Reliability investigation of steam turbine critical components

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Abstract. Several aspects of maintaining and operating steam turbines at the palm oil mill areas have historically resulted in unreliable performance and repetitive failures. The reliability analysis using Weibull probability distribution for various components of steam turbine is discussed extensively. The objective of this reliability assessment is to identify the potential failure path of steam turbine components. The intent herein is to focus on critical components of steam turbine to successfully improve the integrity and reliability of turbines in those components. Areas discussed will be bearing failures, Shaft Seal failures, Control/stop Valve, Main Oil Pump, and Reducing Gear. It is necessary to improve the reliability indices of the steam turbine components by taking some measures such as well-planned and routine maintenance of equipment’s as well as training and retraining of technical human resources of the major equipment like steam turbine.

1. Introduction
Steam Turbine Reliability is the probability of a system to execute required performance for a specified interval of time without any failure under given conditions for which it is planned. The most acknowledged definition of reliability is the capability of an item, system, etc., to function under selected operating conditions for a specific period or number of cycles. The measure of reliability for non-repairable systems is Mean Time to Failure (MTTF) and for repairable system is Mean Time between Failure (MTBF).

In general, reliability assessment aims to determine the condition of equipment [1], measuring the performance of equipment [2], qualifying process design modifications for vendors, and identify the potential failure path of steam turbine components.

The system reliability designated through the deterministically approach or probabilistic approach. Sabri et al. (2012) deal with the probabilistic aspect of maintenance operational performance [3]. In their work they suggested that, in time related failure, the Weibull probability distribution is one of the mostly used technique for reliability assessment of thermal power plant. Deterministic approach of reliability analysis of the system is used to deals with understanding how and why a system is unsuccessful, and how it can plan to avoid such failure from happening or re-happening. This includes analysis such as review of historical field failure reports, understanding scientific theory behind the failure, the role and degree of maintenance policies. Dewangan et al. (2014) reported that it is necessary to improve the reliability indices of the power plant by taking some measures such as well-planned and routine maintenance of equipments as well as training and retraining of technical human resources of the major equipment [4]. A modern power plant is very huge, multifaceted and highly
integrated. Satyendra Dhurvey (2016) suggested that it is important to enhance the reliability records of the power plant by taking a few measures, for example, arranged maintenance routines of types of assets and also preparing and retraining specialized technical human resources of the major equipment [5].

2. Reliability Estimation Of Steam Turbine Components

Reliability is focused on probability, performance requirements, time and conditions of use. Understanding of these four elements fulfils the concept of failure rate which can change as a function of time. In general, reliability will affect the availability of equipment to function properly, especially for repairable steam turbine components.

The measure of reliability for non-repairable systems is Mean Time to Failure (MTTF). To identify reliability as well as the average time of failure that occurs in each component of the Steam Turbine data is collected from the maintenance report.

Reliability studies carried out separately or in combinations of all three functional areas. This work is limited to the assessment of the generation reliability, especially the reliability of steam turbine components. The reliability of steam turbine components has calculated based on last year historical maintenance database of 500 MW steam turbine.

The data used as the research sample is in the period January 2017 - December 2017, which includes: Journal of Steam Turbines to determine the actual time of use of turbine operating hours, set up time, and breakdown time of turbines. Maintenance checklist as a report on the method used in a turbine maintenance system that will explain Planned Downtime. The Manual Book is a turbine manual procedure that contain the application rules for the turbine. Maintenance Card as a replacement data carried out on the components of the turbine.

### Table 1. Amount of steam turbines components failure.

| No | Components          | Amount of failure |
|----|---------------------|-------------------|
| 1  | Casing              | 0                 |
| 2  | Rotor               | 0                 |
| 3  | Shaft Seal          | 2                 |
| 4  | Turbine Bearing     | 3                 |
| 5  | Main Oil Pump       | 7                 |
| 6  | Impulse Stage       | 0                 |
| 7  | Turbine Control Valve | 4         |
| 8  | Turbine Stop Valve  | 2                 |
| 9  | Reducing Gear       | 2                 |

From the table 1, it can be seen the number of failures that occur in the components of the steam turbine. In the steam turbine component, the casing, rotor and impulse stage were found to have never failed.

3. Determination Of Weibull Distribution Parameters

Failure data is obtained from Steam Turbine Journal, Maintenance Check List, and Maintenance Card then followed by 2 parameter Weibull Distribution. Parameter estimation is calculated by looking for the value \( \eta \) (scale parameter) and \( \beta \) (form parameter). Parameter estimation calculate using linear
regression method, \( t_1, t_2, t_3\), is a number of time data between system failure that has been arranged sequentially from the smallest, for \( t_i \) \((i = 1,2,3 \ldots n)\) the following relationship applies:

\[
F(t_i) = \frac{i-0.3}{n+0.4}, \quad x_i = \ln (t_i) \tag{1}
\]

\[
y_i = \ln(\ln(1/(1 - F(t_i)))) \tag{2}
\]

The next step is to calculate the intercept value \((a)\) and slope \((b)\). Then calculate the values of \(\eta\) and \(\beta\) in the following way:

\[
b = \frac{\sum_{i=1}^{N} x_i y_i - \left(\sum_{i=1}^{N} x_i\right) \left(\sum_{i=1}^{N} y_i\right)}{N \sum_{i=1}^{N} x_i^2 - \left(\sum_{i=1}^{N} x_i\right)^2} \tag{3}
\]

\[
a = \frac{\sum_{i=1}^{N} y_i}{N} - b \frac{\sum_{i=1}^{N} x_i}{N} \tag{4}
\]

then from the calculation we get a table of form parameters \((\beta)\) and scale parameters \((\eta)\) for each component in the turbine as follows:

| No | Components            | \(\beta\) | \(\eta\) |
|----|-----------------------|------------|----------|
| 1  | Shaft Seal            | 1.1354     | 367.71   |
| 2  | Bearing               | 0.8841     | 485.347  |
| 3  | Main Oil Pump         | 0.8664     | 3034.49  |
| 4  | Turbine Control Valve | 1.6652     | 2373.72  |
| 5  | Turbine Stop Valve    | 3.3556     | 2141.99  |
| 6  | Reducing Gear         | 2.4205     | 4842.48  |

Calculation of Weibull Distribution Parameters for Steam Turbines components, namely:

| No | \(t_i\) | \(F'(t_i)\) | \(\ln(t_i)\) | \(1-F'(t)\) | \(\ln\left(\frac{1}{1-F(t_i)}\right)\) | \(X_i y_i\) | \(x_i^2\) |
|----|---------|-------------|--------------|--------------|----------------------------------------|-------------|----------|
| 1  | 144     | 0.29166     | 4.9698       | 0.7083       | -1.0647                                | -5.2914     | 24.6990  |
| 2  | 442     | 0.70833     | 6.0913       | 0.2916       | 0.2087                                 | 1.2715      | 37.1040  |
| \(\Sigma\) | 365     |              | 11.0611      |              | -0.856                                 | -4.0198     | 61.8031  |

| No | \(t_i\) | \(F'(t_i)\) | \(\ln(t)\) | \(1-F'(t)\) | \(\ln\left(\frac{1}{1-F(t_i)}\right)\) | \(X_i y_i\) | \(x_i^2\) |
|----|---------|-------------|--------------|--------------|----------------------------------------|-------------|----------|
| 1  | 89      | 0.2058     | 4.4884       | 0.7942       | -1.4678                                | -6.5886     | 20.1478  |
| 2  | 355     | 0.5        | 5.8721       | 0.5          | -0.3665                                | -2.1522     | 34.4817  |
| 3  | 763     | 0.7941     | 6.6372       | 0.2059       | 0.4576                                 | 3.0375      | 44.0531  |
| \(\Sigma\) | 698.33  |              | 16.998       |              | -1.3767                                | -5.7032     | 98.6828  |
| NO | ti  | F'(t) | Ln(t) | 1-F'(t) | \(\ln \left[ \ln \left( \frac{1}{1 - F(t)} \right) \right] \) | Xiyi | xi²  |
|----|-----|-------|-------|---------|-------------------------------------------------|-------|-------|
| 1  | 720 | 0.1590| 6.5792| 0.8409  | -1.7529                                         | -11.5328| 43.2865|
| 2  | 1560| 0.3863| 7.3524| 0.6136  | -0.71673                                        | -5.2697| 54.0583|
| 3  | 2280| 0.6136| 7.7319| 0.3863  | -0.0502                                         | -0.3886| 59.7827|
| 4  | 3480| 0.8409| 8.1547| 0.1590  | 0.6088                                          | 4.9648 | 66.50056|
| ∑  | 5430| 29.8184|       |         | -1.9110                                         | -12.2263| 223.6282|

| NO | ti  | F'(t) | Ln(t) | 1-F'(t) | \(\ln \left[ \ln \left( \frac{1}{1 - F(t)} \right) \right] \) | Xiyi | xi²  |
|----|-----|-------|-------|---------|-------------------------------------------------|-------|-------|
| 1  | 192 | 0.0945| 5.2574| 0.90540 | -2.3088                                          | -12.139| 27.6412|
| 2  | 576 | 0.2297| 6.3561| 0.77028 | -1.3432                                          | -8.5377| 40.4001|
| 3  | 1584| 0.3648| 7.3677| 0.63514 | -0.7898                                          | -5.8194| 54.2831|
| 4  | 2664| 0.5   | 7.8875| 0.5     | -0.3665                                          | -2.890 | 62.2139|
| 5  | 3624| 0.6351| 8.1953| 0.36486 | 0.0081                                           | 0.0671 | 67.1634|
| 6  | 4344| 0.77027| 8.3765| 0.22973 | 0.3858                                          | 3.2320 | 70.1666|
| 7  | 5328| 0.90540| 8.5807| 0.09459 | 0.8578                                          | 7.3612 | 73.6289|
| ∑  | 13745.1| 52.0215|       |         | -3.5565                                         | -18.726| 395.497|

| NO | ti  | F'(t) | Ln(t) | 1-F'(t) | \(\ln \left[ \ln \left( \frac{1}{1 - F(t)} \right) \right] \) | Xiyi | xi²  |
|----|-----|-------|-------|---------|-------------------------------------------------|-------|-------|
| 1  | 1560| 0.2917| 7.3524| 0.70833 | -1.0647                                          | -7.828 | 54.05839|
| 2  | 2280| 0.7083| 7.7319| 0.29167 | 0.20875                                          | 1.61408| 59.78275|
| ∑  | 2700| 15.084|       |         | -0.8559                                         | -6.2139| 113.8411|

| NO | ti  | F'(t) | Ln(t) | 1-F'(t) | \(\ln \left[ \ln \left( \frac{1}{1 - F(t)} \right) \right] \) | Xiyi | xi²  |
|----|-----|-------|-------|---------|-------------------------------------------------|-------|-------|
| 1  | 3120| 0.2916| 8.0455| 0.7083  | -1.06466                                         | -8.5659| 64.7314|
| 2  | 5280| 0.7083| 8.5716| 0.2916  | 0.20876                                          | 1.7893 | 73.4737|
| ∑  | 5760| 16.6172|       |         | -0.85592                                         | -6.7765| 138.205|
From the formula (1) – (4), we get table 9 of form parameters (β) and scale parameters (η) for each component in the turbine. From Table 9, the form parameter (β) shows that the component of Main Oil Pump with the value of β = 0.8664 can be interpreted as failure that occurs due to stress, the period of quality control and inspection. While the Turbine Stop Valve form parameter with a value of 1.6652 can be interpreted as failure due to corrosion, wear, erosion and failure of the bearing.

After calculating the Weibull Distribution parameters on each component of the steam turbine, it is continued by calculating the relative frequency of failure in the time function (PDF), calculating the probability that an equipment will fail before the specified time and reliability of the Steam Turbine components.

a. **Probability Density Function (PDF)**

\[
f(t) = \frac{\beta}{\eta} \left(\frac{t}{\eta}\right)^{\beta - 1} e^{-\left(\frac{t}{\eta}\right)^\beta}
\]  

(5)

b. **Cumulative Distribution Function (CDF)**

\[F(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}
\]

(6)

c. **Reliability**

\[R(t) = e^{-\left(\frac{t}{\eta}\right)^\beta}
\]

(7)

The reliability calculation represented in table 10. Mean time between failures (m), mean time to repair (ζ) and reliability has estimated by processing the historical fault data.

| No | Components            | β     | η     |
|----|-----------------------|-------|-------|
| 1  | Shaft Seal            | 1.1354| 367.71|
| 2  | Bearing               | 0.8841| 485.347|
| 3  | Main Oil Pump         | 0.8664| 3034.49|
| 4  | Turbine Control Valve | 1.6652| 2373.72|
| 5  | Turbine Stop Valve    | 3.3556| 2141.99|
| 6  | Reducing Gear         | 2.4205| 4842.48|

The reliability value of each component of the steam turbine that has experienced failure in table 10 shows that the highest component reliability occurs in the Reducing Gear with a value of 56.19% affected by the number of failures occurring and the time of failure, and the lowest reliability experienced by the Main Oil Pump with a value of 19.75%.
4. Mean Time To Failure (MTTF) For 2-Parameter Weibull Distribution

After the parameters of the 2 parameter Weibull Distribution are known, the MTTF value can be calculated. The MTTF value is a value that indicates the time interval from the time the component is used until the component is damaged. Therefore, the MTTF value can be used as an estimate of the component operating life.

Calculations for MTTF values are:

\[ F = \eta \cdot \Gamma \left( \frac{1}{\beta} + 1 \right), \]  

(8)

Where \( \Gamma(n) = \int_{0}^{\infty} x^{n-1} e^{-x} \, dx \), \( \Gamma = \text{gamma} \), \( \eta = \text{scale parameter} \).

Table 11. show the average time of failure of the steam turbine component.

| No | Components                  | MTTF   |
|----|-----------------------------|--------|
| 1  | MTTF shaft seal             | 463.642|
| 2  | MTTF turbine bearing        | 515.765|
| 3  | MTTF main oil pump          | 3262.98|
| 4  | MTTF turbine control valve  | 2142.33|
| 5  | MTTF turbine stop valve     | 6091.87|
| 6  | MTTF reducing Gear          | 4293.47|

The average failure time for each component of the steam turbine is shown in table 11. Shaft seal and turbine bearing components fail at the same time under the 1000 hour period. Main oil pump that has 19.75% reliability will fail at 3262.98 hours.

5. Conclusion

Reliability of steam turbine components based on Weibull Distribution found the reliability value of each component of Steam Turbine which is 19% main oil pump, 28% turbine bearing, 32% shaft seal, 32% turbine stop valve, 32% turbine stop valve and reducing gear by 56%. According to maintenance record, the mean time to failure of steam turbine components is shaft seal at 463.642 hours, turbine bearing at 515.765 hours, turbine control valve at 2142.33 hours, main oil pump at 3262.98 hours, turbine stop valve at 6091.87 hours and reducing gear at 4293.47 hours.

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