Transmission Line Fault Clearing System Reliability Assessment: Application of Life Data Analysis with Weibull Distribution and Reliability Block Diagram

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Abstract— **High voltage transmission lines are essential assets to electric utility companies as these lines transmit electricity generated by power stations to various regions throughout the country. Being exposed to the surrounding environments, transmission lines are susceptible to atmospheric conditions such as lightning strikes and flora and fauna encroachments. These conditions are called faults. Faults on transmission lines may cause disruption of electricity supply which will affect the overall power system and lead to a wide scale blackout. Therefore, fault clearing system is deployed to minimize the impact of the faults to the power system by disconnecting and isolating the affected transmission lines specifically. One of the main devices in fault clearing system are the protective relays, which serve as the "brain" to provide the decision making element for correct protection and fault clearing operations. Without protective relays, fault clearing system is rendered useless. Hence, it is imperative for power utilities, such as Tenaga Nasional Berhad (TNB), which is an electric utility company in Malaysia, to assess the reliability of the protective relays. In this study, a statistical method called Life Data Analysis using Weibull Distribution is applied to assess the reliability of the protective relays. Furthermore, the fault clearing system is modeled using Reliability Block Diagram to simulate the availability of the system and derive reliability indices which will assist TNB in managing the fault clearing system.**

Index Terms-***Availability, Fault Clearing System, Life Data Analysis, Monte Carlo Simultation, Protective Relays, Reliability, Reliability Block Diagram, Transmission Lines, Weibull Distribution***

I. INTRODUCTION

Transmission lines are vital assets to power utility such as Tenaga Nasional Berhad (TNB) in transmitting electricity generated from power plants to transmission and distribution level substations. These transmission lines are exposed to open environment thus they are vulnerable to faults such as lightning strikes, flora and fauna encroachments and intentional/unintentional human interventions. Such faults could cause the interruption of electricity supply, which may lead to wide area blackouts [1]. Thus, power utilities apply a mechanism called the Fault Clearing System (FCS) in substations to minimize the impact of faults to the transmission lines and power system network. FCS also is applied to protect other substation equipment such as transformers, bus-bar, reactors and capacitor banks.

The philosophy and technology for FCS may differ from one power utility to another. In TNB, a typical FCS consists of multiple power system devices such as protective relays, circuit breaker, current and voltage transformers and 110V DC power supply. For transmission line, tele-protection equipment is included to enable the communication between two FCS in different substations which protecting the same transmission line. Fig. 1 shows the typical FCS design for transmission line protection in TNB.

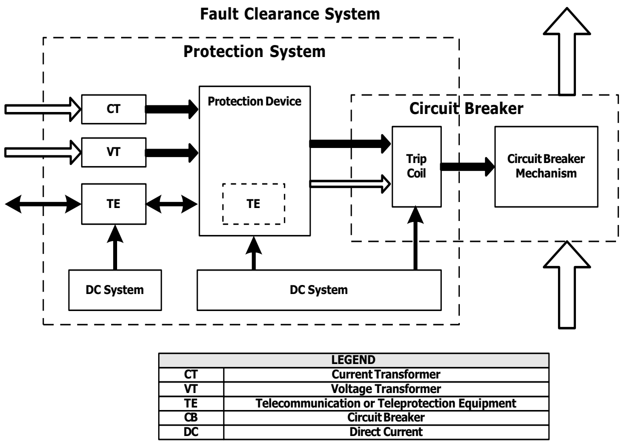

Figure 1. Conceptual Drawing of FCS for Transmission Line in TNB

In the FCS, protective relays provide the decision making element through specific functions using voltage and current as inputs. Protective relays are numerical devices which consist of microprocessors and analog to digital converter [2]. Protective relays digitally sample analog signals, such as voltage and current and convert them into binary signals. These binary signals are passed to microprocessor chips where specific algorithms will perform mathematical calculations to measure the condition of the power system and issue trip signal during fault conditions [2]. Thus, protective relays are the "brain" to determine and ensure a correct FCS operation.

For transmission line, TNB implements main and backup concept for protective relays in FCS. The main protective relay uses current differential (ANSI code 87L) function as the detecting algorithm while the backup protective relay uses distance (ANSI code 21Z). The theories behind the selection

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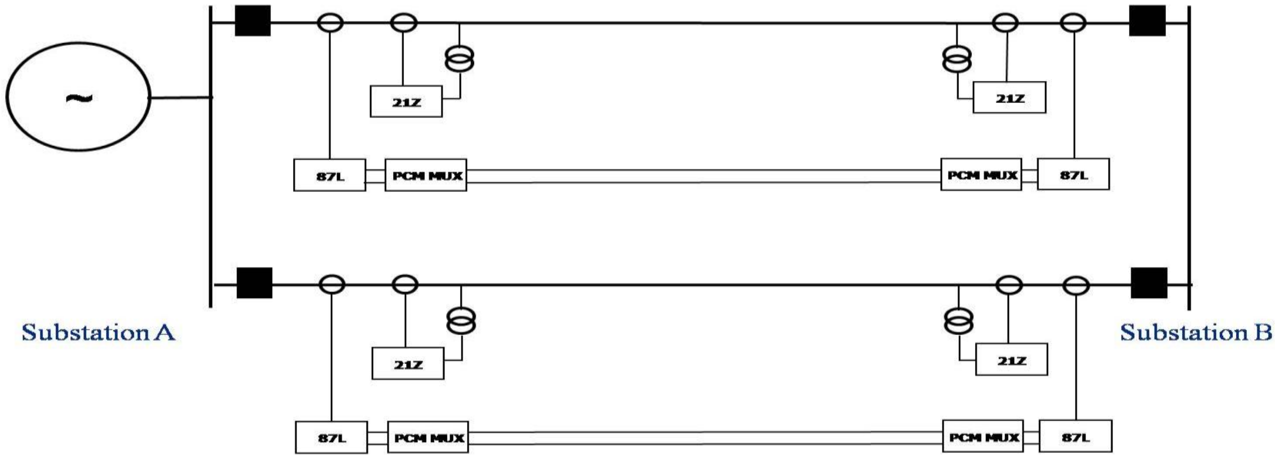

Figure 2. General Configuration of Protective Relays and other FCS Devices

of these functions are beyond the scope of discussion in this paper thus will not be further elaborated. The protective relays in FCS work in pairs, i.e. two protective relays exchange information via the tele-protection equipment and execute the tripping signal to the respective circuit breakers whenever fault occurs at the transmission line. Fig. 2 illustrates the general configuration of protective relays and other devices in FCS which are interconnected between two substations.

Considering the importance of protective relays and the devices in FCS, it is imperative for power utilities such as TNB to assess and evaluate the reliability of these devices. Generally, the reliability of protective relays is defined as dependability and security [1]. Dependability means that the relay should operate when only it is required to operate, while security means that the relay should restrain from operating when it is not required to do so. In this study, the analysis will be focusing on the dependability part of the protective relay reliability.

II. Review of Existing Reliability Assessment Methods for Protective Relays and Fault Clearing System

Various methods and models have been proposed to assess the reliability of protective relays and FCS (or sometimes referred as protection system) by practitioners throughout the years.

Anderson [3] analyzed the need for redundancy in protection systems using Reliability Block Diagram in a substation and concluded that redundancy plays an important factor in determining the availability of the system. Hussain [4] applied a rather deterministic approach by using general probability theory to obtain the reliability indices for protective relays in Commonwealth Edison Company. Ding [5] combined MIL-HDBK-217E model, fault tree diagram and state space diagram to calculate failure rate and evaluate the impact the economic loss using reliability economic index. Ward [6] utilized the techniques in Bellcore calculation method and fault tree diagram to describe the interrelationship between protective device dependability and security. Crossley [7] 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.

Another popular method in analyzing the reliability of protective relays and protection system is by using Markov model. This method describes protective relays and FCS can assume many possible states and the transitions between each state are determined by constant parameters which are independent of time. Anderson and Agarwhal [8] used Markov model to determine the unavailability of FCS. Wang [9] improved the Markov model developed by Anderson by establishing the relationship between relay unavailability and optimal testing time. Singh and Patton [10] designed a Markov model which generalizes the reliability analysis for the protection system and its protected component. Yu and Singh [11] improvise the Markov model in [10] by including failure modes of the protection system in the model. Fig. 3 illustrates the model in [11] which defines λ_{p1} and λ_{p2} as two different protection system failure modes.

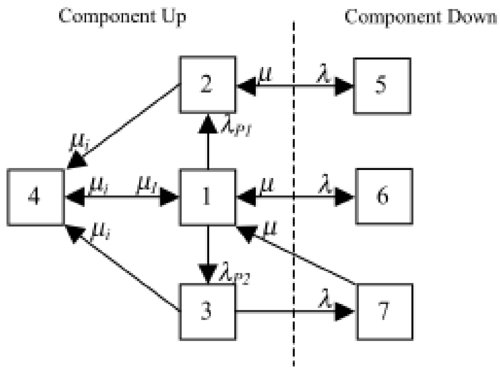

Figure 3. Markov Model by Yu and Singh [11] which considers different failure modes for protection system

De Siqueira [12] describes Markov model using Kolmogorov equations to determine reliability indices for Brazilian electric utility. Kameda [13] implemented Markov model to assess the reliability of FCS in Japan and emphasized the necessity of self-supervision functions of protective relays to achieve high availability. A more detailed application was proposed by Billinton [14] and Seyedi [15] using 15-state Markov model to determine the optimum routine test time and self-supervision internal for protective relays. Fig. 4 illustrates the 15-state Markov model proposed by Seyedi for a transformer protection system.

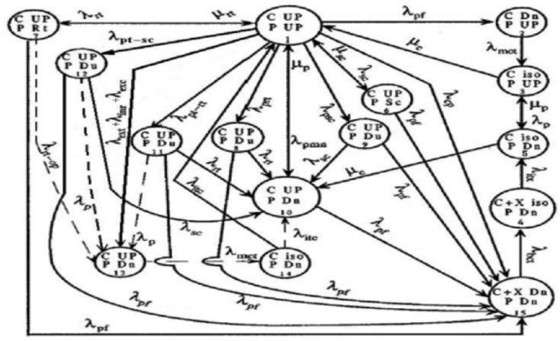

Figure 4. 15-State Markov model by Seyedi [15]

However, it is important to highlight that Markov model assumes that the failure of protective relays is not associated with time, i.e. constant failure rate [1]. Although some practitioners [13, 14, 15] agreed that such assumption is valid for protective relays and FCS, age can be considered as the contributing factor to the failure of most devices and need to be considered when performing reliability analysis and failure predictions [16].

When age factor is taken in to consideration to assess the reliability of protective relays, statistical distribution is suggested as the preferable method in performing the task [17]. Some applications of statistical distribution include Tippachon [18], who applied Weibull distribution to assess the reliability of protective devices in Thailand's distribution network. Kameda [19] also implemented Weibull distribution to investigate the necessity of replacing numerical protective relays by deriving the mean time to failure (MTTF) from the distribution.

This study proposes a method Life Data Analysis which utilizes Weibull distribution and integrates the method with Reliability Block Diagram, along with Monte Carlo simulation to assess the reliability and availability of protective relays and FCS. This approach is considered new in the reliability analysis of protective relays and serves as alternative to the common method using Markov Model.

III. PROPOSED RELIABILITY ASSESSMENT METHOD FOR PROTECTIVE RELAYS AND TRANSMISSION LINE FAULT CLEARING SYSTEM

The Life Data Analysis method which is proposed in this paper does not have a pre-defined assumption such as constant failure rate as mentioned in the above studies which implement Markov Model. This method is solely dependent on the data provided by the user to calculate the parameters needed for reliability analysis. These parameters are then used to design Transmission Line FCS using Reliability Block Diagram. Finally, Monte Carlo simulation is conducted to obtain the reliability indices of Transmission Line FCS. Fig. 5 summarizes the flowchart of the reliability assessment methodologies.

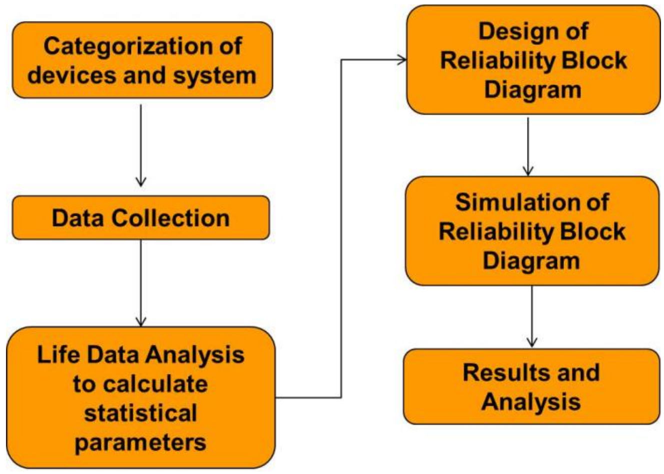

Figure 5. Flowchart of proposed reliability assessment methodologies

A. Categorization of Devices and System

The devices in FCS which are shown in Fig. 1 are categorized into two categories which are non-repairable and repairable. Protective relays, which are the main focus in this paper is assumed as non-repairable device, due to the common practice in TNB where protective relays are replaced once failed. Current and voltage transformers are also assumed as non-repairable to simplify data collection and analysis process. Repairable devices such as tele-protection and circuit breakers are decomposed into small parts, and these parts are assumed as non-repairable. The details of this categorization are shown in Table I.

B. Data Collection

For protective relays, data regarding number of population and number and date of failures are collected for three major protective relays vendors in TNB which are vendor X, Y and Z. Each vendor has different type of protective relay models installed in TNB, thus failure data for each model are also collected. These failure data include protective relays with current differential and distance functions. The summary of the data (excluding date of failure) collected for protective relays are shown in Table II. However, the exact installation date of most protective relays is not available due to lack of record in databases. This limitation requires an assumption to be defined in order to compute to life of protective relays and it is discussed further in Life Data Analysis section below.

For other devices, data are obtained based on discussions with relevant departments and engineering judgment by experienced personnel. Detailed data as per protective relays are not obtained due to unavailability of exact failure date for the devices.

TABLE I. CATEGORIZATION OF FAULT CLEARING SYSTEM COMPONENTS AS REPAIRABLE OR NON-REPAIRABLE

Components	Category	Remarks
Protective Device (relays)	Non-repairable	Current practice in TNB is that protective device will be replaced with a new unit whenever failed. Focus is given to the protective relays where detailed information regarding number of failures and number of surviving units are obtained
Instrument Transformers (Current and Voltage Transformers)	Non-repairable	Instrument Transformers are considered single entity because it will be replaced as a whole when failed
Tele-protection equipment	Repairable	Tele-protection equipment are divided into sub-components which are: 1. Fiber optic 2. PCM module 3. DC power supply 4. SDH module
Circuit Breaker	Repairable	Circuit breaker are divided into subcomponents which are: 1. Solenoid (trip coils) 2. Insulation
Substation DC Power Supply	excluded	Substation DC power supply was excluded for further analysis because of substation DC power supply is a system which requires complex reliability modeling and there are no significant failure records for the components in the system.

TABLE II. SUMMARY OF NUMBER OF POPULATION AND NUMBER OF FAILURES FOR TRANSMISSION LINE NUMERICAL PROTECTIVE RELAYS

Relay Vendor	**X**					**Y**			**Z**		
Relay Model	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**A**	**B**	**C**
No. installed	81	32	28	17	50	13	16	49	33	35	16
No. failures	8	13	15	13	1	0	0	9	6	1	3
Total Population in TNB	296	101	274	126	151	43	59	267	164	82	185

C. *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 [20]. The term life data refers to the measurements of the lifetime of the equipment, whether in hours, years or cycles. It is also important to note that Life Data Analysis only applicable to devices which have one lifetime, i.e. non-repairable devices. In this study, Weibull distribution is chosen to model the life data of protective relays and other devices in FCS. This is because the Weibull distribution has the capabilities of modeling a wide range of data and does not have predefined assumptions such as constant failure rate.

Weibull distribution is expressed in a form which is defined as the probability density function, or pdf, which is given as [16]

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

The parameter β is defined as the shape parameter, which also determines the failure behavior of devices [16]. β with value <1 indicates infant mortality, β =1 indicates constant failure rate and β >1 indicates failures due to aging [20]. The parameter η is the scale parameter which is defined as the time that 63.2% of devices in the population will fail [20]. The parameter t is failure time which can be days, months, years or cycles. To perform reliability analysis, parameters β and η need to be calculated from the failure data obtained for the protective relays. These parameters can be calculated using probability plotting, least square methods or maximum likelihood method [20].

The inputs required to calculate β and η are time to failure for failed devices and age during time of observation (or suspension time) for surviving devices from the same population. In this study, time to failure data was easily obtained from TNB equipment databases and failure records. However, obtaining suspension time for the protective proved to be a challenge as even databases did not capture the exact age of the protective relays. Without the actual suspension for each protective relay, the Weibull parameters can only be obtained using the probability plotting method. Prior to this limitation, the underlying assumptions when implementing Life Data Analysis are as follows:

1. Protective relays are non-repairable devices
2. Protective relays are independent and identically distributed
3. The life span of protective relays is assumed to be 30 years
4. The failure data collected for protective relays is assumed to be valid
5. Failures which were caused by external factors and other hidden causes are excluded from the analysis

The probability plotting method requires the linearization of Weibull distribution unreliability function, which is given as

$$F(t) = 1 - R(t) \tag{2}$$

R (t) is the Weibull reliability function, which is expressed as

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{3}$$

By replacing (3) into (2), the equation becomes

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{4}$$

By applying natural logarithms to both sides, (4) becomes

$$\ln\left(\ln\left(\frac{1}{1-F(t)}\right)\right) = \beta \ln t - \beta(\eta) \tag{5}$$

To obtain β and η from (5), the values for t, time to failure and F (t), the percentage of failure are inserted into the equation. Time to failure, t is directly obtained from the failure records in TNB. The percentage of failure, F(t) is calculated as the cumulative fraction of failure at given time t to the total population multiplied by 100. As an example for this calculation, protective relay vendor X model A which has the total population of 296 units is used. The time to failure and number of failures for this relay are shown in Table III.

TABLE III. TIME TO FAILURE AND NUMBER OF FAILURES FOR PROTECTIVE RELAY FROM VENDOR X MODEL A

Time to failure (year)	Number of failures
2	1
5	2
7	3
13	1

Using the data in Table III, F(t) is calculated and the results is shown in Table IV below

TABLE IV. TIME TO FAILURE AND CUMULATIVE FAILURE PERCENTAGE FOR PROTECTIVE RELAY FROM VENDOR X MODEL A

Time to failure (year)	Cumulative Failure Percentage Over Total Population (%)
2	0.3
5	1
7	2
13	2.4
30	99.7

Since the protective relay life span is assumed to be 30 years, it is also assumed that almost all the protective relays will fail at year 30. With this information, it is possible to obtain the β and η values for this particular relay.

In this study, the calculations are done using reliability analysis software Weibull++™ from Reliasoft Corporation. The tabulation of failure data and cumulative failure percentage for protective relay model A from Vendor X is shown in Fig. 6.

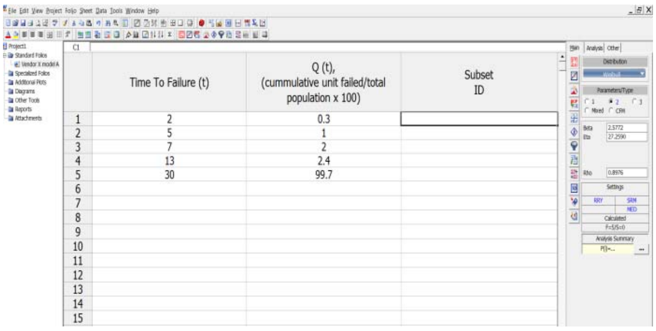

Figure 6. Tabulation of data for protective relay model A from Vendor X in Weibull++TM

The calculation process is repeated for other protective relays to obtain the Weibull parameters for the devices. The similar approach is taken to calculate the parameters for other devices in FCS, except for the parts in tele-protection equipment. For these parts, mean time to failure (MTTF) value which is declared by vendors is used. This was recommended by the respective department in TNB due to unavailability of data for the parts.

D. Reliability Block Diagram Design and Monte Carlo Simulation

Reliability block diagram (RBD) is a pictorial or graphical representation of a system's reliability performance [21]. It shows the logical connection of (functioning) components needed for successful operation of the system [21]. The RBD requires each device in a system to have only two possible states, a functioning state and a failed state [22]. The RBD methodology is also recognized by IEC in the IEC 61078 standard "Analysis Techniques for Dependability-Reliability Block Diagram and Boolean Methods".

In this study, FCS is modeled using a multi-layered RBD using BlockSimTM from ReliaSoft Corporation. Devices in FCS are arranged in "reliability wise" arrangements [21], i.e. in series and parallel arrangements that determine the successful operation of FCS. Fig. 7 illustrates the RBD configuration for transmission line FCS from Fig. 1, with the combination of protective relays from Vendor X model A and Vendor Z Model A.

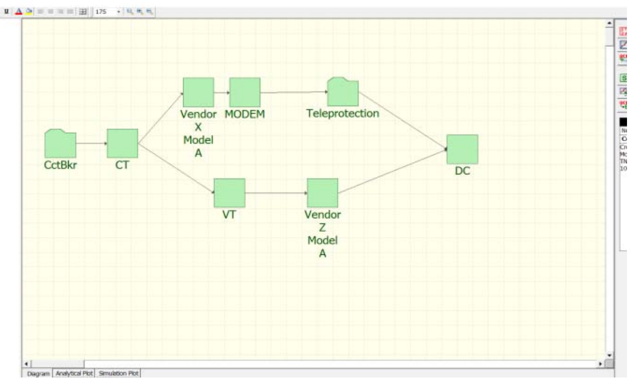

Figure 7. RBD of Transmission Line FCS (Second Layer)

The RBD for the remaining devices in the FCS is shown from Fig. 8 to Fig. 13, where Fig. 8 represents the general configuration of FCS which was shown in Fig. 2 and serves as the first layer.

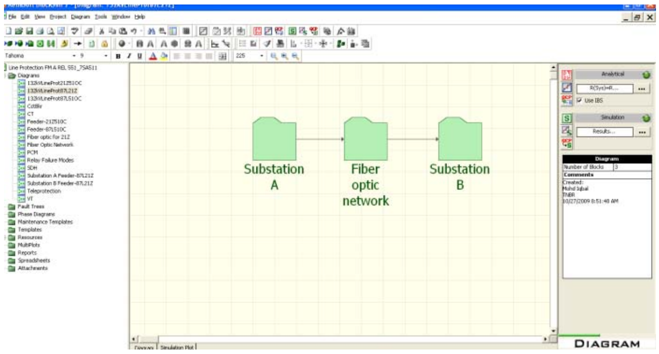

Figure 8. RBD of FCS in Two Substations (First Layer)

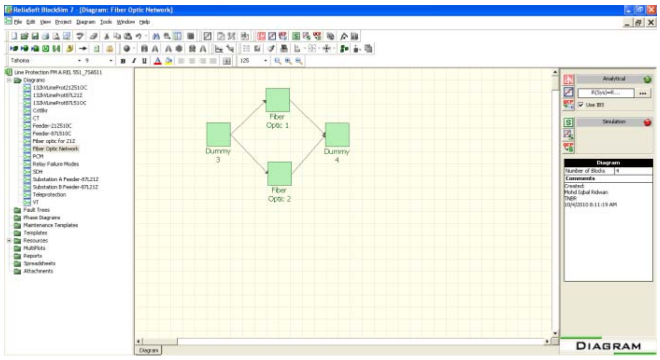

Figure 9. RBD of Fiber Optic Network Connecting the Two Substations in Two Substations (Second Layer)

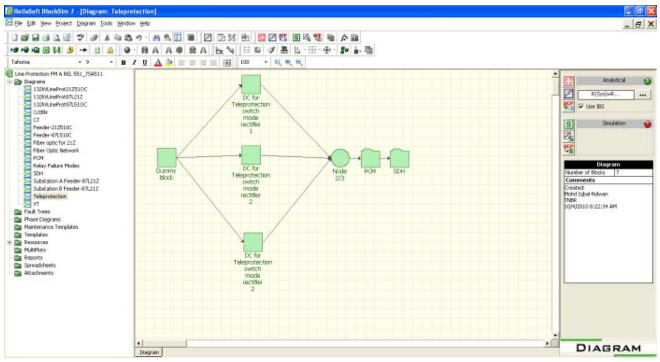

Figure 10. RBD of Tele-protection equipment in the FCS (Third Layer)

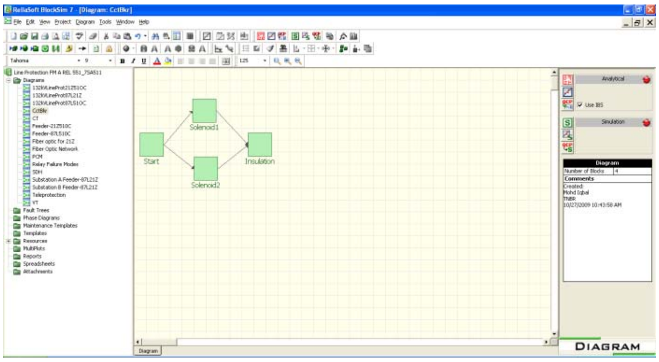

Figure 11. RBD of Circuit Breaker (Third Layer)

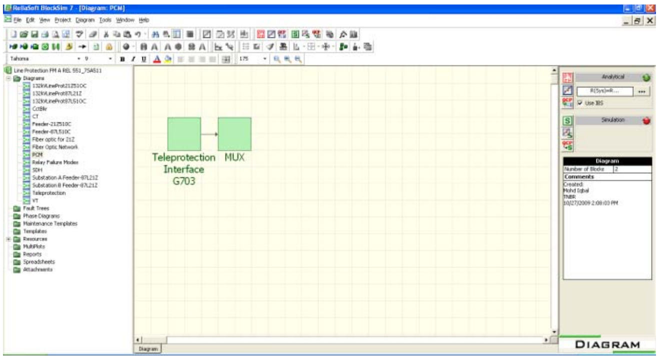

Figure 12. RBD of PCM multiplexer devices in the Tele-protection RBD (Fourth Layer)

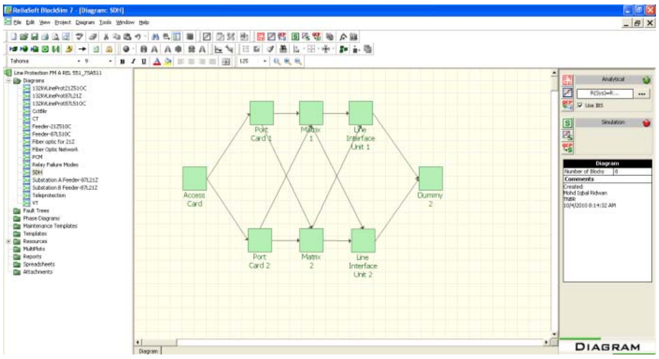

Figure 13. RBD of synchronous digital hierarchy (SDH) in the Tele-protection RBD (Fourth Layer)

In the protective relay RBD, additional parameter which is replacement time of 24 hours is added. This is a typical replacement time for protective relays whenever failure occurs.

However, RBD method alone is a static diagram and the method alone is not feasible to perform reliability assessment of a system [22]. Hence, Monte Carlo Simulation is required to simulate the "typical" lifetime of the system [22]. The advantages of applying Monte Carlo Simulation to simulate the RBD are [23]:

1. The solution time horizon for simulation is longer, hence it will reflect the "actual time" that the system will undergo in real life
2. Simulation can incorporate and simulate any system characteristic and design
3. Simulation can provide a wide range of output parameters and performance indices of the system

The Monte Carlo Simulation in BlockSim[TM] generates random failure times using specific algorithms which utilize the Weibull parameters β and η which were calculated from Life Data Analysis. A uniform number, U_R, which value is between 0 to 1 is generated using post Bays-Durham algorithm to obtain the random failure time, T_R. This is expressed as [21]:

$$T_R = \eta \cdot \{-\ln[U_R[0,1]]\}^{\frac{1}{\beta}} \tag{6}$$

The random failure time, T_R is governed by the shape and scale parameters thus it provides a more realistic insight regarding the stochastic behavior of device failures.

By considering both failure time and replacement time, it is possible to calculate the system availability of the FCS over period of time. The system availability, A_s can simply be calculated using

$$A_s = \frac{Uptime}{OperatingCycle} \tag{7}$$

IV. Results and Discussions

A. Life Data Analysis

Using the simple least square method, the Weibull Distribution shape and scale parameters for protective relays are obtained and shown in Table II. Using these parameters, the reliability for each protective relays is compared to assess which protective relays fail earlier than the others and is shown in Fig. 14 below.

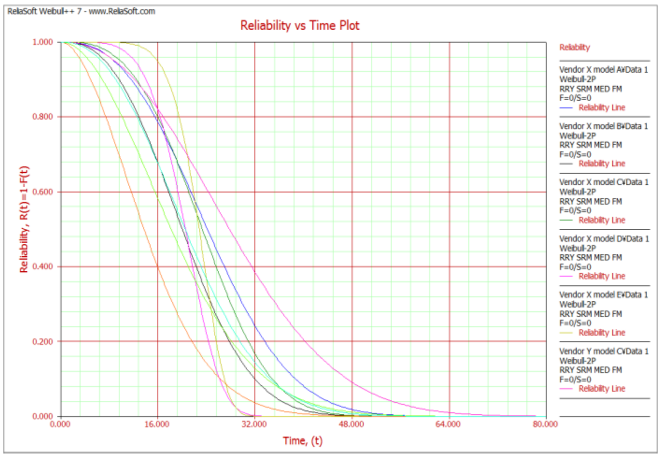

Figure 14. Reliability Comparison for Protective Relays

TABLE V. WEIBULL SHAPE AND SCALE PARAMETER FOR TRANSMISSION LINE PROTECTIVE RELAYS

Relay Vendor	**X**					**Y**	**Z**		
Weibull Parameter	**Model A**	**Model B**	**Model C**	**Model D**	**Model E**	**Model C**	**Model A**	**Model B**	**Model C**
Beta (β)	2.5126	2.5642	2.9954	4.9533	7.2322	2.2715	1.8462	1.9263	2.3065
Eta (η) (years)	28.6766	23.0924	26.3703	22.1097	24.0032	32.6647	16.7257	22.0107	24.0321

From Fig. 14, it can be summarized protective relays from Vendor Z model A has the lowest reliability followed by Vendor X model D. One interesting observation is that although protective relays from Vendor Z model A suffered from lower reliability most of time times, the time it reaches reliability of 0% in longer compared to Vendor X model D and model E. This is due to the fact that the shape parameter value of Vendor Z model A is lower compared to Vendor X model D and E. This observation is valid because from failure investigations, it was found that the protective relays from Vendor X suffers a common failure mode which occur to most of the population after a certain period of time. The pdf comparison which describes the average lifetime of the protective relays is shown in Fig. 15.

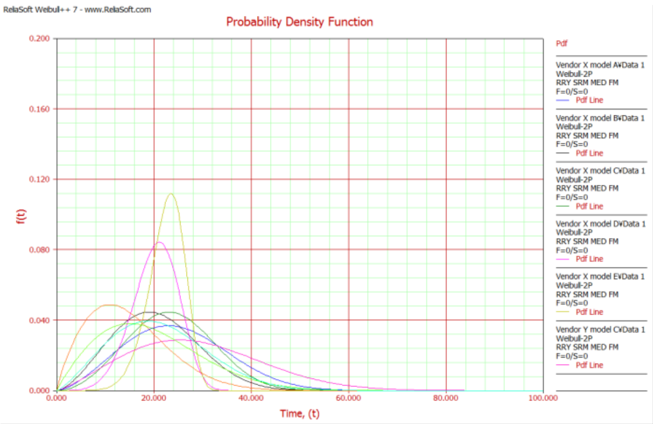

Figure 15. Weibull Pdf Comparison for Protective Relays

Fig. 15 shows that protective relays from Vendor Z model A failed earlier than the others and the average life is also the shortest, which is around **14.58** years. The highest average life is from Vendor Y model C which is around **28.93** years.

B. *Reliability Block Diagram and Simulation*

As mentioned earlier, the RBD designed is a multi-layered model which takes into account that transmission line FCS operates from two substations. Using the Weibull parameters in Table V, the β and η values for protective relays Vendor X model A and Vendor Z model A are entered in their respective RBDs, which is shown in Fig. 16. The η values are converted from years to hours as this provides more easily observable results rather than looking at the fraction of years.

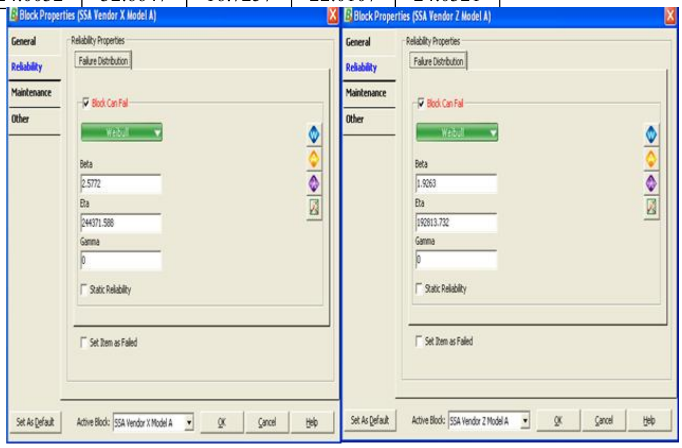

Figure 16. Weibull Parameters for Vendor X model A and Vendor Z model A in BlockSim™

The parameters of RBD for other devices in the FCS are also entered in BlockSim™. Table VI and VII summarizes the parameters for the remaining devices.

TABLE VI. WEIBULL PARAMETERS FOR DEVICES IN FCS EXCEPT FOR TELE-PROTECTION EQUIPMENT

Devices	**β**	**η (years)**
Current Transformers (CT)	2.6544	21.3856
Voltage Transformers (VT)	2.6544	21.3856
DC rectifier for teleprotection equipments	2.7944	14.2757
Relay Modem	3.2887	23.6682
Circuit breaker insulation	5.2245	37.0175
Circuit breaker solenoid (trip coils)	5.2245	37.0175

TABLE VII.

TABLE VIII. MEAN TIME TO FAILURE (MTTF) PARAMETERS FOR TELE-PROTECTION EQUIPMENT IN FCS

Devices	**MTTF (hours)**
Access Card	1200000
Line Interface Unit	1320000
Matrix	367000
Port Card	878000
Multiplexer	833000
Teleprotection Interface G703	513000

For the Monte Carlo Simulation settings, the operating cycle for FCS is simulated for 30 years (262,800 hours) with 1000 times iteration. These configurations offer representative view of the behavior of FCS and its devices throughout the expected life span. The result from the simulation is shown in Fig. 17.

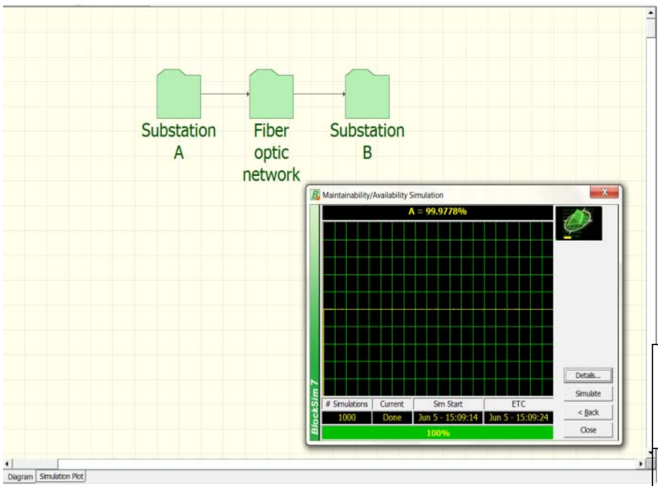

Figure 17. Monte Carlo Simulation result

Fig. 17 depicts that the Availability of the FCS is 99.9778% throughout a 30 year (262,800 hours) simulation. The main reason of this is that the implementation of main and backup protective relays does maintain high availability of FCS. Furthermore, failed FCS devices such as the protective relays are also repaired during the simulation period thus this has helped maintaining the high availability.

For the protective relays, it is discovered that failure does occur during the simulation period. However, it was set that the protective relays are replaced when failed. This also contributes to the high system availability that is shown in Fig. 17. The failure time of the protective relays during the simulation is shown in Fig. 18.

From Fig. 18, it is clearly shown that despite of the failures of the protective relays, the FCS does not undergo any downtime because of the main and backup implementation.

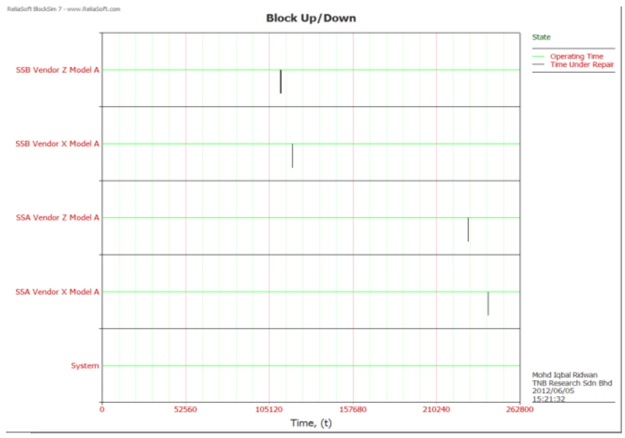

Figure 18. Protective Relays Failure Time during Simulation

The detailed performance indices of that the protective relays Vendor X model A are and Vendor Z model A throughout the 30 year simulation are summarized in Table IX.

TABLE IX. FAILURE INFORMATION OF PROTECTIVE RELAYS FROM A 30-YEAR MONTE CARLO SIMULATION

Block Name (Diagram)	Expected No. of Failures	Block Downtime (hours)	Block Uptime (hours)	Number of Corrective Maintenance
Substation A Vendor X Model A	0.779	18.696	262781.304	0.779
Substation A Vendor Z Model A	1.215	29.16	262770.84	1.215
Substation B Vendor X Model A	0.78	18.72	262781.28	0.78
Substation B Vendor Z Model A	1.183	28.392	262771.608	1.183

V. CONCLUSION

From this study it can be concluded that Life Data Analysis and Reliability Block Diagram with Monte Carlo Simulation methods are capable in quantifying the reliability of devices and system using historical failure data. The integration of these two methods for the reliability analysis of protective relays and FCS provides alternative to the Markov Model which is commonly used for the same purpose. The utilization of actual data using the methods will reflect the actual failure behavior of the protective relays and with the assistance of simulation, practitioners are capable in predicting the future performance of the protective relays.

VI. FURTHER WORKS

This study only considers the dependability part in the definition of protective relay reliability. Similar method can also be applied to analyze the security part of protective relay as this is also an important aspect in assessing the performance of protective relays.

Furthermore, the methods proposed in this study can be further enhanced by integration with Markov Model. This integration is known as Non-Homogeneous Markov Model or Weibull-Markov Model [24]. The integration involves a more complex mathematical model but is able to provide a more accurate representation of the devices or system which combines both the aging factor and multi-state modeling.

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