# Failure Rate Analysis of Circuit Breaker and Its Preventive Maintenance Application

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***Abstract*— This paper presents an analysis of failure rates of power circuit breakers at the 230 kV voltage class. First of all, the 20-year historically recorded failure data of existing power circuit breakers (CB) in high voltage substations in Thailand were retrieved. Subsequently, the data were analyzed and classified by causes of failure related to CB sub-component types. The failure rates based on individual sub-component types were examined and then were categorized into three main CB component categories depending upon their functionalities, which are live parts and insulation, operating mechanism, and control. The failure rates of individual CB sub-components were calculated and their associated probability distributions were estimated using Weibull distribution functions. The resulting Weibull distribution parameters were subsequently utilized in CB preventive maintenance application to aid a decision making process for setting maintenance schedule of CB components. The proposed method can also be applied to other high voltage equipment in power systems.**

***Keywords—Failure rate, mean time between failure (MTBF), preventive maintenance, Weibull distribution, circuit breaker.***

## I. INTRODUCTION

Power circuit breaker is one of the key elements for control and protection purposes in the power system. Its function is to make, carry and break the current for both normal and abnormal conditions. The current interruption can be performed by team work with several equipments. Firstly, the instrument transformer will sense the system conditions and send it to protective relay. Protective relay will decide whether the system state is normal or abnormal. In case of abnormal condition, it will close its contact to energize the trip coil of power circuit breaker. Then the tripping mechanism starts to operate and interrupts the faulted part. Because of such extreme requirement from power system, the failure statistic of power circuit breakers should be determined and intensively analyzed to prevent the unexpected failure. Therefore, the reliability of circuit breakers components should be determined. However in practical power system, a large number of power circuit breaker from different technologies and manufactures were installed and in service. This creates the complexity in the data analysis. Moreover, the deterioration of power circuit breakers depends on equipment quality, operating conditions such as loading stress, maintenance practice and strategy, surrounding or environmental conditions such as ambient temperature, humidity and moisture, pollution level, etc.

In this paper, power circuit breakers at 230 kV system voltage obtained from a systematic statistical failure data recorded by installation, operation, and maintenance engineers of a utility in Thailand into a enterprise resource planning (ERP) database system. It consists of 486 total number of failure events during the period from 1992 to 2011 have been analyzed. The objective of this paper is firstly to describe a method for estimating the key reliability parameters of power circuit breaker, such as failure rate and mean time between failure (MTBF) from recorded failure data of an utility in Thailand, by using Weibull distribution technique. The determined parameters from practical system will be subsequently used to improve the accuracy of system reliability evaluation. Finally, the preventive maintenance schedule or renovation tasks of power circuit breaker can be performed with the minimum cost.

## II. CLASSIFICATION OFCIRCUIT BREAKER COMPONENT AND STATISTICAL FAILURE RECORDS

Normally, the correct operation of power circuit breaker depends on the ability of several components working together such as high voltage components, operating mechanisms and control circuit. The capability and performance of each individual component have significant impact to the successful operation and reliability of power circuit breakers. In this paper, components of circuit breaker are divided into three major parts [1]-[2] as live parts and insulation, operating mechanism, and control circuit and the sub-components of each major part are shown in Table 1. According to the recorded failures, the numbers of breaker failures for the three main parts are 53 (live parts and insulation), 303 (operating mechanism), and 130 (control) as shown in Table I. The failure contributions (percentage) of sub-components within the three main parts are shown in Figs. 1 to 3. For the first part (live parts and insulation), the most failure rate occurs 40% at main insulation to earth for live parts and insulation, 37% at the making and breaking units and 23% at auxiliary interrupter unit. Similar to the second part (operating mechanism), the highest failure is 19% at damping device while failures diversify to other components in this part. In the last part (control), all four components are mostly equal percentages.

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TABLE I. FAILURES OF 230 KV CIRCUIT BREAKER COMPONENTS

| CB main parts | CB sub-components | No. failure (times) |
|---|---|---|
| Live parts and insulation (Major HV components) | Main insulation to earth | 20 |
| | Making and breaking unit | 30 |
| | Auxiliary interrupter | 3 |
| Operating mechanism | Actuator (converting hydraulic energy into mechanical energy) | 107 |
| | Compressor unit (compressor, motor, pump, pipe and others) | 89 |
| | Control element | 13 |
| | Damping device | 26 |
| | Energy storage (accumulator, spring, air reservoir) | 24 |
| | Mechanical transmission (latch, link, gear, chain, coupling) | 43 |
| | Non-return device (contractor, relay, heater, thermostat, fuse, switch, etc.) | 1 |
| Control circuit | Contactor unit (relays, heaters and other) | 93 |
| | Gas density supervision | 15 |
| | Tripping and closing circuit | 11 |
| | Auxiliary switch and associated drive | 11 |
| Total | (all sub-components) | 486 |

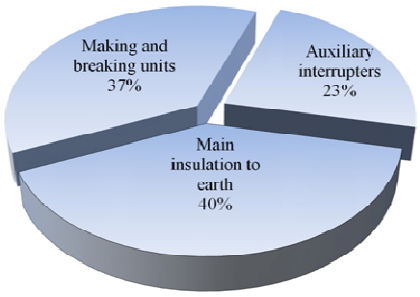


Fig. 1. Failure percentage for live parts and insulation

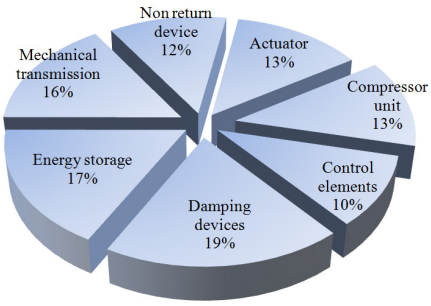


Fig. 2. Failure percentage for operating mechanism part

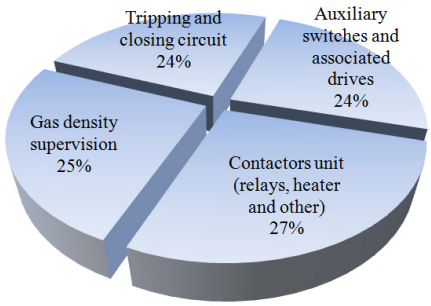


Fig. 3. Failure percentage for control part

## III. WEIBULL PARAMETERS ESTIMATION AND MODELLING

### A. *Method for Estimating Relaibility Parameters [3]-[5]*

Weibull distribution technique is one of the most widely used for accurate failure analysis, failure forecast, aging and reliability. In this failure analysis, the statistical recorded failure data of existing 230 kV power circuit breakers in high voltage substations are firstly collected and analyzed. Next, an order of failure events is ranked. The median rank $F_i$ of failure event "$i$" is calculated by Eq. (1).

$$F_i = \frac{i-0.3}{N+0.4} \tag{1}$$

If a circuit breaker is separately considered for each individual component, "$i$" is the adjusted rank of age of such component failed;"$N$" is the total ranking number of such component.

The Weibull parameters can be determined by using straight line formula as given in Eq. (2).

$$y_i = mx_i + c \tag{2}$$

and

$$x_i = \ln(t_i) \tag{3}$$

where $t_i$ is independent age (year) of such failed component in rank $i$, and then $y_i$ can be determined from Eq. (4).

$$y_i = \ln\ln\left[\frac{1}{1-F_i}\right] \tag{4}$$

From Eq. (2) to Eq. (4), then the Weibull shape parameter ($\beta$) can be calculated as given in Eq. (5).

$$\beta = m = \frac{\sum_{i=1}^{N} x_i y_i - \frac{\sum_{i=1}^{N} x_i \sum_{i=1}^{N} y_i}{N}}{\sum_{i=1}^{N} x_i^2 - \frac{\left[\sum_{i=1}^{N} x_i\right]^2}{N}} \tag{5}$$

and

$$c = \frac{\sum_{i=1}^{N} y_i}{N} - m\frac{\sum_{i=1}^{N} x_i}{N} \tag{6}$$

Then, the life or scale parameter ($\eta$) can be calculated as given in Eq. (7).

$$\eta = e^{-\left[\frac{c}{m}\right]} \tag{7}$$

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The Weibull Probability Distribution Function *f(t)* represents the probability of failure at specific time (*t*), as written by Eq. (8).

$$f(t)=\left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} e^{-\left[\frac{t}{\eta}\right]^{\beta}} \tag{8}$$

The Weibull cumulative distribution function *F(t)* represents the probability of failure at specific time "*t*", that can be written by Eq. (9) while reliability function $R(t)$ and failure rate $\lambda(t)$ are written in Eq. (10) and Eq. (11), respectively.

$$F(t)=1-e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{9}$$

$$R(t) = 1-F(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \tag{10}$$

$$\lambda(t) = \frac{f(t)}{R(t)} = \left(\frac{\beta}{\eta}\right)\left(\frac{t}{\eta}\right)^{\beta-1} \tag{11}$$

The Mean Time Between Failure (*MTBF*) of individual component is calculated by using Eq. (12).

$$MTBF=\eta\,\Gamma\left[1+\frac{1}{\beta}\right] \tag{12}$$

where $\Gamma\left[1+\frac{1}{\beta}\right]$ is the gamma function evaluated at the value of $(1+ 1/\beta)$.

TABLE II. EXAMPLE FOR RELIABILITY PARAMETER CALCULATION OF A SAMPLE COMPONENT

| **Rank** ***i*** | **Age** $t_i$ | $F_i=\frac{i-0.3}{N+0.4}$ | $x_i=\ln(t_i)$ | $y_i=\ln\ln\left[\frac{1}{1-F_i}\right]$ |
|---|---|---|---|---|
| 1 | 2 | 0.1296 | 0.693 | -1.9744 |
| 2 | 3 | 0.3148 | 1.099 | -0.9726 |
| 3 | 15 | 0.5 | 2.708 | -0.3665 |
| 4 | 17 | 0.6851 | 2.833 | 0.14476 |
| N = 5 | 25 | 0.8703 | 3.219 | 0.71445 |
| ***Reliability Parameters Results*** | | | | ***Unit*** |
| Shape paramenter $\beta$ | | | 0.8675 | - |
| Scale paramenter $\eta$ | | | 14.5296 | - |
| $MTBF(t)$ | | | 15.6113 | Year |
| $f(t)$ | | | 0.02908 | - |
| $F(t)$ | | | 0.5816 | - |
| $R(t)$ | | | 0.41831 | - |
| $\lambda(t)$ | | | 0.06097 | frequency/CB-year (freq./CBa) |

Example on Weibull parameters calculation can be described in Table II. Regarding to real life case study by comparing parameters in mathematic model with the parameters in real case of each individual component, "*Rank i*" is simple rank of failure event "*i*" by age, "Age $t_i$" is actual breaker age of event "*i*", $F_i$ is the median rank failure event "*i*" by using Eq. (1), and *N*" is the total ranking number of such component. By using Eqs. (2) to (12), parameters $\beta$, $\eta$, $F(t)$, $R(t)$, $\lambda(t)$, MTBF of such individual component are then calculated. Similarly, the same parameters of all components are also calculated. It is important to note that in order to analyze equipment failure rate, the accuracy term used in Eq. (12) should be the mean time to failure (MTTF) rather than the mean time between failure (MTBF). Given that the MTBF and MTTF are relatively similar when the mean time to repair (MTTR) of the equipment is quite small [6]. Therefore, the MTBF, which is the typical recorded data by utilities, was used in this paper to estimate the failure rate of CBs.

The Weibull distribution is a very flexible life distribution model that can be used to characterize failure distributions in all three phases of the bathtub curve (i.e. burn-in, normal operating life, and wear-out). The shape factor, beta, is the key feature of the Weibull distribution that enables it to be applied to any phase of the bathtub curve. When the shape factor is greater than 1.0, the increasing Weibull hazard rate function can be observed, which is subject to aging in the sense that an older component has a higher chance of failing during the next small time increment d than a younger component. The Weibull distribution is, therefore, appropriate when trying to characterize the random lifetime of system components. In addition, other distinct distribution shapes such as exponential, Rayleigh and normal distributions can be characterized as the Weibull distributions with shape factors of 1, 2 and 3.5, respectively.

### *B. Failure Rate Analysis for Preventive Maintenance*

All components of power circuit breaker in TABLE I are considered as critical component for the operation of power circuit breaker and its reliability. Therefore, the failure of each individual component leads to the failure of the whole power circuit breaker operation. From the aforementioned explanation, all components are considered as series connection for reliability evaluation. Then, the total failure rate can be written as,

$$\lambda_{total}(t)=\sum_{i=1}^{n}\lambda_i(t) \tag{13}$$

where $\lambda_i(t)$ is the failure rate of component *i* and n is total number of the sub-components. Therefore, the total failure rate of power circuit breaker is the summation of individual failure rate of each component.

The individual failure rate together with its mean time to failure will be further applied to plan the preventive maintenance. The time schedule for preventive maintenance of individual sub-components is set up according to the failure rate and MTBF of each component. Finally, the failure rate of the whole circuit breaker $\lambda_{CB}(t)$ can be determined as written in Eq. (14).

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$$\lambda_{CB}(t) = \lambda_{total}(t) - \sum_{i=1}^{m} \lambda_i(t) \qquad (14)$$

where "m" denotes number of replaced components "$i$ = 1 to $m$" in year "$t$". For example, if m = 3, there are 3 components will be replaced. The failure rates of those components are $\lambda_1(t)$, $\lambda_2(t)$, and $\lambda_3(t)$. Finally, the overall failure rate of circuit breaker in year "t" will be $\lambda_{CB}(t) = \lambda_{total}(t)$-$\lambda_1(t)$-$\lambda_2(t)$-$\lambda_3(t)$.

However, Eq. (14) is used to calculate the total failure rate at any specific preventive maintenance at year "$t$" by defining that the deteriorated sub-components will be replaced by the new one before reaching their mean time between failures. Then the total failure of circuit breaker $\lambda_{CB}(t)$ will be reduced according to the failure rate $\lambda_i(t)$ of the recently replaced sub-components. Thereafter, the failure rate will be gradually increased again because the failure rate $\lambda_i(t)$ of the recently replaced sub-components always increases every year.

## IV. Statistical Failure Rate Analysis

The failure rate analysis using Weibull distribution technique involves data acquisition, data ranking, data plotting and outcome interpreting.

### A. Weibul Parameters for All Breaker Components

Weibull parameters, MTBFs, and failure rates for all sub-components are calculated using the procedure described in Section III and shown in Table III. Similarly, the Weibull parameters for the three main parts (combined sub-components in each part) and for the CB as a whole are shown in Table IV. Based on the estimation of the Weibull parameters for individual CB sub-components presented in Table III, the probability distributions of the time between failure for all sub-components are depicted in Figs. 4 to 6 categorized by the three main parts. For comparison purposes, the exponential distribution (i.e. $\beta$=1 as shown by the dashed line) that often uses as a baseline distribution in reliability studies is plotted against with the estimated Weibull distribution obtained from the actual data by using y-axis on the left-hand scale as shown in Figs. 4 to 6. The MTBF of the exponential and Weibull distributions illustrated in Figs. 4 to 6 are kept the same in order to provide a reasonable comparison. In addition, the histogram of the raw data is plotted by using y-axis on the right-hand scale to show how close the data follows Weibull distribution. From Figs. 4 to 6, it is obvious that the most often used baseline distribution (exponential) establishes quite different distribution shapes from the estimated distribution obtained using the actual failure data. The assumption of modeling the time between failure using the exponential distribution results in a constant hazard function (memoryless), which implies that the remaining life of a component is independent of its current age. In other words, the exponential distribution provides no insight of the time-dependent characteristic the equipment whereas the Weibull distributions derived from the actual failure data tend to suggest that the failure rate characteristic is more likely to fail with time. From the maintenance standpoint, the use of the time-dependent failure model such as the Weibull distribution based on the estimated parameters derived in this paper can enhance the decision making process for setting preventive maintenance schedule of CB components, i.e. when should maintenance be regularly scheduled? This application is discussed in the following section.

TABLE III. Reliability Parameters, MTBF, and Failure Rate for Each Sub-component

| Type of Components | Weibull Parameters | | MTBF (year) | λ (freq./ CBa) |
|---|---|---|---|---|
| | *Shape β* | *Scale η* | | |
| Main insulation to earth | 2.1019 | 19.0168 | 16.843 | 0.0967 |
| Making and breaking unit | 2.2384 | 20.7218 | 18.353 | 0.0929 |
| Auxiliary interrupter | 5.2644 | 32.0278 | 29.494 | 0.1157 |
| Actuator | 2.5673 | 23.5261 | 20.889 | 0.0906 |
| Compressors unit | 1.5132 | 25.9385 | 23.391 | 0.0553 |
| Control element | 1.4558 | 34.1187 | 26.692 | 0.0407 |
| Damping device | 2.3849 | 16.2350 | 14.390 | 0.1243 |
| Energy storage | 1.9102 | 18.2335 | 16.177 | 0.0940 |
| Mechanical transmission | 2.0911 | 19.8594 | 17.590 | 0.0922 |
| Contractor unit | 1.5996 | 16.2066 | 14.673 | 0.0922 |
| Gas density supervision | 1.1804 | 18.8105 | 17.7712 | 0.0621 |
| Tripping and closing circuit | 1.7496 | 18.3500 | 16.343 | 0.0874 |
| Auxiliary switch and associated drive | 2.0405 | 19.4527 | 17.234 | 0.0912 |

TABLE IV. Reliability Parameters, MTBF, and Failure Rate of Each Main Part

| Type of Components | Weibull Parameters | | MTBF (year) | λ (freq./CBa) |
|---|---|---|---|---|
| | *Shape β* | *Scale η* | | |
| Live parts and insulation | 2.244 | 20.7202 | 18.3522 | 0.09315 |
| Operating mechanism | 2.0201 | 22.7842 | 20.1885 | 0.07837 |
| Control circuit | 1.6349 | 16.8357 | 15.0659 | 0.0905 |
| Total | 1.88804 | 20.9408 | 18.5859 | 0.0811 |

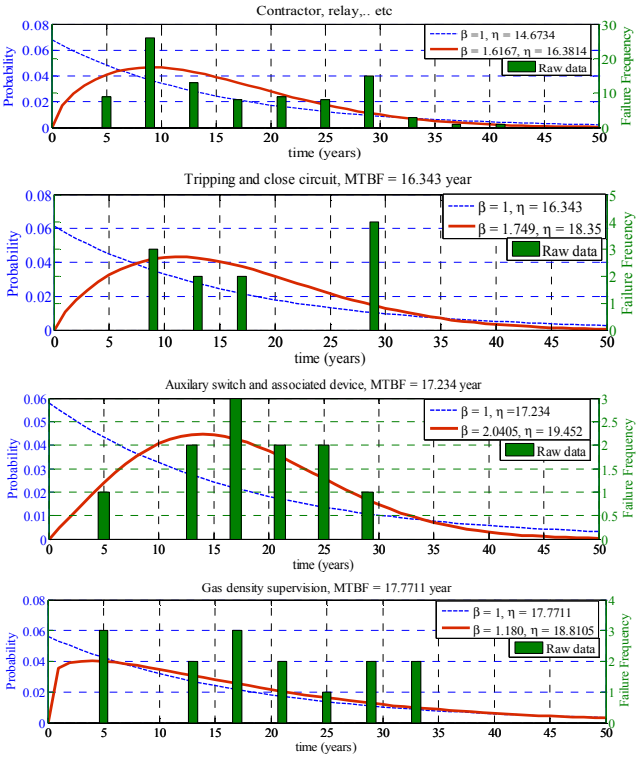


Fig. 4. Probability distribution of the time between failure for the control circuit

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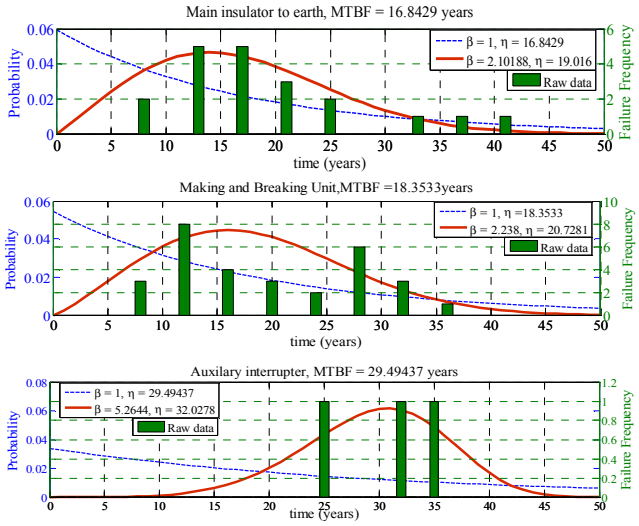


Fig. 5. Probability distribution of the time between failure for the live parts and insulation

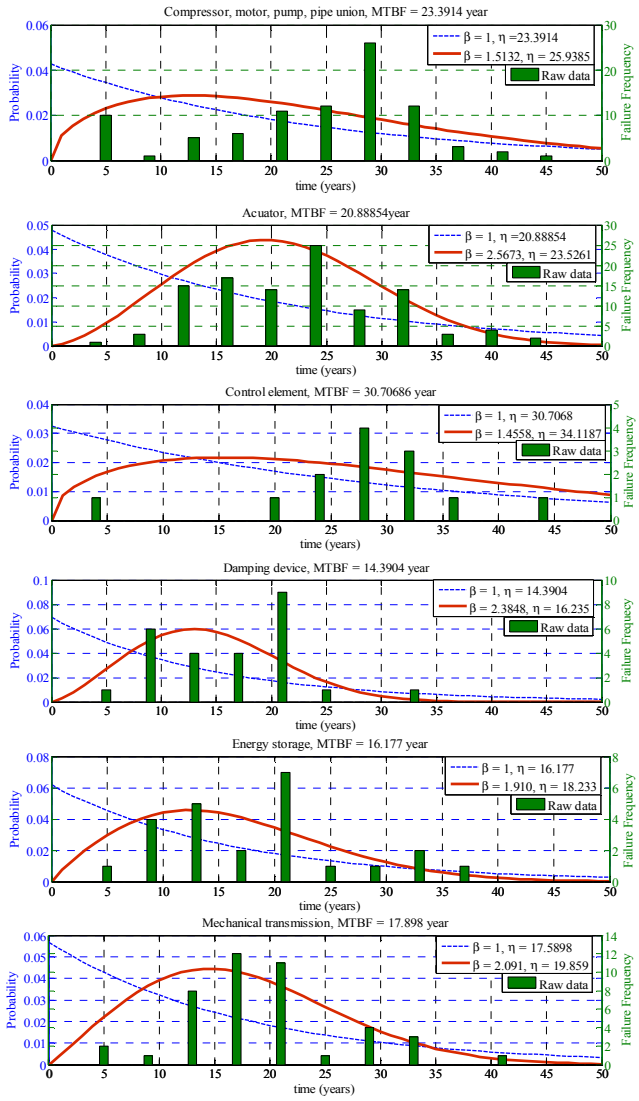


Fig. 6. Probability distribution of the time between failure for the operating mechanism

### *B. Investigation on Failure Rate in Proper Preventive Maintenance Schedule*

Generally, the preventive maintenance has been performed to maintain the high voltage equipment in the transmission network for decades. The deteriorated equipment is replaced by the new one before its mean time between failures. Thus from the known MTBF of every individual sub-components obtained from the above analysis are arranged and grouped together. The sub-components having relatively similar MTBF are grouped together and replaced at the same scheduled maintenance of inspection and overhauling in order to reduce the forced outage time, supply interruption and maintenance cost. With this determined scheduled maintenance and replacement, the critical components are known and carefully focused for maintenance and replacement. The traditional routine maintenance and major inspection as every 6 years period can be reduced and adjusted according to the statistical result analyzed from record dataset of individual utility.

According to the obtained result, the maintenance schedule for replacing 3 groups of components is proposed as presented in Table V. The first group with MTBF approximately 14.4 – 17.6 years is scheduled to replace at the year 13 in service. The second group with MTBF approximately 18.3 – 23.4 years is scheduled to replace at the year 18 in service. The first group with MTBF approximately 27 – 30 years is scheduled to replace at the year 26 in service. The probability distribution function by Weibull distribution of the three proposed groups of sub-components listed in Table V is then presented in Fig. 7.

TABLE V. PROPOSED MAINTENANCE SCHEDULEFOR COMPONENTS

| Group | Year of PM | Replaced component | $\lambda_{total}(t)$ before PM | $\lambda_{CB}(t)$ after PM |
|---|---|---|---|---|
| Group 1 | 13rd | Damping device | Point A 0.7700 | Point B 0.1756 |
| | | Contractor unit | | |
| | | Gas density supervision | | |
| | | Energy storage | | |
| | | Tripping and close circuits | | |
| | | Auxiliary switches and associated drives | | |
| | | Main insulation to earth | | |
| | | Mechanical transmission | | |
| Group 2 | 18th | Making and breaking unit | Point C 0.5249 | Point D 0.3141 |
| | | Actuator | | |
| | | Compressor unit | | |
| Group 3 | 26th | Control elements | Point E 0.8014 | Point F 0.6961 |
| | | Auxiliary interrupters | | |

Fig. 8 illustrates the failure rates for the combined sub-components with the proposed preventive maintenance schedule. In Fig. 8, the dashed line represents the constant failure rate, i.e. the exponential baseline distribution. The continuous line is a time-dependent failure rate based on the estimated Weibull distribution. It can be seen that the total failure $\lambda_{CB}(t)$ is reduced according to the three replacements of the deteriorated components. With this method, the failure rate of power circuit breaker can be maintained within the acceptable level by appropriately replacing the deteriorated sub-components, whose service age nearly reaches MTBF. Therefore, the performance of power circuit breaker and

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power supply can be effectively maintained by such strategic replacement. Finally, the better system reliability can be achieved.

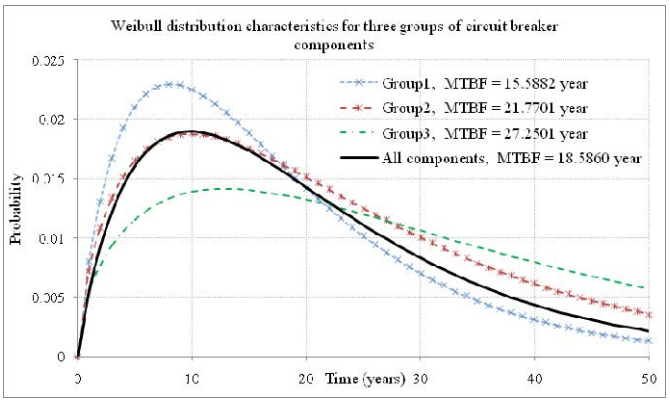


Fig. 7. Failure rate function of exponential distribution

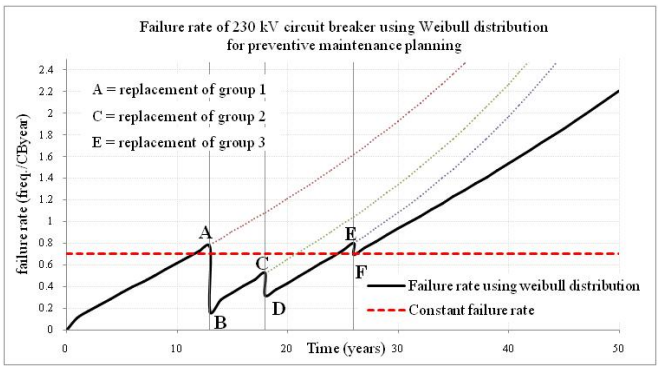


Fig. 8. Failure rates associated with the proposed maintenance schedule

## V. CONCLUSIONS

In this paper, the analysis of the failure rates of the 230 kV circuit breakers based on the 20-year recorded failure data of existing circuit breakers in high voltage substations in Thailand is presented. All the CB sub-components were classified into the three main categories that are the live parts and insulation, the operating mechanism, and the control. The failure rates for all sub-components and for the three main parts were calculated using Weibull statistic distribution technique. The resulting values of the Weibull shape parameter ($\beta$) can help explaining the failure characteristic of the equipment. According to the results, the values of the shape parameter ($\beta$) for the three main parts are greater than 1. This implies that the failure rates are very low at the beginning and significantly higher with increasing time. Therefore, the most often use exponential distribution as a baseline distribution may not be accurate enough for reliability studies in particularly when applied to maintenance schedule of the equipment. The resulting Weibull parameters derived in this paper can overcome this issue as its model provides the time-dependent failure information that in turn can aid a decision making process for preventive maintenance schedule of the circuit breakers. The scheduled maintenance of each group is setup by the coordination of the MTBFs of all components. Components having relatively similar MTBFs as group 1 to group 3 in Table V are grouped together and scheduled to be maintained or replaced before such MTBFs as preventive maintenance. Such grouping of components for preventive maintenance is performed in order to reduce scheduled shutdown, maintenance cost and increase the equipment reliability.

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