International Journal of Power Electronics and Drive Systems (IJPEDS)
Vol. 14, No. 4, December 2023, pp. 2064~2071
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v14.i4.pp2064-2071

Comparison between the multi-shaft and the single-shaft combined cycle power plants

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Article Info

Article history:

Received Sep 15, 2022
Revised May 11, 2023
Accepted May 25, 2023

Keywords:

Combined cycle power plant
Markov model
Multi-shaft
Reliability
Single-shaft

ABSTRACT

A multi-shaft system has been adopted by power plants in Thailand for decades; however, for newer units, single-shaft systems have become more popular. This paper compared reliability measures—the system means failure rate, system mean repair rate, and system unavailability indices—between multi-shaft and single-shaft combined cycle power plants (CCPPs). The results showed that the long-term system availability of one multi-shaft CCPP was higher than each of the single-shaft units by 40.70%. In addition, the multi-shaft unit had a 42.14% longer mean time to failure (MTTF) than the single-shaft unit. Finally, the multi-shaft CCPP had 34.59% higher expected capacity than that of the single-shaft system.

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1. INTRODUCTION

In Thailand, the Electricity Generating Authority of Thailand (EGAT) is responsible for generating electricity for the public, providing 34.70% of the total electricity produced in the country [1]. A combined cycle power plant (CCPP) is the most common type of power plant in Thailand, responsible for 51.53 % of the entire EGAT power production [2]. Generally, in a CCPP, the exhaust gases from a gas turbine are used to produce electricity in a steam turbine [3]. In addition, the CCPP is approximately 60 percent efficient, while a gas turbine power plant is about 40 percent efficient [4]. In fact, CCPP is the most popular type of power plant globally, operating with either a single-shaft or a multi-shaft system. To date, there has not been any large-scale plant owned by EGAT that has explored the potential of integrating either solar energy [5], [6] or biomass energy [7]–[9] with CCPP. This can be further studied for potential and efficiency assessment. Farhad *et al.* [10] suggested a method based on pinch technology and exergy analysis to reduce the fuel consumption and condenser load that resulted in higher plant efficiency. In terms of increasing efficiency, studies such as Franco and Casarosa [11], and Kotowicz and Brzęczek [12] both proposed potential methods to increase CCPP efficiency from approximately 60% to a target of 65%.

A multi-shaft system has been adopted by EGAT for power generation for decades; for newer units, EGAT has acquired two single-shaft systems—one is at the North Bangkok Power Plant and the other one is at the Chana Power Plant. The North Bangkok Power Plant has two CCPP units. The first unit is a multi-shaft system, with two gas turbines and one steam turbine (in service since 2010), while the second unit is a single-shaft system with two gas turbines and two steam turbines (in service since 2016) with capacities of 704 MW and 848.30 MW, respectively [13]. The Chana Power Plan also has two units. The first one is a multi-shaft system similar to the North Bangkok one (two gas turbines and one steam turbine) with capacity of 731 MW (in service since 2008). The second one is a single-shaft system, also with two gas turbines and two steam turbines with capacity of 800 MW (in service since 2014). Another single-shaft unit (in service since 2016) is owned by the electricity generating public company, Limited, which is a privately owned company. The single-shaft CCPP was claimed to have the advantage of being more efficient than a multi-shaft one [14]. In terms of stability of speed, a single-shaft CCPP performed better; however, considering performance with a partial load, the multi-shaft system may be better [15]. Another example of single-shaft CCPP was explored in Miah *et al*. [16] in Bangladesh. In this study, the authors found that single-shaft CCPP was economically feasible in Bangladesh.

Sabouhi *et al.* [17] established a Markov model of the Montazer-e-Ghaem multi-shaft CCPP in Iran. In this plant each of three units has capacity of 332.80 MW. Each unit has two gas turbines (each with capacity of 116.40 MW) and one steam turbine (with capacity of 100 MW). Many studies have extended or referred to the results in [17]. For example, Pourahmadi *et al.* [18] later adapted the model in [17], [19] to identify critical components of power systems from the overall reliability system using the concepts in game theory. Ibrahim *et al.* [20] established a model using MATLAB 10 A with the objective to optimize setting conditions for the combined cycle gas turbine (CCGT) in [17], with various configurations. Arani *et al.* [21] performed economic analysis of the thermal system from [17], which considered the availability of the system. Carpitella *et al.* [22] developed a formula for calculating the availability of a k-out-of-n system. The formula has been proven to be consistent with the Markov chain theorem, as shown in [17]. In the current study, since the single-shaft system is relatively new in Thailand, it is worth comparing reliability aspects between the single-shaft and the multi-shaft systems by applying the reliability measures established in [17] to the single-shaft system.

2. METHOD

The technique used began by constructing a Markov model for a single-shaft CCPP. The multi-shaft CCPP Markov model in our study was adopted from Sabouhi *et al.* [17]. Then, from the constructed single-shaft Markov model, the state probabilities, departure rates, and long-term system availability were carefully derived, as shown in the following subsections. In addition, critical component analysis was conducted for the proposed single-shaft CCPP Markov model. Finally, since the single-shaft results would be compared with the multi-shaft results, discussion of the assumed capacity was also provided in the last subsection.

2.1. Constructing Markov model for single-shaft CCPP

Any type of CCPP (either single-shaft or multi-shaft) consists of a gas turbine and a steam turbine, as shown in Figure 1 and Figure 2. The exhaust gases from the gas turbine flow into heat recovery steam generators (HRSG) to produce steam for the steam turbine. For the single-shaft CCPP, the gas and the steam turbines use the same generator, as shown in Figure 1, where the generator is located between the gas turbine and the steam turbine. The steam turbine is connected or disconnected using a clutch. A typical multi-shaft CCPP consists of two or more gas turbines, each with its own HRSG and generators, as shown in Figure 2. This type of power plant can be designed to increase the capacity by increasing the number of gas turbines [3].

This paper considered a single-shaft CCPP with no additional firing (as shown in Figure 1), consisting of one gas and one steam turbine. The Markov model was constructed as shown in Figure 3. If the gas turbine fails, the entire system shuts down. On the contrary, if the steam turbine fails, the system can still generate electricity partially. The two down states in Figure 3 can be combined as one Down state shown in the equivalent Markov model in Figure 4. The equivalent Markov model in Figure 4 consists of three states: the up state, when both the gas and the steam turbines are up; The derated state, when the gas turbine is up but the steam turbine is down; and the down state, when the gas turbine is down.

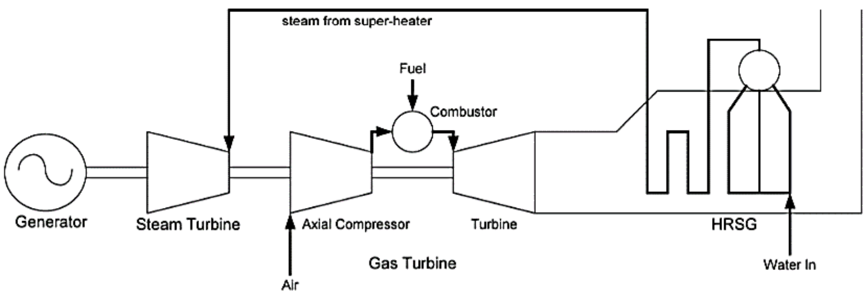

Figure 1. Single-shaft combined cycle power plant (taken from [13])

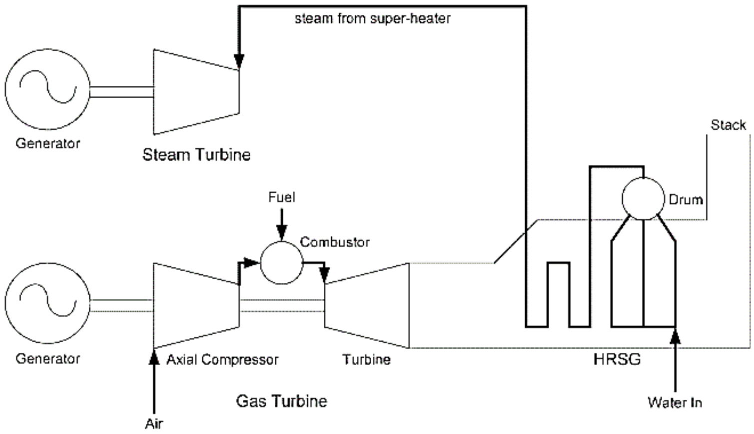

Figure 2. Multi-shaft combined cycle power plant (taken from [13])

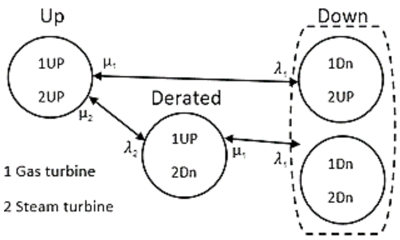

Figure 3. Markov model of single-shaft combined cycle power plant

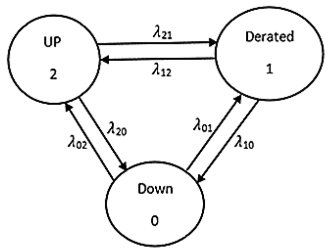

Figure 4. Equivalent Markov model of single-shaft combined cycle power plant

2.2. Calculation of long-term system availability and mean time to failure of a single-shaft CCPP

Any engineering system consists of several subsystems in which each component in the subsystem is connected in series or parallel arrangements. The CCPP was assumed to have repairable components. The system equivalent failure rate and the system equivalent repair rate can be calculated using (1) to (4). In these (1)-(2) are for parallel arrangements and (3)-(4) are for series arrangements [23]. All necessary parameters are defined in Table 1.

$$\mu_s = \sum_{i \in N} \mu_i \tag{1}$$

$$\lambda_s = \left(\prod_{i \in N} \frac{\lambda_i}{\lambda_i + \mu_i}\right) \bullet \left(\sum_{i \in N} \mu_i\right) \bullet \left(1 - \prod_{i \in N} \frac{\lambda_i}{\lambda_i + \mu_i}\right)^{-1} \tag{2}$$

$$\lambda_s = \sum_{i \in N} \lambda_i \tag{3}$$

$$\mu_s = \left(\prod_{i \in N} \frac{\mu_i}{\lambda_i + \mu_i}\right) \bullet \left(\sum_{i \in N} \mu_i\right) \bullet \left(1 - \prod_{i \in N} \frac{\mu_i}{\lambda_i + \mu_i}\right)^{-1} \tag{4}$$

The state probabilities and departure rates in Figure 4 were assumed as shown in (5) and (6). The long-term system availability (As) were derived using (7)-(10), based on [24].

$$\lambda_{12} = \mu_2, \lambda_{21} = \lambda_2, \lambda_{10} = \lambda_1 \tag{5}$$

$$\lambda_{01} = \frac{\mu_1 \lambda_2}{\lambda_2 + \mu_2}, \lambda_{20} = \lambda_1, \lambda_{02} = \frac{\mu_1 \mu_2}{\lambda_2 + \mu_2} \tag{6}$$

$$P_{0s} = \frac{\lambda_1 \lambda_2 + \lambda_1 \mu_2}{(\lambda_1 + \mu_1)(\lambda_2 + \mu_2)} \tag{7}$$

$$P_{1s} = \frac{\lambda_2\mu_1}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \tag{8}$$

$$P_{2s} = \frac{\mu_1\mu_2}{(\lambda_1+\mu_1)(\lambda_2+\mu_2)} \tag{9}$$

$$\sum_{j\in B} P_j = P_{1s} + P_{2s} \tag{10}$$

Table 1. Nomenclature

Designation	Symbol
Index of a single component	I
Number of components	N
The component failure rate and repair rate	μ_i, λ_i
The system failure rate and repair rate	μ_s, λ_s
Departure rate of state *i* to *j*	λ_{ij}
Steady state probability for the Down state of the single–shaft CCPP	P_{0s}
Steady state probability for the Derated state of the single–shaft CCPP	P_{1s}
Steady state probability for the Up state of the single–shaft CCPP	P_{2s}
Steady state probability for state j of the single–shaft CCPP	P_i
The set of states that the system is still in operation (Up and Derated states)	B
Steady state probability of the Up state for the multi–shaft CCPP	P_{u2m}
Steady state probability of the Derated 1 state for the multi–shaft CCPP	P_{d1m}
Steady state probability of the Derated 2 state for the multi–shaft CCPP	P_{d2m}
Steady state probability of the Derated 3 state for the multi–shaft CCPP	P_{d3m}
System means failure and repair rates	λ_{sys}, μ_{sys}
System unavailability index	U_{sys}

The mean time to failure (MTTF) was calculated using the Kolmogorov forward equations and the Laplace transformation. We assumed that at time t = 0, the gas and the steam turbines were at the operating state. The state probabilities were calculated as shown in (11)-(12) and the MTTF was calculated using (13).

$$P_{1s}^*(0) = \frac{\lambda_2}{\lambda_1(\lambda_1+\lambda_2+\mu_2)} \tag{11}$$

$$P_{2s}^*(0) = \frac{\lambda_1+\mu_2}{\lambda_1(\lambda_1+\lambda_2+\mu_2)} \tag{12}$$

$$MTTF = P_{1s}^*(0) + P_{2s}^*(0) = \frac{\lambda_1+\lambda_2+\mu_2}{\lambda_1(\lambda_1+\lambda_2+\mu_2)} \tag{13}$$

2.3. Critical component analysis of single–shaft CCPP

Since [17] and [25] used the system mean failure rate, system mean repair rate, and system unavailability indices as measures to identify critical components, we also used these measures to compare the results of the single-shaft unit from our study with those of the multi-shaft unit from [17]. The (14) determined the reduction of the system mean failure rate. The (15) determined the reduction of the system mean repair rate. Finally, in (16) determined the system unavailability index with respect to the failure rate and the repair rate of component i, respectively. After the model was formulated for the single-shaft CCPP, since the data of the North Bangkok Power Plant was not readily available, we based our analysis on the data for failure rates and repair rates of individual components, obtained from [17].

$$C_{\lambda_i}^{\lambda_{sys}} = -\left(\frac{\partial\lambda_{sys}}{\partial\lambda_i}\right)\Delta\lambda_i, C_{\mu_i}^{\lambda_{sys}} = -\left(\frac{\partial\lambda_{sys}}{\partial\mu_i}\right)\Delta\mu_i \tag{14}$$

$$C_{\lambda_i}^{\mu_{sys}} = -\left(\frac{\partial\mu_{sys}}{\partial\lambda_i}\right)\Delta\lambda_i, C_{\mu_i}^{\mu_{sys}} = -\left(\frac{\partial\mu_{sys}}{\partial\mu_i}\right)\Delta\mu_i \tag{15}$$

$$C_{\lambda_i}^{U_{sys}} = -\left(\frac{\partial U_{sys}}{\partial\lambda_i}\right)\Delta\lambda_i, C_{\mu_i}^{U_{sys}} = -\left(\frac{\partial U_{sys}}{\partial\mu_i}\right)\Delta\mu_i \tag{16}$$

2.4. Expected value of capacity used in comparison study

The assumed capacity for the single-shaft model was based on the actual capacity of the Montazer-e-Ghaem CCPP in [17]. Since the two gas and the one steam turbines in the multi-shaft unit in [17] had capacities of approximately 200 MW and 100 MW, respectively, we assumed these capacities for the gas and the steam turbines of a single-shaft unit as well. The expected values for the capacities of the single-shaft and multi-shaft combine cycle power plants were calculated using (17)-(18).

$$EV = (600 \times P_{2s}) + (400 \times P_{1s}) \quad (17)$$

$$EV = (500 \times P_{u2m}) + (400 \times P_{d1m}) + (400 \times P_{d2m}) + (500 \times P_{d3m}) \quad (18)$$

3. RESULTS AND DISCUSSION

At steady state, the long-term system availability levels (As) of the two single-shaft power generating systems were 0.3136, 0.3137, while that for the multi-shaft power generating system was 0.5288, as shown in Figure 5. The MTTF for each single-shaft combined cycle power plant was 155.65 hours and the MTTF for the multi-shaft combined cycle power plant was 269.03 hours, as shown in Figure 6. These results are credible, since there was only one gas turbine in one single-shaft unit compared to two gas turbines in the multi-shaft unit. Hence, by comparing one single-shaft unit with one multi-shaft unit, in terms of MTTF, the multi-shaft unit seemed to be more reliable. The expected total capacity of the multi-shaft unit for the two gas and one steam turbines was 154.26 MW, while for the two gas and two steam turbines single-shaft unit it was 235.84 MW.

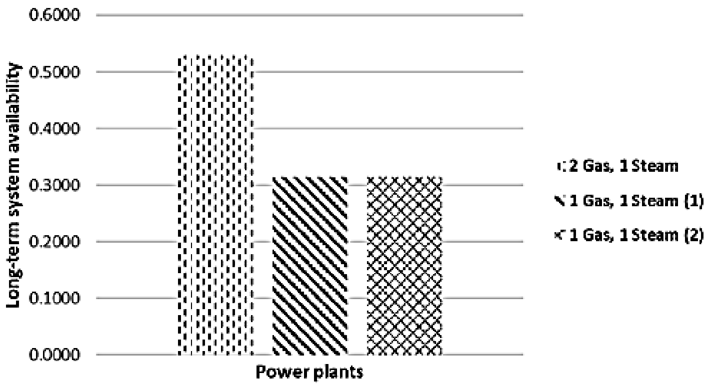

Figure 5. Long-term system availability comparison between single-shaft and multi-shaft systems

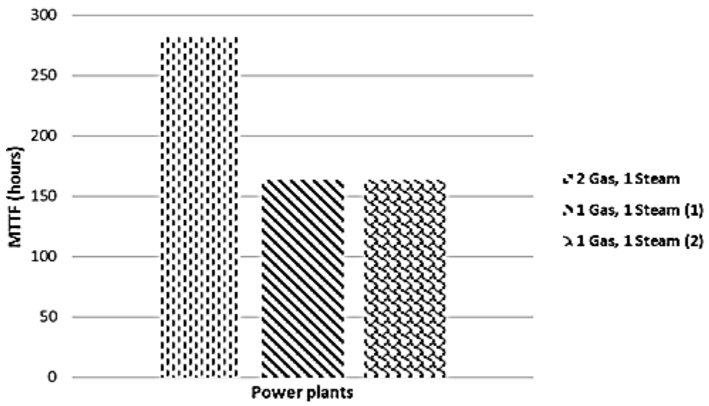

Figure 6. Mean time to failure comparison between single-shaft and multi-shaft systems

In general, similar to the multi-shaft system, a gas turbine seemed to be more critical than a steam turbine, as shown in Figure 7, since most of the components of the gas turbine affected the unavailability rates more than those in the steam turbine if the failure rate was changed. In particular, the top-5critical components of the steam and the gas turbine in Figure 7 are listed in Table 2. Figure 8 shows that the important components in the gas turbine are the main oil pump, emergency oil pump, auxiliary oil pump, combustion chamber, and crossfire tube. For the steam turbine, the criticality measures were either zero or negative. The components whose repair rates affected the single-shaft CCPP overall unavailability the least were the cooling water pump, stan pipe, water balance, water spray system, and motor valves, as listed in Table 3. For the multi-shaft CCPP, we did not have access to the critical component values as shown in Table 3. However, Sabouhi *et al.* [17]

reported that the critical components for the multi-shaft system gas turbine were the extraction system, trust bearing, journal bearing, and casing system and for the steam turbine were the water balance, HP system, IP system, feed water system, and LP system.

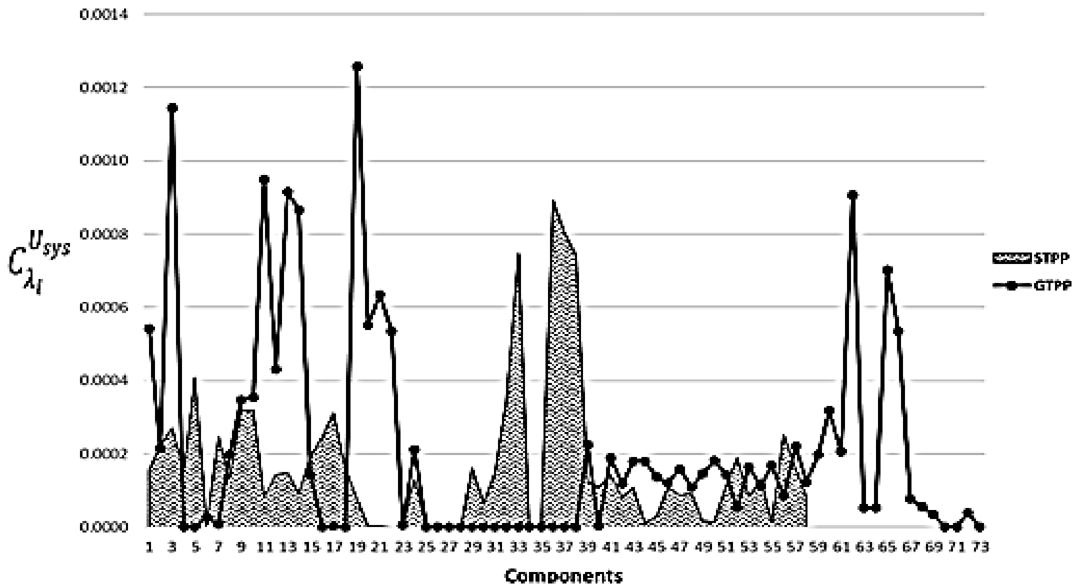

Figure 7. Criticality measurement of component failure rate on single-shaft overall unavailability

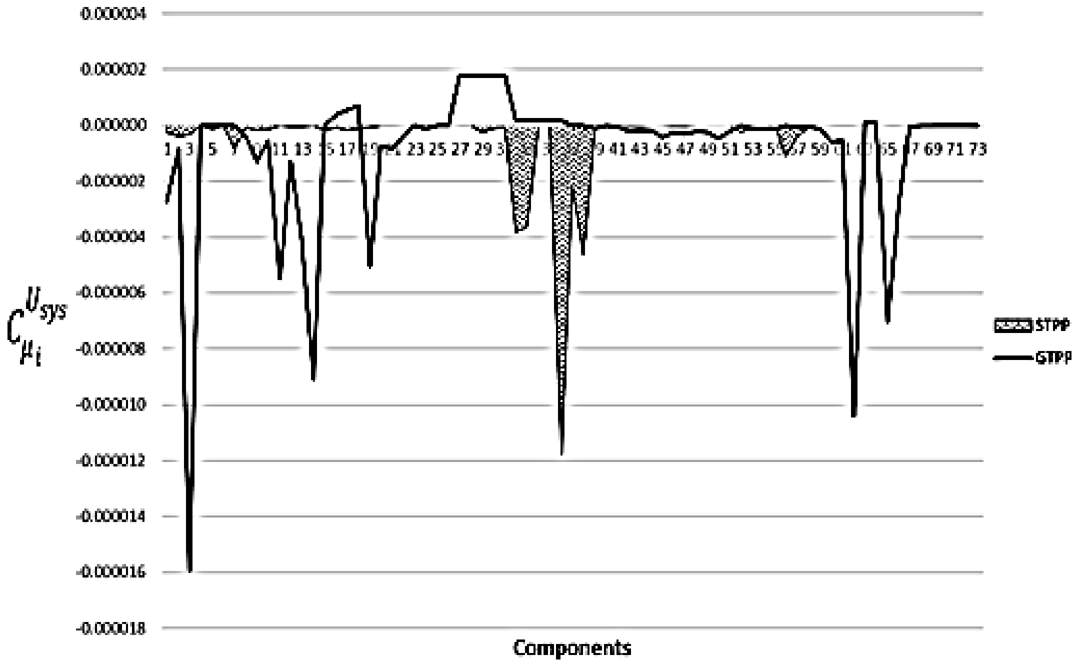

Figure 8. Criticality measurement of component repair rate on single-shaft overall unavailability

Table 2. Critical components of gas turbine and steam turbine of the single-shaft CCPP

Components of gas turbine	$C_{\lambda_i}^{U_{sys}}$	Components of steam turbine	$C_{\lambda_i}^{U_{sys}}$
Oil and pipeline	12.59×10^{-4}	Cooling water pump	89.42×10^{-5}
Low pressure strainer	11.44×10^{-4}	Motor valves	80.79×10^{-5}
Flow divider	95.06×10^{-5}	Water spray system	74.65×10^{-5}
Relief valve	91.53×10^{-5}	Stan pipe	74.37×10^{-5}
Gear box	90.57×10^{-5}	Blow down & blow off	40.85×10^{-5}

Table 3. Critical components of gas turbine and steam turbine of the multi-shaft CCPP

Components of gas turbine	$C_{\mu_i}^{U_{sys}}$	Components of steam turbine	$C_{\mu_i}^{U_{sys}}$
Combustion chamber	17.90×10^{-7}	Cooling water pump	-11.76×10^{-6}
Auxiliary oil pump	6.80×10^{-7}	Stan pipe	-45.94×10^{-7}
Emergency oil pump	5.70×10^{-7}	Water balance	-38.04×10^{-7}
Main oil pump	3.72×10^{-7}	Water spray system	-36.31×10^{-7}
Crossfire tube	1.82×10^{-7}	Motor valves	-22.07×10^{-7}

4. CONCLUSION

This paper compares reliability measures between a multi-shaft and a single-shaft CCPP. The comparison indices were based on reliability measures studied in the Montazer-e-Ghaem power plant in Iran. In addition, all data on the failure and repair rates for that plant were adopted and applied in the current study. The results showed that the long-term system availability of one multi-shaft CCPP was higher than for each of single-shaft units by 40.70%. Furthermore, the multi-shaft unit had a 42.14% longer MTTF than the single-shaft unit. The multi-shaft CCPP had 34.59% higher expected capacity than that of the single-shaft system.

Our results showed that even though the single-shaft system required less space and had a higher efficiency than the single -shaft one, there was a tradeoff in terms of reliability. Unfortunately, in this study, we could not obtain the actual failure and repair rates for any single-shaft CCPP in Thailand. However, for comparison purposes, our results could be considered reliable, since the data used in the comparison were based on the same failure and repair rates making it an unbiased comparison. This study provided some useful information for power plant businesses during the decision–making stage regarding acquiring a single-shaft system. Further studies that could further improve CCPP reliability should be conducted on failure analysis caused by vibration or on monitoring system failure of rotating machines.

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