Failure Analysis of Protective Devices in Power Distribution Systems for Reliability Purpose

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Abstract- **This paper presents the reliability study of failure rate, mean time to failure (MTTF), and failure mechanism of protective devices installed in power distribution systems of the Provincial Electricity Authority (PEA) of Thailand during the period from 1997 to 2005. Such protective devices include 27 breakers, 109 reclosers, 2,151 fuses, and 79 switches (disconnecting, airbreak and loadbreak switches). According to the Kolmogorov-Smirnov Test on failure data, the lifetime of these devices can be described by the Weibull distribution. As a result, their failure rate and MTTF are estimated based on Weibull distribution properties. Finally, failure mechanism of the above protective devices is discussed for improving the reliability of distribution systems.**

I. Introduction

The fundamental role of power utilities is to provide customers electrical energy as economically as possible with an acceptable degree of reliability and quality. The system reliability generally depends on reliability of individual components installed and mutually operated in the system. In a power distribution system, protective devices including breakers, reclosers, fuses and switches (disconnecting, airbreak and loadbreak switches) are considered very important because their operating conditions directly affect the reliability, security and economics of the system. [2]

In this paper, all protective devices including 27 breakers, 109 reclosers, 2151 fuses and 79 switches operated in the 22 kV distribution system of the Provincial Electricity Authority (PEA) of Thailand during the period from 1997 to 2005 have been analyzed for reliability purpose.

The objective of this paper is to describe a method for estimating the key reliability parameters such as failure rate and mean time to failure (MTTF) from the recorded failure data of the PEA. Using Kolmogorov-Smirnov test on the Weibull distribution, the failure rate and MTTF of breakers, reclosers, fuses and switches are calculated. Finally, failure mechanism of the above protective devices is discussed for improving the reliability of distribution systems.

II. Reliability Analysis

A number of publications and research related to reliability analysis mostly use a bathtub curve as an adequate representation of component failure modes. Such a curve can be divided into 3 periods or failure modes as follows: early failure period, random failure period and wear-out failure period. Different failure modes can be simulated by different mathematical models. The Weibull distribution, which is a flexible and convenient life distribution model, is most widely used for this task because of its versatile ability to represent all the modes.

Among the above three failure periods of the bathtub curve, we are most interested in the random failure mode. It is not only related to production procedures of manufacturers but also possibly to usage conditions under which a user may utilize. Consequently, the analysis in this paper is focused on the random failures [6]. The life times t of protective devices, which are over 1 year, are summarized from historical records in order to determine the reliability parameters as illustrated in the following section.

III. Method for Estimating Reliability Parameters

The Weibull cumulative distribution function (CDF) has the expression given by Equation (1).

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad (1)$$

where β is the shape parameter and α is the scale parameter. The parameters can be obtained from linear curve fitting as described by Equation (2).

$$y = Mx - A \quad (2)$$

where $y = \ln\ln\left\{1/\left[1 - F(t)\right]\right\}$ and $x = \ln t$.

The Empirical cumulative frequency is defined as Equation (3).

$$F'(t) = \sum_{i=1}^{m} \frac{m_i}{n} \quad (3)$$

where m is the total number of failed devices and n is the total number of devices, including failed and not failed. The shape and scale parameters can be determined from a linear curve expressed by Equation (2) such that $\beta = M$ and $\alpha = e^{\left(\frac{A}{M}\right)}$.

IV. The Kolmogorov-Smirnov Test

In the Kolmogorov-Smirnov Test, the maximum difference between $F(t)$ and $F'(t)$ is a measure of how good the fit is. Let the maximum difference be denoted by Equation (4).

$$D_n = \max\left|F(t) - F'(t)\right| \quad (4)$$

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This difference, a random variable that in turn varies with the selected samples, is compared with the critical values (CV) for Kolmogorov-Smirnov Test in [4]. The critical values at various significant levels can be found in the Probability Tables. If the observed D_n < CV, the proposed distribution is acceptable at the selected significance level.

V. The Equation of MTTF and Failure Rate

The mean time to failure (MTTF) is the expectation of life time and has the form as given in Equation (5).

$$MTTF = \alpha\Gamma\left[\frac{1}{\beta}+1\right] \tag{5}$$

where $\Gamma(v)$ is the gamma function.

The failure rate (λ) function is expressed as Equation (6).

$$\lambda = \frac{1}{T}\left[\frac{T}{\alpha}\right]^{\beta} \tag{6}$$

where T is a definite time in the tail cut test.

VI. The Calculation of MTTF and Failure Rate

The period from January 1st, 1997 to December 31st, 2005, is chosen as the period of definite time (T). The total numbers of failed breakers, reclosers, fuses and switches are 6, 32, 619 and 10 units respectively. The life time test is used for calculating the MTTF and failure rate as shown in Table I-IV and Figure 1-4 for breakers, reclosers, fuses, and switches respectively.

TABLE I
The Kolmogorov-Smirnov Test for Breakers

t	m_i	$\sum_{i=1}^{m} m_i$	$F'(t_i)$	$F(t_i)$	$\lvert F(t)-F'(t)\rvert$
1<t≤2	2	2	0.0741	0.0986	0.0245
2<t≤3	2	4	0.1481	0.1298	0.0184
3<t≤4	1	5	0.1852	0.1572	0.0280
4<t≤5	1	6	0.2222	0.1819	0.0403
5<t≤6	0	6	0.2222	0.2047	0.0176
6<t≤7	0	6	0.2222	0.2258	0.0035
7<t≤8	0	6	0.2222	0.2455	0.0233
8<t≤9	0	6	0.2222	0.2641	0.0419

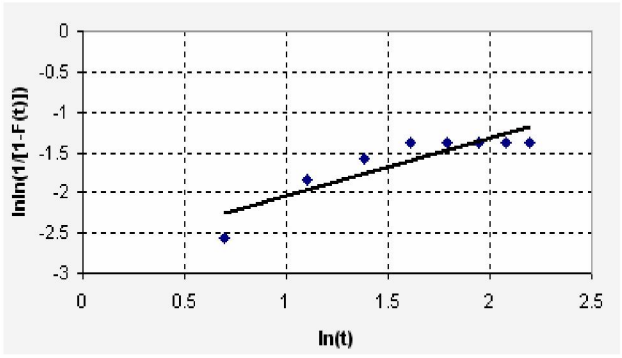


Figure 1. The straight line of F(t) for breakers.

TABLE II
The Kolmogorov-Smirnov Test for Reclosers

t	m_i	$\sum_{i=1}^{m} m_i$	$F'(t_i)$	$F(t_i)$	$\lvert F(t)-F'(t)\rvert$
1<t≤2	13	13	0.1193	0.1389	0.0196
2<t≤3	8	21	0.1927	0.1756	0.0171
3<t≤4	3	24	0.2202	0.2066	0.0136
4<t≤5	4	28	0.2569	0.2338	0.0231
5<t≤6	1	29	0.2661	0.2582	0.0078
6<t≤7	2	31	0.2844	0.2805	0.0039
7<t≤8	0	31	0.2844	0.3010	0.0166
8<t≤9	1	32	0.2936	0.3200	0.0264

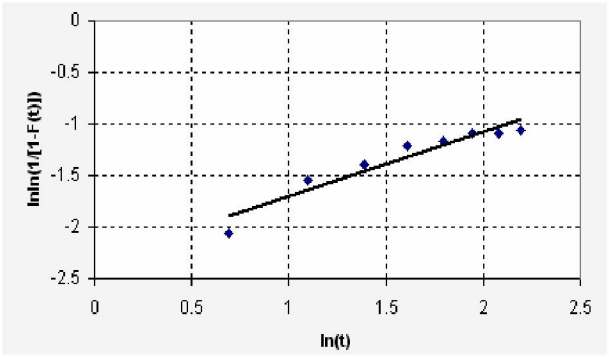


Figure 2. The straight line of F(t) for reclosers.

TABLE III
The Kolmogorov-Smirnov Test for Fuses

t	m_i	$\sum_{i=1}^{m} m_i$	$F'(t_i)$	$F(t_i)$	$\lvert F(t)-F'(t)\rvert$
1<t≤2	308	308	0.1432	0.1580	0.0149
2<t≤3	110	418	0.1943	0.1915	0.0028
3<t≤4	90	508	0.2362	0.2189	0.0173
4<t≤5	52	560	0.2603	0.2424	0.0180
5<t≤6	40	600	0.2789	0.2631	0.0159
6<t≤7	10	610	0.2836	0.2817	0.0019
7<t≤8	6	616	0.2864	0.2987	0.0123
8<t≤9	3	619	0.2878	0.3143	0.0265

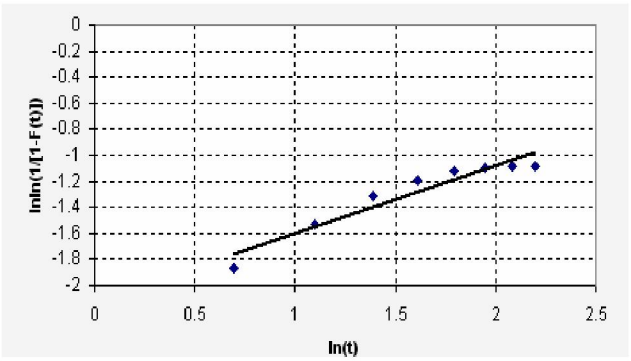


Figure 3. The straight line of F(t) for fuses.

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TABLE IV
THE KOLMOGOROV-SMIRNOV TEST FOR SWITCHES

t	m_i	$\sum_{i=1}^{m} m_i$	$F'(t_i)$	$F(t_i)$	$\lvert F(t)-F'(t)\rvert$
1<t≤2	2	2	0.0253	0.0370	0.0117
2<t≤3	4	6	0.0759	0.0547	0.0212
3<t≤4	1	7	0.0886	0.0720	0.0166
4<t≤5	0	7	0.0886	0.0889	0.0003
5<t≤6	2	9	0.1139	0.1054	0.0085
6<t≤7	1	10	0.1266	0.1216	0.0050
7<t≤8	0	10	0.1266	0.1375	0.0109
8<t≤9	0	10	0.1266	0.1530	0.0264

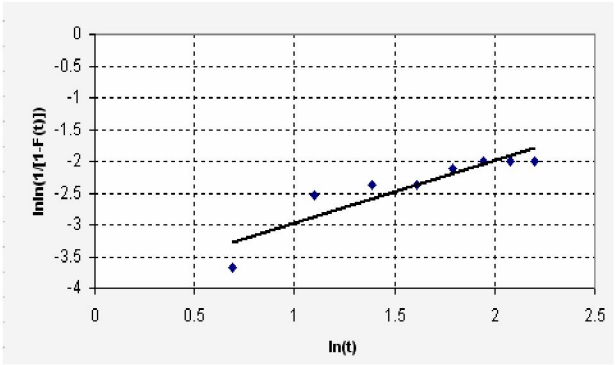


Figure 4. The straight line of F(t) for switches.

The Weibull distribution parameters (β and α) of the breakers, reclosers, fuses and switches are estimated from the linear plots in Figure 1-4, and are shown in Table V. Verification of the validity of the Weibull distribution is shown in Table VI, for the failed units of those devices at a significance level of 0.05.

In general, the value of shape parameter (β) can describe the failure modes of the devices. In Table V, the shape parameters of breakers, reclosers, fuses and switches are all less than 1 that means the probability density and failure rate are very high at the beginning, and will decrease rapidly with increasing time. This has shown a high rate of early failure of the protective devices.

TABLE V
RELIABILITY PARAMETERS, MTTF, AND FAILURE RATE OF PROTECTIVE DEVICES

Protective devices	Weibull Parameters		MTTF (years)	Failure rate (f/year)
	β	α		
Breakers	0.7201	46.4709	57.3028	0.0428
Reclosers	0.6298	40.8630	57.8882	0.0578
Fuses	0.5221	58.2274	107.8577	0.0618
Switches	0.9852	55.6783	56.0371	0.0187

TABLE VI
VERIFICATION OF WEIBULL DISTRIBUTION ON CALCULATION OF CRITICAL VALUE (CV) AT SIGNIFICANT LEVEL OF 0.05

Protective Devices	n	Dn	CV	Verified
Breakers	27<40	0.0419	0.2544	Yes
Reclosers	109>40	0.0264	0.1303	Yes
Fuses	2151>40	0.0265	0.0293	Yes
Switches	79>40	0.0264	0.1530	Yes

VII. CLASSIFICATION OF FAILURE MECHANISM

During the period of study, 1997-2005, different types of failure mechanism of breakers, reclosers, fuses and switches are classified in Figure 5-8. A majority of failure mechanism present on failed protective devices is stated as below. First, the percentage of trouble mechanism and wrong operation is 66.66% of the total number of failed breakers. Second, the percentage of wrong operation is 68.75% of the total number of failed reclosers. Next, the percentage of swing, prolapse, explosion, and distension is 73.35% of total failed fuses. Lastly, the percentage of leaking and arcing is 70.00% of total number of failed switches.

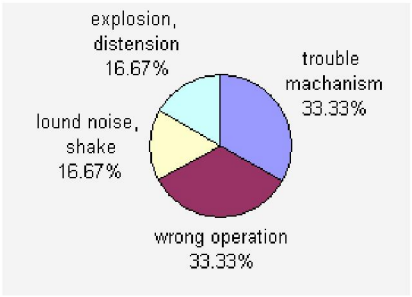


Figure 5. Percentage of failed breakers.

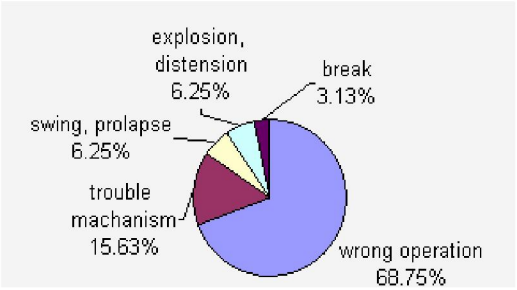


Figure 6. Percentage of failed reclosers.

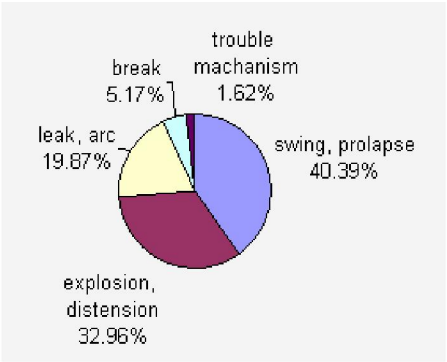


Figure 7. Percentage of failed fuses.

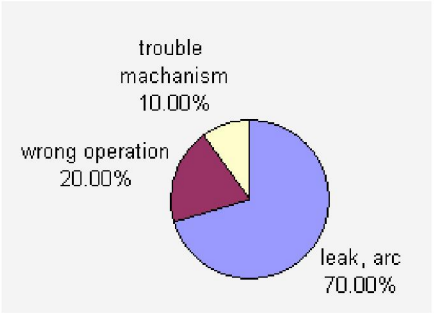


Figure 8. Percentage of failed switches.

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VIII. CONCLUSIONS

In this paper, the life times of breakers, reclosers, fuses and switches (disconnecting, airbreak and loadbreak switches) are extracted from the recorded failure data of the PEA. According to the Kolmogorov-Smirnov test, the life time distribution of the above protective devices can be described by the Weibull distribution. This results in a statistical estimation of the reliability parameters including failure rate and mean time to failure (MTTF) of the protective devices.

As the failure mode of breakers, reclosers, fuses and switches can be represented by a Weibull distribution function, each group of such protective devices has different MTTF and failure rate. The MTTF of breakers, reclosers, fuses, and switches installed in 1997 is 57.3028, 57.8882, 107.8577, and 56.0371 years respectively. Meanwhile, the failure rate of breakers, reclosers, fuses, and switches is 0.0428, 0.0578, 0.0618, and 0.0187 f/year respectively.

According to the results, the reliability evaluation can be carried out using the estimated failure rates. In addition, the MTTF that is an approximated life time of the devices is informative for strategy planning on reliability centered maintenance. Finally, the study results of failure mechanism of different protective devices may shorten the repair time, which all help to improve the SAIFI and SAIDI of the distribution systems.

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