LIFE ESTIMATION OF HIGH VOLTAGE SF6 CIRCUIT BREAKERS

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Abstract: In order to predict the reliability of 550 kV SF_6 circuit breakers, it is necessary to obtain the circuit breaker's operational data and maintenance records for analysis. The estimation of reliability is derived from their multiple censoring data since a censored component of circuit breakers has different probability of failure before or after the next failure. Moreover, the actual maintenance data have to be clearly withdrawn from the statistical survey as the effect of maintenance is already included in the field operation. With reference to the installation population's age, the statistical failure distributions can be considered as the life management of the high voltage SF_6 circuit-breakers. Finally, the confidence intervals are given to quantify statistical uncertainty for the failure distributions due to a large divergence of circuit breakers.

1 INTRODUCTION

In the case of circuit breakers, it is difficult to carry out any laboratory experiments due to the big variety of circuit breakers' types, manufacturers and generations that would be tested in order to make the general model. Consequently, most models have to be constructed using operational field data. In order to obtain operational field data for circuit breakers, some source of statistics is needed or this type of statistics can be obtained by carrying out a study of failure statistics. The previous statistic surveys are of high quality but are of limited use as the effect of the actual maintenance measures is already included in field operation. These data prevents the accurate estimation of the intrinsic failure for equipment.

We are then given the task of performing statistical analysis of this data. The aim of the analysis is to correlate the descriptive variables and various parameters of the probability distribution of equipment to failure times and failure rates. Stochastic models about service experience in the form of statistics for failure rates is important for owners of circuit breakers. With such a curve it is possible to choose the reliability level for the particular application and to make the appropriate measures of maintenance. Traditionally, circuit breakers' failure rates are computed by dividing the number of failures of the installation population subject to the calendar year considered in the studies. In fact, however, failure rates should include failure mode, equipment type and equipment age instead of installation year.

Moreover, a common problem in analysing reliability data comes from the data of censored components. On our investigation of the failure data, the number of failures is only 4% by the population of all investigated circuit breakers [1-2]. In the majority of cases, components are removed from consideration prior to their failure or the observation is completed prior to all components failing. For censored components, the lifetime distribution of the removal components is not assumed to be the same as that of those failed components since a removal component has some probability of failure before or after the next failures. Not to consider censored components rightly in the analysis would eliminate valuable information and would bias the results.

2 FAILURE LOCATION AND FAILURE MODE

A User Forum of circuit breakers was compiled in the domestic 550 kV power grids as shown in Table 1. The User Forum manages a database containing detailed technical information about the population of 550 kV SF_6 circuit – breakers circuit breakers, such as year of installation, type of mechanism and about failures that occurred. All generations of circuit breakers which have been on the Chinese market since the 1987 are represented, and all severe failures are included, possibly with very few exceptions. The service experience information gathered concerns only the specific failures that occurred and does not include any kind of indexing or assessments of the technical condition of the circuit breakers [1].

The age is reported from the year of installation, operation date, failure date or removal/retirement date of the observed components. Often data received from the field, because of the method of collecting and recording failures may be grouped into intervals in which individual failure times are not preserved. These data are suitable for statistical analysis for which the age of the failed circuit breakers together is taken as input. In order to theoretically investigate the substantial nature of component ageing, the actual maintenance data has to be clearly withdrawn at first. That is, the first observed failure record can only be considered for the same component. Therefore, the data used for the life model does not consider the effect of maintenance in terms of reduction in failure probability.

Table 1: Location and failure mode of 550 KV SF_6 circuit breaker

Failure location	No	Failure mode	Failed fraction	Operating mechanism
Hydraulic valve	1	Unstopped pumping	3.6%	Hydraulic mechanism (525)
	2	Oil leakage	1.9%	
Pressure control switcher	3	N_2 leakage	9.1%	
	4	Fault of pumping	6.5%	
	5	Wrong signal	2.5%	
High pressure accumulator	6	Mechanical defect	1.5%	
Hydraulic circuit	7	Oil leakage	4.8%	
Pneumatophore in oil circuit	8	Unable to set pressure	5.7%	
Air compressor	9	Fault of pumping	19.2%	Pneumatic mechanism (78)
	10	Air leakage	11.5%	
	11	Oil leakage	7.7%	
	12	Damaged compressor	6.4%	
Operating mechanism	13	Protection trip	6.4%	Hydraulic, pneumatic and spring mechanism (825)
	14	Electrical and mechanical defects	1.8%	
Heater	15	Damaged temperature control switcher and heater	4.6%	
SF_6 density relay	16	Damaged pressure meter	1.2%	
	17	Damaged relay	1.1%	
Parallel capacitor	18	Oil leakage	2.5%	
	19	Damaged capacitor	1.3%	
Switch count	20	Defect	2.3%	
Opening/closing coil	21	No indicator	3.0%	
	22	Damaged relay	2.1%	
Control and protect system	23	Abnormal protection	3.8%	
	24	Abnormal signal	2.7%	
	25	Disconnection	2.1%	
	26	Inconsistent with three phases	1.7%	
	27	Defect of power source	1.6%	
	28	Abnormal indicator	1.3%	
	29	Grounding	1.2%	
	30	Insulation aging	1.2%	
	31	Damaged gate of cabinet	0.6%	
	32	Unsealed cabinet	0.5%	
Circuit breaker	33	SF_6 leakage	4.1%	
	34	Overheat of primary terminal	0.6%	

3 RELIABILITY ESTIMATION

For the statistical evaluation of data obtained from the 550 kV SF_6 circuit breakers, the most popular models is Weibull distribution. The failure probability $F(t)$ of the Weibull distribution is given by

$$F(t)=1-\exp\left[-\left(\frac{t}{\theta}\right)^{\gamma}\right] \qquad (1)$$

where γ and θ are the shape and scale parameters, respectively.

The probability density function $f(t)$ of the Weibull distribution is given as

$$f(t)=\frac{\gamma}{\theta}\cdot\left(\frac{t}{\theta}\right)^{\gamma-1}\cdot\exp\left[-\left(\frac{t}{\theta}\right)^{\gamma}\right] \qquad (2)$$

A typical expression for the failure rate $h(t)$ is

$$h(t)=\frac{\gamma}{\theta}\cdot\left(\frac{t}{\theta}\right)^{\gamma-1} \qquad (3)$$

The reliability function of the Weibull distribution $R(t)$ is given below

$$R(t)=\exp\left[-\left(\frac{t}{\theta}\right)^{\gamma}\right] \qquad (4)$$

When multiply censored data are present, the likelihood function must be modified to reflect the fact that at the censored times no failure occurred. The objective of the method is to derive, directly from the failure times, the failure distribution. Let t_i be the ordered failure time and n_i be the size at risk, a logical estimate for the distribution function $F(t)$ is

$$F(t)=1-\prod_{i=1}^{n}\left(1-\frac{1}{n_i}\right) \qquad (5)$$

Confidence intervals are one of the most useful ways of quantifying uncertainty due to the sampling error arising from limited sample sizes. Thus the interval $[\underline{v}(t),\tilde{v}(t)]$ forms the confidence interval of the estimated parameter $\hat{v}$ with confidence coefficient of (1-α), i.e.

$$[\underline{v}(t),\tilde{v}(t)]=\hat{v}(t)\pm z_{(1-\alpha/2)}\sqrt{\hat{V}ar[\hat{v}(t)]} \qquad (6)$$

where the estimated parameter and the variance $\hat{V}ar$ are

$$\hat{v}(t) = \int_0^\infty t f(t) dt \qquad (7)$$

and

$$\hat{V}ar[\hat{v}(t)] = \int_0^\infty [t - \hat{v}(t)]^2 f(t) dt \qquad (8)$$

z_α is the number of the standard normal distribution. The confidence intervals have a specified “level of confidence,” typically 1-α = 95% expressing one’s confidence that a specific interval contains the quantity of interest.

The standard deviation, accounts of the variation in the sampling process, provides a measure of the resulting uncertainty in the estimated reliability.

$$\hat{V}ar[\hat{v}(t)] = \hat{v}(t)^2 \sum_{j=1}^{i} \frac{1}{n_j (n_j - 1)} \qquad (9)$$

The remaining lifetime *RLT*(*t*) can be determined by the failure probability *F*(*t*):

$$RLT(t) = \int_t^\infty \frac{1 - F(x)}{1 - F(t)} dx \qquad (10)$$

4 CASE STUDIES

To simulate the failure probability and to estimate the failure rate and the remaining lifetime of the high voltage SF_6 circuit breakers, the statistical survey on failure probability with the operational history was gathered from the practical operational experiences. The useful information about the occurrences of failure with the location and the mode of failures for 550 kV SF_6 circuit breakers is given. The set of data comes from a large population of 550 kV SF_6 circuit breakers with a relatively large number of failures. These data help us to develop the reliability model.

The different components of the switchgear assembly fail according to different failure modes at the location of failure. According to the cause and the consequence of failures with reference to their functions and their components, the failure mode and effect analysis shall be applied to recognize, classify and choice which monitoring parameter affects the aging condition of equipment to a greater degree than other parameters. By this means, a more detailed view can be obtained regarding failure mode of the different components of the circuit breaker shown in Table 1. The 550kV SF_6 failed circuit breakers are grouped into 525, 78 and 825 occurrences of failure according to hydraulic mechanism, pneumatic mechanism and all hydraulic, spring as well as pneumatic mechanisms, respectively. We have come to know from Table 1 that the leakage and the defect of pumping are the main cause of trouble for hydraulic- and pneumatic mechanisms while the heater and the protection- and control system are the most important fault components.

The probability distribution are simulated to estimate the failure rate, the remaining lifetime and the number of failures in coming years (Figures 1 - 12). In the majority of cases the statistical failure probabilities in dependence on the age show a large derivation from the practical values as shown in Figures 1, 4, 7 and 10. The reason is the consideration of a mix of different failure events and of a mix of different technologies as well as relatively small operating period of circuit breakers. In consequence, the combination of these influencing factors often increases the uncertainty of derived failure probabilities. These uncertainties result in certain requirements on data management processes as (1) clear definitions of all events; (2) classification of different technologies; (3) mandatory data pooling to achieve high quantities; (4) standardized guidelines for recording processes.

We are interested in the characteristics illustrated by the entire bathtub curve, from which it is known whether the population of equipment shows infant mortality or an aging failure characteristic. The infant mortality period is a time when the failure rate is dropping, but is undesirable because a significant number of failures occur in a short time, causing early customer dissatisfaction and warranty expense. Theoretically, the failures during normal life occur at random but with a relatively constant rate when measured over a long period of time. Because these failures may incur warranty expense or create service support costs, we want the bottom of the bathtub to be as low as possible. And we don't want any wear-out failures to occur during the expected useful lifetime of the product.

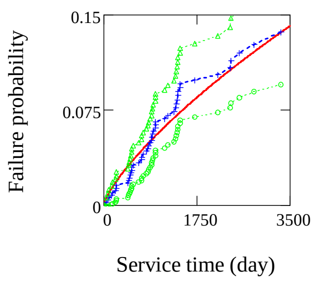

Figure 1: Calculated and measured failure probabilities as well as up- and down confidence intervals for the N_2 leakage in the pressure control switch

Base on the analysis it can be concluded from Figures 5, 8 and 11 that in the all population of circuit breakers, 65% of the failures are a result of aging in the steep slope of wear-out region of the bathtub curve. The other failure rates of circuit breakers have the decreasing trends and the longer remaining lifetime whereas 70% of decreasing failure rates are involved in control- and protect system (Figures 2 and 3). For the mechanical defect of high pressure accumulator, pneumatophore in oil circuit and oil leakage of parallel capacitor it can be seen that the failure rate is relatively stable in coming years. The hydraulic valve and hydraulic circuit, air compressor (Figures 5 and 6) as well as count switcher are the components with the highest contribution of failures and failures can be expected in coming years. The SF_6 leakage of circuit breakers (Figures 8 and 9) and the overheat of primary terminal (Figures 11 and 12) shall also be paid attention due to their high failure rates. They show the most rapid change of the remaining lifetime at the same service time. It is recognized from Table 1 that the leakage is the primary reason to reduce the lifetime of the circuit breakers which lifetime is not longer than 30 years. Statistical methods, also the simple ones, can be applied to support important maintenance decisions, using the data obtained from the failure survey.

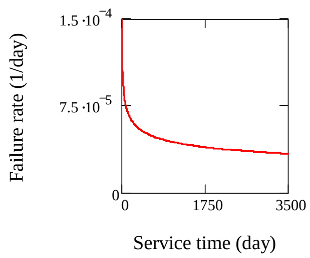

Figure 2: Calculated failure rate for the N_2 leakage in the pressure control switch

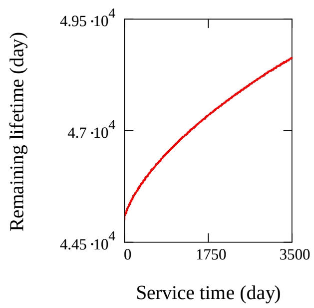

Figure 3: Calculated remaining lifetime for the N_2 leakage in the pressure control switch

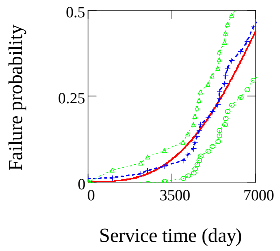

Figure 4: Calculated and measured failure probabilities as well as up- and down confidence intervals for the fault of pump in the air compressor

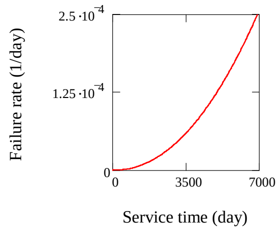

Figure 5: Calculated failure rate for the fault of pump in the air compressor

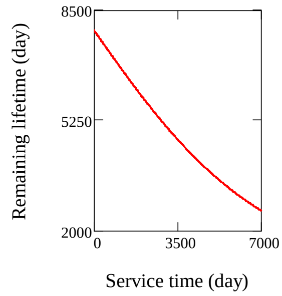

Figure 6: Calculated remaining lifetime for the fault of pump in the air compressor

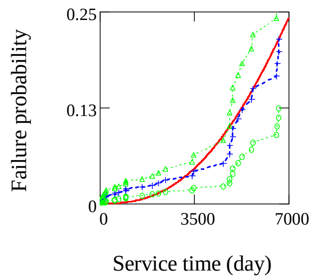

Figure 7: Calculated and measured failure probabilities as well as up- and down confidence intervals for the SF_6 leakage in the circuit breaker

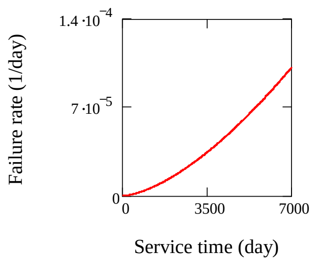

Figure 8: Calculated failure rate for the SF_6 leakage in the circuit breaker

Infant mortality does not mean “components that fail within 90 days” or any other defined time period. Infant mortality is the time over which the failure rate of a component is decreasing, and may last for years. Electronic components in the protection- and control system as well as pressure control switch, unlike mechanical assemblies, rarely have wear-out mechanisms. Failures during infant mortality are highly undesirable and are always caused by (1) component doesn’t meet requirement; (2) poor design; (3) lack of quality in manufacturing; (4) component installed incorrectly; (5) component constantly stopping and starting; (6) power surges; (7) operator not starting up component according to standard operating procedure. As infant mortality begins to take effect, the prediction of lifetime exists a large derivation and the reliability of circuit breaker is becoming less controllable. To truly reduce the likelihood of infant mortality and improve reliability, those issues must be addressed and prioritized by risk.

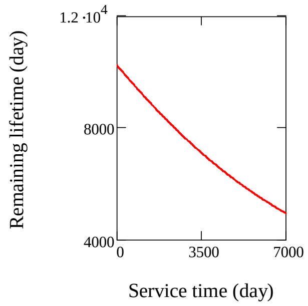

Figure 9: Calculated remaining lifetime for the SF_6 leakage in the circuit breaker

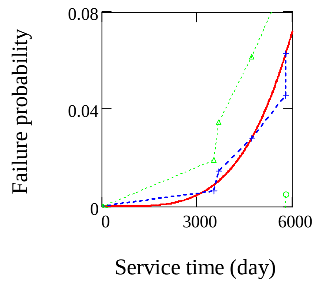

Figure 10: Calculated and measured failure probabilities as well as up- down confidence intervals for the overheat of primary terminal in the circuit breaker

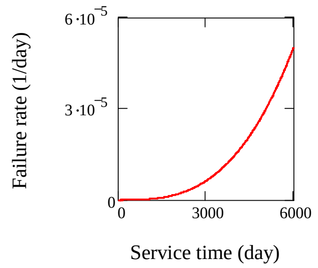

Figure 11: Calculated failure rate for the overheat of primary terminal in the circuit breaker

As we have already observed, after some time, the new circuit breaker is still working, then it is probably through the infant mortality period and can expect long years of reliable service. That is, failures from infant mortality defects get spread out so much that they appear to be approximately random in time that is very close to the classical normal life period.

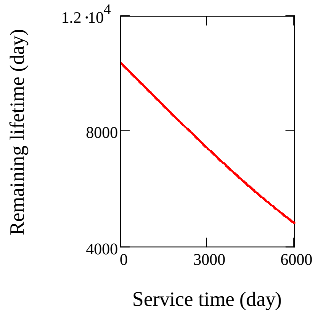

Figure 12: Calculated remaining lifetime for the overheat of primary terminal in the circuit breaker

Conversely, wear-out will not always happen long after the expected component life. It is a period when the failure rate is increasing, and has been observed in components after just a few months of use. This, of course, is a disaster from a warranty standpoint! For many mechanical- and thermal defects such as the fault of pump, the SF_6 leakage and the overheating of primary terminals, the wear-out time will be shorter than the desired operational life of the whole circuit breaker and replacement of failed assemblies can be used to extend the operational life of the circuit breaker. With some items, wear-out is expected and replacement is a normal routine. In designing a circuit breaker, the engineer must assure that the shortest-lived component lasts long enough to provide a useful service life. If the component is easily replaced, such as relays, replacement may be expected and will not degrade the perception of the circuit breaker's reliability. If the component is not easily replaced and not expected to fail, failure will cause customer dissatisfaction.

5 CONCLUSION

As the number of failures was only 4% by the population of all investigated circuit breakers, a statistical approach to investigate the reliability of 550 kV SF_6 circuit breakers was developed by use of the multiple censoring data. With reference to the installation population's age, the models can describe the intrinsic ageing of the circuit breakers by means of the maintenance-free data. Furthermore, confidence intervals for parameter and no-parameter distributions were given to quantify statistical uncertainty due to a large divergence of circuit breakers.

6 REFERENCES

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