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# ESTIMATION OF RELIABILITY PARAMETERS FOR POWER TRANSFORMERS

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**Abstract**

*Power transformers play an important role in the efficient delivery of power to consumers. Their failure leads to significantly higher losses and maintenance costs. Therefore, it is essential to have an optimal maintenance strategy in place for the transformers. However, to design an effective maintenance strategy, real failure data of the transformers need to be collected and studied to identify the failure patterns. To facilitate the analysis presented in this paper, five years of real failure data of a transformer system is collected from a power distribution company. The best-fit distribution for the failure times data of the system is found using AIC, BIC, and LKV values. Useful reliability parameters of the system are evaluated using the Maximum Likelihood Estimation and Rank Regression Method. Life data analysis is performed to estimate the reliable life, mean time to failure, and remaining lifetime of the entire system and its subsystems.*

**Keywords:** Best-fit distribution, Maximum likelihood estimation, Rank regression, reliability, Transformer.

## Acronym

- AIC → Akaike Information Criterion.
- BIC → Bayesian Information Criterion.
- LKV → Likelihood Value.
- MLE → Maximum Likelihood Estimation.
- RRM → Rank Regression Method.

- MTBF → Mean Time Between Failures.
- MTTR → Mean Time to Repair.
- SD → Standard Deviation.
- CB → Confidence Bounds.
- LRB → Likelihood Ratio Confidence Bounds.
- FM → Fisher Matrix Confidence Bounds.
- MED → Median Rank.

## I. Introduction

In this fast-developing world, the demand for electricity is increasing daily. To meet the growing demand for electricity, the electrical systems need to be kept in continuous operation mode. Continuous operation of these systems gradually reduces their performance and results in occurrences of failure among various components. Power transformers are the most critical components of power distribution systems. Failures in transformers (repair, replacement, etc.) result in loss of power and can cause a high cost of maintenance due to their complexity in nature. Therefore, it is important to study the performance of power transformers with a reliability perspective.

Extensive studies have been carried out in reliability analysis for different complex industrial systems. Nabila Al Balushi [X] presented a literature review of various studies dealing with reliability analysis for different types of complex industrial systems. Mirzai et al. [XIII] performed reliability analysis for power transformers operating in Iran. Seyedi et al. [XV] developed a reliability model to determine the optimum routine test and self-checking intervals for power transformer protection systems. Taj and Rizwan [XVII] studied the reliability of a complex industrial system using best-fit distribution for repair/restoration times. Singla et al. [XVI] used a genetic algorithm to optimize the reliability of a degraded system under preventive maintenance. Oliveira Neto et al. [XII] developed a probabilistic model for power transformers fitting the failure times sample and obtained the model parameters employing the Method of Least Squares (MLS) and Maximum Likelihood Estimation (MLE). Vahidi and Tenbohlen [XX] presented a detailed statistical analysis of European substation transformers. Tang et al. [XIX] discussed a reliability model for power transformers with maintenance outage dividing the transformers into two groups of components described by different Markov space state models. The performance of power transformers in Egypt at different voltage levels was discussed by El-Bassiouny et al. [IV]. In this study, the remaining lifetime of power transformers in different subsystems was estimated using different probability distributions, and the results were compared to see the best-fitted distribution. Jagtap et al. [V] performed RAM analysis for a water circulation system used in a thermal power plant employing three approaches namely reliability block diagram, fault tree analysis, and Markov birth-death probabilistic approach. Kumar et al. [VI] analyzed the performance of a computer system under hardware repair, software upgrade, and load recovery using Weibull distribution with different scale and standard shape parameters. Maihulla et al. [VII] proposed Reliability, Availability, Maintainability, and Dependability (RAMD) analysis to estimate the three parameters of Weibull distribution using Maple software.

Cheng et al. [III] considered censoring and truncation problems while proposing a deep learning-based model to evaluate Weibull parameters for power transformers. Wei et al. [XXI] assessed the reliability of a transformer insulating oil using accelerated life testing. Reliability analysis of different industrial systems has been performed by different authors (Padma et al. [XIII]; Taj et al. [XVIII]; Yaqoob Al Rahbi et al. [XXII]).

In this paper, a probabilistic analysis of power transformers is presented considering the failure times data to be right censored. The paper consists of five sections. The introduction is given in the first section. The methodology and material used for the study are discussed in section two. The third section sheds light on the basic concepts of reliability analysis, possible probability distributions for the failure data, and methods of selecting the best-fit distribution. The fourth section presents the results of reliability analysis, distribution fitting, and life data analysis. Section five concludes the paper.

## II. Materials and Methods

The materials used in this paper correspond to the failure data of power transformers collected from a power distribution company located in the Dhofar region of Oman. The company distributes electricity across Dhofar through 44 power substations consisting of 88 power transformers. The distribution network is divided into four zones. Zone 1A is the biggest zone as it covers the central area of Salalah which is the most crowded region in Dhofar. Zone 1B covers the industrial area, while zones 2 and 3 cover the mountain, desert, and coastal regions. In October 2020, zone 1A experienced a sharp rise in temperature leading to a considerable increase in the number of transformer faults. Table 1 provides the number of transformers and the total number of faults in each zone from January 2017 to February 2021.

**Table 1: Zone-wise Number of Transformer Faults**

| Zone | Number of faults | Number of transformers |
|---|---|---|
| Zone 1A | 16 | 17 |
| Zone 1B | 8 | 6 |
| Zone 2 | 2 | 2 |
| Zone 3 | 3 | 2 |

Table 2 shows the distribution of transformers according to the year of manufacturing. More than 60% of the transformers have a life expectancy of less than 10 years. Whereas 10 transformers are seen to have a life expectancy of more than 20 years.

**Table 2: Age of Transformers**

| Year of manufacturing | No of transformers |
|---|---|
| More than 20 years | 10 |
| 10 to 20 years | 23 |
| Less than 10 years | 55 |

The methodology adopted in this paper follows the given sequence of steps:

Step 1: Collect real failure data of transformers from a power distribution company.

Step 2: Apply possible probabilistic models to the data considering it to be right censored.

Step 3: Estimate model parameters using MLE and RRM.

Step 5: Graphically interpret the probability density function, likelihood surface plot, and reliability function.

Step 6: Summarize the life data analysis.

Step 7: Find the reliable life of transformers at each level of reliability.

## III. Theoretical Background

### III.i. Likelihood Value Test (LKV)

LKV computes the value of the log-likelihood function given the parameters of the distribution (Myung [IX]). Suppose we have a random sample $T_1, T_2, T_3, .. T_n$ for which the probability density function of each T is $f(t_i; \theta)$. Then $L(\theta\ )$ is known as the maximum likelihood function of the parameter.

$$L(\theta\ ) = f(t_1; \theta) * f(t_2; \theta) * f(t_3; \theta) * \ldots * f(t_n; \theta) \quad (1)$$

where $\theta$ is the parameter of the probability density function.

### III.ii. Akaike Information Criterion (AIC)

AIC is a Mathematical method used to compare different models and determine the best fit for the data (Akaike [I]). The lower the AIC, the better the model is.

$$AIC = 2k - \ln(\dot{L}) \quad (2)$$

where, k is the number of estimated parameters and L is the likelihood function of the model.

### III.iii. Bayesian Information Criterion (BIC)

BIC works similarly to AIC, but it places more penalty on the model with more parameters (Schwarz [XIV]).

$$BIC = k \ln(n) - 2\ln(\dot{L}) \quad (3)$$

where, k is the number of estimated parameters and $\dot{L}$ is the maximum likelihood function for the model.

### III.iv. Maximum Likelihood Estimation (MLE)

Maximum likelihood estimation is a technique used to estimate the value of the parameter that maximizes the likelihood function (Myung [IX]). Let T represent the time to failure that follows an exponential distribution. For complete data, the log-likelihood function for the exponential distribution is given as:

$$L(\lambda \backslash t_1, t_2, .. t_n) = \prod_{i=1}^{n} f(t_i; \lambda) \quad (4)$$

where; $\lambda$ is the parameter to be estimated.

Taking the natural log of the function, the log-likelihood has the form:

$$\ln(L) = \sum_{k=0}^{n} f(t_i; \lambda) \tag{5}$$

Taking the derivative concerning $\lambda$ and setting it equal to zero, gives:

$$\frac{\partial \ln(L)}{\partial \lambda} = \frac{n}{\lambda} - \sum_{k=0}^{n} t_i = 0 \tag{6}$$

Solving for $\lambda$, we get:

$$\hat{\lambda} = \frac{n}{\sum_{k=0}^{n} t_i} \tag{7}$$

For data sets containing suspended data or right censored data, the process of estimation is different. The likelihood function includes an additional term for suspensions.

$$L(\lambda \backslash t_1, t_2, .. t_n) = \prod_{i=1}^{n} f(t_i; \lambda) . \prod_{j=1}^{m} (1 - F(s_j; \lambda)) \tag{8}$$

where, m is the number of suspended data points, $s_j$ is the $j^{th}$ suspension and $F(s_j; \lambda)$ is the cumulative distribution function.

**Rank Regression Method (RRM)**

The rank regression method involves applying the rank transformation to the response and predictor variables and then fitting a linear model to the rank using the least squares method (Chen et al. [II]).

## IV. Results and Discussions

This section presents the results obtained following the methodology discussed in section 3. The power distribution company under study has a total of 88 transformers divided into four zones (1A, 1B, 2, 3).

Tables 3 and 4 present year-wise and zone-wise summary of the system performance respectively. A yearly increase in the system availability can be observed, being highest in the year 2021, whereas the failure rate decreases every year. It can also be observed that zone 2 has the lowest availability with the least operating time of 416 hours, whereas all zones have almost the same reliability of about 99%.

**Table 3: Yearly MTBF, MTTR, Availability, and Reliability of the Transformers**

| Year | No. Of failures | Outage Time | Operating time | MTBF | MTTR | Reliability | Availability | Failure Rate |
|---|---|---|---|---|---|---|---|---|
| 2017 | 12 | 389.96 | 1194.04 | 99.5 | 32.5 | 0.99 | 0.7538 | 0.0100 |
| 2018 | 9 | 428.93 | 1371.02 | 152.3 | 47.7 | 0.993 | 0.7617 | 0.006 |
| 2019 | 2 | 397.21 | 1450.79 | 725.4 | 199 | 0.9986 | 0.7850 | 0.0013 |
| 2020 | 2 | 436.8 | 1459.2 | 729.6 | 218 | 0.998 | 0.7696 | 0.0013 |
| 2021 | 4 | 414.86 | 1697.14 | 424.3 | 104 | 0.9976 | 0.8035 | 0.0023 |

**Table 4: Zonal MTBF, MTTR, Availability, and Reliability of the Transformers**

| Zone | No. of Failures | Outage Time | Operating Time | MTBF | MTTR | Reliability | Availability | Failure Rate |
|---|---|---|---|---|---|---|---|---|
| 1A | 16 | 1199 | 4105 | 257 | 74.9 | 0.9961 | 0.7739 | 0.0038 |
| 1B | 8 | 523 | 1757 | 220 | 65.4 | 0.9954 | 0.7706 | 0.0045 |
| 2 | 2 | 127 | 416 | 208 | 63.6 | 0.9952 | 0.7575 | 0.0048 |
| 3 | 3 | 208 | 777 | 259 | 69.2 | 0.9961 | 0.7891 | 0.0038 |

The collected data are fitted to 11 possible distributions and ranked according to the lowest value of LKV, AIC, and BIC. The results of the distribution fitting are displayed in Table 5. It clearly shows that the best-fitted distribution for the given failure data is an exponential distribution with 2 parameters.

**Table 5: Results of Distribution Fitting (all)**

| Distribution | Rank | LKV | AIC | BIC |
|---|---|---|---|---|
| 2P-Exponential | 1 | -418.4 | 843.54 | 840.81 |
| Gamma | 2 | -422.84 | 852.41 | 849.67 |
| Lognormal | 3 | -422.86 | 852.46 | 849.72 |
| Loglogistic | 4 | -422.9 | 852.53 | 849.8 |
| 2P-Weibull | 5 | -423.03 | 852.79 | 850.06 |
| G-Gamma | 6 | -422.43 | 854.96 | 850.86 |
| 3P-Weibull | 7 | -422.63 | 855.36 | 851.25 |
| Normal | 8 | -427.11 | 860.96 | 858.22 |
| Logistic | 9 | -430.52 | 867.78 | 865.05 |
| 1P-Exponential | 10 | -435.68 | 874.72 | 873.36 |
| Gumbel | 11 | -435.6 | 877.93 | 875.2 |

The parameter values are estimated using MLE and RRM. Both methods reveal that there is no significant difference in the parameter estimate. The summary of the analysis after fitting the exponential model is presented in Table 6. The estimated parameter values for the model are $\lambda$=1.5862-06 and $\gamma$=43800 hours. This shows that the failures occur after 43800 hours of operation with a failure rate of 1.5862-06 per hour.

**Table 6: Analysis of Distribution Fitting (exponential-2P)**

| Analysis | MLE | RRM |
|---|---|---|
| CB | LRB | FM |
| Ranking | MED | MED |
| Mean Time (hrs) | 630417.93 | 653157.93 |
| $\lambda$ | 1.5862-06 | 1.5310-06 |
| Gamma (hrs) | 43800 | 43800 |
| LKV | -418.48 | -418.42 |
| Rho | -0.95 | -0.95 |

Fig. 1. presents the probability density function of the data over time which allows us to visualize the distribution of the data set.

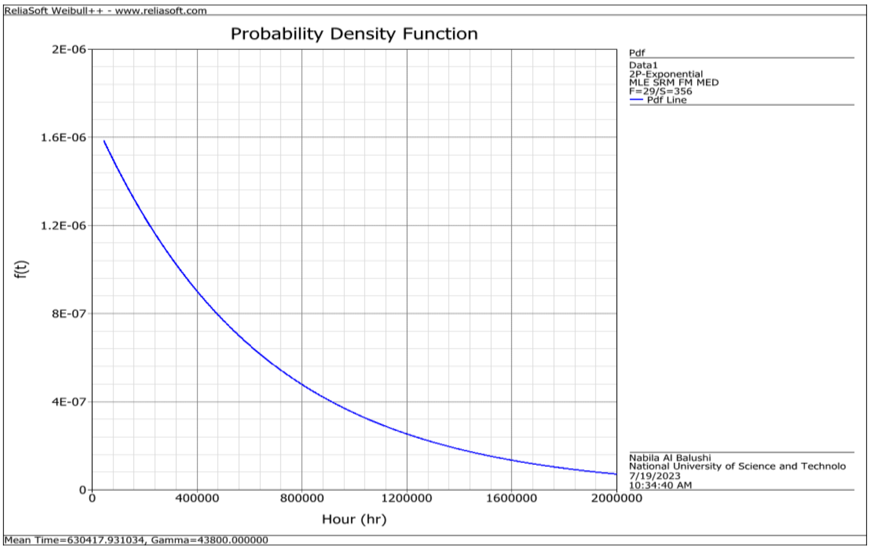


**Fig. 1.** Probability density function

Fig. 2. shows the reliability values over time capturing the behavior of system failure. The data points are seen clustered above the reliability of 0.8, except for two observations with reliability between 0.6 and 0.8. These two observations could be considered outliers and excluded from the analysis.

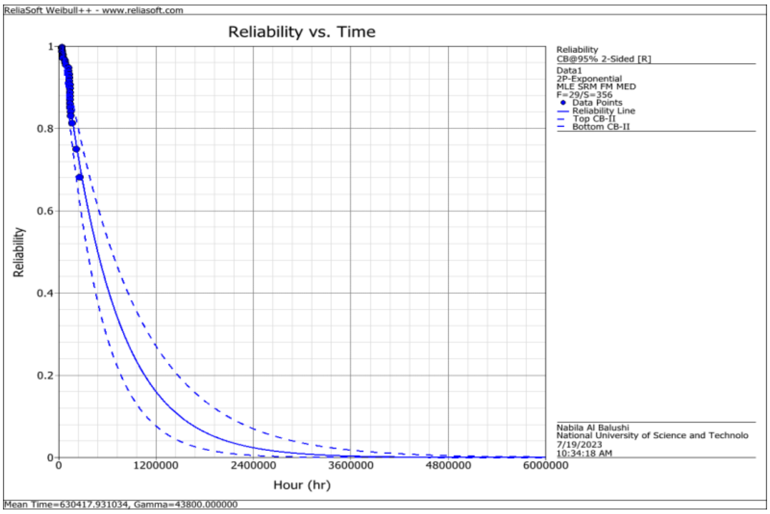


**Fig. 2.** Reliability with respect to time

A surface plot of the likelihood function against possible values of the parameters is shown in Fig. 3. It can be seen that the maximum values of the likelihood function occur at the estimated values of parameters displayed in Table 6.

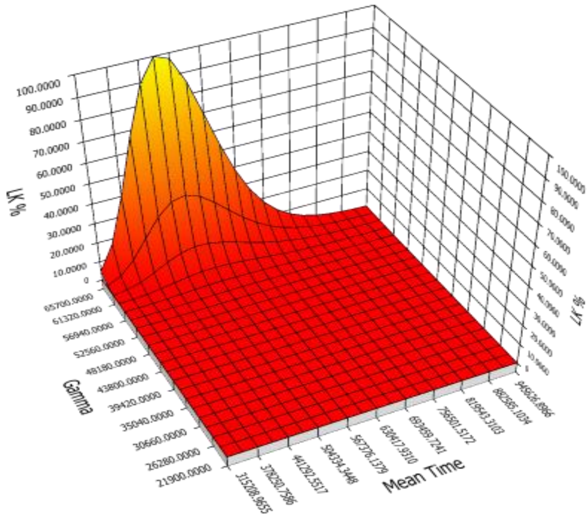


**Fig. 3.** Likelihood surface plot

Table 7 presents a summary of life data analysis for the power transformer system. The following can be interpreted from Table 7:

- There is a 98% chance of successful system operation after 55000 hours of working. There is only a 0.0317% chance that the system will fail after 200 hours given that the system was already in operation for 50000 hours.
- The average expected time of system operation before failure is 56536 hours.
- The mean remaining lifetime for the power transformers is 630417 hours. The 95% confidence bound is (449143.10, 884855.55).
- There is a 10% chance that the transformers will fail before 110221.16 hours of operation.

**Table 7: Life Data Analysis**

| | Estimate | Lower Bound (0.025) | Upper Bound (0.975) |
|---|---|---|---|
| Reliability R (t = 55000 hrs) | 0.982391 | 0.975372 | 0.987422 |
| Probability of failure | 0.017609 | 0.012578 | 0.024628 |
| Conditional reliability R (t1 = 200hrs \| t2 = 50000 hrs) | 0.999683 | 0.999555 | 0.999774 |
| Conditional probability of failure Q (t1=200hrs \| t2=50000 hrs) | 0.000317 | 0.000226 | 0.000445 |
| Reliable life (hrs) | 56536.15 | 52873.90 | 61676.48 |
| BX% life (hrs) | 110221.15 | 91121.95 | 137028.84 |
| Mean life (hrs) | 674217.93 | 492943.10 | 928655.55 |
| Mean remaining life (hrs) | 630417.93 | 449143.10 | 884855.55 |
| Failure rate (/hr) | 0.000002 | 0.000001 | 0.000002 |
| MTBF | 630417.93 | 449143.10 | 884855.55 |

From Table 8, it can be observed that the best-fitted distribution for all zones is exponential except for the largest zone 1A for which the best-fitted distribution is normal with a mean of 200995.21 hours and SD of 51596.32. Also, zone 3 has the highest failure rate and zone 1B has the lowest failure rate.

**Table 8: Best Fit Distribution (Zone wise)**

| | Zone 1A | Zone 1B | Zone 2 | Zone 3 |
|---|---|---|---|---|
| Distribution | Normal | 2P Exponential | 1P Exponential | 2P Exponential |
| Parameters | Mean = 200995.211<br>SD = 51596.317 | Mean = 761025<br>Gamma = 43800 | Mean = 884760 | Mean = 505160<br>Gamma = 52560 |
| Failure rate | 1.2610-07/hr | 0.000001/hr | 0.000001/hr | 0.00002/hr |

The reliable life of the system, both overall and zonal, is evaluated at different levels of reliability. The results are shown in Table 9. It is observed that an overall system reliability of 95% can be attained if all maintenance tasks are completed before 76136.21 hours.

**Table 9: Reliable Life of the System**

| Reliability Level | 95% | 85% | 75% | 65% | 55% |
|---|---|---|---|---|---|
| Overall System | 76136.21 | 146254.85 | 225159.94 | 315373.27 | 420687.17 |
| Zone 1A | 74859.89 | 142210.89 | 218001.56 | 304654.13 | 405811.22 |
| Zone 1B | 82835.48 | 167480.97 | 262733.25 | 371636.57 | 498768.9 |
| Zone 2 | 45382.25 | 143790.25 | 254529.59 | 381139.49 | 528942.26 |
| Zone 3 | 78471.32 | 134658.06 | 197885.47 | 270174.29 | 354563.33 |

In Table 10, zone wise reliability at different time intervals is presented. The results show that zone 2 has the lowest reliability at various time intervals, making it the most critical zone, this is also supported by the results previously shown in Table 4. As a result, the maintenance team must take significant steps to improve the reliability of zone 2.

**Table 10: Reliability at Different Time Intervals**

| Time (hrs) | Zone 1A | Zone 1B | Zone 2 | Zone 3 |
|---|---|---|---|---|
| 50000 | 0.98 | 0.99 | 0.94 | 0.99 |
| 55000 | 0.98 | 0.98 | 0.94 | 0.99 |
| 60000 | 0.97 | 0.97 | 0.93 | 0.98 |
| 65000 | 0.96 | 0.97 | 0.92 | 0.97 |

## V. Conclusion and Future Work

The methodology of identifying the best probabilistic model which fits the failure times data of power transformers is discussed in this paper. Significant emphasis is also laid on the estimation of various reliability parameters for the transformers.

The exponential distribution with two parameters is found to be the best-fitted distribution for the failure times data of transformers. The parameters of the model are estimated using the Maximum Likelihood Estimation and Rank Regression Method. The scale and shape parameters are estimated to be 1.5862-06 and 43800 hours respectively. This indicates that the failures started to occur after 43800 hours of operation with a failure rate of 1.5862-06 per hour. The study supports the maintenance team in identifying the optimum time for performing various maintenance tasks. The results reveal that the mean system operating time before failure is 653157.9 hours with a reliability of 98% after 55000 hours of working and a reliable life of 76136.21 hours with 95% reliability. The outcomes of this paper are well supported by the deductions made in Nabila Al Balushi et al. [XI] where the reliability analysis of power transformers was conducted using Markovian and regenerative processes. However, the zonal and yearly performance of the system was not evaluated by the authors. Thus, in this paper, the yearly and zonal performance of the transformers is also considered. The results reveal that zone 2, which has only 6 transformers is the most critical one. The system availability at zone 2 is the lowest, making the maintenance of transformers in this zone mandatory before 45382.25 hours. Zone 3, which covers the mountainous and coastal regions is found to have the highest failure rate as compared to other zones. Comparing the yearly system availability, it is noted to be highest in the year 2021. The results reveal generally high values of system reliability, this can be credited to the ongoing practice of keeping backup transformers in each substation which facilitates load shifting and thus prevents interruptions.

Power transformers in the Dhofar region of Oman are distributed into four zones, 1A and 1B cover the highly populated region, and 2 and 3 cover the mountains, desert, and coastal region.

The Dhofar region is known to have a diverse atmosphere. Thus, it is highly recommended to note the weather conditions whenever a fault occurs, this will help in understanding the effect of weather on the power distribution system. If so, it will be possible to conduct a detailed statistical analysis to see the effect of environmental factors on the performance of transformers in each zone.

During the Khareef season (June to September), Dhofar witnesses rainy and humid conditions, and a huge number of tourists visit the region leading to a significant increase in load on the transformers. Hence, as a future direction, a study can be conducted to examine the performance of transformers exclusively during the Khareef season.

Further, integration of deep learning into transformer fault detection may be explored, possibly leading to a paradigm shift offering higher accuracy, real-time processing, and adaptability to various data types.

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## Conflicts of interest

All authors declare that they have no conflicts of interest.

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