World Academy of Science, Engineering and Technology
International Journal of Electrical and Computer Engineering
Vol:4, No:12, 2010

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

Mohd Iqbal Ridwan[1], Kerk Lee Yen[2], Aminuddin Musa[3], Bahisham Yunus[4]

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf

***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.

De Siqueira [5] describes Markov model using Kolmogorov equations to determine reliability indices for Brazilian electric utility. Kameda [6] also implemented Markov model to assess the reliability of protection system in Japan and emphasized the necessity of self supervision functions inside protective relays.

Hussain [7] applied general probability theory to obtain the reliability indices for protective relays in Commonwealth Edison Company. Ding [8] used MIL-HDBK-217E model, fault tree diagram and state space diagram to calculate failure rate and the impact the economic loss using reliability economic index. Ward [9] used Bellcore calculation method and fault tree diagram to describe the interrelationship between protective device dependability and security. Crossley [10] applied event tree diagram as functional models, hardware model and hardware/function interface to identify preferred function integration scenario with maximum reliability of substation protection and control system.

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

[1] TNB Research Sdn Bhd, No.1 Lorong Ayer Hitam Kawasan Insitusi Penyelidikan 43000 Kajang Selangor Malaysia (phone: 603-8922-5121; fax: 603-8926-8829; e-mail: miqbal.ridwan@tnbr.com.my).

[2] Asset Management Department, TNB Transmission Divison, 3rd Floor Transmission Building 129 Jalan Bangsar 59200 Kuala Lumpur Malaysia (e-mail: kerkly@tnb.com.my).

[3] Engineering Department, TNB Transmission Division 4th Floor Lobby 2 Crystal Plaza Jalan 51A/223 46100 Petaling Jaya Selangor Malaysia (e-mail: aminuddinmu@tnb.com.my).

[4] Electrical Power Engineering Department, Universiti Tenaga Nasional Putrajaya Campus Km 7 Jalan Kajang-Puchong 43009 Kajang Selangor Malaysia (e-mail: bahisham@uniten.edu.my)

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf

line and cable feeders. The types of overcurrent relays that are used in these installations are:

1. Inverse Definite Minimum Time (IDMT) Overcurrent relay for phase fault
2. IDMT Overcurrent relay for phase and earth fault
3. Directional IDMT Overcurrent

III. OVERVIEW OF LIFE DATA ANALYSIS

Life data analysis is a process to make predictions about the life of all equipment in a population by assuming a statistical distribution to life data from a representative sample of units [13]. The term life data refers to the measurements of the lifetime of the equipment, whether in hours, years or cycles. Before applying life data analysis, there are a few important factors that need to be taken into considerations, such as:

1. Determination of repairable or non-repairable
2. Data types, i.e. complete data or censored data
3. Statistical distribution for calculating reliability indices

A. Determination of repairable or non-repairable

The determination of repairable or non-repairable for equipment will affect the types of reliability indices and accuracy of the results from the analysis [14]. Non-repairable type can be defined as equipment which serve as micro components of a device or system. Non-repairable type equipment, also as the name implies, are the equipment that cannot be repaired when failed and has to be replaced with a new one [14]. Examples of non-repairable type equipment are electronic circuit board, optical mouse, LCD monitor, automobile tires, etc. For repairable type equipment, it can be defined as equipment where the functionalities can be restored in the event of failure [14]. Repairable type equipment also consist of multiple sub-devices or sub-systems in one single entity [14]. Examples of repairable type equipment are cars, airplane, air-conditioning system, etc.

Life Data Analysis only deals with one lifetime of the equipment. Therefore, it is not applicable to equipment that are considered as repairable. In this study, numerical overcurrent relays are assumed to be non-repairable. This assumption was derived from discussions with protection personnel in TNB, which concluded that in general, numerical overcurrent protective relays will be replaced with a new one once failed.

B. Data Types

Another important factor in life data analysis is the type of data that are used for the analysis. This is because life data analysis considers the failure time of the equipment, but at the same time there are equipment that are still functioning at the observed failure time. These surviving equipment are called suspensions [15]. Also, there are situations when the exact failure time of the equipment is unknown, due to failure between inspection periods or failure of detecting equipment. These data are called censored data [15]. Table I describes the type of data that are taken into considerations when performing life data analysis.

TABLE I
TYPES OF DATA

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 is 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 II
TYPES OF STATISTICAL DISTRIBUTION AND ITS PRE-DEFINED ASSUMPTIONS

Statistical Distributions	**Pre-defined Assumptions**
Exponential	Constant failure rate
Normal	Increasing failure rate
Weibull	Flexible, i.e. can be increasing, decreasing or constant depending on the data
Lognormal	Increasing, then decreasing asymptotically to zero

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

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf

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.

TABLE III
DATA OF MANUFACTURER A OVERCURRENT RELAY

Number of Relays	Failure or Suspension	Relay Age (year)
1	F	1
32	S	1
75	S	2
46	S	3
1	F	4
130	S	4
1	F	5
62	S	5
2	F	6
77	S	6
2	F	7
45	S	7
3	F	8
69	S	8
2	F	9
96	S	9
3	F	10
128	S	10
5	F	11
49	S	11
6	F	12
60	S	12
1	F	13
98	S	13
1	F	14
20	S	14
3	S	15
1	F	16
3	S	16
2	S	17
4	S	18
6	S	19
7	S	20

TABLE IV
DATA OF MANUFACTURER B OVERCURRENT RELAY

Number of Relays	Failure or Suspension	Relay Age (year)
6	F	1
54	S	1
3	F	2
43	S	2
4	F	3
44	S	3
3	F	4
39	S	4
4	F	5
38	S	5
1	F	6
55	S	6
1	F	7
22	S	7
14	S	8
10	S	9
14	S	10
1	S	13
1	S	14

B. *Characteristics of Weibull Distribution*

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

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

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

$$R(t)=e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{2}$$

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

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (3)$$

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]

$$L(\theta_1,\ldots,\theta_k \mid T_1,\ldots,T_R,S_1,\ldots,S_M) = \prod_{i=1}^{R} f(T_i;\theta_1,\theta_2,\ldots,\theta_k) \bullet \prod_{j=1}^{M}[1 - F(S_j;\theta_1,\theta_2,\ldots,\theta_k)] \quad (4)$$

where θ_1, θ_2,..., θ_k are the k unknown parameters which need to be estimated from R observed failures at T_1, T_2 ... T_R, and M observed suspensions at S_1, S_2 ... 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]

$$\begin{bmatrix} \hat{Var}(\hat{\theta}_1) & \hat{Cov}(\hat{\theta}_1,\hat{\theta}_2) \\ \hat{Cov}(\hat{\theta}_1,\hat{\theta}_2) & \hat{Var}(\hat{\theta}_2) \end{bmatrix} = \begin{bmatrix} -\dfrac{\partial^2 \Lambda}{\partial \theta_1^2} & -\dfrac{\partial^2 \Lambda}{\partial \theta_1 \partial \theta_2} \\ -\dfrac{\partial^2 \Lambda}{\partial \theta_2 \partial \theta_1} & -\dfrac{\partial^2 \Lambda}{\partial \theta_2^2} \end{bmatrix}^{-1} \quad (5)$$

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

$$\overline{T} = \eta \bullet \Gamma\left(\frac{1}{\beta} + 1\right) \quad (6)$$

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

The failure rate function is given as [13]

$$\lambda(t) = \frac{f(t)}{R(t)} = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} \quad (7)$$

In this study, the life data analysis was conducted using Weibull++ ^{TM} 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 β =**3.1511** and η =**30.0893**. Figure 1 shows how the parameters are plotted and maximized in a 3D plot.

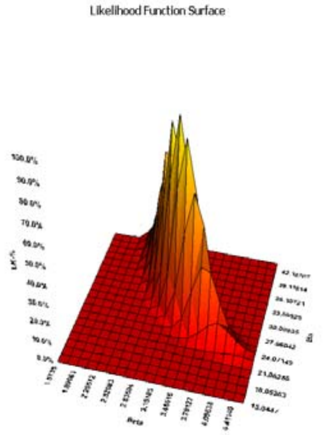

Fig. 1 3D plot for β and η

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

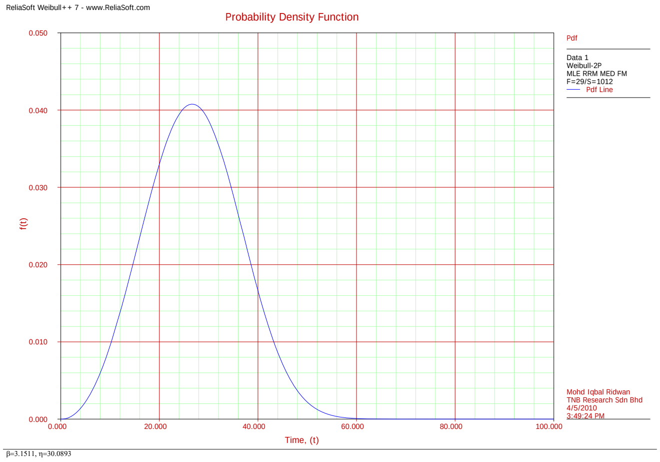

Fig. 2 Pdf plot for Manufacturer A

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.

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf

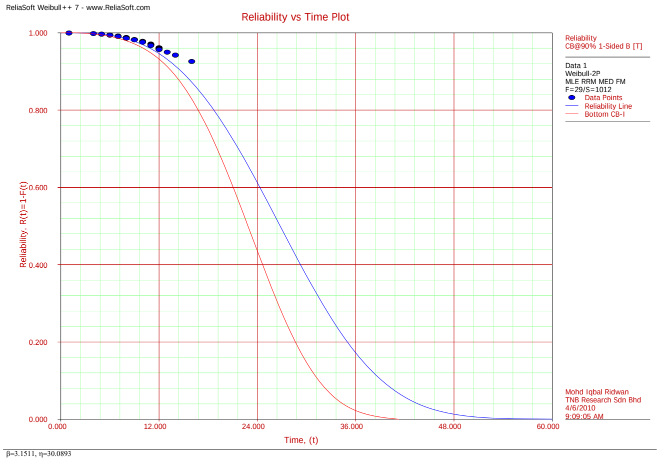

Fig. 3 Reliability vs. Time plot for Manufacturer A

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.

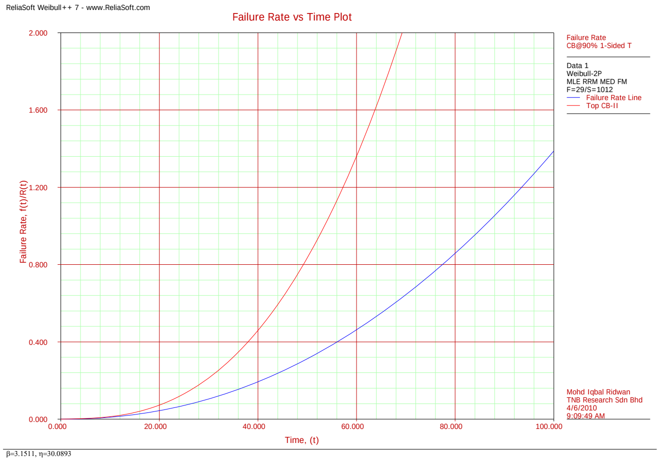

Fig. 4 Failure rate vs. Time

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 β =**1.2881** and η =**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.

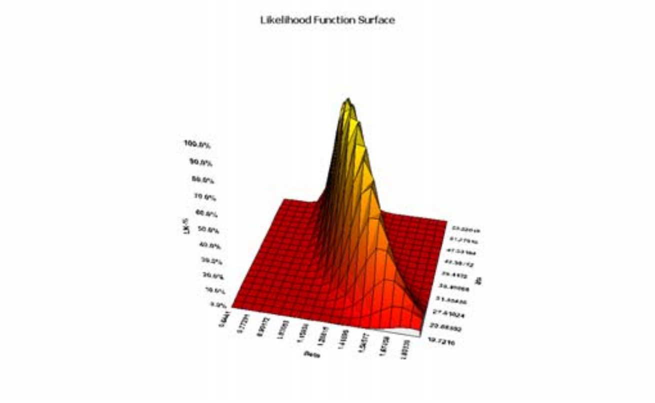

Fig. 5 3D plot for β and η

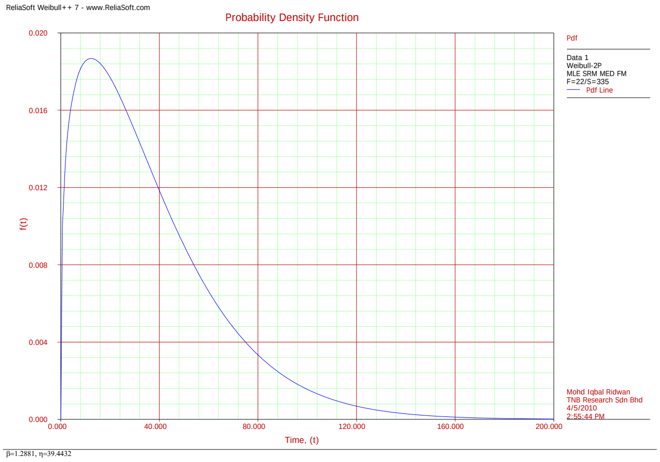

Fig. 6 Pdf plot for Manufacturer B

Reliability is also calculated for Manufacturer B. Using the expected average numerical relay life of 15 years, the result yields that R (15) is **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.

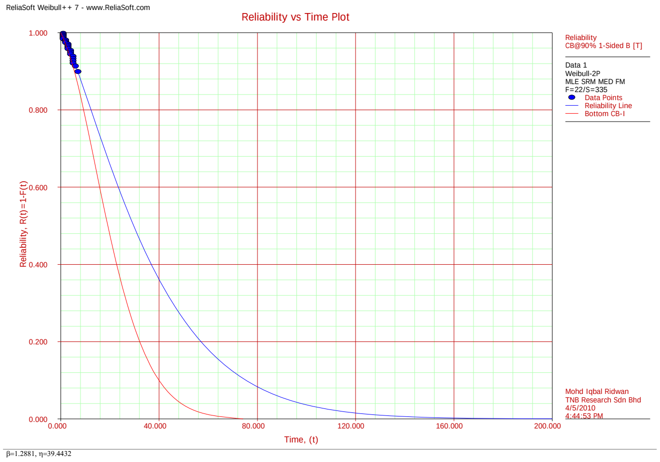

Fig. 7 Reliability vs. time plot for Manufacturer B

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf

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.

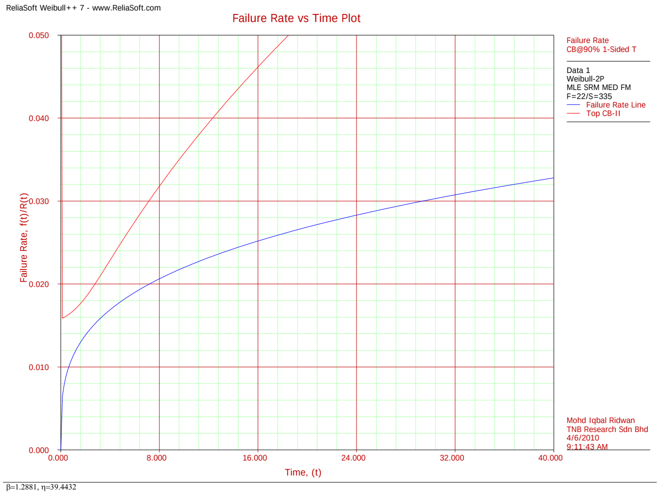

Fig. 8 Failure rate vs. Time

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 β =1.2881 is approximately 1, which is a special case for Weibull distribution that when β =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].

ACKNOWLEDGEMENT

The authors would to thank the Asset Management Department, TNB Transmission Division for co-operation in providing the failure data for the protective relays. The authors also would like to thank protection specialist group and management of Engineering Department, TNB Transmission Division, and the management of TNB Research Sdn Bhd for their continuous support in our research for this paper. Weibull++ ^{TM} is the trademark of Reliasoft Corporation.

REFERENCES

[1] P.M. Anderson, "Reliability Modeling of Protective Systems", IEEE Transaction on Power Apparatus and Systems, Vol. PAS-103, No. 8, August 1984.

[2] P.M. Anderson, S.K. Agarwhal, "An Improved Model of Protective System-Reliability", IEEE Transactions On Reliability, vol. 41, no. 3, September 1992.

[3] P.M. Anderson et. al. "An Improved Reliability Model for Redundant Protective Systems-Markov Models", IEEE Transactions on Power Systems, Vol. 12, No. 2, May 1997.

[4] Qingliang Wang "Reliability Analysis of Protective Relays in Low Voltage Distribution Network" IEEE 2006.

[5] I. Patriota De Siqueira, "Reliability of Protective Apparatus and its Impact on Power System Performance", CIGRE 1996: 34-201.

[6] H. Kameda, K. Yamashita "Reliability Analysis for Protection Relays" 16th Power System Computation Conference, July 14-18, 2000 Glasgow, Scotland.

[7] B. Hussain *et al.* "Transmission System Protection: A Reliability Study" IEEE 1996.

[8] Ding Mao Sheng et al. "Reliability Analysis of Digital Relay", IEE 2004.

[9] S. Ward et al. "Improving Reliability for Power System Protection", 58th Annual Protective Relay Conference Atlanta, GA April 28 - 30, 2004.

[10] Peter A. Crossley et al. "How substation protection and control systems reliability can be enhanced by functional integration" IEEE 2004.

[11] P. M. Anderson "Power System Protection" IEEE Press 1999, pp. 56-57.

[12] AREVA T&D Automation & Information System "Network Protection & Automation Guide" © AREVA 2005, pp 133.

[13] Life Data Analysis Reference, ReliaSoft Publishing, © 1992-2008

[14] Margaret S. Elliot, "Knowledge-Based Systems for Reliability Analysis" IEEE 1990 Proceedings Annual Reliability And Maintainability Symposium

[15] E.E. Lewis, "Introduction to Reliability Engineering", John Wiley & Sons, Inc., Hoboken, New Jersey, 1994, pp 215-221

[16] Donald W. Benbow and Hugh W. Broome "The Certified Reliability Handbook", American Society of Quality, Quality Press, Milwaukee, 2009, pp. 53-56

[17] Marvin Rausand and Arnjolt Hoyland, "System Reliability Theory: Models and Statistical Methods" John Wiley & Sons, Inc., Hoboken, New Jersey, 2004, pp 18-21

[18] Adamantios Mettas, Marios Savva, "System reliability analysis: the advantages of using analytical methods to analyze non-repairable systems" IEEE 2001 Proceedings Annual Reliability And Maintainability Symposium," Philadelphia, Pennsylvania, USA, January 22-25, 2001

Open Science Index, Electrical and Computer Engineering Vol:4, No:12, 2010 publications.waset.org/3496.pdf