeiri and Haselbacher [17] studied the transient analysis of gas turbine power plants using the huntorf compressed air storage plant. They developed a computational method, which permits an accurate simulation of any gas turbine. They developed a modular computer program CORTAN which calculated the transient behavior of the individual component. They analyzed mass flow transients in the various components, the dynamic behavior of turbines, and behavior of rotor speed during the loss of load, blow off, and presented a brief description of a mathematical method for safe and reliable operation of gas turbines.

Furthermore, many researchers have done numerous works in the field of reliability such as Ram et al. [18] and Manglik and Ram [19, 20]. The authors studied the stochastic analysis of a standby system with waiting repair strategy, stochastic modeling of a multi-state manufacturing system under three types of failures with perfect coverage and behavioral analysis of a hydroelectric power plant under reworking scheme. The authors investigated the reliability of a standby system incorporating waiting time to repair and concluded that the availability of the system is higher when it is free from any human error and the lowest whenever there is a waiting for repair. Manglik and Ram [18] presented a Markov process based mathematical model for a hydroelectric power plant and evaluated the different reliability indices by assuming the different failure rates of components. The authors analyzed that hydroelectric power stations showed adequately maintain for avoiding unreliable performance.

Apart from the above research, the authors have considered a general gas turbine power plant, which consists of six different components such as a generator, gas turbines, compressor, combustor, fuel and nozzle and seven types of different failure rates including human failure. The transition state diagram of the gas turbine power plant has been shown in Fig.1.

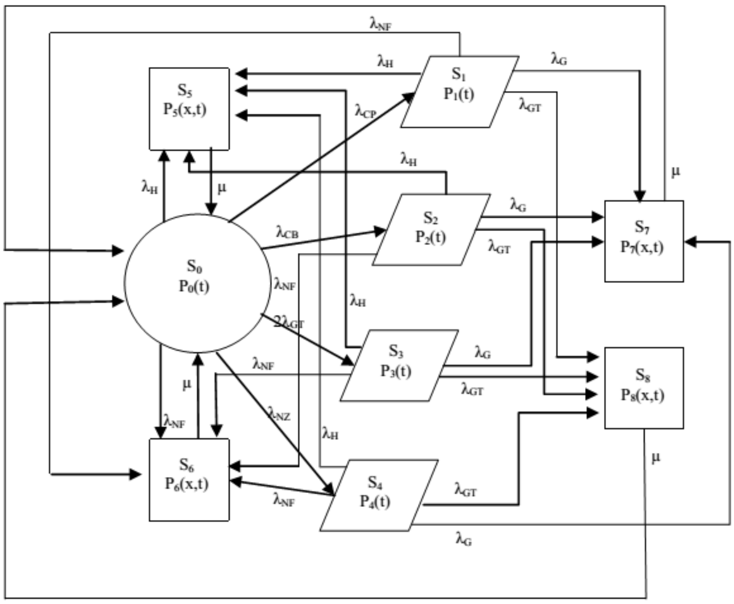

Fig. 1. State transition diagram.

2. Assumptions and State Descriptions

The following assumptions are used in this work:

(a) At the starting stage, all the components are in good conditions.
(b) This model contains three states, good, degraded and failed.
(c) This model contains some important components of the system.
(d) A single repair facility is available.
(e) After repairing the system works like a new one.

Each state in transition state diagram can be described as

S_0 In this state, all components are in good condition; therefore, this state is a good state.

S_1 In this state, the compressor has failed with the failure rate λ_{CP}, but other components are in working condition, therefore this state is degraded.

S_2 In this state, the combustor has failed with the failure rate λ_{CB}, but other components are in working condition, therefore this state is also degraded.

S_3 In this state, the secondary turbine has failed with the failure rate $2\lambda_{GT}$, but other components are in working condition, therefore this state is degraded.

S_4 In this state, the component nozzle has failed with the failure rate λ_{NZ}, but other components are in working condition, therefore this state is degraded.

S_5 This state is a failed state due to human failure with failure rate λ_H.

S_6 This state is also a failed state due to non-availability of fuel with failure rate λ_{NF}.

S_7 In this state, the generator has failed with the failure rate λ_G, therefore this state is failed state.

S_8 In this state, the primary gas turbine has failed with the failure rate λ_{GT}, therefore, this state is failed state.

3. Formulation of the Model

At any time t, if the system is in state S_i, then the probability of the system to be in that state is defined as: probability that the system is in state S_i at time t and remains there in interval $(t, t+\Delta t)$ or/and if it is in some other state at time t then it should transit to the state S_i in the interval $(t, t+\Delta t)$ provided transition exists between the states. So, with the help of state transition diagram, authors developed the following set of differential equations, by using supplementary variable technique and Markov process.

$$P_0(t+\Delta t) = (1-\lambda_H \Delta t)(1-\lambda_{CP}\Delta t)(1-\lambda_{CB}\Delta t)(1-2\lambda_{GT}\Delta t)(1-\lambda_{NZ}\Delta t)(1-\lambda_{NF}\Delta t)P_0(t) + \sum_j P_j(x,t)\mu\, dx\,\Delta t, \quad j = 5 \text{ to } 8 \tag{1}$$

$$P_1(t+\Delta t) = (1-\lambda_G \Delta t)(1-\lambda_H \Delta t)(1-\lambda_{GT}\Delta t)(1-\lambda_{NF}\Delta t)P_1(t) + \lambda_{CP} P_0(t)\Delta t \tag{2}$$

$$P_2(t+\Delta t) = (1-\lambda_G \Delta t)(1-\lambda_H \Delta t)(1-\lambda_{GT}\Delta t)(1-\lambda_{NF}\Delta t)P_2(t) + \lambda_{CB} P_0(t)\Delta t \tag{3}$$

$$P_3(t+\Delta t) = (1-\lambda_G \Delta t)(1-\lambda_H \Delta t)(1-\lambda_{GT}\Delta t)(1-\lambda_{NF}\Delta t)P_3(t) + 2\lambda_{GT} P_0(t)\Delta t \tag{4}$$

$$P_4(t+\Delta t) = (1-\lambda_G \Delta t)(1-\lambda_H \Delta t)(1-\lambda_{GT}\Delta t)(1-\lambda_{NF}\Delta t)P_4(t) + \lambda_{NZ} P_0(t)\Delta t \tag{5}$$

$$P_j(x+\Delta x, t+\Delta t) = (1-\mu\Delta t)P_j(x,t), \quad j = 5 \text{ to} 8 \tag{6}$$

Boundary conditions are,

$$P_5(0,t) = \lambda_H\left[P_0(t)+P_1(t)+P_2(t)+P_3(t)+P_4(t)\right] \tag{7}$$

$$P_6(0,t) = \lambda_{NF}\left[P_0(t)+P_1(t)+P_2(t)+P_3(t)+P_4(t)\right] \tag{8}$$

$$P_7(0,t) = \lambda_G\left[P_1(t)+P_2(t)+P_3(t)+P_4(t)\right] \tag{9}$$

$$P_8(0,t) = \lambda_{GT}\left[P_1(t)+P_2(t)+P_3(t)+P_4(t)\right] \tag{10}$$

Initially, $P_0(0)=1$ and other probabilities are zero. Applying the limit as $\Delta t \to 0$ in Eqs. (1) to (6), we get

$$\left[\frac{\partial}{\partial t}+\lambda_H+\lambda_{CP}+\lambda_{CB}+2\lambda_{GT}+\lambda_{NZ}+\lambda_{NF}\right]P_0(t) = \sum_j \int_0^\infty P_j(x,t)\mu dx; \quad j = 5 \text{to} 8 \tag{11}$$

$$\left[\frac{\partial}{\partial t}+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]P_1(t) = \lambda_{CP}P_0(t) \tag{12}$$

$$\left[\frac{\partial}{\partial t}+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]P_2(t) = \lambda_{CB}P_0(t) \tag{13}$$

$$\left[\frac{\partial}{\partial t}+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]P_3(t) = 2\lambda_{GT}P_0(t) \tag{14}$$

$$\left[\frac{\partial}{\partial t}+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]P_4(t) = \lambda_{NZ}P_0(t) \tag{15}$$

$$\left[\frac{\partial}{\partial t}+\frac{\partial}{\partial x}+\mu\right]P_j(x,t) = 0; \quad j = 5 \text{to} 8 \tag{16}$$

Taking the Laplace transformations from Eqs. (7) – (10) and (11) –(16), we get

$$\left[s+\lambda_H+\lambda_{CP}+\lambda_{CB}+2\lambda_{GT}+\lambda_{NZ}+\lambda_{NF}\right]\overline{P}_0(s) = 1+\sum_j \int_0^\infty \overline{P}_j(x,s)\mu dx; \quad j = 5 \text{to} 8 \tag{17}$$

$$\left[s+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]\overline{P}_1(s) = \lambda_{CP}\overline{P}_0(s) \tag{18}$$

$$\left[s+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]\overline{P}_2(s) = \lambda_{CB}\overline{P}_0(s) \tag{19}$$

$$\left[s+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]\overline{P}_3(s) = 2\lambda_{GT}\overline{P}_0(s) \tag{20}$$

$$\left[s+\lambda_G+\lambda_H+\lambda_{GT}+\lambda_{NF}\right]\overline{P}_4(s) = \lambda_{NZ}\overline{P}_0(s) \tag{21}$$

$$\left[s+\frac{\partial}{\partial x}+\mu\right]\overline{P}_j(x,s) = 0; \quad j = 5 to 8 \tag{22}$$

$$\overline{P}_5(0,s) = \lambda_H\left[\overline{P}_0(s)+\overline{P}_1(s)+\overline{P}_2(s)+\overline{P}_3(s)+\overline{P}_4(s)\right] \tag{23}$$

$$\overline{P}_6(0,s) = \lambda_{NF}\left[\overline{P}_0(s)+\overline{P}_1(s)+\overline{P}_2(s)+\overline{P}_3(s)+\overline{P}_4(s)\right] \tag{24}$$

$$\overline{P}_7(0,s) = \lambda_G\left[\overline{P}_1(s)+\overline{P}_2(s)+\overline{P}_3(s)+\overline{P}_4(s)\right] \tag{25}$$

$$P_8(0,s) = \lambda_{GT}\left[\overline{P}_1(s)+\overline{P}_2(s)+\overline{P}_3(s)+\overline{P}_4(s)\right] \tag{26}$$

From Eq. (26),

$$\overline{P}_j(x,s)=\overline{P}_j(0,s)\exp\{-sx-\int_0^x \mu dx\};\ j=5\ \text{to}\ 8 \tag{27}$$

On solving these equations, authors get the state transition probabilities of the system as,

$$\overline{P}_0(s)=\frac{1}{(s+c_1+c_3)-\left\{c_1+\frac{(c_1+c_2).c_3}{(s+c_1+c_2)}\right\}\overline{S}(s)} \tag{28}$$

$$\overline{P}_1(s)=\frac{\lambda_{CP}\ \overline{P}_0(s)}{(s+c_1+c_2)} \tag{29}$$

$$\overline{P}_2(s)=\frac{\lambda_{CB}\ \overline{P}_0(s)}{(s+c_1+c_2)} \tag{30}$$

$$\overline{P}_3(s)=\frac{2\lambda_{GT}\ \overline{P}_0(s)}{(s+c_1+c_2)} \tag{31}$$

$$\overline{P}_4(s)=\frac{\lambda_{NZ}\ \overline{P}_0(s)}{(s+c_1+c_2)} \tag{32}$$

$$\overline{P}_5(s)=\lambda_H\left[\frac{s+c_1+c_2+c_3}{s+c_1+c_2}\right]\left(\frac{1-\overline{S}(s)}{s}\right)\overline{P}_0(s) \tag{33}$$

$$\overline{P}_6(s)=\lambda_{NF}\left[\frac{s+c_1+c_2+c_3}{s+c_1+c_2}\right]\left(\frac{1-\overline{S}(s)}{s}\right)\overline{P}_0(s) \tag{34}$$

$$\overline{P}_7(s)=\lambda_G\left[\frac{c_3}{s+c_1+c_2}\right]\left(\frac{1-\overline{S}(s)}{s}\right)\overline{P}_0(s) \tag{35}$$

$$\overline{P}_8(s)=\lambda_{GT}\left[\frac{c_3}{s+c_1+c_2}\right]\left(\frac{1-\overline{S}(s)}{s}\right)\overline{P}_0(s) \tag{36}$$

where,

$$c_1=\lambda_H+\lambda_{NF} \tag{37}$$

$$c_2=\lambda_G+\lambda_{GT} \tag{38}$$

$$c_3=\lambda_{CP}+\lambda_{CB}+2\lambda_{GT}+\lambda_{NZ} \tag{39}$$

The Laplace transformation of upstate and downstate system's probability are

$$\overline{P}_{up}(s)=\overline{P}_0(s)+\overline{P}_1(s)+\overline{P}_2(s)+\overline{P}_3(s)+\overline{P}_4(s)$$
$$=\left[\frac{s+c_1+c_2+c_3}{s+c_1+c_2}\right]\overline{P}_0(s) \tag{40}$$

$$\overline{P}_{down}(s)=\overline{P}_5(s)+\overline{P}_6(s)+\overline{P}_7(s)+\overline{P}_8(s)$$
$$=\left[\frac{(s+c_1+c_2+c_3).c_1+c_2.c_3}{s+c_1+c_2}\right]\left(\frac{1-\overline{S}(s)}{s}\right)\overline{P}_0(s) \tag{41}$$

4. Particular Examples

For the practical utility of the proposed model authors give some numerical example on the basis of past research [7, 9, 13].

4.1. Availability analysis

To discuss the availability of the gas turbine power plant, putting the value of failure and repair rates as $\lambda_G = 0.005$, $\lambda_{NF} = 0.008$, $\lambda_G = 0.004$, $\lambda_{GT} = 0.006$, $\lambda_{CP} = 0.009$, $\lambda_{CB} = 0.002$, $\lambda_{NZ} = 0.003$, $\mu = 1$ in Eq. (40) and then taking inverse Laplace transformation, one get the availability of the system as

$$P_{up}(t) = 0.9820229673 + \begin{bmatrix} 0.01797703269\,Cosh(0.4817302150t) \\ -0.007170394415\,Sinh(0.4817302150t) \end{bmatrix} e^{-0.531t} \quad (42)$$

By varying the time t =0 to 15 in (42), one can obtain the graph of availability of the gas turbine power plant as shown in Table 1 and represents graphically in Fig. 2.

Table 1. Availability vs. time.

Time	Availability	Time	Availability
0	1.00000	8	0.98566
1	0.99173	9	0.98549
2	0.98857	10	0.98532
3	0.98728	11	0.98516
4	0.98667	12	0.98501
5	0.98632	13	0.98487
6	0.98607	14	0.98473
7	0.98586	15	0.98460

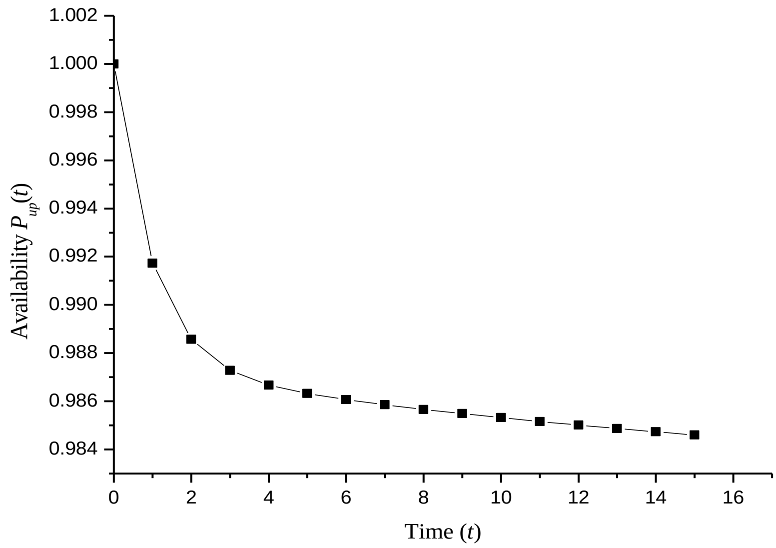

Fig. 2. Availability vs. time.

4.2. Reliability analysis

To evaluate the reliability of the gas turbine power plant, putting the repair rate zero in Eq. (40) and taking the inverse Laplace transformation, the reliability of the system as a function of time is obtained as,

$$R(t) = \frac{-c_3.e^{-(c_1+c_2)t} + (c_1+c_2)e^{-c_3 t}}{c_1+c_2-c_3} \tag{43}$$

where, $c_1 = \lambda_H + \lambda_{NF}$, $c_2 = \lambda_G + \lambda_{GT}$ and $c_3 = \lambda_{CP} + \lambda_{CB} + 2\lambda_{GT} + \lambda_{NZ}$. Now, putting the values of different failure rates as $\lambda_G = 0.005$, $\lambda_{NF} = 0.008$, $\lambda_G = 0.004$, $\lambda_{GT} = 0.006$, $\lambda_{CP} = 0.009$, $\lambda_{CB} = 0.002$, $\lambda_{NZ} = 0.003$ in Eq. (43), and obtained the reliability of the gas turbine power plant as shown in Table 2. The graph of the reliability of the gas turbine power plant is revealed in Fig. 3.

Table 2. Reliability vs. time.

Time	Reliability	Time	Reliability
0	1.00000	8	0.98318
1	0.99970	9	0.97906
2	0.99884	10	0.97546
3	0.99743	11	0.96970
4	0.99551	12	0.96452
5	0.99310	13	0.95901
6	0.99023	14	0.95321
7	0.98622	15	0.94714

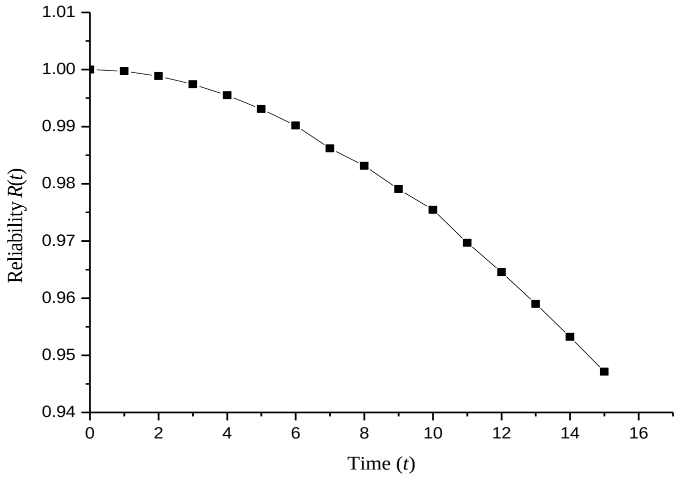

Fig. 3. Reliability vs. time.

4.3. Mean time to failure (MTTF) analysis

To obtain the MTTF, putting the repair rate zero and assuming the Laplace variable ‘*s*’ approaches to zero in Eq. (40), we get

$$MTTF = \frac{\lambda_H + \lambda_{NF} + \lambda_G + 3\lambda_{GT} + \lambda_{CP} + \lambda_{CB} + \lambda_{NZ}}{(\lambda_{CP} + \lambda_{CB} + 2\lambda_{GT} + \lambda_{NZ})(\lambda_H + \lambda_{NF} + \lambda_G + \lambda_{GT})} \quad (44)$$

Putting $\lambda_G = 0.005$, $\lambda_{NF} = 0.008$, $\lambda_G = 0.004$, $\lambda_{GT} = 0.006$, $\lambda_{CP} = 0.009$, $\lambda_{CB} = 0.002$, $\lambda_{NZ} = 0.003$ and varying λ_G, λ_{GT}, λ_{CP}, λ_{CB}, λ_{NF}, λ_{NZ} and λ_H respectively as 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009 in Eq. (44), one can obtain the variation of MTTF of gas turbine power plant with respect to failure rates as shown in Table 3 and Fig. 4.

Table 3. MTTF vs. failure rates.

Variations failure rates	MTTF with respect to failure rates						
	λ_H	λ_{NF}	λ_G	λ_{GT}	λ_{CP}	λ_{CB}	λ_{NZ}
0.001	91.09311	100.96153	88.46153	118.05555	99.03381	83.47826	85.14492
0.002	88.46153	097.28506	86.08058	108.18713	96.10983	81.93979	83.47826
0.003	86.08058	094.01709	83.91608	100.00000	93.47826	80.51529	81.93979
0.004	83.91608	091.09311	81.93979	093.07359	91.09730	79.19254	80.51529
0.005	81.93979	088.46153	80.12820	087.12121	88.93280	77.96101	79.19254
0.006	80.12820	086.08058	78.46153	081.93979	86.95652	76.81159	77.96101
0.007	78.46153	083.91608	76.92307	077.38095	85.14492	75.73632	76.81159
0.008	76.92307	081.93979	75.49857	073.33333	83.47826	74.72826	75.73632
0.009	75.49857	080.12820	74.17582	069.71153	81.93979	73.78129	74.72826

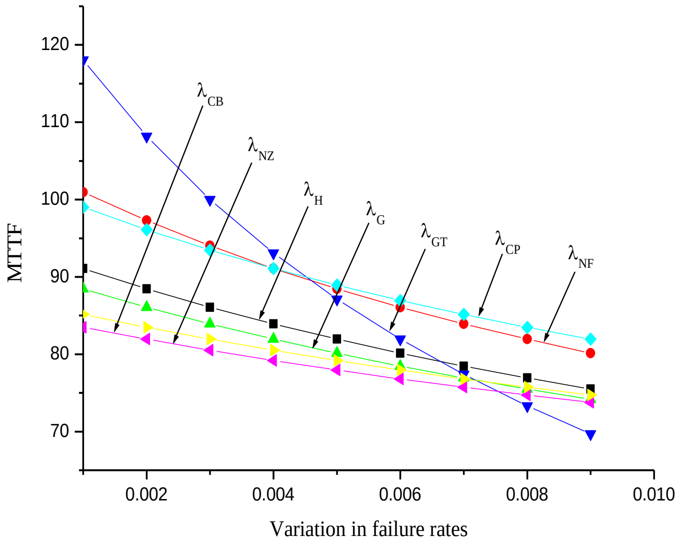

Fig. 4. MTTF vs. failure rates.

4.4. Expected profit

The expected profit during the interval [0, t) is given as

$$E_P(t) = K_1 \int_0^t P_{up}(t)dt - tK_2 \quad (45)$$

where K_1 and K_2 are revenue and service cost per unit time respectively. Substituting the value of $P_{up}(t)$ in Eq. (45) from Eq. (42) and obtain the expected profit in terms of time unit t as

$$\begin{aligned} E_p(t) &= 0.9820229673t - 0.01241565954\cosh(1.012730215t) \\ &\quad - 0.1096680072\cosh(0.049269785t) \\ &\quad + 0.01241565954\sinh(1.012730215t) \\ &\quad + 0.1096680072\sinh(0.049269785t) + 0.1220836668 - tK_2 \end{aligned} \tag{46}$$

Putting K_1= 1 and K_2= 0.01, 0.02, 0.04, 0.06, 0.08, 0.1 and 0.12 respectively in Eq. (46), one can get Table 4 and Fig. 5.

Table 4. Expected profit vs. time.

Time (t)	Expected Profit $E_p(t)$						
	K_2= 0.01	K_2=0.02	K_2=0.04	K_2=0.06	K_2=0.08	K_2=0.1	K_2=0.12
0	0	0	0	0	0	0	0
1	0.98520	0.97520	0.95520	0.93520	0.91520	0.89520	0.87520
2	1.96511	1.94511	1.90511	1.86511	1.82511	1.78511	1.74511
3	2.94295	2.91295	2.85295	2.79295	2.73295	2.67295	2.61295
4	3.91990	3.87990	3.79990	3.71990	3.63990	3.55990	3.47990
5	4.89639	4.84639	4.74639	4.64639	4.54639	4.44639	4.34639
6	5.87259	5.81259	5.69259	5.57259	5.95259	5.33259	5.21259
7	6.84855	6.77855	6.63855	6.49855	6.35855	6.21855	6.07855
8	7.82432	7.74432	7.58432	7.42432	7.26432	7.10432	6.94432
9	8.79990	8.70990	8.52990	8.39990	8.16990	7.98990	7.80990

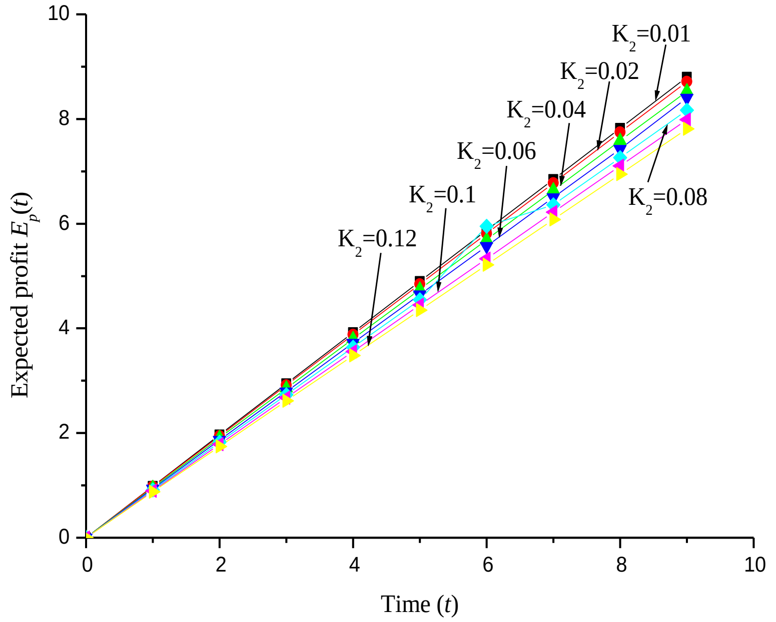

Fig. 5. Expected profit vs. time.

4.5. Sensitivity analysis

Sensitivity is defined as the partial derivative of the function with respect to input factor. These factors are failure rates in the following analyses.

5.4.1. Reliability sensitivity

The sensitivity analysis of reliability can find out by differentiating the reliability function with respect to different failure rates such as λ_G, λ_{GT}, λ_{CP}, λ_{CB}, λ_{NF}, λ_{NZ} and λ_H respectively. By setting the values of $\lambda_G = 0.005$, $\lambda_{NF} = 0.008$, $\lambda_G = 0.004$, $\lambda_{GT} = 0.006$, $\lambda_{CP} = 0.009$, $\lambda_{CB} = 0.002$, $\lambda_{NZ} = 0.003$ in the partial derivatives of reliability such as $\frac{\partial R(t)}{\partial \lambda_H}$, $\frac{\partial R(t)}{\partial \lambda_{NF}}$, $\frac{\partial R(t)}{\partial \lambda_G}$, $\frac{\partial R(t)}{\partial \lambda_{GT}}$, $\frac{\partial R(t)}{\partial \lambda_{CP}}$, $\frac{\partial R(t)}{\partial \lambda_{CB}}$ and $\frac{\partial R(t)}{\partial \lambda_{NZ}}$ and taking *t* = 0 to 9, one may obtain Table 5 and Fig. 6.

Table 5. Reliability sensitivity vs. time.

Time (*t*)	$\frac{\partial R(t)}{\partial \lambda_H}$	$\frac{\partial R(t)}{\partial \lambda_{NF}}$	$\frac{\partial R(t)}{\partial \lambda_G}$	$\frac{\partial R(t)}{\partial \lambda_{GT}}$	$\frac{\partial R(t)}{\partial \lambda_{CP}}$	$\frac{\partial R(t)}{\partial \lambda_{CB}}$	$\frac{\partial R(t)}{\partial \lambda_{NZ}}$
0	0	0	0	0	0	0	0
1	-0.01172	-0.01172	-0.01172	-0.03417	-0.01122	-0.01122	-0.01122
2	-0.04581	-0.04581	-0.04581	-0.13355	-0.04387	-0.04387	-0.04387
3	-0.10069	-0.10069	-0.10069	-0.29351	-0.09640	-0.09640	-0.09640
4	-0.17489	-0.17489	-0.17489	-0.50965	-0.16738	-0.16738	-0.16738
5	-0.26696	-0.26696	-0.26696	-0.77779	-0.25541	-0.25541	-0.25541
6	-0.37556	-0.37556	-0.37556	-1.09394	-0.35918	-0.35918	-0.35918
7	-0.49939	-0.49939	-0.49939	-1.45433	-0.47747	-0.47747	-0.47747
8	-0.63723	-0.63723	-0.63723	-1.85531	-0.60904	-0.60904	-0.60904
9	-0.78788	-0.78788	-0.78788	-2.29349	-0.75280	-0.75280	-0.75280

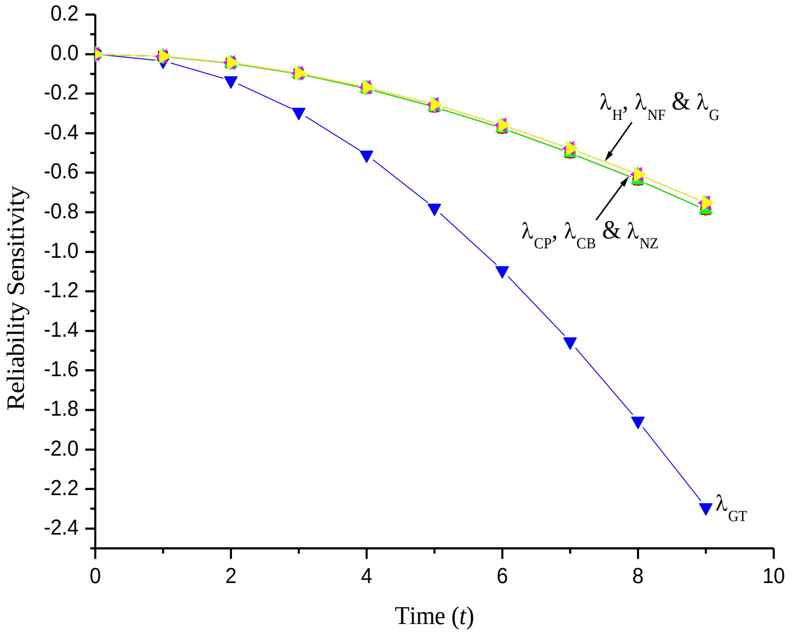

Fig. 6. Reliability sensitivity vs. time.

4.5.2. MTTF sensitivity

The sensitivity analysis of MTTF of the gas turbine power plant can find out by differentiating the function of MTTF with respect to different failure rates λ_G, λ_{GT}, λ_{CP}, λ_{CB}, λ_{NF}, λ_{NZ} and λ_H respectively. By using the values of failure rates as $\lambda_G = 0.005$, $\lambda_{NF} = 0.008$, $\lambda_G = 0.004$, $\lambda_{GT} = 0.006$, $\lambda_{CP} = 0.009$, $\lambda_{CB} = 0.002$, $\lambda_{NZ} = 0.003$, one can determine the value of $\frac{\partial MTTF}{\partial \lambda_H}$, $\frac{\partial MTTF}{\partial \lambda_{NF}}$, $\frac{\partial MTTF}{\partial \lambda_G}$, $\frac{\partial MTTF}{\partial \lambda_{GT}}$, $\frac{\partial MTTF}{\partial \lambda_{CP}}$, $\frac{\partial MTTF}{\partial \lambda_{CB}}$ and $\frac{\partial MTTF}{\partial \lambda_{NZ}}$.

Varying the failure rates respectively as 0.001, 0.002, 0.003, 0.004, 0.005, 0.006, 0.007, 0.008, 0.009 in the partial derivatives of MTTF, one obtains the results of MTTF sensitivity of gas turbine power plant as shown in Table 6 and Fig. 7.

Table 6. MTTF Sensitivity vs. time.

Variations in failure rates	$\frac{\partial MTTF}{\partial \lambda_H}$	$\frac{\partial MTTF}{\partial \lambda_{NF}}$	$\frac{\partial MTTF}{\partial \lambda_G}$	$\frac{\partial MTTF}{\partial \lambda_{GT}}$	$\frac{\partial MTTF}{\partial \lambda_{CP}}$	$\frac{\partial MTTF}{\partial \lambda_{CB}}$	$\frac{\partial MTTF}{\partial \lambda_{NZ}}$
0.001	-71.8184	-75.6143	-70.6164	-116.723	-73.0513	-65.0364	-66.0982
0.002	-21.0419	-21.6333	-20.8502	-32.9052	-21.2363	-19.9298	-20.1089
0.003	-9.88884	-10.0781	-9.82694	-15.2564	-9.95133	-9.52598	-9.58506
0.004	-5.72331	-5.80635	-5.69602	-8.76922	-5.75079	-5.56247	-5.58880
0.005	-3.72683	-3.77038	-3.71248	-5.68642	-3.74126	-3.64197	-3.65591
0.006	-2.61832	-2.64392	-2.60986	-3.98385	-2.62681	-2.56821	-2.57646
0.007	-1.93977	-1.95608	-1.93438	-2.94549	-1.94518	-1.90775	-1.91303
0.008	-1.49449	-1.50551	-1.49084	-2.26590	-1.49815	-1.47280	-1.47638
0.009	-1.18662	-1.19442	-1.18404	-1.79701	-1.18921	-1.17126	-1.17380

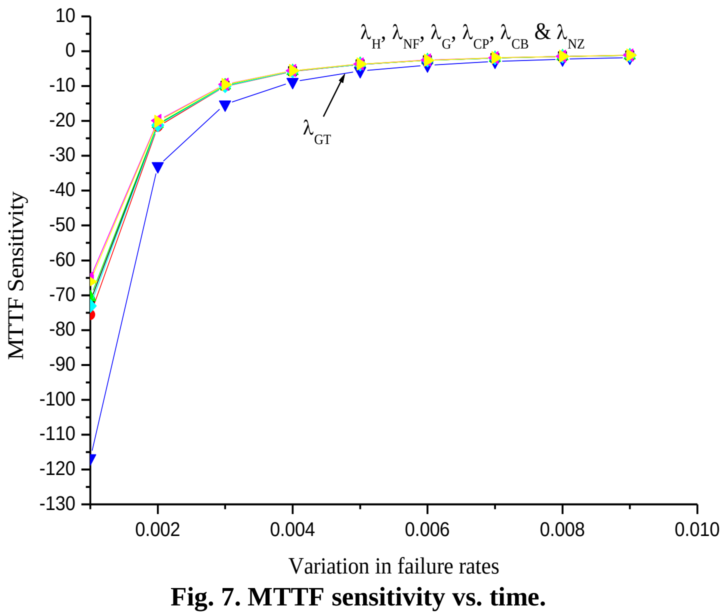

Fig. 7. MTTF sensitivity vs. time.

5. Results Discussion

The authors discussed the various reliability features of the gas turbine power plant to observe and enhance the overall performance of the plant.

Figure 2 shows the availability as a function of time. This graph shows that with the passage of time, availability of the gas turbine power plant decreases. With the help of graph of availability, one can see that from t = 0 to 4 the availability of the system decreases rapidly and after t = 4 the availability decreases slightly.

Figure 3 shows the reliability of the gas turbine power plant as a function of time. This graph also shows that as the time increases, its reliability decreases. From Fig. 3, one can observe some slight fluctuation from t = 6 to 8 and after t = 8, the reliability decreases rapidly. This observation reflects that the gas turbine power plant requires extra care within this time interval.

The mean time to failure is described graphically in Fig. 4. This graph shows a comparative study of MTTF of the gas turbine power plant with respect to variation in different failure rates. From this graph, one can easily see that the MTTF of the system is rapidly decreasing with respect to the failure of gas turbine and slightly decreasing with respect to the failure of compressor and non-availability of fuel and with respect to human failure, generator, combustor and nozzle.

Figure 5 shows the expected profit as a function of failure rates. This graph also shows a comparative study of expected profits when the service cost increases. From this graph, one can easily understand that when the service cost increases then profit decreases.

Sensitivity analysis plays a very important role in the measurement of the system's performance and shows that how much our system is sensitive with respect to different failure rates. Figures 6 and 7 show the sensitivity analysis of reliability and MTTF. From Fig. 6, one can easily see that the system is very much sensitive with respect to the failure of gas turbines and almost same for the failure of the generator, compressor, combustor, nozzle, non-availability of fuel and human failure. Similarly, from Fig. 7, the graph of the sensitivity of MTTF also shows that the system is very much sensitive with respect to the failure of gas turbines and almost same for the failure of any other components. So the system is very much sensitive with respect to the failure of the gas turbine.

6. Conclusions

In the past researches, the authors analysed the reliability, availability and maintainability by using the traditional method. They also identify the critical components but they did not analyse mean time to failure, expected profit and sensitivity analysis. Apart from the previous research, this paper investigated the different reliability indices of the general gas power plant system such as reliability, availability, MTTF, expected profit and sensitivity analysis of reliability as well as MTTF of the gas turbine power plant system by using mathematical modelling, supplementary variable technique, Markov process and Laplace transformation. With the help of different reliability characteristics, the author concluded that reliability and availability are decreases when the time passes but, one can see that at any instant t, the reliability of the gas turbine power plant is very much high as compared to its availability. MTTF of the gas turbine power plant with respect to the failure of the gas turbine is decreased rapidly. More emphasis should be given to the failure of gas turbines because the system is more sensitive with respect to the failure of gas turbines. So, the gas turbine required extra care for the improvement of performance of the plant. The results of this study are very helpful for the reliability engineers, designers, etc. to determine and enhance the performance of gas turbine power plant in future.

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