Application of Life Data Analysis for the Reliability Assessment of Numerical Overcurrent Relays

Mohd Iqbal Ridwan¹, Kerk Lee Yen², Aminuddin Musa³, Bahisham Yunus⁴

Abstract—Protective relays are components of a protection system in a power system domain that provides decision making element for correct protection and fault clearing operations. Failure of the protection devices may reduce the integrity and reliability of the power system protection that will impact the overall performance of the power system. Hence it is imperative for power utilities to assess the reliability of protective relays to assure it will perform its intended function without failure. This paper will discuss the application of reliability analysis using statistical method called Life Data Analysis in Tenaga Nasional Berhad (TNB), a government linked power utility company in Malaysia, namely Transmission Division, to assess and evaluate the reliability of numerical overcurrent protective relays from two different manufacturers.

Keywords—Life data analysis, Protective relays, Reliability, Weibull Distribution.

I. INTRODUCTION

Many studies and literatures in the past have shown that the reliability of protective relays can be assessed using statistical methods.

Anderson [1] designed a Reliability Block Diagram for a protection system in a substation and concluded that redundancy plays an important factor in determining the availability of the system. A further work by Anderson and Agarwhal [2] used Markov model to determine the unavailability of protection system. The model assumed both repair and failure rates are constant. A more complicated model using Markov model was developed by Anderson [3]. It modeled the redundancy of the protective relays and suggested an optimal time for the testing of protective devices using the model. Wang [4] improved the Markov model developed by Anderson by establishing the relationship between relay unavailability and optimal testing time.

However, most of the studies above assumed that protective relays follows a constant failure rate, i.e. a fixed number of failures will occur during the useful life period of the protective relays. This assumption however, may not be applicable in real life cases as such assumption does not consider aging factor of the relays, as equipment will start to age the moment they are installed and commissioned in a system. Hence, this paper proposed the application of Life Data Analysis which utilizes the historical failure data to evaluate the reliability of protective relays. In this study, numerical protective relays with overcurrent functions from two manufacturers are analyzed and the results are compared to observe the variation from the engineering judgment which was decided before the study by engineering personnel in TNB.

II. OVERVIEW OF OVERCURRENT PROTECTIVE RELAYS IN TNB

Overcurrent relay can be defined as a relay that operates or picks up when its current exceeds a pre-determined value or setting [11]. Overcurrent relays are not inherently directional, which requires another directional control facility, such as voltage inputs, to determine the direction of the fault [11, 12]. Generally, phase and earth fault overcurrent relays are applied on distribution network which require relay coordination for fault discrimination.

In TNB Transmission Division, overcurrent relays are applied as backup protection for transformer, reactor feeders, bus tie (bus section and bus coupler) and some installation in...
Data Types | Definition
--- | ---
Complete Data | Exact failure time is known and recorded, no surviving equipment
Right Censored Data | Failure time is known for certain equipment while other equipment still functioning in the population
Interval Censored | Failure time is known to be somewhere between inspection period
Left Censored | Failure time is only known before a certain period of time

In this study, the failure data for the overcurrent relays are considered right censored, as the failure time is known through reporting by technical personnel and the internal relay failure (IRF) or self supervision function signal from the relay.

C. Statistical Distribution

Statistical distribution is applied to the analysis to identify which reliability model will fit the behavior of the failure data. Statistical distribution is also defined as probability density function (pdf), as it describes the probability distribution of a stochastic process [16]. In life data analysis, statistical distribution represents the failure behavior of the equipment population through time, and subsequently it is possible to calculate the reliability indices of the equipment [13], such as:

1. Reliability, R(t) : Probability of survival observed by time t
2. Unreliability, F(t) : Probability of failure observed by time t
3. Mean Life: Average time to failure
4. Failure rate: Number of failures per unit time

Table II shows some examples of life distributions that are commonly used in reliability analysis and its pre-defined assumptions [17].

<table>
<thead>
<tr>
<th>Statistical Distributions</th>
<th>Pre-defined Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exponential</td>
<td>Constant failure rate</td>
</tr>
<tr>
<td>Normal</td>
<td>Increasing failure rate</td>
</tr>
<tr>
<td>Weibull</td>
<td>Flexible, i.e. can be increasing, decreasing or constant depending on the data</td>
</tr>
<tr>
<td>Lognormal</td>
<td>Increasing, then decreasing asymptotically to zero</td>
</tr>
</tbody>
</table>

In this study, Weibull Distribution is chosen for life data analysis, considering the fact that it has no predefined assumptions and its behavior is dependent on the failure data.

IV. DATA AND ANALYSIS

As mentioned earlier, the main objectives of this study are:
1. To assess the reliability of numerical overcurrent relays between two manufacturers.
2. To observe and compare the results of engineering judgment based on technical evaluations by engineers

The assumptions made in performing the life data analysis are:

1. The numerical overcurrent relays are independent and identically distributed
2. The failure data are right censored
3. The numerical overcurrent relays are non-repairable, i.e. it will be replaced when failed
4. The failure modes are generalized into two, which are failure or suspension, i.e. surviving

This section will discuss on the source of data and the characteristics of Weibull Distribution used in the life data analysis

A. Source of Data

The data for the analysis were obtained from TNB databases such as Protection Operations Settings (CAPE), Centralized Tripping Information System (CTIS) and Operation Planning Unit Database.

Overall, there are a total of 4,873 units of overcurrent relays installed in TNB as at June 2008. This is inclusive of non-numerical protective relays such as static and electromechanical relays, which will not be discussed in this study.

Manufacturer A has 1,041 units of numerical overcurrent relays installed in TNB. Throughout a 20 year observation, 29 failures have been observed. Engineering judgment made by TNB protection and asset management personnel concluded that these failures were mostly due to the relays were reaching their end of life, which was expected to be around 15 to 20 years.

Manufacturer B has 357 units of numerical overcurrent relays installed in TNB. Throughout a 14 year observation, as the relays from Manufacturer B were introduced in TNB 14 years ago, 22 failures have been observed. Engineering judgment made by TNB protection and asset management personnel concluded that the relays from Manufacturer B suffered from batch problem due to design error which resulted in the relays failed earlier than expected.

The summary of the data used for life data analysis for both manufacturers are described in Table III and IV.

B. Characteristics of Weibull Distribution

The probability density function for a 2 parameter Weibull distribution is given by [13]

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

(1)

where \( t \) is the failure time, \( \beta \) is the shape parameter and \( \eta \) is the scale parameter. The Reliability, \( R(t) \) for a 2 parameter Weibull Life Distribution is defined as [13]

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

(2)

From (2), the Unreliability is given as [13]

### TABLE III

<table>
<thead>
<tr>
<th>Number of Relays</th>
<th>Failure or Suspension</th>
<th>Relay Age (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>1</td>
</tr>
<tr>
<td>32</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>75</td>
<td>S</td>
<td>2</td>
</tr>
<tr>
<td>46</td>
<td>S</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>4</td>
</tr>
<tr>
<td>130</td>
<td>S</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>F</td>
<td>5</td>
</tr>
<tr>
<td>62</td>
<td>S</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>6</td>
</tr>
<tr>
<td>77</td>
<td>S</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>7</td>
</tr>
</tbody>
</table>

### TABLE IV

<table>
<thead>
<tr>
<th>Number of Relays</th>
<th>Failure or Suspension</th>
<th>Relay Age (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>F</td>
<td>1</td>
</tr>
<tr>
<td>54</td>
<td>S</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>2</td>
</tr>
<tr>
<td>43</td>
<td>S</td>
<td>2</td>
</tr>
<tr>
<td>4</td>
<td>F</td>
<td>3</td>
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<td>44</td>
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<td>1</td>
<td>F</td>
<td>6</td>
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<tr>
<td>55</td>
<td>S</td>
<td>6</td>
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<tr>
<td>1</td>
<td>F</td>
<td>7</td>
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<tr>
<td>22</td>
<td>S</td>
<td>7</td>
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<tr>
<td>14</td>
<td>S</td>
<td>8</td>
</tr>
<tr>
<td>10</td>
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<td>9</td>
</tr>
<tr>
<td>14</td>
<td>S</td>
<td>10</td>
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<tr>
<td>1</td>
<td>S</td>
<td>13</td>
</tr>
<tr>
<td>1</td>
<td>S</td>
<td>14</td>
</tr>
</tbody>
</table>

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The shape and scale parameters are estimated using the Maximum Likelihood Estimation (MLE) method because this method is preferred when conducting analysis with censored data. The MLE for right censored data is defined as [13]

\[ L(\theta_1, \ldots, \theta_k | T_1, \ldots, T_R, S_1, \ldots, S_M) = \prod_{i=1}^{R} f(T_i; \theta_1, \theta_2, \ldots, \theta_k) \times \prod_{j=1}^{M} [1 - F(S_j; \theta_1, \theta_2, \ldots, \theta_k)] \]

where \( \theta_1, \theta_2, \ldots, \theta_k \) are the k unknown parameters which need to be estimated from R observed failures at \( T_1, T_2, \ldots, T_R \), and M observed suspensions at \( S_1, S_2, \ldots, S_M \), \( f \) is the probability density function and \( F \) is the Unreliability function.

Statistical confidence bounds also have been added to the calculation to ensure the accuracy of the calculation. The confidence bounds are calculated using Fisher Matrix, which is defined as [13]

\[
\begin{bmatrix}
\text{Var}(\hat{\theta}_i) & \text{Cov}(\hat{\theta}_i, \hat{\theta}_j) \\
\text{Cov}(\hat{\theta}_i, \hat{\theta}_j) & \text{Var}(\hat{\theta}_j)
\end{bmatrix}^{-1}
\begin{bmatrix}
\frac{\partial^2 \Lambda}{\partial \theta_i^2} & \frac{\partial^2 \Lambda}{\partial \theta_i \partial \theta_j} \\
\frac{\partial^2 \Lambda}{\partial \theta_j \partial \theta_i} & \frac{\partial^2 \Lambda}{\partial \theta_j^2}
\end{bmatrix}
\]

For a 2 parameter Weibull distribution, the mean life is defined as [13]

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

where \( \Gamma() \) refers to Gamma Function.

The failure rate function is given as [13]

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

In this study, the life data analysis was conducted using Weibull++ from ReliaSoft Corporation.

V. RESULTS AND DISCUSSION

This section will discuss the results of life data analysis for the numerical overcurrent relays from Manufacturer A and B and also highlight the interrelationship of the results with the engineering judgment stated earlier.

A. Results for Manufacturer A

From the data in table IV, (1) and (4), shape and scale parameters are calculated and the results are \( \beta = 3.1511 \) and \( \eta = 30.0893 \). Figure 1 shows how the parameters are plotted and maximized in a 3D plot.

By substituting the values of \( \beta \) and \( \eta \) to (2), the probability density function (pdf) is shown in Figure 2.

From (2), it is possible to calculate the reliability of the numerical overcurrent relay by specifying the time together with the confidence bound. Figure 3 describes how the reliability of the relays changes over time.

Given that an expected average life for a numerical relays is 15 years, at year 15, the reliability, \( R(15) \) is 0.8644 at a 90% lower one sided confidence bound. This means that after 15 years in service, there is 86% chance that the relays in the population will survive at 90% confidence level. Conversely, using (3), the Unreliability, or the probability of failure for the relays at 15 years is 14% at 90% confidence level.

From (6), the mean life for relays is calculated and the result is of 22.9665 years at 90% lower one sided confidence bounds. In the other words, 50% of the relays in the population will fail after 23 years in service at a 90% confidence level.
From (7), it is possible to calculate the failure rate of the relays in the population. Figure 4 describes the change failure rate of the relays over time.

From figure 4, it is observed that the failure rate of the relays increases over time. This indicates that the numerical overcurrent relays displayed a certain 'wear-out' characteristics during their life in service over a time period in TNB. This result is *idem quod* the engineering judgment made earlier which stated that the numerical overcurrent relays from Manufacturer A failed because of aging.

**B. Results for Manufacturer B**

The scale and shape parameters for Manufacturer B are $\beta = 1.2881$ and $\eta = 39.4432$. Figure 5 describes the parameters in a 3D plot.

The probability density function for Manufacturer B is described in Figure 6. The difference between this probability density function and the previous pdf for Manufacturer A can be observed where the pdf shape for Manufacturer B is leaned towards the Y axis as compared to the pdf of Manufacturer A in Figure 2.

Reliability is also calculated for Manufacturer B. Using the expected average numerical relay life of 15 years, the result yields that $R(15) = 0.6183$ at a 90% lower one sided confidence bound. This means that after 15 years in service, there is 62% chance that the relays in the population will survive at 90% confidence level, which is lower than Manufacturer A. The reliability plot is shown in Figure 7.
The mean life for Manufacturer B yields 19.7031 years at 90% confidence level.

The failure rate is also plotted and observed for Manufacturer B and is shown on Figure 8.

Unlike Manufacturer A, it is observed that the failure rate for Manufacturer B increases drastically during the early age of the relays. This indicates that the failures for the overcurrent relays from Manufacturer B are concentrated on their early age. The value of the shape parameter, which is $\beta=1.2881$, is approximately 1, which is a special case for Weibull distribution that when $\beta=1$, the distribution becomes an exponential distribution [13]. Although the result proved that engineering judgment was true by stating early failures, further analysis need to be conducted by revising the failure data.

C. Limitations of Life Data Analysis in the study

In this study, only two failure modes are defined for the relays, which are ‘failed’ and ‘not failed’ for the reliability assessment. This assumption can be argued in the sense that the numerical relays will have other failure modes such as CPU failure, power supply card failure, software failure and human error. These failure modes can be analyzed separately by detailing the analysis. This can be performed by categorizing the numerical relays that have failed because of each failure mode, and then subsequently perform a life data analysis to calculate the reliability indices for each of the mode. Failure modes that have the highest contribution to the failure of the relays can be identified.

VI. POSSIBLE APPLICATIONS OF LIFE DATA ANALYSIS

In spite of the limitations mentioned earlier, some possible applications using Life Data Analysis has been identified, such as,

1. Spare parts determination of the relays for maintenance purposes
2. Reliability indices as benchmarks
3. Determination of optimal warranty period for protective relays

A. Spare parts determination of the relays for maintenance purposes

By applying statistical distribution to a set of failure data, as per life data analysis, it is possible to determine percentage of the equipment in the population which will fail after certain period of time. This is called B(X) life, and this can be achieved by performing a linearization on the pdf function from the statistical distribution [13]. By applying this method, it is possible for power utilities to prepare adequate spare relays based on the prediction provided.

B. Reliability indices as benchmarks

Although protective relay manufacturers will declare the reliability of their equipment, usually in terms of Mean Time before Failure (MTBF), the actual reliability figure of the relays may vary depending on the relay installation and operation over period of time. The reliability indices calculated using life data analysis will provide more accurate or realistic information as it uses the historical failure data of the relays. This could be used as a benchmark to set a reliability figure baseline that can be used as a guide for manufacturers.

C. Determination of optimal warranty period for protective relays

Based on earlier analyses, some numerical overcurrent protective relays failed earlier than the expected life. The reliability indices from life data analysis may be used by the utility to determine and specify the optimal warranty period and expected average life required for protective relays.

VII. CONCLUSION

Even though certain assumptions are required in carrying out the study, life data analysis is able to provide the information on the reliability indices such as reliability, unreliability, mean time to failure and failure rate. These assumptions can be minimized by applying qualitative analysis such as FMEA to classify the failure modes of the relays and by conducting correct data mining activity to obtain the failure data of the relays.

Life data analysis can also be applied in various domains in TNB to analyze equipment such as switchgear, transformers, cables and other substation equipment. With adequate and credible equipment historical data, the application of life data analysis will definitely enhance the operations in the company which will lead to a positive impact, technically and economically.

VIII. FURTHER WORKS

Further clarification of the failure data needed to be conducted to ensure the ‘reliability’ of the data itself. This can be performed through qualitative process such as interviews and discussions with a wider number of technical personnel who are familiar with the protective relays. As mentioned earlier, life data analysis could be enhanced by analyzing the failure modes that had caused failures to the relays. The main challenge is to identify, collect and categorize the data correspond to each failure modes. Furthermore, as protective relays are a part of a power system protection, it is possible to...
use the parameters of the statistical distribution calculated in life data analysis as an input to calculate power system protection availability. This can be done using Reliability Block Diagram (RBD) methodology together with a random number generator [18].

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REFERENCES